University of the Witwatersrand

School of Geography, Archaeology and Environmental Sciences

PHENOLOGICAL RESPONSE OF CITRUS FLOWERING TO CLIMATE VARIABILITY AND CHANGE IN IRAN: 1960-2010

Dissertation submitted to the Faculty of Science in fulfilment of the requirements for the degree Master of Science.

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Declaration

I hereby declare that this dissertation is my own, original work, except where otherwise acknowledged. It is being submitted for the degree MSc to the University of the Witwatersrand, Johannesburg. I have not submitted it previously, for the purpose of obtaining any degree, qualification or otherwise at this, or any other, university.

Jennifer Fitchett

23/04/2013
Date

Abstract

Phenology refers to “the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelationship among phases of the same or different species” (Badeck et al., 2004: 295). This discipline has recently gained popularity in bio-geographical climate change studies, as it is recognized as an accurate and easily measured signature of the impact that changing temperature and precipitation over recent decades have had on plants. A five-decadal dataset (1960-2010) comprising daily temperature and rainfall records, and of the annual timing of peak flowering of five citrus types (orange, tangerine, sweet lemon, sour lemon and sour orange) was acquired for the Iranian cities of Gorgan, Kerman and Shiraz. The cities are geographically and climatically distinct, with arid Kerman located on the central Iranian plateau, humid Gorgan on the Caspian lowlands and Shiraz situated at the foot of the Zagros Mountains with a semi-arid climate. These climate data for Kerman and Shiraz reveal strong, statistically significant increases in T_{max} of 0.03°C/yr, and even stronger increases in T_{min} of 0.05°C/yr-0.07°C/yr, whilst Gorgan presents a statistically significant decrease in precipitation of 4.69mm/yr over the study period. Significant increases in daily sunshine hours of 7.09h/yr and 19.01h/yr are demonstrated for Gorgan and Kerman respectively. Negligible delays in the timing of peak flowering for the five citrus types in Gorgan by 0.05-0.01d/yr, and more considerable advances in the timing of flowering for Kerman (0.12-0.17d/yr) and Shiraz (0.56-0.62d/yr), occur concurrently with these climate trends. These differences in the direction of shift in flowering dates, combined with differences in climate trends, highlight the extent to which the location of the crops, and the associated abiotic forces, influence flowering dates. Significant relationships between the flowering dates of the citrus types and T_{max} are demonstrated for Kerman and Shiraz, equating to advances of 1.85-3.08d/°C and 6.14-7.86d/°C respectively, with similar advances in flowering dates associated with increases in T_{min}. Significant relationships between the timing of peak flowering and precipitation are demonstrated for Kerman. Across the majority of the climate variables studied, the strongest monthly relationships with flowering dates were for the month in which peak flowering occurs, suggesting a direct effect on control over this phenophase. The development of multiple regression models facilitated the simultaneous analysis of the effects of all of the climate variables, and increased the associated explanatory potential. The rate of change in peak flowering dates observed for the period 1960-2010, and the relative influence of some climate variables over others, highlight the importance of monitoring fruit tree phenology in a water scarce region such as Iran. With decreases in precipitation, increases in T_{min} and T_{max} and the potential for heightened frost risk by the end of the century due to the increased likelihood of late-winter flowering, citrus cultivation in Kerman is under threat. Shiraz is likely to survive continued climate variability and change throughout the 21st century, provided that sufficient water is available either naturally or through irrigation. Gorgan demonstrates the greatest capacity to continue successful citrus farming, and the greater Caspian Lowlands hold potential as a suitable location for the expansion of citrus farming required to compensate for any yields lost in the more arid areas of Iran and the Middle East.

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* Significant correlations indicated by a single asterisk, particularly strong correlations ($r \geq 0.7$) indicated by a double asterisk.

**Statistically significant models are indicated with an asterisk, models which are able to explain 70% or more of the variation in flowering dates are indicated by a double asterisk.

List of Acronyms, Abbreviations and Statistical Terms

AIC: Akaike Information Criterion

AO: Atlantic Oscillation

AVHRR: Advanced Very High Resolution Radiometer

BBCH*: Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie

CGASA: Citrus Growers' Association of South Africa

DOY: Day of year

ENSO: El Niño Southern Oscillation

EVI: Enhanced Vegetation Index

GDD: Growing Degree Day

GDP: Gross Domestic Product

GPS*: Global Positioning System

hPa*: hecto Pascals

HU: Heat Units

IPCC: Intergovernmental Panel on Climate Change

ITCZ: Inter-Tropical Convergence Zone

JD: Julian Dates

masl*: meters above sea level

MODIS*: Moderate Resolution Imaging Spectroradiometer

NAO: North Atlantic Oscillation

NASA*: National Aeronautics and Space Administration

NCP: North Sea-Caspian Pattern

NDVI: Normalized Difference Vegetation Index

NOAA: National Oceanic and Atmospheric Administration

RGB: Red-Green-Blue

WMO: World Meteorological Organization

°C/yr : degrees Celsius change in temperature per year.

d/°C: change in flowering date in response to 1°C change in temperature.

d/mm: shift in flowering date in response to 1mm change in rainfall.

d/td: change in flowering date in response to a 1 day change in the number of days exceeding threshold temperatures.

d/yr: shift in day of occurrence of peak flowering per year.

h/yr: change in the number of total daily sunshine hours per year.

mm/yr: millimetre change in rainfall per year.

T_{avg}: the average of the minimum and maximum temperature recorded in a 24 hour period.

$T_{max} > 35°C$: days in which the maximum temperature exceeds 35°C.

T_{max}: maximum temperature recorded in a 24 hour period.

$T_{min} < 13°C$: days in which the minimum temperature is below 13°C.

T_{min}: minimum temperature recorded in a 24 hour period.

Statistical Terms

r: Pearson Correlation Coefficient – a number between -1 and +1 providing a measure of the strength of the correlation between two factors. Values tending to 0 indicate a poor correlation, while values close to -1 indicate a strong negative correlation, and values close to +1 indicate a strong positive correlation.

R^2: Coefficient of Determination – a number between 0 and 1 providing a measure of the degree to which the dependant variable can be explained by one or more determining factors. Values closer to 1 indicate a stronger explanatory potential.

p value: A measure of the statistical significance of the outcome of a correlation or regression analysis. Smaller numbers indicate greater statistical significance.

n value: The total number of data entries.

RMSE (σ_{est}): root mean squared error/ standard error of the estimate. Explores the standard deviation of the error term, the larger the value the less accurate the model.

Δ_i: Difference in AIC values between the best fitting model and that of the model in question.

ANOVA: Analysis of variance.

MANOVA: Multivariate analysis of variance.

Chapter 1

INTRODUCTION

[1]

1.1 Phenology: A 'Hot' Topic in Climate Change Research

Phenology – the timing of annually recurrent biological events such as leaf unfolding, flowering and harvest; or in the case of animals, birdsong, hibernation, spawning, egg laying and hatching – is arguably both the most accurate and easily measured signature of the impact of climate variability and change on flora and fauna (Sparks and Carey, 1995; Badeck et al., 2004). The discipline has developed considerably over the past four decades; most notably to include the contribution that climate, and climate variability and change during the anthropocene, has had on shifts in the timing of phenological events (Schwartz, 1999; Sparks et al., 2005). It is becoming an increasingly broad field, and now includes non-biological applications such as the study of the timing of freeze-up events, seasonal glacial melt, flow of perennial rivers, and of natural burn cycles such as those required by Fynbos species to promote regrowth, particularly where these are influenced by, and related to, long term climate variability and change (Latifovic & Pouliot, 2007).

Whilst annually recurrent events such as flowering dates are not absolute indicators of likely plant yields for a particular period, except in cases of failed flowering, they do have direct influence through prolonging or restricting the growing season, and hence shift the minimum and maximum limits of potential production (Doi, 2007; Croitoru et al., 2012). More important than the inter-annual determination of crop yields through phenology, however, is the information that shifts in the timing of phenological events may provide on the extent to which the crop is responding to shifts in climatic variables such as temperature and rainfall, and ultimately the potential for the crop to adapt to climate variability and change, and hence its potential future viability and yields in a particular region (Rötzer & Chmielewski, 2001; Hegland et al., 2009; Blanc, 2012). Furthermore, phenological responses of crops are highly species and location specific, and hence such information about the response of a specific species in a particular region better allows for high resolution vulnerability adaptation solutions (Grab & Craparo, 2011; Siebert & Ewert, 2012).

Fruit trees in temperate regions reflect changes in ambient weather conditions and long-term climate through their phenology, as they have a distinct seasonality (Peñuelas et al., 2009; Luedeling & Gassner, 2012). Citrus phenology is particularly sensitive to changes in temperature and precipitation, as the flowering phase requires a period of either cool temperatures or drought conditions to release dormancy (García-Luís et al., 1992; Rosenzweig et al., 1996; Srivastava et al., 2000). Thereafter, a period of warm conditions with sufficient moisture availability is required to induce full bloom (Southwick & Davenport, 1986; García-Luís et al., 1992). The Islamic Republic of Iran (hereafter referred to as Iran) is a particularly interesting region to study citrus phenological responses to climate change, since, depending on the region, both rainfall and temperature may function as limiting factors to vegetative and reproductive plant growth (Modarres & Da Silva, 2007; Sharifan et al., 2010). Thus, in determining and quantifying the nature and extent to which climate variability and change has had an impact on citrus crops in the region, which is only marginally suited to agriculture, the study of phenology presents a particularly valuable tool.

1.2 Citrus Agriculture

Citrus fruits (classified as the genus *Citrus*) are the highest value fruit crop in international trade (UNCTAD, 2005). Whilst citrus varieties are cultivated in over 140 countries with climates ranging from tropical through to temperate, 70% of the total production is from the northern hemisphere (UCTAD, 2005). Total mean annual citrus production was estimated at over 105 million tons for the period 2000-2004, with oranges (*Citrus sinensis*) comprising more than 50% of the annual production yields. There has been a steady increase in citrus production since 1960, due to both an increase in cultivation and shifts in consumer preferences (Abbasi et al., 2005; UNCTAD, 2005).

With an annual average citrus production of 3.5 million tons for 2009/2010 and a similar average of 3.53 million tons for the period 2001-2010, the Islamic Republic of Iran is the 8th largest generic citrus producer in the world, with yields accounting for 3% of the global total (Abbasi et al., 2005; Khanali et al., 2007; CGASA, 2011; *Figure 1.1*). Of this, and in line with global statistics, the highest citrus production in Iran is that of oranges, followed by lemons (*Citrus limonin*) (UNCTAD, 2005). Further, in 2003 Iran was the sixth largest orange producing nation, fifth largest lemon and lime producer, and the fourth largest global tangerine producer (McFarlane & Burnside, 2008). Despite this high production, Iran does not contribute significantly to global citrus export, since much of the agricultural produce remains within the country for domestic consumption, and stringent export restrictions on the size of fruit and packaging deter international trade (Ward et al., 1994; Khanali et al., 2007).

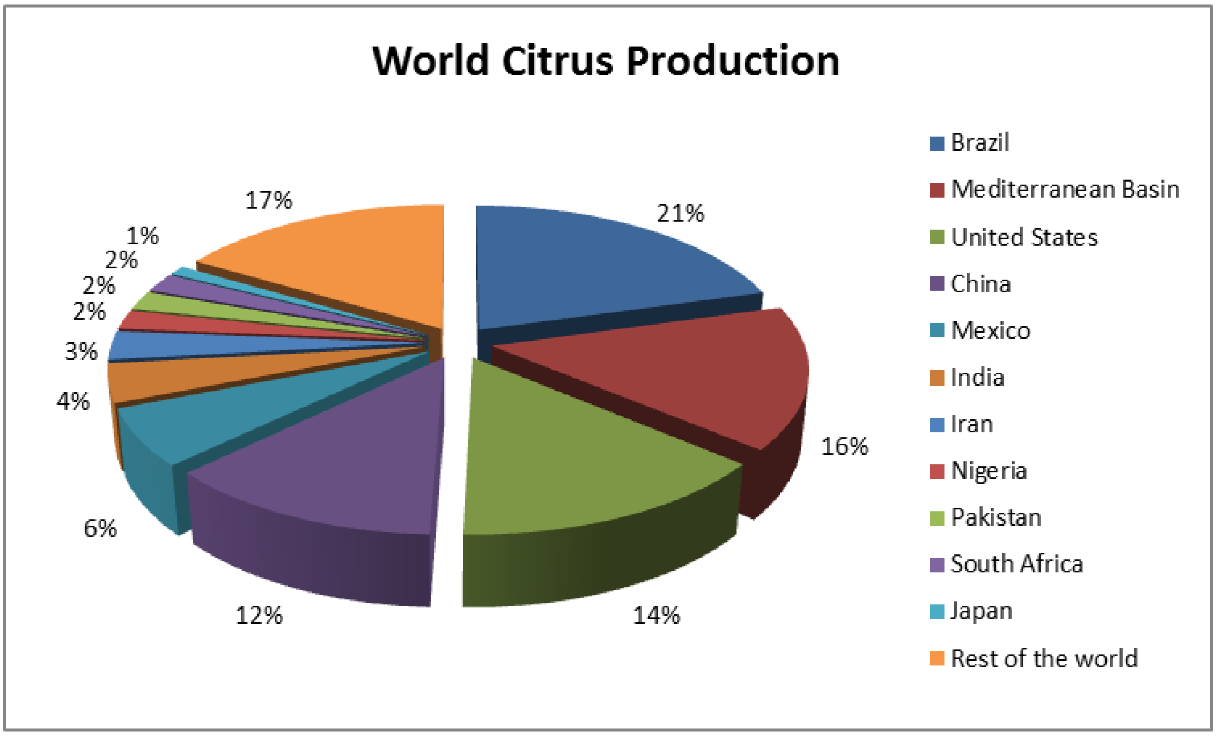

Figure 1.1: Pie chart indicating the percentage contribution of top citrus producing countries to total global annual citrus production (after UNCTAD, 2005).

Despite the economic policy of Iran requiring that agricultural efforts be made first to ensure self-sufficiency, the agricultural sector has been responsible for 10–17% of the country's Gross Domestic Product (GDP) over the past decade, and is responsible for 11-13% of the current GDP (Atieh Bahar, 2008; Ministry of Commerce, 2009; Ilias, 2010). Furthermore, agriculture accounts for 20% of Iran's labour force, with over 23 million people earning their liveable income directly from agriculture (Allahyari et al., 2008; Atieh Bahar, 2008). Agriculture forms the primary land use across 20% of the total surface area of Iran, covering approximately 123 000km^2 (Faramazi, 2010). The cultivation of fruit and vegetables accounts for 12% of this cropped area, whilst only 2% of land within cities is used for agriculture (Ward, 1994). These figures are significant considering that Iran is predominantly arid to semi-arid, receiving less than one third of the global mean annual precipitation (Modarres & Da Silva, 2007; Mostafa, 2008). Furthermore, half of the terrestrial region of Iran is mountainous, 33 tons of soil per hectare is potentially mobile through erosion and destruction, and 15% of farmland is suffering from high sodium concentrations due to excessive irrigation (Haftlang, 2003; Allahyari et al., 2008).

In addition to the considerable economic benefits of citrus production for both domestic and export trade to a country such as Iran, the continued production and subsequent consumption of citrus is of importance for food security (Porter & Semenov, 2005). There are concerns about the agricultural capacity to meet both present and future food requirements under increasing global populations and the threat of climate variability and change. The focus of these concerns predominantly surrounds staple crops such as wheat and rice. However, fruits, which are considerably higher in vitamins and nutrients, are of as great, if not greater, importance for ensuring food-secure populations (Pimentel et al., 1997; Economos & Clay, 1999; Parry et al., 2004). Citrus has long been recognized as a particularly important crop for health purposes due to the high vitamin C concentration, and was consequently used as a cure for scurvy amongst sailors and soldiers during past centuries (Economos & Clay, 1999). More recently, high vitamin C concentrations are known to improve iron uptake, improve collagen formation, and relieve the symptoms of the 'common cold'. The potassium levels, which act as an important electrolyte and maintain the body's water and acid balance, and phytochemicals such as carotenoids, limonoids and monoterpenes, act together with the antioxidant properties of citrus to prevent chronic diseases such as heart disease, cataracts and cancers (Block et al., 1992; Jacques at al., 1997; Economos & Clay, 1999). It has also been postulated that the consumption of citrus may aid in preventing and controlling osteoporosis, kidney stones and asthma (Hatch, 1995; New et al., 1997; Economos & Clay, 1999). With these considerable medical benefits, the role of sustained global citrus production is of critical importance to the sustained food security and health status of developing countries, which are currently the greatest citrus consumers (UCTAD, 2005).

With a 0.6˚C warming in mean global temperatures over the past century, a 10% decrease in snow cover and ice extent in the mid to high latitudes, and substantial fluctuations in rainfall experienced world-wide, climate variability and change is becoming increasingly difficult to ignore (Walther et al., 2002; Root et al., 2003, Faisal, 2008). The warming over the past century has predominantly taken place during two distinct periods, the first from 1910 to 1945, and the second from 1976 onwards (Walther et al., 2002). Changes during this second period have been more than twice as extreme as during the first, and have occurred at a rate greater than any such temperature increases over the past 1000 years (Walther et al., 2002). In addition to this, there has been a worldwide decrease in the diurnal temperature range, as minimum temperatures are rising at a faster rate than maximum temperatures (Walther et al., 2002). Concurrent are latitudinal variations in warming, with the poles warming faster than the equator, and the Northern hemisphere as a whole faster than the Southern hemisphere (Walther et al., 2002; Parmesan, 2007). Whilst rainfall has not changed as uniformly as temperature, both increases and decreases in the long term quantities of precipitation are of concern, notwithstanding the additional impacts of floods and droughts across the world. With the 4th report of the Intergovernmental Panel on Climate Change (IPCC) predicting temperature increases in the order of 1.8-4°C by the end of the 21st century, the study of the nature and extent of current climate change impacts on the earth's agricultural (eco)systems is becoming increasingly important (IPCC 2007, cited in Guédon & Legave, 2008; Rosenzweig et al., 2008).

Of particular concern is the impact that these changes in temperature and rainfall are having on plant and animal species, both in terms of the stress on biodiversity, and the economic impacts on industries such as agriculture and forestry. Temperature increases of as little as 1.5-2.5°C are predicted to increase the risk of plant and animal extinction by 20-30%, as a consequence of habitat loss, water stresses, and an inability to adapt to changing temperatures (Flannery, 2005; Faisal, 2008). Of more immediate concern is the impact that warming over the last couple of decades has already had on individual plant and animal species, as well as their associated ecosystems. Parmesan and Yohe (2003) calculate a global mean species range shift of around six kilometres pole-ward per decade, whilst Primack et al. (2009a) report similar shifts in species to higher altitudes as their original habitats become increasingly too warm for their survival. Warming is noted to have an effect on the timing of spring phenological events, with a global mean advance of over 2 days per decade across 1700 species (Parmesan & Yohe, 2003).

These responses are of particular concern in agriculture where ranges cannot shift, and consequently changes in the dates of phenological events may have considerable effects on the length of the growing season, and ultimately on the size and quality of yields (Rötzer & Chmielewski, 2001; Haggerty & Galloway, 2011). In particular, where the agricultural sector contributes significantly to the Gross Domestic Product (GDP) of the country, as in Iran, and where regional and global food security are of concern, any reduction in the yields of crops is of concern (Ward, 1994; Economos & Clay, 1999; Ilias, 2010). It is thus important to understand and quantify the trends in climatic factors which drive changes in crop phenology, so as to better determine the nature and extent to which any future fluctuations, variability or long term change in climate may have on a particular crop in a specific location (Parry et al., 1988).

1.3 Citrus Phenology

This study focuses on shifts in the annual timing of peak flowering of five citrus types – orange, tangerine, sweet lemon, sour lemon and sour orange – in response to climate variability and change in the three Iranian cities of Gorgan, Kerman and Shiraz, for the period 1960-2010. These cities were selected on the basis of data availability. Due to the scarcity of phenological data for regions such as the Middle East, all three cities for which phenology and climate data were available were included in the study. The cities are geographically and climatically distinct and yet capable of profitably cultivating the same group of five citrus types, which facilitates particularly interesting analysis into the climate variables responsible for driving any changes in flowering dates which may have occurred. Such analysis undertaken based on a statistical comparison of flowering dates with climate indices derived from daily temperature, rainfall and sunshine hour data. This incorporates both the investigation of these basic variables, and factors such as the counts of days in which temperatures exceed thresholds suitable for citrus growth, heat unit accumulation, and the temporal onset of the rainfall season. Such a study thus relies on an understanding of the climatic conditions of the country, as well as the standard phenological pattern of the *Citrus* genus.

As for most temperate fruit species, citrus fruits show a marked seasonality, with a flowering period in early spring, and vegetative growth occurring in three flushes during spring, summer and autumn (Guardiola, 1997; Tan & Swain, 2006). It must be noted that when cultivated in the tropics, citrus trees develop both vegetative and reproductive shoots throughout the year, and have no marked period of dormancy (Mendel, 1968; Susanto et al., 1992). However, with Iran located in the mid-latitude semi-arid to arid region of Asia, year round production does not occur (Mendel, 1968). Phenological phases are broadly described by the visible plant changes such as bud-burst, flowering, leaf emergence and leaf colouration (Cannell & Smith, 1986; Menzel, 2002; Badeck et al., 2004). More specific classification is made using the BBCH scale, a numbering system to differentiate between groups of phenological stages such as leafing and flowering, in addition to more detailed stages such as bud-burst, first flowering and peak flowering (van Vliet et al., 2003; Kalbarczyk, 2009; Morisette et al., 2009). This scale is discussed in more detail in the *Data and Methods* chapter. An outline of the phenological stages of citrus is presented in *Tables 1.1 and 1.2*. The benefits of selecting the flowering stage for analysis in this study, beyond its availability, are discussed in the *Literature Review* chapter.

Table 1.1: The timing of seasonal vegetative and reproductive phenological events for citrus for regions in the temperate Northern Hemisphere (after Connellan et al., 2010).

<table>
<tr><td rowspan="2">Phenological stage</td><td colspan="3">Winter</td><td colspan="3">Spring</td><td colspan="3">Summer</td><td colspan="3">Autumn</td></tr>
<tr><td>December</td><td>January</td><td>February</td><td>March</td><td>April</td><td>May</td><td>June</td><td>July</td><td>August</td><td>September</td><td>October</td><td>November</td></tr>
<tr><td>Shoot growth flushes</td><td></td><td></td><td colspan="4">Spring flush</td><td colspan="2">Summer flush</td><td></td><td colspan="3">Autumn flush</td></tr>
<tr><td>Root growth</td><td></td><td></td><td></td><td></td><td colspan="3">Root flush</td><td></td><td colspan="3">Root flush</td><td></td></tr>
<tr><td rowspan="3">Fruit growth stages</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Stage I cell division</td><td colspan="4">Stage II cell expansion</td><td>Maturation →</td></tr>
<tr><td colspan="3">Floral induction and initiation</td><td colspan="4">Flowering and fruitset</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Harvest →</td></tr>
</table>

Table 1.2: Annually recurrent reproductive events of citrus phenology, and their timing for the temperate Northern Hemisphere (after Meier, 2001; Connellan et al., 2010).

CITRUS REPRODUCTIVE PHENOLOGY (NORTHERN HEMISPHERE)			
Time of the Year	**Phenological Stage**	**BBCH Code**	**Description**
December - January	Floral induction and initiation	51	Bud differentiation and release from dormancy
February	Pre-bloom	55	Early indication of final crop load
March	Bud break	60	First buds start to open
March-May	Start of bloom	61	5% of flowers open
	Full bloom	65	50% of flowers open
	End of petal fall	69	80% petal drop
May-June	Fruit set	71	Fertilized flowers develop into fruit
May-July	Cell division	71	Mitosis
July	End of natural fruit drop	71	10-15mm fruitlets
July-October	Cell expansion	72	Final number of cells determined, cells increase in size
	Colour change	73	Colour change from pale green to light yellow
November-January	Fruit maturation	85	Internal maturity measured by the brix/acid ratio

1.4 Contribution to Existing Knowledge

Due to the species and location specificity of plant responses to climate change, the ability to understand and predict future plant responses to heightened climate changes relies on the study of as many species in as many locations, as possible (Parmesan, 2007; Siebert & Ewert, 2012). Unfortunately, whilst the study and recording of phenological dates, such as flowering, has been extensive in regions such as Europe, Japan and China, few suitable datasets exist elsewhere in the world (Grab & Craparo, 2011). Consequently, recent studies have encouraged the study of phenology and climate datasets in previously neglected regions, requiring phenology data to be sought at scales as small as a single farm, or as large as continental regions. Despite the proliferation of studies in the early 2000s in Europe, Japan, China and the United States, very little work on the phenological response to climate change has focussed on the Middle East, or more specifically, on Iran. Of that work undertaken, the focus has been on annual crops, for which the phenological events are more strongly influenced by management decisions (such as sowing date) and seasonal weather variability, rather than by longer-term climate changes (Gholipoor & Sinclair, 2011).

Not only has the Persian region been home to agriculture for some 10 000 years, as an area predominantly covered by desert and one already experiencing substantial seasonal temperature variability, it is also likely to be seriously impacted by future climate change (Zohary and Spiegel-Roy, 1975; Evans, 2009; Modarres & Sarhadi, 2009). Consequently, studying the relationships between increasing climate variability and ongoing climate change recorded over past decades, and their potential effects on any phenological shifts in perennial crops, would provide critical information on the role that they have on agriculture in the Middle East. Furthermore, it would contribute to the global analysis and understanding of these species, particularly in the context of location specific relationships between recurrent annual floral events in response to shifts in local climate.

Whilst studies elsewhere have examined the phenological response of deciduous fruit trees to climate change, no such work has focussed specifically on the C*itrus* genus. This is a large oversight, not only as the citrus group contributes substantially to world fruit production and trade, but also, unlike the majority of perennial fruit trees in which the induction of flowering is driven primarily by temperature, the induction of flowering in citrus either follows a period of sufficient temperature chilling or a period of water stress, depending on which control is more intense (García-Luís et al., 1992; Tan & Swain, 2006). Accordingly, a considerably complex relationship should exist between any shifts in citrus phenophases – particularly flowering – and the changes in both temperature and precipitation occurring as a consequence of increasing climate variability and ongoing climate change (Tan & Swain, 2006).

1.5 Study Aims and Objectives

With the primary aim of contributing to the existing pool of research on plant phenological response to increasing climate variability and ongoing climate change, the detailed aims and methods are similar to those of studies undertaken on the long term shifts in the timing of perennial fruit tree flowering in various regions across the world, such as for apples and cherries in Germany (Chmielewski et al. 2004), apples and pears in South Africa (Grab & Craparo 2011), peaches and almonds in China (Lu et al. 2006), and cherries in Japan (Primack et al. 2009b). In particular, the aim is to contribute knowledge on the nature and extent of recent climate change and its consequences over the period 1960-2010 in three geographically and climatologically different cities of Iran (Gorgan, Kerman and Shiraz), and the effects of any such climate change and variability on the flowering dates of five citrus groups (orange, tangerine, sweet lemon, sour lemon and sour orange). This study thus investigates geographic locations and species for which the phenological response to climate change has not yet been studied.

The research aims are to determine:

1) The flowering time of each of the five citrus types (orange, tangerine, sweet lemon, sour lemon and sour orange); and related to the climatic conditions in each of three cities – Shiraz in the southwest of the country, Kerman on the central plateau, and Gorgan in the north (Caspian lowlands) – and more specifically to determine:
    a. the average climatic conditions over the period of 1960-2010;
    b. the extent and nature of the variability in the peak flowering dates with the climatic conditions over this period.

2) The nature of any changes and trends in temperature and rainfall, and in indices of these climate variables, over the period 1960–2010 for Gorgan, Kerman and Shiraz; and more specifically to determine:
    a. the magnitude, direction and statistical significance of any such trends;
    b. patterns of similarity and difference between any trends and changes in the climatic variables experienced in each of the three cities.

3) The nature of any changes and trends in the peak flowering dates for each of the five citrus types in the cities of Shiraz, Kerman and Gorgan over the period 1960-2010; and more specifically to determine:
    a. the amplitude, direction and statistical significance of any changes and trends in the peak flowering dates;
    b. the patterns of similarity and difference between the trends in the timing of flowering across the citrus types for each of the three cities; and across the three cities for each of the citrus types.

4) Whether any significant relationships exist between changes in the timing of flowering with trends, variabilities and changes in climate factors for each of the five citrus types and three cities. If so, the study aims to establish patterns of similarity and difference in the phenological response of the timing of flowering to climate change, both between species and between geographic regions.

Chapter 2

LITERATURE REVIEW

[2]

2.1 Phenology

2.1.1 Introduction

The biological components of the natural environment exist in their current locations as a consequence of habitat selection and progressive adaptation to that region best suited to their requirements and survival (Walther et al., 2002; Hegland et al., 2009). With the rapid climate change observed over the past century, and the even more rapid changes predicted for the decades to come, these habitats inevitably change in their suitability for the plant and animal species that they host (Walther et al., 2002; Parmesan & Yohe, 2003; Rosenzweig et al., 2008). Whilst this is not always detrimental, as climate changes which may be detrimental for one species could be beneficial for another, it necessarily results in a response from the local species; be it a physical change in their range or location, their population numbers, or in the timing of their life cycle events (Parmesan & Yohe, 2003; Root et al., 2003; Primack et al., 2009a). Parmesan and Yohe (2003) calculated a global mean species (n = 1700) range shift of approximately six kilometres pole-ward per decade over the past century, whilst Primack et al. (2009a) reported similar shifts in a selection of species (n = 12) to higher altitudes during the period 1953-2005, as their original habitats became increasingly warmer. Warming has affected the timing of spring events, with a global mean advance of approximately two days per decade over the past century for the start of the growing season of 1700 plant species (Parmesan & Yohe, 2003). These changes may be problematic, not only for the farmer whose land is less or no longer suitable for cultivating a particular crop suited to a region's previously cooler temperatures and rainfall patterns, but also critically threatening at an ecosystem scale, with the potential for large numbers of species mismatches and extirpations (Visser & Hollerman, 2001; Visser et al., 2006; Hegland et al., 2009; Primack et al., 2009a).

Phenology, as defined by the International Biological Programme, is "the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelationship among phases of the same or different species" (Badeck et al., 2004: 295). This includes the timing of recurrent biological events such as leaf unfolding, flowering, harvest and leaf fall; or in animals, frog calling, arrival and departure dates of migratory species, hibernation, egg laying and hatching (Sparks & Carey, 1995; van Vliet et al., 2003; Visser & Both, 2005). These phenological responses may be both the most accurate and easily measured signature of the impacts of changing temperature and, to a lesser extent, changing precipitation frequency and intensity on flora and fauna (van Vliet et al., 2003; Badeck et al., 2004). This is because the initiation of these annually recurrent events is driven predominantly by patterns in the external climate associated with the change of seasons, rather than by intrinsic controls (Badeck et al., 2004; Dreyer et al., 2006). Therefore, changes in the timing of these phenological events can be more accurately and directly attributed to any changes in the climate at the location of a species over that period, than to any other biological changes or responses that such climate change may induce (Badeck et al., 2004; Sherry et al., 2007). Within plant species, temperature most strongly controls the date of flowering, which marks the beginning of the spring season in both annual and perennial species, together with the shift from dormancy to the reproductive phase (García-Luís et al., 1992; Guédon & Legave, 2008). Whether flowering is induced by an increase above a critical threshold temperature or the fulfilment of a prerequisite chilling period, any changes in the local climate, particularly in the preceding months, result in a change in the timing of flowering, with warmer temperatures typically resulting in earlier bloom or failed flowering (Chmielewski & Rötzer, 2001).

The magnitude of this shift in the timing of flowering is dependent on species, on whether warming or the fulfilment of chilling days induces flowering, and that species' associated threshold temperatures (Zavalloni et al., 2006; Faisal, 2008). This is evident in the differences between the advance in the flowering dates of apples by 4.2 days/°C in South Africa (Grab & Craparo, 2011) and only 2.4 days/°C in Poland (Kalbarczyk, 2009), and between Chinese cotton flowering dates shifting earlier by 0.66 days/°C, whilst wheat grown in the same region has experienced flowering advances of as much as 3.4 days/°C (Wang et al., 2008). As a consequence of such species and location specific phenological responses, reports are increasingly emerging of co-dependent species struggling to survive through the early reproductive season, until their respective spring cues overlap (Parmesan & Yohe, 2003; Primack et al., 2009a). A combination of these phenological mismatches, the decreasing suitability of environments, and changes in competitive dynamics, motivate predictions of an increase in the risk of plant and animal species extinctions by 20-30%

associated with temperature increases of as little as 1.5-2.5°C (Stenseth & Mysterud, 2002; Visser & Both, 2005; Faisal, 2008). If any anthropogenically assisted adaptation to the predicted climate change for the following decades is to succeed, it will require a thorough understanding of the effects that climate changes over the past century have had on as many plant and animal species, in as many locations, for which historical data exist (Ledneva et al., 2004; Miller-Rushing et al., 2008a).

The recording of phenological events has taken place for many centuries in some areas in the world, either as a hobby amongst naturalists, or through the reporting of cultural events associated with phenological events, such as the Japanese Cherry Blossom Festival (Cleland et al., 2007; Morisette et al., 2009). A 200-year record of the phenological events of plants on the Marsham family estate in the United Kingdom, and an even more impressive 1 300 year record of cherry blossoming dates in Kyoto, derived from the timing of the Cherry Blossom Festival, can now be used to provide information on the pattern and trends of shifts in phenology dating back to times before the effects of anthropogenic climate change became evident (Sparks et al., 2000; Cleland et al., 2007; Morisette et al., 2009). From trends in these records, it becomes apparent that studies on phenology and climate change are intimately connected, and that when combined, can provide substantial information on the effect that continued climate change may have on plant species (Cannell & Smith, 1986; Chmielewski & Rötzer, 2001). Phenological gardens were thus established across Europe in the 1960s to both track plant phenology and to study the role between changes in the timing of phenological events and concurrent abiotic forces, and numerous studies on the effect of climate change on phenology have since been undertaken, based both on findings from these gardens, and from more localized farm and naturalist phenological records in China, Japan, the United States and Australia (Root et al., 2003; Ledneva et al., 2004; Miller-Rushing et al., 2008b; Miller-Rushing & Primack, 2008a). This has subsequently allowed for meta-analyses, both summarising, and subsequently studying, patterns and inconsistencies between these reported findings (Parmesan & Yohe, 2003; Root et al., 2003). In recent times, remotely-sensed satellite data have been included in phenological studies, particularly for the detection of ‘green waves’ associated with leaf unfolding, which is a key indicator of the beginning of spring across large geographical areas; and for models of phenological events to supplement incomplete datasets, which are important for projecting future changes through Global Climate Models (Chmielewski & Rötzer, 2002; Arora & Boer, 2005; Chen et al., 2005; Zavalloni et al., 2006).

The phenology section of this literature review is divided into four sub-sections in which topics in the aforementioned introduction are examined in detail. The first sub-section focuses on approaches to the study of phenology, and particularly on the four primary methods of obtaining phenological data from which statistical analyses are undertaken; namely (i) ground level, species and location specific historical observations, (ii) satellite imagery, (iii) digital repeat photography and (iv) phenological models. A brief analysis of the statistical methods of data analysis is undertaken, with a more detailed description to be provided in the *Methods* chapter. The second sub-section addresses questions of the selection of the study targets in the context of phenology studies, drawing contrasts between: animal versus plant species; tropics versus mid-latitudes versus polar regions, and the climatic implications of their locations on phenology; within plant species, agricultural responses to climate change and the differences between annual crops and perennial fruit trees; and finally, the selection of the phenological stage of interest for particular studies. The third sub-section deals with the species and location specificity of phenological responses to climate variability and change, confirming the extent to which these occur, and then discussing the resultant species mismatches within ecosystems. The last sub-section addresses the current applications of the outputs of phenological research, with a focus on their application in biodiversity indices and climate models, their value in advising the agricultural sector, and their potential application as proxies for climate change where phenological records extend to times before the recording of instrumental climate records.

2.1.2 Approaches to Studying Phenology

2.1.2.1 Ground Observations

The principal approach to the collection of data for application in studies of plant and animal phenological responses to climate variability and change is sourcing historical ground level records on the timing of phenological events for a particular species in a specific location.

This ground level collection of phenological records dates back to the Kyoto Cherry Festival records in 1 300AD, and has continued to present through records of the dates of similar cultural festivals associated with phenological events, the diaries and log books of naturalists, and since the mid-1800s, through phenology networks established for the monitoring of these events (Ledneva et al., 2004; Cleland et al., 2007; Primack et al., 2009b). These records have only recently been used for the purposes of studying climate change manifestations (Menzel, 2002; Cleland et al., 2007). In early studies of climate change impacts on plant phenology, Reich and Borchert (1984) investigated the effect of water stress on tree phenology in Costa Rica, whilst Cannell and Smith (1986) examined the role of warming on inducing earlier budburst and hence a greater risk of frost damage to the plants, using self-collected datasets for both phenology and climate change. Whilst the methods used and concerns raised in these pioneering studies continue to be incorporated into more recent phenology research, it became apparent that to determine and quantify the effect that climate change has had on phenology, considerably longer datasets were required (Schwartz, 1999; Faisal, 2008). This is highlighted in Sparks and Carey's (1995) work on determining contemporary climate change signals from the 200-year Marsham Record; Fitter et al.'s (1995) study on the relationship between first flowering dates and temperature in England; and Walker et al.'s (1995) study on the inter-annual variability of phenological events of alpine forbs in response to inter-annual climate variability.

Increasing numbers of phenological studies allows for comparison between study sites and subjects, and highlights that the extent to which plant and animal phenology respond to the local climate change is dependent on both the species and location (Kramer et al., 2000; Menzel et al., 2006a; Gordo, 2007). Whilst the cogency of these findings is discussed later in this chapter, it is important to note that this potential specificity resulted in considerable expansion of this field of study, with intentions to study as many species in as many locations as possible (Rötzer & Chmielewski, 2001; van Vliet et al., 2003; Schwartz et al., 2006). The World Meteorological Organization (WMO) requirement of a dataset needing to span at least three decades in order to detect climate variability and change limits the application of these phenology studies, despite incorporating numerous species and an extensive range of locations (Ahas et al., 2002; Chmielewski et al., 2004; Gordo & Sanz, 2006; Koch et al., 2007; Parmesan, 2007). The obvious reaction to fulfilling this temporal requirement was to establish phenological networks across Europe, and to scrutinize the journals and log books of naturalists, the recordings of dates of phenologically-associated cultural festivals, and farm records (Sparks et al., 2005; Primack et al., 2009b).

With subtle changes in phenology over the past half-century averaged at less than a day per year, these records required consistent daily monitoring of the studied species to ensure accurate and reliable dates for the timing of the phenological events (Menzel, 2002; Miller-Rushing et al., 2008a). This is seldom the case for farm records and phenological gardens, where the person recording observations is not guaranteed to be in attendance every day of the year, or even consistently throughout a growing period (Ledneva et al., 2004). In the case of naturalist diaries, records are obtained as a result of a hobby, and hence often contain a changing set of locations, varying times of day, and can have considerable gaps (Ledneva et al., 2004). Even where records are complete, and extend over periods of at least three decades, they are often collected by more than one observer, and so the consistency between observers, their level of commitment and hence the frequency of observations, and the yardsticks against which they compare the appearance of events, can lead to irregularities in the data (Sparks et al., 2000; Ahas et al., 2002; Gordo & Sanz, 2005; Koch et al., 2007). This leads to a third concern: the definition and delineation of individual phenological events. Whilst events such as flowering, leaf unfolding and leaf colouration represent significant changes in the appearance of a tree or shrub, it is less easy to identify the first leaf or flower, or even to determine when a tree, or orchard of trees, has reached 50% bloom (Menzel, 2002; Miller-Rushing et al., 2008a). This is important where the transition between two or more phases may occur within small temporal periods, rendering the date ascribed to the event invalid. Not only is there the likelihood that a single observer may not be able to judge these events consistently, but when there are multiple observers, consistency in observations becomes increasingly difficult to ensure. Consequently, it has become increasingly common for researchers to search for and use datasets covering more than one location, and in so doing, eliminate much of the statistical noise resulting from such observational inconsistencies (Sparks et al., 2000; Gibbs & Breisch, 2001). Indeed, part of an analysis of ground level historical phenological and climate data is an exploration of the potential errors and limitations associated with the collection of the data. However, Sparks and Carey (1995), Ledneva et al., (2004), and Miller-Rushing et al. (2008a) highlight there are far too few phenological data in existence to justify ignoring 'imperfect' records. Rather, all phenological records available should be critically examined, and assessed for their response to climate variability and change. To facilitate improved collection of ground level phenological data, phenological networks are increasingly developing detailed observation forms which when used by volunteers, decreases some of the potential for error (van Vliet et al., 2003).

For cross-study comparison, which enables an increasingly complete understanding of climate change impacts on various species in different geographic and climatic regions, consistency in the method of data analysis is necessary (Parmesan, 2007). Consequently, the majority of analyses on ground based observation were undertaken using Pearson correlation coefficients to determine the strength of the relationship between a phenological event and the local climate variables in each year of the study, together with regression analysis used to quantify the rates of change (Ahas et al., 2002). The resultant trends in climate variables are then reported as a change in days, degrees Celsius, or millimetres of rainfall per annum or per decade, depending on the temporal extent of the dataset (Keatley et al., 2002; Gordo & Sanz, 2009). However, it is also important to study the relationships between changes in phenology and the concurrent changes in climate variables, as is performed through similar correlation and regression analyses in studies by Chmielewski (2002), Menzel et al., (2006a) and Grab and Craparo (2011), since coincidental change in both temperature and phenological dates over a study period cannot necessarily be inferred as climate driving shifts in phenophases. Some studies used alternate methods of time-trend analysis, such as the Mann Kendall test. They not only found very similar results to those using Pearson correlation and regression approaches, but also by using only an alternate method, made the comparison of results from existing studies considerably, and unnecessarily, more difficult (Croitoru et al., 2012). A necessary change in methodology, however, arose from the inclusion of change point models. As climate change has not occurred uniformly over the past decade, but rather with a period of considerably larger temperature increases since the 1970s, it is of interest to detect these change points in climate data and determine whether they are associated with concomitant changes in phenological variables (Cleland et al., 2007; Keatley & Hudson, 2012). Whilst studies of a particular species' trend in a specific region (whether a single site or averaged over across a study area) are best undertaken through trend analysis, studies involving a large number of climatically different regions, or different species, require the use of additional statistical methods to detect patterns of similarity and difference in their behaviour over the common time period (Ohashi et al., 2011; Croitoru et al., 2012). These most commonly include cluster analysis and principle and canonical component analysis (Chmielewski & Rötzer, 2001; Gordo & Sanz, 2005; Ohashi et al., 2011).

2.1.2.2 Remote Sensing

With the advent of satellite remote imaging in the 1970s, and more particularly the development of Advanced Very High Resolution Radiometer (AVHRR) technology in 1983, which allowed organisations such as NOAA to collect course spatial resolution reflection data for most of the earth's surface, satellite imagery represent a second approach to the study of phenology and provides historic records of phenology across far greater regions than ground observations, including locations where no ground level records exist (Schwartz, 1999; Stöckli & Vidale, 2004). The band availability of the AVHRR imagery in the near infrared and red-visible spectra allowed for the Normalized Difference Vegetation Index (NDVI) to be calculated (Schwartz, 1999; Pettorelli et al., 2005). NDVI is the ratio of red-visible and near infrared radiation reflected back to the satellite sensors (Stöckli & Vidale, 2004; Pettorelli et al., 2005). With chlorophyll absorbing the red-visible band, whilst mesophyll leaf structures scatter the near infrared radiation, an NDVI value between -1 and +1 returns a relative lack of vegetation in negative values, whilst an increase in photosynthetically active vegetation is detected as the values progress into the positive integers (Pettorelli et al., 2005). Consequently NDVI allows for the identification of sudden increases and decreases in a region's 'greening', which can be interpreted as the beginning and end of the growing season of a region or ecosystem respectively, and is used to determine the length of the 'green' (vegetative growing) season, in addition to the timing of the period of maximum vegetation in which peak photosynthetic activity occurs (Schwartz, 1999; Pettorelli et al., 2005).

The global scale coverage of these NDVI values has the potential to be particularly useful retrospectively in phenological studies; for those regions where there are no available historical phenological records, and where the development of phenological networks is of low priority (Morisette et al., 2009). Furthermore, the global to regional scale focus is consistent with many of the associated climatological drivers, allowing for synoptic scale analysis of phenological trends, and a spatially relevant study of the effects of the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NOA) cycles on phenology (Zhang et al., 2003). The scale is also more closely aligned with that suitable for global climate models, where species level information is too detailed for seamless inclusion (Morisette et al., 2009). The benefit of phenological study across far greater regions than the traditional species level scale were first highlighted by Justice et al.'s (1985) seminal paper on the application of NDVI indices in examining the productivity of African grasslands, Indian tropical forests and Chinese agriculture. The necessity for phenological studies at regional to global scales, in order to improve the understanding of phenological processes, determine the effect of increasing climate variability and ongoing climate change on phenology, and to better integrate phenological findings into climate and ecological models, has been argued over the past two decades (Schwartz & Reed, 1999; Stöckli & Vidale, 2004; Pettorelli et al., 2005).

Of primary importance when determining whether these satellite derived measures can contribute to a global understanding of both phenology and its response to increasing climate variability and ongoing climate change, is their physiological and statistical validity Whilst positive NDVI values are known to accurately represent the increase in greening across a region, and can identify the beginning of the growing season at the community level, they do not necessarily indicate any specific phenological stage for a particular species, and may represent an average with a variance that is too large to be of value in conjunction with other measures of phenology. To address this, several studies have compared NDVI derived findings, either with phenology models for a region, or with available ground level phenological observations for the species present (Schwartz & Reed, 1999; Badeck et al., 2004; Stöckli & Vidale, 2004; Chen et al., 2005; White et al., 2009). Whilst it would be ideal for such comparisons to be undertaken in all studies, limited species-level data prevents this. However, the existing comparisons allow for precautions to be taken where patterns of irregularity have been detected, and for an increase in the number of studies for species and biomes for which irregularities are few (Chen et al., 2005; Morisette et al., 2009). Through scale comparisons, Schwartz and Reed (1999) found NDVI results to be well correlated with modelled phenological data for the eastern United States, whilst Stöckli and Vidale (2004) argue that the satellite observations for European phenology closely agree with the ground level observations from the European Phenological Network. In addition, NDVI measures for the green wave (leaf unfolding) and brown wave (autumn leaf colouring) are calculated to most closely correlate with the ground level phenological stages of 50% leaf unfolding and 50% leaf colouration in eastern China (Chen et al., 2005).

Comparisons between NDVI measures, phenological model outputs and ground level observations have contributed to an improved understanding of the regions and species groups for which NDVI values are most valid. For example, satellite NDVI results closely match the modelled values for deciduous forest and mixed woodland, but correlated most poorly with values for short grasses (Schwartz and Reed, 1999). This is in line with concerns of the bias of NDVI measurements towards the canopy and top layer vegetation, rather than the under-story species (Schwartz, 1998; Schwartz, 1999). Furthermore the capability for NDVI to accurately determine the start of spring was highest in high latitude, but lowest in arid, tropical and Mediterranean eco-regions (White et al., 2009). However, Stöckli and Vidale (2004) argue that because the successful determination of phenology through satellite observation requires distinct seasonality, and given that the NDVI can confuse snow cover for leaf increase, mid-latitude regions are best suited to this approach.

Further concerns have highlighted errors and limitations inherent with the use of NDVI in capturing particular phenophases. Concerns on the temporal frequency of AVHRR imagery for individual regions have been raised since the earliest work using NDVI in phenological studies (Justice et al., 1985; Morisette et al., 2009). With a pass-over frequency of a minimum of 24 hours, and days with cloud cover preventing NDVI calculation, dates for the timing of phenological events have an upper accuracy limit of approximately a week (Justice et al., 1985; Schwartz, 1998; Schwartz & Reed, 1999; Morisette et al., 2009). As Parmesan and Yohe (2003) report a mean global shift in phenological events of 2.3 days per decade, such error margins could greatly over- or under-estimate shifts in phenology (Schwartz & Reed, 1999). Further concern exists over species averaging. Not only is this likely to be problematic given the species specificity of phenological responses, but it also fails to detect multiple crop cycles and seasons with more than one period of maximum rainfall (Zhang et al., 2003).

Many of the issues surrounding the application of satellite imagery to determine phenological events stem from the use of AVHRR, which was never intended for land applications, and consequently is more accurate in applications such as monitoring the breakup of ice (Zhang et al., 2003; Latifovic & Pouliot, 2007). More recently, since 1998, AVHRR has increasingly been replaced by the higher spatial resolution, land surface designed MODIS imagery, with the introduction of the Enhanced Vegetation Index (EVI) in 2000, with the intent to replace NDVI (Peñuelas et al., 2004; Pettorelli et al., 2005). This however raises two key issues associated with the use of satellite imagery in the study of phenology: namely consistency of methodology and the time period of study. In a study which used 10 different methods for measuring phenology through satellite imagery for a single region, White et al. (2009) report that the results from each of the individual methods differ by up to 60 days. Thus, whilst developments in satellite technology allow for improved measurements of phenological events, they do not easily facilitate the later comparison of results from different studies, and between regions and time periods (White et al., 2009). Furthermore, with satellite applications to phenology only beginning in 1983, and the introduction of the more suitable MODIS imagery and EVI measurements in 1998 and 2000 respectively, this approach does not allow for a robust testing of phenological response to climate change within the required 30 year study period as outlined by the WMO, but only for testing inter-annual variability (Schwartz, 1999; Ahas et al., 2002; Faisal, 2008). However once a robust approach to using satellite imagery to monitor phenology is developed and when used in operation for a few decades, it could be of substantial value to the study of phenology, particularly when used in conjunction with ground level observations and models (Cook et al., 2005; Morisette et al., 2009).

2.1.2.3 Digital Repeat Photography

Digital Repeat Photography (Sonnentag et al., 2012), also referred to as Near Surface Remote Sensing (Wingate et al., 2008; Polgar & Primack, 2011) is the most recent addition to the suite of methods used in phenological data collection, and one which meets the shortfalls of both ground based observations and satellite derived data. Using the images captured regularly from digital cameras, which were originally mounted either on instrumentation towers or installed at lookouts for the purposes of weather, traffic or animal surveillance, analysis of the oblique view of vegetation canopies can provide information on the timing of onset and duration of seasons (Jacobs et al., 2009; Sonnentag et al., 2012). Whilst visual assessment of the timing of the start, peak and end of seasons may be undertaken through an examination of the collection of images captured and stored by these cameras, similar to that from satellite imagery, such an analysis can increasingly be automated, thus removing all potential for human bias and error (Richardson et al., 2009). With the extraction of Red-Green-Blue (RGB) colour channel brightness information from the digital images in numeric format, information for a region of interest in an image can automatically be analysed through colour indices such as excess green, to determine the timing of canopy green-up and green-down occur (Wingate et al., 2008; Richardson et al., 2009; Sonnentag et al., 2012). Through the inclusion of additional colour indices, not only can spring green-up and autumn green-down be seen for both deciduous and coniferous forest canopies, but increasingly also as an additional autumn red peak for deciduous forests (Richardson et al., 2009). The information from the colour indices derived from these numerous repeat photographic images allows for a far more accurate determination of the start, end, peak and duration of the growing season, and the rates of green-up, green-down and leaf-colouring than by any other existing method (Wingate et al., 2008; Richardson et al., 2009).

Digital Repeat Photography has the advantage of being able to retain species and location specificity in observations, whilst recording data at a far finer and more consistent temporal resolution and a far broader spatial scale than ground-based observations can feasibly achieve (Richardson et al., 2009; Polgar & Primack, 2011). Furthermore, it removes the logistical issues of cloud cover in satellite images, and of consistency, continuity and objectivity in ground-based observations (Polgar & Primack, 2011; Sonnentag et al., 2012). With the current storage capability of images captured at an interval of at least every half hour, Digital Repeat Photography provides a temporal resolution which neither satellite images, nor ground-based observations can achieve (Richardson et al., 2007; Wingate et al., 2008). With many outdoor webcams already "accidentally" recording phenological data, much of these data can be collected at minimal cost, and even where cameras need to be installed, they are relatively easy to maintain (Richardson et al., 2007; Wingate et al., 2008; Jacobs et al., 2009). As fixed point cameras, often now with GPS antennas included in their hardware, it is relatively easy to determine and record the exact position of the camera, and hence facilitate both ground-truthing and integration with data from the nearest weather station (Jacobs et al., 2009). Possibly the greatest advantage of data from Digital Repeat Photography, is that they form a permanent record which can be re-checked and re-used at any time, thus removing the potential for bias in interpretation of phenological information collected through ground based observation (Richardson et al., 2007).

As a new approach to the collection of phenology, there is still considerable uncertainty as to the validity of these "accidental data", and their value as a scientific tool. The greatest concern is that these often "bottom-of-the-range" digital cameras are not calibrated scientific instruments (Richardson et al., 2009; Sonnentag et al., 2012). Consequently, there are differences in the actual images captured by different camera types, their configuration and image file types, and in the RGB channel brightness captured (Richardson et al., 2007; Richardson et al., 2009; Sonnentag et al., 2012). In analysing data from a network of cameras, it is preferable that they all be of the same specification, manufacture, and configuration (Richardson et al., 2007). However, this does not resolve inconsistencies between studies due to a lack of precision calibration (Richardson et al., 2007; Sonnentag et al., 2012).

There are also considerable concerns as to variability in scene illumination (Sonnentag et al., 2012). Variations in the illumination of a photographed scene occur as a result of changes in the sun's position throughout the day and year, cloud cover, and shade cast over the photographed area or a portion thereof, can result in false readings of changes in the RGB channel brightness, and consequently provide incorrect dates on the timing of seasonal shifts (Richardson et al., 2007; Bradley et al., 2010a; Sonnentag et al., 2012). The high temporal resolution of data, and associated large file sizes, result in problems arising from the storage of large numbers of images at a high enough resolution format that enables high precision analysis, particularly in developing countries (Jacobs et al., 2009). A fourth concern arises from the potentially poor representivity of the true regional vegetation canopy, particularly when images from pre-existing outdoor webcams are used (Hufkens et al., 2012). Whilst a photograph may capture a wide swath of vegetation, this vegetation may well be specific to that location, and not representative of the greater region (Hufkens et al., 2012). Without an indication of the broader scale vegetation, this issue potentially requires ground-truthing to be undertaken to confirm the representivity of images for all cameras in a network in order to calibrate results (Hufkens et al., 2012).

Despite these limitations, the application of Digital Repeat Photography as a means of data collection for phenology has tremendous potential, particularly when combined with either, or both, satellite and ground based observations (Wingate et al., 2008). The use of Repeat Digital Photography in phenology is becoming increasingly easier with the development of websites which facilitate the digital quantification of colour change from images, whilst enabling comparison with meteorological data (Bradley et al., 2010a,b). More recent websites also facilitate synthesis of the webcam data with MODIS satellite imagery (Bradley et al., 2010a,b).

2.1.2.4 Phenology Models and Experiments

The fourth approach to the collection of data for research on the phenological response of plant and animal species to climate variability and change is different from the former three, in that it does not rely on the availability of historic phenology and climate data spanning a period of decades. Rather, relationships between changes in climate variables and the resultant phenological responses of a species are either experimentally tested across a season, or longer, or are mathematically modelled (Schwartz, 1999). Once this has been undertaken, only a historic climate record for a region is required to predict what the phenological response of a particular species has likely been, and with a far greater number of weather stations than phenological records around the world, this potentially allows for a much greater number of "phenological studies". These inferred phenology records cannot be used to determine the phenological response to climate change over a period, as the use of climate data in their production renders this self-referentially fallacious. However they can, and do, contribute significantly to the inclusion of phenology into climate models and biodiversity indices (Schwartz, 1999; Morisette et al., 2009).

Phenological, or more generically agro-meteorological, experiments are undertaken to determine the response of plants to a controlled change in the ambient climatic conditions (Schwartz, 1999). Not only do they allow for effects of different climatic changes such as precipitation and temperature to be tested in isolation, but they also allow for the thresholds of particular species to extremes in climatic variables to be verified (Wookey et al., 1993; Morisette et al., 2009). These thresholds are included in future phenological studies, allowing farmers to prepare accordingly (Chmielewski & Köhn, 1999). These studies include controls on temperature and rainfall, to which a group of crops are exposed for a period, such as a long-term field experiment in Berlin, dated 1952-1990 (Chmielewski & Köhn, 1999). The findings of this study demonstrate different responses of each of the crop species to the universally administered changes, with some crops such as oats responding more strongly to precipitation changes, whilst others including wheat, are far more dependent on temperature (Chmielewski & Köhn, 1999). The study also determined the climatic variables of greatest significance to changes in crop phenology and yields, namely chilling units, heating units, absolute minimum and maximum temperatures, average minimum and maximum temperatures, average frost free period, and annual precipitation (Chmielewski & Köhn, 1999). This not only allows for better climate change adaptation strategies, but contributes to an improved understanding of the physiological drivers of phenological changes, and so is of value in the interpretation of ground level and satellite recorded phenological data.

The effects that the timing and rate of snow melt and ice break-up have on arctic and sub-arctic plants are of considerable interest for improving the predictive strength in phenological models. This is partly because they are seldom recorded by meteorological stations, and thus cannot be included in ground based phenological studies (Dunne et al., 2003). These are important factors given that climate warming is expected to be most extreme in polar-regions, thus resulting in considerably different patterns of future snow and ice extent, and far shorter freezing periods (Wookey et al., 1993). The timing and duration of snow and ice cover creates a more constrained dormancy period, insulates the underlying soil, and upon melting, provides invaluable moisture to the soil (Kudo, 1991; Dunne et al., 2003). In one experiment, snow covered regions in which arctic and subarctic plants grew were insulated using tents, and subjected to both heat and water treatment (Wookey et al., 1993). It was found that whilst rapidly increasing temperatures in the arctic are of concern, the insulation of snow cover enabled these plants to endure temperature increases up to 7°C (Wookey et al., 1993). Similar tests as to whether the timing and duration of flowering in subalpine meadows of Colorado were governed by the same factors were undertaken using radiative heaters to control the date of snowmelt, soil temperature and soil moisture content (Dunne et al., 2003). The results demonstrated that the duration of flowering of early flowering species is the most affected by these snowmelt-associated factors (Dunne et al., 2003).

Phenology models are mathematical rather than physiological approaches to simulating the effects of changes in various climatic variables on the phenological events of particular species (Cook et al., 2005). Their aim is to use commonly available meteorological variables to predict the response of various phenological stages of a particular species, with as minimal an error margin, and as physiologically accurately, as is possible (White et al., 1997; De Melo-Abreu, 2004). They are consequently often tested against either ground level observations or satellite derived data for a period of at least two years in order to determine how closely they are able to model the plant-climate interactions (De Melo-Abreu, 2004;

Zavalloni et al., 2006). Many of these models are developed with the aim of projecting future phenol-temporal changes for a particular species, particularly in the context of crop management. These include predicting the flowering dates of five species of olives in Cordoba, Spain, based on chilling and heating requirements (De Melo-Abreu, 2004); and the model PHENOM, developed using both NDVI data and growing date summations, used by Cook et al. (2005) to predict the future impact of the North Atlantic Oscillation on mixed and boreal forest across Europe. They also include simulation models developed to understand the past phenological responses to climate variability of cherries in Michigan, USA and chickpeas in Gorgan, Iran (Zavalloni et al., 2006; Gholipoor and Shahsavani, 2008).

Other models aim to mathematically fill gaps in the study of the effects of climate change on phenology. A regional phenology model has been developed by White et al. (1997) to better integrate spring ‘green up’ and autumn ‘brown up’ dates with synoptic level climate changes. This 20km x 20km resolution model has a maximum average error at the 95% confidence level of 10-14 days, and differentiates between the driving factors both for ‘green’ and ‘brown up’, and for the deciduous broadleaf and grassland groups (White et al., 1997). In an attempt to interpolate breaks in a three-century dataset for use in determining periods of maximum phenological change, Rutishauser et al. (2007) developed a statistical ‘Spring Plant’. This substitutable spring phenological value, which could be used in place of missing data, was developed through a weighted average of the mean flowering dates for apple and cherry, and the mean budburst for beech in Switzerland for the three century period (Rutishauser et al., 2007). These models are subsequently tested against other models, as well as with historical phenological data, so as to determine the most robust model for a particular study (Črepinšek & Kajfež-Bogataj, 2006).

Whilst these experiments and models provide little information as to the extent of climate change over the past century, and more importantly, the role which this climate change may have had on any changes in phenological events of species, they are of value when developing future projections (Schwartz, 1999). When developed to be both statistically sound and physiologically accurate, they are a necessary tool which should continue to be advanced within this field, and integrated into both ground level and statistical studies (Morisette et al., 2009).

2.1.3 Selection of Target Species and Location

2.1.3.1 Animal versus Plant Species

It may be argued that a species has three possible ways in which to respond to a changing climate: adapt, become extinct, or migrate to a more suitable micro-habitat or location (Hassall et al., 2007). With plants, phenological shifts such as earlier flowering may be an adaptation response to the change in climate; but once rooted in a particular location, the option of migration is only available to propagules, and even then is limited within the range of seed dispersal (Durant et al., 2007; Visser et al., 2006). With animals, the option of migration is considerably easier, and consequently any phenological shifts as a consequence of climate change, such as breeding time or egg hatching, are only a secondary response to climate stress (Parmesan & Yohe, 2003; Hassall et al., 2007). Therefore, studies on the response of animals to climate change have focussed on changes in range and location, and on changes in phenological events such as breeding (Post & Stenseth, 1999; Stevenson & Bryant, 2000; Gibbs & Breisch, 2001; Parmesan & Yohe, 2003).

Increasingly, studies on animal phenological responses to climate change focus on changes in the arrival, departure, flight time and duration of stay of migratory species such as birds, Odonata and butterflies (Roy & Sparks, 2000; Cotton, 2003; Hassall et al., 2007; Miller-Rushing et al., 2008b,c). Concerns exist as to the accuracy of first and last appearance dates, even more so than with plant flowering or leafing, which occurs in a specific location on a pre-identified unmoving species (Miller-Rushing et al., 2008b). The first call or sighting of a migrant animal can depend considerably on the observer being in the right place at the right time, and on factors such as the species population size for that particular year (Miller-Rushing et al., 2008b). The use, rather, of peak appearance or arrival dates of species overcomes these problems, without significantly altering or skewing the strength of the correlation with the climate variables (Roy & Sparks, 2000; Hassall et al., 2007; Miller-Rushing et al., 2008b,c). From these arrival and departure dates, species responses to large scale climate systems such as winter temperatures in Sub-Saharan Africa, the strength of an El Niño event, and patterns in the South Indian Oscillation over the Sahel, can be analysed (Cotton, 2003; Gordo & Sanz, 2006; Hassall et al., 2007).

Studies on animal phenological responses to climate variability and change also include breeding patterns. These include the effect of changing temperatures on the breeding patterns of Red Deer and Reindeer in North America and northern Europe, and the resultant chance of survival for juveniles born in seasons following detrimental weather conditions (Post and Stenseth, 1999). The patterns of size and timing of hatching of great tit birds, and the dependence on temperature, were examined by Stevenson and Bryant (2000). Similar concerns of the role of temperature were raised for the hatching of caterpillars, although the problem is clearly related to the availability of food, and hence on the response of plant leafing too (Visser et al., 2006).

The role of animals as critical members of regional ecosystems makes the study of these climate related changes in phenology, location, and migration as important as those of plant species, including agricultural crops (Visser et al., 2006). Furthermore, with many animals acting as pollinators for plant species, any changes in their location, reproductive patterns, and timing of peak populations in a particular region, could potentially prevent plant species from achieving successful fruit and seeding yields (Hegland et al., 2009). However, as animal responses to climate change are not only phenological, plant species are far more accurately able to detect the climate signal in historical phenological data.

2.1.3.2 Regional Location

Whilst it is uncontested that shifts in phenological events occurring in response to climate variability are a global phenomenon, the nature of both increasing climate variability and ongoing climate change, as well as plant responses to the local ambient climate, are significantly varied. The poles are warming considerably faster than equatorial regions and changes in both atmospheric and ocean circulations are likely to have considerable effect on the regional climate in different areas of the world (Beaubien & Freeland, 2000; Walther et al., 2002). Concurrently, changes in phenology are driven by different climatic factors, dependant on the predominant stresses in a particular environment (Reich & Borchert, 1984; Ruml at al. 2011). Whilst these differences are in part responsible for the species and location specific changes in phenological events, it is also important to note the dominant driving factors for each of the major regions for which these are similar (Parmesan, 2007).

Tropical regions are perhaps the least suited to phenological studies due to their weak seasonality, and hence the predominance of evergreen forests for which no green wave can be detected, either by satellite or ground level observations (Corlett & Lafrankie, 1998). Whilst temperature and incoming solar radiation is relatively uniform throughout the year, considerable fluctuations in rainfall are common in the tropics (Corlett & Lafrankie, 1998; Chapman et al., 2005). Changes in rainfall are responsible for the timing of leaf fall, a physiological response to low rainfall periods to compensate for water stress, or in the timing of bud break and anthesis during periods of higher rainfall in the tropical dry forests of Costa Rica (Reich & Borchert, 1984). Similarly, significant sub- and supra-annual variations in the plant growth and reproduction of aseasonal tropical Asian regions were established by Corlett and Lafrankie (1998) to have occurred as a consequence of changes in water availability; whilst considerable increases in the percentage fruiting in Kibale National Park were found to correlate significantly with an increase in rainfall in Uganda over the past few decades (Chapman et al., 2005).

Whilst there is considerably less variation in insolation at the tropics than at the mid-latitudes, Wright and van Schaik (1994) argue that photoperiod may not be an insignificant factor in tropical plant phenology. Whilst the incoming solar radiation and solar angle may be inter-annually constant, the cloud cover extent is often not. Variability in the number of sunshine hours as a consequence of cloud cover are argued to account for the 31% more radiation recorded for the March Equinox than the September Equinox in Panama (Wright & van Schaik, 1994). As changes in precipitation may have a significant impact on the timing of phenological events, the related variability in the photoperiod as a consequence of cloud cover may also be significant (Wright & van Schaik, 1994).

Whilst high-latitude and high-altitude regions have considerable seasonal fluctuations in temperature, incoming solar radiation, and precipitation, they too present limitations for studying phenological responses to climate variability and change owing to the effect of snowmelt timing (Walker et al., 1995). Snowmelt, together with the role that it plays in spring soil temperature and moisture, has a considerable effect on both leafing and flowering phenology (Walker et al., 1995). Shorter snow-free periods were found to reduce flowering and seeding, and encourage the production of vegetative rather than reproductive shoots (Kudo, 1991). However, unlike climatic variables such as daily temperature and rainfall, snow melt dates are seldom recorded other than for the purpose of specific scientific studies. This is problematic, as in addition to the direct impacts that the snow melt dates have on phenology, they also influence the relative importance of other climatic variables on phenology. In the high latitudes of the artic, where there is snow cover year round, temperature is found to be of greater influence, whilst in the sub-arctic regions with seasonal snow cover, rainfall is of greater importance to the timing of phenological events (Wookey et al., 1993). Recent studies on recorded snow melt dates report that these influences on phenology are significant. These include an advance in flowering dates by 11 days when exposed to a two week earlier snowmelt date, or a 2°C warmer spring (Dunne et al., 2003). Similarly a very strong correlation between snowmelt and first flowering dates is calculated by Inouye (2008) for Colorado, with snowmelt dates statistically accounting for 73.4% of changes in this phenological event. Whilst the timing of snowmelt is dependent on temperature, it responds to more local temperatures than are often the focus of phenology studies, with a considerable reliance on the amount of shade and wind to which the snow is exposed.

Mid-latitude regions, with highly seasonal, temperate climatic conditions, enable the most accurate attribution of climate variability to long term shifts in phenology (Schwartz & Reiter, 2000; Chmielewski et al., 2004). Whilst annual temperature, photoperiod and precipitation are all of importance, the sub-annual periods in which each of the factors is most significant to the phenology of a particular species are not necessarily uniform. Moreover, data for all of these variables are generally easily available and hence phenological response can, for the most part, be accounted for (Hänninen, 1995; Badeck et al., 2004). The most difficult factor to include in statistical analysis for the mid-latitudes is the risk of frost damage, particularly where warmer spring temperatures induce considerably earlier flowering (Cannell & Smith, 1986; Inouye, 2008; Rigby & Porporato, 2008). However, as a more direct function of the daily minimum temperature, the effect of frost can be included into the understanding of changes in phenological events and yields far more easily than snow melt (Rigby & Porporato, 2008). Consequently, studies aiming to attribute changes in phenological events to climate variability and change would be able to do so with greatest relative confidence in the mid-latitude regions.

At a more local scale two further factors should be considered. The first is the distance from major water bodies, particularly if the coastline is in close proximity to a major current, particularly those comprising the thermohaline circulation (Beaubien & Freeland, 2000). Whilst the proximity to large water bodies has a moderating effect on climate, changes both in sea or water surface temperatures, and water temperatures, together with changes in the thermohaline circulation, are likely to have an increasing effect on the climate experienced in these regions, and consequently on the phenological response (Beaubien & Freeland, 2000). The second is the position of the study region in relation to urban areas. If plants are located close to, or within, an urban centre, not only are they likely to experience greater levels of warming due to the urban heat island effect, but may also experience different phenological responses due to the more artificially controlled temperature, photoperiod and water availability (Rötzer et al., 2000; Lu et al., 2006). Whilst neither of these two factors is necessarily detrimental to the study of phenology, they should be taken into account before and during any such studies.

2.1.3.3 Annual versus Perennial Species

The third choice to be made for a phenology study, particularly one investigating the phenological responses of agricultural plants to climate change, is between annual and perennial species. Annual crops such as wheat, oats, corn and millet make up the staple foods of almost all cultural groups in the world, and so are of greater concern both economically and in terms of food security under climate change (Blanc, 2012). However, because they are planted annually, any phenological shifts can be compensated within a few months, either by changing the location in which they are grown, or more easily by changing the sowing date (Gholipoor & Sinclair, 2011). Whilst this is advantageous as it allows for a high level of adaptation by the farmer, it means that any historical records will indicate little on shifts in plant phenological responses over the time period (Chmielewski et al., 2004; Estrella et al., 2007). Studies do attempt to account for these management related changes in order to uncover any trace of climate influence on phenology. However, management changes cannot compensate for climate changes indefinitely (Estrella et al., 2007). It is thus useful to study these trends for the sake of agricultural management, despite them being of little statistical value (Menzel et al., 2006b).

In perennial plants very few management related changes have any success in facilitating adaptation to changing environmental conditions, and so the climate signal on phenological changes is potentially stronger (Rosenzweig et al., 1996; Chmielewski et al., 2004; Menzel et al., 2006b). Perennial plants, such as agricultural fruit trees, require a period of two to ten years after planting to reach maturity (Furr et al., 1947; Chapman et al., 2005; Tan & Swain, 2006). Thereafter, phenological events take place regularly from year to year, and the tree is able to produce profitable fruit yields (Chapman et al., 2005; Tan & Swain, 2006). This commitment of up to ten years in order to receive yields, together with the difficulty in successfully moving a tree of any age, means that changing the plant's location is not an option (Furr et al., 1947; Rosenzweig et al., 1996). Phenological responses are thus likely to be more apparent, as this is the only response of the tree to its changing environment. Whilst farmers may compensate for shortages or deleterious fluctuations in water availability through the use of irrigation, little can be done to mitigate for changes in temperature and photoperiod (Rosenzweig et al., 1996). Consequently, these perennial plants offer far greater value in determining the role of climate change on plant phenology.

2.1.3.4 Phenological Stage or Event

Despite an increasing awareness of the value of phenological data in climate change studies, very few datasets which are not sourced from a dedicated phenological network will have records for more than one phenological event (Gordo & Sanz, 2005; Amano et al., 2010). Consequently, in the selection of a dataset, a site with data for a phenological stage which is more strongly controlled by climate, such as the spring events of leafing and flowering, is arguably preferable (Schwartz, 1999; Beaubien & Freeland, 2000).

Autonomous phenological events are preferable, unless no other data are available. Management events such as harvest dates which are ultimately decided by the farmer, rather than intrinsically by the plant, tolerate considerable external control which would obscure a climate trend (Menzel et al., 2006b; Estrella et al., 2007). With farmers harvesting either early or later than the time of natural fruit drop in order to meet economic demand, harvest dates can vary by months, and hence correlate poorly with the timing of other phenological events for that plant (Menzel et al., 2006b; Estrella et al., 2007). Farmers of annual crops have the advantage of being able to sow crops according to the climatic conditions, and to facilitate more predictable ripening dates (Chmielewski et al., 2004; Menzel et al., 2006b; Estrella et al., 2007). Furthermore, even if the farmer were to harvest at the time at which fruit fall would occur, or a set time after fruitset, the timing of harvest is further controlled by intrinsic factors such as the hormone levels resulting from the previous year's yield, which too will obscure the climate signal, as is the case for fruit drop by wild plants (Chapman et al., 2005; Estrella et al., 2007).

The preference is then for spring phenological phases such as leaf unfolding, bud burst, and flowering, rather than the autumn phases such as fruit fall, leaf colouring and leaf fall (Schwartz & Reiter, 2000; Chmielewski & Rötzer, 2002). Not only do spring events often have a double temperature control through chilling requirements for the breaking of dormancy, followed by warming to induce the shift to the next ontogenetic stage, but having followed this period of dormancy, they do not suffer from cumulative effects (Beaubien & Freeland, 2000; Chmielewski & Rötzer, 2002; Nordli et al., 2008). Both within the tree and the external climate, cumulative effects of delayed or hastened phenological events, and the resultant changes in photosynthetic activity, water stress, and mineral levels can interact to alter the dates of autumn phenological events (Chmielewski et al., 2004;

Badeck et al., 2004). These serve to obscure the impact which climate alone has on phenological shifts.

Whilst leaf unfolding is a clearly distinguishable event and has considerable potential for use in ground based and satellite observations concerned with phenological shifts and the green wave, it is induced by both intrinsic and the external climate controls (Pettorelli et al., 2005; Schwartz et al., 2006). Particularly in evergreen trees with continuous leaf presence, or deciduous trees which may have multiple leaf flushes, the leaf unfolding date is to a lesser extent triggered by environmental factors, and more by internal controls such as carbohydrate deficits and water availability, which is only indirectly associated with rainfall (Zhang et al., 2003; Stöckli & Vidale, 2004; Arora & Boer, 2005). The timing of flowering, however, is more under the control of climate, with a reliance on both winter temperatures for the fulfilment of chilling requirements, and spring warming to induce budburst (Sparks et al., 2000; Nordli et al., 2008). Not only are these climatic controls more robust, but intrinsic controls have a lesser effect on flowering, with any deficits addressed through changes in leaf, shoot and root growth (Arora & Boer, 2005).

With flowering as the preferable phenological event in climate studies, it is necessary to decide on the relative suitability the stages of bloom (whether 50%, 75% or peak bloom) and first flowering dates. First flowering dates, which record the first visible open flower for a species, are often easiest to record, as they do not rely on human judgement of the point at which 50% or even 100% of the flowers on a plant are open (Fitter et al., 1995; Amano et al., 2010). However, the use of first flowering dates is open to considerable error due to the nature of measuring an extreme stage. At the stage of data collection, errors could arise from the first flower blooming at a time or date for which observations are not made, or on a plant located away from the observation point (Miller-Rushing et al., 2008a). If the first flower to bloom is located well above eye level, it is less likely to be noticed and recorded than a first flower located in a more visible position on the plant. There are also intrinsic errors which result from the nature of recording an event of a single flower rather than the group in the case of 50%, 75% or peak flowering. A first flowering date reduces the sample number, and consequently could occur much earlier or later inter-annually, during a period in which peak bloom may remain relatively constant (Fitter et al., 1995; Miller-Rushing et al., 2008a; Amano et al., 2010). It could also be triggered due to the short term occurrence of favourable conditions – sufficient to cause a few buds to open, but followed by a cold period preventing peak bloom (Fitter et al., 1995; Miller-Rushing et al., 2008a). Thus, to have a more statistically accurate measure of the occurrence of flowering, with less likelihood of error or bias, peak or 50-75% bloom are preferred (Miller-Rushing et al., 2008a).

2.1.4 Species and Location Specificity

The magnitude of the phenological shift which occurs in a plant in response to climate variability and change is dependent on the species, on whether warming or the fulfilling of chilling days is required to induce a phenological event, the time period in which climate is most influential, and that species' associated threshold temperatures (Visser & Holleman, 2001; Parmesan, 2007; Faisal, 2008). This is manifested in region specific shifts in temperature and rainfall, as is evident in the differences between the shifts in the flowering dates of apples from 4.2 days/°C earlier in South Africa to only 2.4 days/°C earlier in Poland (Kalbarczyk, 2009; Grab & Craparo, 2011), and between Chinese cotton flowering dates shifting earlier by 0.66 days/°C, whilst wheat grown in the same region experienced flowering advances of as much as 3.4 days/°C (Wang et al., 2008).This is heightened by the high species and location specificity of the phenological response of plants to climate change, for example, considerable differences in the phenological response of 500 plant and animal species to climate change in Concord Massachusetts (Miller-Rushing & Primack, 2008a). Further species and location specificity can be noted in the summary of over 30 regional studies on plant response to climate change (*Table 2.1*).

Table 2.1: Summary of publications addressing the effect of climate change on spring plant phenology

Author	Year	Time Period	Location	Taxon*	Phenological Response
Cannelll & Smith	1986	1921-1950	England	Apple	7-9 d/°C
Fitter et al.	1995	1954-1989	Central England	267 species	4-6 d/°C
Sparks & Carey	1995	1736-1925	England	Multi-species	4 d/°C
Kramer	1996		Europe	*Fagus Sylvatica*	3.6 d/°C
Walkovszky	1998	1851-1930; 1952-1981; 1983-1994	Hungary	Locust Tree	5-10 d/°C
Roy & Sparks	2000	1976-1998	British Isles	Butterflies	2-10 d/°C
Sparks et al.	2000	1875-1947	British Isles	11 plant species	2-10 d/°C
Chmielewski & Rötzer	2001	1969-1998	Europe	White Birch, Sweet Cherry, Mountain Ash, Alpine Currant	5 d/°C
Chmielewski	2002	1961-2000	Europe	Multi-species	6.7 d/°C
			Germany	Apple and Cherry	5 d/°C
Chmielewski & Rötzer	2002	1969-1998	Europe	Multi-species	8 d/0.8°C
Keatley et al.	2002	1940-1962	Australia	*Eucalyptus sp.*	41.4 d/°C increase +5% rain decrease
Wielgolaski	2003	1995-1997	Norway	Multi-species	4-6 d/°C
Chmielewski et al.	2004	1961-2000	Germany	Apple	4.6 d/°C
				Cherry	4.7 d/°C
De Melo-Abreu et al.	2004	*Modelled*	Portugal	Olives	5.2-7.4 d/°C
Ledneva at al.	2004	1970-2002	Southern Massachusetts	Goldthread	3 d/°C
				Spice Bush	0.45 d/°C
				Wood Anemone	1.13 d/°C
Sparks et al.	2005	1980-2000	England	Agricultural plants	4-12 d/°C
Črepinšek & Kajfež-Bogataj	2006	1955-2000	Slovenia	Hazel	8 d/°C
				Apple and Plum	4-6 d/°C
Lu et al.	2006	1950-2004	Beijing	Peach	2.88 d/°C
				Almond	2.19 d/°C
				Lilac	2.43 d/°C
				Acacia sp.	2.89 d/°C
Menzel et al.	2006	1971-2000	Europe	542 plants, 19 animals	2.5 d/°C
Tao et al.	2006	1981-2000	China	Wheat	2.98 d/°C
Estrella et al.	2007	1951-2004	Germany	20 agricultural plants	4.31 d/°C
Hassall et al.	2007	1960-2004	England	Odonata *(flight period)*	3.08 d/°C
Miller-Rushing et al.	2007	1981-2005	Japan	Cherry	2-9 d/°C
Miller-Rushing et al.	2008	1970-2002	Massachusetts	Gray Catbird	0.35 d/°C
Miller-Rushing & Primack	2008	1852-1858; 1878-1902; 1963-1993; 2003-2006	Concord, Massachusetts, USA	43 species	3.4 d/°C
Wang et al.	2008	1983-2004	Northern China	Wheat	3.4 d/°C
				Cotton	0.66 d/°C
Gordo & Sanz	2009	1943-2003	Spain	21 species	8.21 d/°C
				Beech	7.62 d/°C
Kalbarczyk	2009	1966-2004	Poland	Granny Smith Apple	2.4 d/°C
				Ground Cucumber	3.68 d/°C
Miller-Rushing & Inouye	2009	1973-2006	Colorado	Delphinium wildflower	6.1-7.1 d/°C
Primack et al.	2009a	800-2007	Japan	Cherry	3-5 d/°C
Primack et al.	2009b	1953-2005	Japan and Korea	*Prunus*, *Taraxacum* and *Camellia sp.*	4 d/°C
Amano et al.	2010	1891-1947 *(1753-2010 modelled)*	Central England	405 plant species	5 d/°C
Beaubien	2011	1936-2006	Alberta, Canada	7 plant species	1.5-5.3 d/°C
Grab & Craparo	2011	1973-2009	South Africa	Golden Delicious Apple	4.2 d/°C
				Granny Smith Apple	2.4 d/°C
Chen & Xu	2012	1986-2005	China	Siberian Elm	2.8 d/°C
Darbyshire et al.	2012	1963-2009	Australia	Apple and Pear	2.8 to 7.5 d/°C
Liu & Hu	2012	2000-2009	Tibetan Plateau	Meadow species	8.17 d/°C
				Steppe species	5.69 d/°C
Panchen et al.	2012	1840-2010	Greater Philadelphia	28 piedmont species	2.7 d/°C

* Individual species, up to a maximum of five, are listed where known
**All shifts are towards EARLIER dates
Studies that do not present shifts in phenology resultant from changes in climate variables are excluded from this table; only phenological shifts of spring events (leaf unfolding, budburst, flowering) are reported.

These species and location shifts are most apparent when analysing the differences from species-specific studies examining the phenological response of plants to increasing climate variability and ongoing climate change. It is when comparing these results that the value of consistency in the reporting of changes becomes evident. Not only is it misleading to report only trends in climate and phenology over a time period, and from the similarities in direction and magnitude of the trends alone, infer a relationship, but it also renders it impossible to compare with studies which have taken this third methodological step. Consequently, the summary presented in *Table 2.1* only contains those studies which have presented changes in the date of a phenological event in response to a unit change in one or more climatic variables.

2.1.4.1 Species Mismatches

Species and location specificity of both plant and animal phenological responses to climate variability and change are not only scientific problems for the generalization of phenological responses for application in climate models and ecosystem studies, but a further indirect effect of these climate changes to plant and animal communities (Stenseth & Mysterud, 2002). Overlaps between predators and prey, flowering and the presence of pollinators, and species varieties for cross pollination, both in time and space, have evolved through natural selection to enable species to match their environmental conditions (Stenseth & Mysterud, 2002; Durant et al., 2007; Hegland et al., 2009). However, with variable responses to climate change, both across species and locations due to differences in the driving forces determining their physiological phenological changes, many of these overlaps are likely to weaken (Durant et al., 2007).

The theory of species match and mismatch was developed in marine biology, with issues of availability of plankton, which fish larvae require for early growth, in seasons with unsuitably high or low temperatures (Durant et al., 2007). This is a particular problem for species such as the Georges Bank Haddock, for which the timing and location of spawning is temperature dependant, thus increasing the chances of a mismatch in a year in which the plankton and fish do not have parallel responses to temperature change (Durant et al., 2007). Similar issues of predator-prey mismatches have been observed in terrestrial environments, such as the winter moth hatching up to three weeks earlier than the unfolding of oak leaves, which are their primary food source (Visser & Holleman, 2001). This mismatch results from the winter moth taking a hatching cue from warming temperatures, whilst the oak has a chilling requirement to ensure leafing (Visser & Holleman, 2001; Durant et al., 2007). Even where both species take their phenological cues from warming temperature, mismatches can arise should the time duration for which temperatures are important differ (Visser et al., 2006). This is the case for the hatching of the great tit and the peak availability of caterpillars on which the young birds feed, with the birds determining the date for egg laying on March temperatures, whilst caterpillar peak availability is based on temperatures as late as May (Visser et al., 2006).

Mismatches do not only exist between predators and their food source, but also have an effect on pollination. Variable times in the flowering of plants and the availability of pollinators – again potentially changing for both species – can considerably decrease the likelihood of pollination, and consequently the quality and size of seed and fruit yields (Hegland et al., 2009). This problem can be driven by changes in the duration of flowering and quantity of flowers alone, and is considerably enhanced for plants pollinated by insects rather than wind (Hegland et al., 2009). Similarly, for cross pollination of self-incompatible species, an overlap between different individuals within a small enough range is required to maintain high yields of good quality (Moghadam et al., 2009). This becomes particular difficult in species such as cherries, for which the flowering duration is less than a week (Moghadam et al., 2009).

These mismatches, which are already being observed, are of considerable concern for species and their associated ecosystems. However, Visser and Both (2005) argue that they may provide a necessary yardstick against which to measure the extent of climate change effects on plant survival. In addition, they argue that there may be a considerable under-reporting of cases in which mismatches are not found to occur as species are responding in parallel to climatic changes, and that the problem is exaggerated through the need to publish remarkable results (Visser & Both, 2005; Parmesan, 2007).

2.1.5 Applications of Phenology

In addition to the contribution that investigations of new species and locations by individual studies and a larger network of phenology studies have made to the discipline of phenology, these studies additionally have the potential to contribute significantly to improving biodiversity indices, climate models, and agricultural management (Morisette et al., 2009). To a lesser degree phenological data and studies have been used in fields such as health, addressing the influences of these phenological shifts on pollen and disease carrying insects, and as a proxy for climate change where phenological records extend back further than climate records (Menzel, 2002; van Vliet et al., 2003; Črepinšek & Kajfež-Bogataj, 2006).

2.1.5.1 Biodiversity Indices

A combination of species mismatches, decreasing suitability of environments, and changes in competitive dynamics over past decades, motivate forecasts for an increase in the risk of plant and animal species extinctions by 20-30% in association with temperature increases of as little as 1.5-2.5°C (Faisal, 2008). There is consequently a significant need for the development of biodiversity indices which allow for the health of ecosystems to be monitored and, where possible, managed (Spano et al., 1999; Dawson et al., 2011). Not only are phenological observations good indicators of the extent to which plants and animals are being affected by, and responding to, climate variability and change, but these findings also form critical components of broader ecosystem assessments (Kramer et al., 2000; Črepinšek & Kajfež-Bogataj, 2006; Dawson et al., 2011). Meta-analyses of the existing phenology literature aim to uncover "globally coherent fingerprints" (Parmesan & Yohe, 2003, p. 37) of the effects of climate change on the phenology, location and range of plant and animal species, allowing for the broad-based inclusion in biodiversity indices (Root et al., 2003). However, even single species studies may be of value, particularly if the species are highly sensitive to climate change, and if the study sets out to contribute to such indices (Spano et al., 1999; Dreyer et al., 2006; Dawson et al., 2011).

The species mismatches resulting from differences in phenological responses to local climate variability and change are of greatest importance to ecosystem studies and the development of biodiversity indices, as they examine the effects of climate change across trophic levels (Stenseth & Mysterud, 2002; Durant et al., 2007). Whilst an individual species may show a considerable response to climate variability and change through a shift in flowering or leafing dates of up to a few weeks, it is only when this shift has a direct impact on the survival of that species, or inter-dependent species, that it becomes an immediate issue to biodiversity (Durant et al., 2007; Visser et al., 2009). Consequently, these studies investigating the mismatch between the hatching of the winter moth and the leafing of oak trees required to feed the moth, and those of mismatches between plants and their pollinators, are essential to biodiversity indices by quantifying the impact of climate change on survival (Visser & Holleman, 2001; Hegland et al., 2009).

2.1.5.2 Climate Models

Another primary value of phenology studies is in the development of, and incorporation into, regional and global climate models. Whilst changes in phenology, particularly those of spring events, are driven predominantly by climate variability and change, these shifts in phenology also have a vital impact on future climate change due to the resultant feedbacks to the atmospheric system (Hogg et al., 2000; Peñuelas et al., 2009). With the timing of leaf phenology (both onset and senescence) significantly altering the surface albedo, water balance, carbon intake, and surface roughness, even a few years of considerably early or late onsets of leafing could have a significant effect on the local to regional climate (Arora & Boer, 2005; Peñuelas et al., 2009).

Whilst the nature of these feedbacks, particularly from forest environments, is well understood, the challenge lies in modelling leaf phenology to allow future phenological changes to be included in climate prediction models (Hogg et al., 2000; Arora & Boer, 2005). Not only are the majority of studies undertaken on past phenological change undertaken at the species level, rather than the synoptic scales required in climate models, but the modelling of leafing, even with historical data, is particularly difficult (White et al., 1997; Arora & Boer, 2005). Much of the difficulty exists because the shifts in phenology of plants are driven, to a large extent, by the same climate change that these models attempt to project. Thus, as an event which is both driven by climate change and which in turn has a causal effect on future climate change, leaf phenology becomes considerably more difficult to model (Arora & Boer, 2005). This can, however, be compensated for through modelling leaf phenology on the plant's carbon budget, rather than temperature, thus allowing for the more easily accounted for carbon levels to be used in modelling (Arora & Boer, 2005). Whatever the approach to including phenological climate change studies into the prediction of future climate change, considerably more information is required across much greater scales than is presently available (Peñuelas et al., 2009). This particular value of phenology studies highlights the importance of further developing the network of investigation.

2.1.5.3 Agricultural Management

The third, and by far the most extensive, application of studies examining the response of phenology to climate change is in agricultural management. Decisions on when to plant crops; where to establish farms; which area of a farm is best suited to a particular species or variety; how much, how often and when to irrigate; and most importantly when and how large the yields for a particular year may be expected, all require both an understanding of, the response of a plant to the local climate, and of any variability and change in those climatic conditions (Chang, 2002; Blanc, 2012). This is particularly important in regions where there is little scope for early response adaptation through changes in irrigation, either due to water scarcity or insufficient capital and infrastructure (Blanc, 2012).

Increasingly, phenological studies are recognising the importance of studying agricultural species, with the timing of flowering influencing the length of the growing season, quality of the fruit, and in cases of frost risk, the success of a particular year's yields (Chmielewski, 1992; Sparks et al., 2005; Doi, 2007; Croitoru et al., 2012). As yields are influenced by a number of non-climatic factors, such as the amount and quality of fertilizer, irrigation (a considerable concern in the arid cities of Iran), the effect of windbreaks, and the previous year's fruit load, the influence of climate cannot always be differentiated from other yield drivers. Phenology studies, whilst unable to determine absolute changes in the production of a plant, are able to detect far more clearly the effect of increasing climate variability and ongoing climate change of a species in a particular location, and thus can allow for the future success of farming that crop to be inferred (Chmielewski et al., 2004; Estrella et al., 2007; Croitoru et al., 2012). Consequently, studies aiming to assist in agricultural management with regard to both current and future climate variability and change are best able to do so when they combine both phenology and yield data (Sparks et al., 2005; Tao et al., 2006).

2.2. Timing of Citrus Flowering

2.2.1 Introduction

Citrus fall into the class of deciduous, woody plants with more than one seasonal leaf flush (Tan & Swain, 2006). Unlike annual crops, deciduous fruit trees require a cooling period in order to break dormancy and induce budburst, followed by a period of spring warming to encourage anthesis (García-Luís et al., 1992; Tan & Swain, 2006). Also characteristic of deciduous fruit trees, citrus trees ordinarily go through a juvenile stage of two to ten years before beginning to flower, after which the plant settles into an annual cycle of three growth flushes (Guardiola, 1997; Tan & Swain, 2006). In temperate regions, of the shoots produced in these three flushes – one in spring, one mid-summer, and one in autumn – only the first bears flowers, with the further two flushes producing purely vegetative shoots (Guardiola, 1997; Tan & Swain, 2006). The timing and success of flowering of citrus is driven predominantly by the local atmospheric temperatures of the preceding winter, both in fulfilling the plant's chilling requirements, and the spring warming to induce anthesis. Consequently, they provide an ideal subject for the study of the phenological response to climate variability and change. However, other than a 10-year field study undertaken in Israel by Lomas and Burd (1983), and the inclusion of *Citrus* in a multi-species study on the effects of climate change on agricultural yields in Taiwan (Chang, 2002), no such historical studies have been undertaken, and certainly none with a focus and time period required to reveal the response of this genus to a changing climate.

This section examines the literature on the effects of both climate variables, and the intrinsic plant controls, on the timing of flowering in order to develop an understanding the role of climate variables on anthesis. First, the period of winter dormancy and the chilling requirements which need to be fulfilled for dormancy to be broken, will be discussed. The progression to the initiation and floral development will then be analysed, addressing the role of the period of spring warming and the resultant bud differentiation into flowers or vegetation. Here the risk of frost, both on the flowers and the later fruit set and yields, will be addressed. Finally, this section examines the climate thresholds required to ensure that the plant is only subjected to beneficial stress.

2.2.2 Dormancy

Deciduous trees grown in sub-tropical and mid-latitude regions, respond to the distinct seasonality with a dormant period in the cooler, and for certain regions, drier winter months (Hänninen, 1995; Peñuelas et al., 2009; Luedeling & Gassner, 2012). During this time, the plant conserves energy, and the buds develop their hardiness to frost (Srivastava et al., 2000). In order for this period of dormancy to be broken in spring, not only are warmer temperatures required, but first the satisfaction of the winter chilling period needs to be met (Moss, 1976; Southwick & Davenport, 1986; García-Luís et al., 1992).

In citrus, the release from dormancy in spring can occur either as a result of this winter chilling period being fulfilled, or as a result of either cyclical or continuous water stress of at least four to five weeks (Mendel, 1968; Southwick & Davenport, 1986; Srivastava et al., 2000). Consequently, in water stressed regions such as India, a chilling sum of as few as 10 to 15 days below 10°C, together with a water shortage, rather than the couple of months of mean daily temperatures below 15°C required in wetter regions, can provide sufficient 'beneficial stress' for dormancy release (Mendel, 1968; Moss, 1976; Srivastava et al., 2000). The extent to which water stress can contribute to dormancy release is considerably more specific to the citrus variety than the effect of lowered temperatures, with varieties such as the Tahiti Lime responding well, even to extreme water stress, whilst the effects of water stress on Sweet Orange trees have the potential to be harmful (Srivastava et al., 2000; Koshita & Takahara, 2004; Valiente & Albrigo, 2004).

Unlike many deciduous fruit trees, citrus can be successfully cultivated in tropical regions. Here, as there is no defined winter period, there is no resultant dormancy of the plant (Susanto et al., 1992; Rosenzweig et al., 1996). Consequently, both vegetative and reproductive shoots develop throughout the year, and fruits are produced almost continually (Guardiola, 1997; Albrigo et al., 2002). As the risk of frost in these regions is very low, the buds do not need to develop hardiness through an accumulation of cold days in order to survive through to anthesis and later fruitset (Susanto et al., 2002; Srivastava et al., 2000). However, both the quality of the fruitset and the size of the yields are greatly enhanced following a single, heavy annual bloom (Rosenzweig et al., 1996).

Another difference between citrus and the majority of deciduous fruit trees is in the timing of bud differentiation between those which will develop into vegetative and reproductive shoots (Lord & Eckhard, 1985; García-Luís et al., 1992). For most deciduous fruit trees, vegetative and reproductive buds are physiologically different throughout dormancy (Lord & Eckhard, 1985). By contrast, in citrus the differentiation of floral organs does not occur until the first stages of sprouting, with vegetative and reproductive buds being anatomically indistinguishable during dormancy (García-Luís et al., 1992). Vegetative buds have a far less extreme chilling requirement, and so sprout more readily in spring, and have the potential to continue to bud in growth flushes through the remaining warm seasons (García-Luís et al., 1992). The floral buds, which have a greater chilling requirement, can thus only form part of the spring flush (García-Luís et al., 1992).

2.2.2 Floral Initiation and Development

Once dormancy has been broken, in response to the fulfilment of chilling requirements, the initiation of both leafing and floral development can begin (Moss, 1976; Young, 1981). Whilst initiation and floral development are two phenologically separate events, they are less clearly defined than the ontogenetic switch from dormancy, and are both induced by the increase in temperature (Moss, 1976; Rosenzweig et al., 1996). This process of heat accumulation required for flowering is consistent with that of the flowering of other deciduous trees; once the atmospheric temperatures of the location have increased sufficiently above a threshold temperature for a sufficiently long period, floral initiation and development can begin (Moss, 1976; Rosenzweig et al., 1996; Luedelling & Gassner, 2012). These heat sums, either of the number or hours or days above a certain threshold temperature, and excluding any temperatures below this, increase far quicker during a warm period in which the temperatures summed are higher, and in which fewer days or hours need to be excluded (Cleland et al., 2007). Consequently, warmer spring temperatures will result in this heat accumulation being reached earlier, inducing earlier flowering than in cooler spring seasons for which a far greater number of days is required for the heat sum to be met (Young, 1981; Susanto et al., 1992).

Citrus species are self-compatible, and thus pollination is not at risk should the timing of flowering of different citrus varieties shift and consequently no longer overlap, removing concern over future cross pollination as observed in the timing of cherry cultivars in Iran (Guardiola, 1997; Moghadam et al., 2009). However, there is still concern surrounding the effect that changes in flowering date, particularly in species so highly dependent on climate, would have on increasing the risk of failed flowering, the length of the growing season, the yield and quality of the fruits, and management practices (Valiente & Albrigo, 2004; Tan & Swain, 2006).

2.2.3 Temperature Thresholds and the Risk of Frost

Earlier flowering resulting from warmer early spring temperatures, whilst potentially able to extend the growing season, also places both the flowers and fruit at a substantially greater risk from frost damage (Cannell & Smith, 1986; Susanto et al., 1992; Inouye, 2008). Such frost damage can prevent buds from reaching anthesis, reduce pollen viability, and should it occur after fruitset has begun, can damage fruits and prevent ripening (Susanto et al., 1992; Inouye, 2008). In addition, the occurrence of frost before anthesis can delay flowering by 8 to 10 days following a single frost event (Lomas & Burd, 1983). This highlights the importance of understanding the threshold temperatures under which increasing climate variability and ongoing climate change change can occur without significant damage to the tree or its yields.

The period of dormancy for citrus requires average daily temperatures of less than 15°C for a period ranging from two weeks to three months, depending on the extent of water stress (Moss, 1976; Srivastava et al., 2002). The period of frost hardening requires minimum and maximum temperatures within the range of -4°C and 14°C, whilst the subsequent pre-bloom period of dormancy requires frost free conditions, and temperatures within the range of 0°C and 14°C (Young, 1981; Rosenzweig et al., 1996). Following this, the initiation of flowering requires a heat accumulation period in which the daily mean temperature seldom drops below 20°C (Rosenzweig et al., 1996). For successful anthesis, daily minimum and maximum temperatures within the range of 10°C to 27°C are required, with daily maximum temperatures more significantly determining the time of flowering (Rosenzweig et al., 1996; Susanto et al; 2002). Towards the end of bloom, every day with maximum temperatures above 38°C results in decreased fruitset, whilst a single day with temperatures over 48°C may halve the potential fruitset (Rosenzweig et al., 1996). These are generic thresholds, and location specific thresholds may be applicable to a particular variety or species. This is the case in Israel, where Lomas and Burd (1983) found that each 1°C decrease in the average daily minimum temperature delayed the commencement of four orange species flowering by five days in the Jordan Valley, but by ten days on the coastal plain.

2.2.4 Intrinsic Controls on Flowering

Whilst the timing of flowering in citrus is most dependent on the local atmospheric temperature, both in the preceding winter and during the spring, intrinsic controls still contribute towards flowering regulation (Moss, 1976; Bellows & Morse, 1986; Albrigo et al., 2002). Whilst these cannot be quantified from historical phenological data, they have the potential to improve the understanding of limited explanatory power of these findings. Most significant is the role of carbohydrate as a limiting factor to flower formation (Goldschmidt et al., 1985; Sanz et al., 1987). Should the citrus plant experience low carbohydrate levels, flowering will be delayed or prevented in order for those carbohydrates to be used for the preservation of the plant (Goldschmidt et al., 1985). In citrus, gibberellins, which are produced naturally in fruits, act to inhibit carbohydrate levels, and hence the accumulation of elevated gibberellin following a large fruitset may potentially inhibit flowering in the following season (Goldschmidt & Monselise, 1970). However, there remains much contention as to whether carbohydrates or gibberellin actually do have an effect on flowering time and quantity, and if so, to what extent. (Sanz et al., 1987; Koshita & Takahara, 2004).

Related to the limiting actions of carbohydrate levels, are the effect of water stress outside of the dormant period on leaf fall, and the result that this may have on the flowering of the citrus (Koshita & Takahara, 2004). A common response of deciduous fruit trees to water stress in the growing period is to shed leaves, thus reducing the water demand of the plant (Borchert, 1983; Koshita & Takahara, 2004). Whilst this is an effective response to water shortage, it dramatically reduces the photosynthetic potential of the tree, and hence the potential production of carbohydrate (Sanz et al., 1987; Koshita & Takahara, 2004). Should the concerns of Goldschmidt et al. (1985) have any import, this is particularly problematic for flowering in the following spring.

The third intrinsic factor which may affect flowering in citrus is the age of the buds. Tested with the pruning of citrus trees (but of practical concern should branches bearing older buds be damaged), the age of the bud affects both the number of shoots, and the proportion of axillary shoots (Krajewski & Rabe, 1995). As these numbers are found to decrease with age, a set of particularly old buds would not only produce considerably fewer flowers, but consequently would have a much smaller statistical chance of early flowering (Krajewski & Rabe, 1995; Miller-Rushing et al., 2008a).

Whilst the findings of many of these studies on the controls of citrus flowering are inconclusive, they do provide insight as to possible internal factors which may control the timing of flowering. These internal factors are likely responsible for any shifts in flowering time which cannot be statistically accounted for by the climate variables included in such studies.

2.3. Climate Change in Iran

2.3.1 Introduction

There is considerable climatic variability both between and within countries in the Middle East, and Iran is no exception (Zhang et al., 2005; Tabari & Hosseinzadeh Talaee, 2011). The country is bordered in the north and south by the Caspian Sea and the Gulf of Oman respectively, and along the eastern and western boundaries by the countries Iraq and Turkey, and Pakistan, Afghanistan and Turkmenistan respectively (Nazemosadat & Ghasemi, 2004). Within the borders of Iran, climate is further influenced by the position and orientation of two mountain ranges: the Alborz to the north and the Zagros to the east (Nazemosadat & Ghasemi, 2004; Modarres & da Silva, 2007). The resulting shift from an arid interior plateau, to Mediterranean conditions in the south and sub-tropical conditions in the north, leads to considerable climatic variability across the country (Koocheki et al., 2006, Modarres & Sarhadi, 2009). This is manifested in contemporary diurnal temperature variations from sub-zero to 40°C in a day within the country, and a difference in mean annual rainfall of between 62.1mm and 1500mm (Koocheki et al., 2006; Modarres and da Silva, 2007). With 18.7 million hectares of agricultural land, and domestic agriculture currently supplying 80% of the Nations' food, any changes in this already highly variable climate have the potential to cause considerable damage, both to the economy and food security (Rajabian, 2005; Koockecki et al., 2006; Roshan & Grab, 2012).

This section of the literature review provides an overview of the current understanding of increasing climate variability and ongoing climate change in both Iran and the greater region of the Middle East, together with projections for future climatic conditions. The literature on climate variability and change for the region of the Middle East is presented first. This is followed by a presentation of the literature on the known climate variability and change experienced in Iran over recent decades, focussing specifically on the temperature and rainfall trends. This section then addresses the current projections for future climate change in Iran. Finally, it addresses the climate drivers responsible for both the past and future climate variability, examining the effect of the 500hPa trough, ENSO, desertification, and incoming solar radiation.

2.3.2 Climate Trends in the Middle East

Despite considerable climatic differences within the Middle East, common trends in anthropogenically induced climate change, particularly since the early 1970s, have been detected (Zhang et al., 2005; Tabari & Hosseinzadeh Talaee, 2011). A study examining the temperature and precipitation trends for 15 countries between 1950 and 2003, found increasing trends for annual maximum and minimum temperatures, the number of summer nights, and the number of days in which temperature exceeded the top 10th percentile; whilst decreasing trends were found for the number of days in which temperatures were below the 10th percentile, and for the temperature range (Zhang et al., 2005). For these 15 countries, a gradual reduction in the number of extreme cold days was found to have occurred since the 1970s, whilst the increase in the number of extreme warm days has been a more recent phenomenon, beginning in the early 1990s for all countries (Zhang et al., 2005). However, both within the countries studied, and averaged across them, there were no significant trends in precipitation, which is consistent throughout the Middle East (Zhang et al., 2005; Tabari et al., 2011a,b).

When examining individual countries in the central region of the Middle East, more variability becomes apparent. Hasanean (2001) found a positive trend in mean air temperature for Jerusalem (Israel) and Tripoli (Lebanon), whilst negative trends were observed for Amman (Jordan). For the neighbouring country of Turkey, significant increases in minimum temperatures were found for all seasons and all regions, with particularly strong increases in spring between 1930 and 1993 (Turkes et al., 2002; Turkes & Sumer, 2004). However, only very weak warming trends were recorded for maximum temperatures over the same period, resulting in a decrease in the diurnal temperature range for most regions of Turkey (Turkes et al., 1996; Turkes & Sumer, 2004). This decrease in the diurnal range has been attributed, in part, to the effect of urban warming (Turkes et al., 2002).

Similar findings have been observed for other Middle Eastern countries. A significant increase in minimum temperatures has occurred in Jordan since 1957; here too resulting in a decrease in the diurnal temperature range (Smadi, 2006; Hamdi et al., 2009). Whilst Smadi

(2006) argues that there has been some warming in daily maximum temperatures in Jordan since 1967, Hamdi et al. (2009) report no change in either daily maximum temperatures or rainfall in the country. This decrease in the diurnal temperature range is reported also for the western extremity of the Middle East, Egypt, for the period 1941-2002, with an additional interesting decrease in mean temperature in the north of the country and an increase in mean temperatures in the south (Domroes & El-Tantawi, 2005). Such results demonstrate an increase in climate variability. For both Egypt and Israel, temperatures have increasing trends in the summer months, and decreasing trends in the winter months, increasing the extremity of seasons (Ben-Gai et al., 1999; Domroes & El-Tantawi, 2005).

2.3.3 Climate Change in Iran over Past Decades

Both temperature and precipitation changes for Iran over the past few decades have been similar to those from the broader Middle Eastern region. Whilst there are very few clear trends for rainfall, temperature generally appears to be increasing (Raziei et al., 2005; Modarres & da Silva, 2007; Tabari et al., 2011b). However, due to considerable differences between microclimates, differences in the magnitude, strength and direction of trends occur between these regions (Soltani & Soltani, 2008; Tabari et al., 2011b).

2.3.3.1 Changes in temperature variables

In a study on temperature trends in the Middle East from 1950-1990, Nasrallah & Balling (1995) calculate a linear increase in mean temperature for Iran of 0.09-0.23°C/decade. The greatest warming has occurred in spring and the least in winter, with the most significant warming occurring since the 1970s (Nasrallah & Balling, 1995; Gholipoor & Sinclair, 2011; Tabari & Hosseinzadeh Talaee, 2011). However, this national average obscures the variability in results, both for average temperatures at different stations, and even more so for the trends in averaged minimum and maximum temperatures. In a study focussing on 30-year records from 34 meteorological stations across Iran, only 50% showed positive mean annual temperature trends, whilst a further 41% showed negative trends (Ghahraman, 2006). The maximum positive trends were found in arid, desert climates, whilst the weakest trends (no change) were found for cool, humid climates (Ghahraman, 2006).

Separating out the effects of minimum and maximum temperatures from the daily mean, the largest increase in maximum temperatures from 1966 to 2005 were found to have occurred in January, whilst the largest increases in minimum temperatures were in September (Tabari & Hosseinzadeh Talaee, 2011). There is contention as to the direction and uniformity of temperature changes: whilst Tabari & Hosseinzadeh Talaee (2011) report a strong increase in minimum temperatures across all seasons and in all 19 stations studied, Gholipoor and Sinclair (2011) report far more variable changes in minimum temperatures, with positive, negative and zero trends all appearing. Studying data from sites in the north-east of Iran for the period 1950 to 2004, Soltani and Soltani (2008) highlighted differences between Bojnord, where only an increase in minimum temperatures (0.29°C/decade) demonstrated a significant trend, Masshad where both minimum and maximum temperatures were found to increase significantly (0.45°C/decade and 0.24°C/decade respectively), with both the magnitude of change and the occurrence of increased daily temperatures attributed to the effect of the urban heat island, and Birjand where negative trends were found for both minimum and maximum temperatures (-0.23°C/decade and -0.26°C/decade respectively). The temperature decreases there were attributed to the prolonged drought in the nearby Sistan province, which resulted in an increased aerosol load and consequent cooling as a result of greater reflectance of insolation.

These differences in the direction, magnitude and statistical significance of changes in temperatures demonstrate no obvious spatial pattern, other than that of higher temperatures and lower diurnal temperature ranges being associated with large urban areas (Soltani & Soltani, 2008; Gholipoor & Sinclair, 2011; Tabari & Hosseinzadeh Talaee, 2011). However, if results are analysed by location as undertaken by Soltani and Soltani (2008), clear spatial patterns may appear. Whilst there are considerable differences between temperature trends in these regions, there is a positive evapotranspiration trend resulting primarily from rising temperatures rather than increased surface water availabiltiy (Tabari et al., 2011b).

2.3.3.2 Changes in precipitation

There is considerably more contention as to whether there have been any clear changes in precipitation in Iran over the past few decades, and if so, of what magnitude and direction. In a study on rainfall trends in Iran from 1965 to 2005, Raziei et al. (2005) found that whilst 60% of their studied sites showed no trends in precipitation, of the remaining 40%, many stations in arid and semi-arid areas showed negative trends in annual rainfall, but these trends were not statistically significant. Modarres and Sarhadi (2009) similarly found that annual rainfall had decreased at 67% of the 145 stations they studied across Iran, but that daily rainfall volumes had increased in 50% of stations, with a significant increase since the early 1970s. These increasing trends in daily rainfall volumes were found to predominantly occur at stations in the arid and semi-arid regions of Iran (Modarres & Sarhadi, 2009). These are broadly the same regions for which Raziei et al. (2005) reported decreasing trends in annual rainfall. Whilst this can be explained by a smaller annual precipitation volume occurring in fewer, more intense storms, further contradiction exists for the majority of stations (67%). Here Modarres and Sarhadi (2009) found decreasing rainfall trends, which are located in the sub-tropical north and northwest of the country, rather than the arid to semi-arid regions. Raziei et al. (2005) found the strongest decreasing trends in annual rainfall for the northeast of the country, a region for which Soltani and Soltani (2008) found no statistically significant trends in rainfall.

Claims of no clear trends in precipitation arise both from poor trends and from equal numbers of contradicting trends. This is the case with Tabari et al (2011a), who report increases in precipitation for stations in Jask, Saghez and Sanandaj, whilst decreasing trends are calculated for Abadan, Ahwaz and Hamedan. For the remaining stations, trends were weak and statistically insignificant (Tabari et al., 2011a). Similar mixed trends of increasing and decreasing rainfall between spatially unrelated stations are reported by Modarres and da Silva (2007). No significant variations in rainfall were reported by Soltani et al. (2012), however, without clearly stating which years were studied, and whether the same years were used for each station.

Whilst annual trends in precipitation are at best uncertain, and in some cases contradictory, there may be sub-annual trends in rainfall of greater significance (Modarres & da Silva, 2007; Soltani et al., 2012). There appears to be a far more significant seasonal shift in rainfall concentration to winter and spring, but with particular increases in rainfall in July (Modarres & da Silva, 2007; Soltani et al., 2012).

2.3.4 Climate Change Projections for Iran

Projections developed from 18 climate models, using the historical data for 36 Iranian weather stations for the period 1968 to 2000, suggest mean temperature increases of 2.7°C and a 12% decrease in rainfall by 2050 (Koocheki et al., 2006). Projections to the end of the century, based on a similar set of 20 climate models from data for the period 1961 to 1990, present an increase in temperatures for all regions of Iran, with a magnitude of up to 4.25°C by 2100 (Roshan & Grab, 2012). However, in contradiction to Koocheki et al.'s (2006) 2050 projections of decreasing rainfall, Roshan and Grab (2012) present predictions of a rainfall increase of 36% by 2100. These rainfall increases were qualified as being limited to autumn and winter, whilst spring rainfall has a projected decrease of ~33% by 2100, and must be taken with caution given the errors and uncertainties associated with projections made that far into the future (Roshan & Grab, 2012). For autumn, winter and spring (the seasons critical to the growth of wheat), the focus of that particular study, Roshan and Grab (2012) model temperature increases to be most extreme in arid regions (1.19°C by 2025, 4.32°C by 2100), and least extreme in humid regions (0.82°C by 2025 and 3.69°C by 2100). This is in agreement with the historical trends in temperature reported by Ghahraman (2006).

For the greater region of the Middle East, temperature increases of 1.4°C are projected for the mid-21st century (2045-2054) and 4°C by the late 21st century (2090-2097), together with rainfall decreases over these periods (Evans, 2009). These temperature increases are projected to be most extreme in inland regions, with the east Mediterranean and Black Sea regions projected to experience temperature increases of 2°C less than that for the adjacent interior, whilst the Persian and Gulf Seas are projected to experience even less warming (Evans, 2009). For countries with a Mediterranean climate, such as Iran, there is a projected shift in the timing of maximum precipitation towards November due to a decrease in mid-latitude cyclone storm tracks over the Mediterranean, resulting from shifts in the Inter-Tropical Convergence Zone (ITCZ) (Evans, 2009). These changes in the timing of precipitations are consistent with, albeit slightly lower than the projections for Iran.

The projected changes in precipitation and temperature have been argued to result in a decrease of 170 000 km^2 of viable rain-fed agriculture across Israel, Lebanon, Syria, Iraq and Iran (Evans, 2009). This is consistent with the projections by Roshan and Grab (2012), who calculated that 55% of current wheat producing regions in Iran will require irrigation by 2050, and 77% of these regions by 2100. Koockecki et al. (2006) highlighted potential threats to agriculture; whilst they projected that the length of the growing season would increase by up to 16 days due to a shortening of the frost period, this was concurrent with an increase in the length of the dry period by up to 22 days. Similar projections of decreases in crop production by between 5-40% by 2080 were presented by Rosenzweig and Parry (1994), resulting from decreases in the feasible crop growth period in Iran. These projections depend on whether rainfall will in fact decrease, and in which seasons. The precipitation changes indicated in these projections are not likely to benefit agriculture in Iran or the Middle East (Koocheki et al., 2006; Evans, 2009; Roshan & Grab, 2012).

2.3.5 Climate Drivers in Iran

Whilst these historical climate records are analysed, and climate projections are made, taking into account climate influences and driving factors such as the distance from large water bodies, the location and orientation of mountain ranges, wind and pressure systems, and the existing climate conditions, there are additional factors which influence climate variation in Iran, and which are likely to continue to do so over the century to come (Koocheki et al., 2006; Modarres & Sarhadi, 2009; Gholipoor & Sinclair, 2011). Literature on these includes the effects of variations in the 500hPa flow patterns, the role of desertification, El Niño Southern Oscillation (ENSO), and solar irradiance.

2.3.5.1 500hPa Circulation

Located in the mid-latitudes, Iran is affected by troughs and ridges in 500hPa circulation developed by westerlies (Alijani, 2002). The formation of 500hPa troughs causes an intrusion of cold air, which results in instability and hence precipitation, together with the cooler temperatures (Alijani, 2002). By contrast, ridges are associated with the introduction of warm, southerly air and hence local temperature increases (Alijani, 2002). Three 500hPa troughs potentially influence the climate of Iran during winter months: the Caspian trough influencing central and eastern Iran; the Mediterranean trough influencing northeast Iran; and the Syrian trough influencing western Iran. These troughs have considerable potential for inducing climate variability, both between regions, and inter-annually (Alijani, 2002). The direction of flow of these 500hPa troughs has the potential to influence climate; north-westerly movement reduces precipitation and temperatures, whilst south-westerly movement increases precipitation and temperature (Alijani, 2002). In isolation, the behaviour of these 500hPa troughs has little explanatory power, however, they should be considered in conjunction with other climate drivers in both historical climate studies and in the development of future projections (Alijani, 2002).

2.3.5.2 The Impact of Desertification

Nasrallah and Balling (1995) argued that the increasing desertification in Iran over the last few decades has been responsible for warming, and that it is likely to continue to increase warming patterns in years to come. By means of regression analysis, it was argued that desertification over the period of 1950-1990 accounts for 30% of the 0.07°C/decade warming trend over this period (Nasrallah & Balling, 1995). They further suggested from the intercept of their regression slope, that without the desertification over these four decades, temperatures would have been 0.03°C cooler (Nasrallah & Balling, 1995). However, this contradicts an analysis of the role of desertification on local atmospheric temperatures through increasing the aerosol content and consequently increasing the near-surface albedo, the proportion of reflected radiation, and hence cooling temperatures (Charney, 1975; Soltani & Soltani, 2008). Whilst Nasrallah and Balling (1995) contest the argument of Charney (1975), sufficient empirical evidence from both Iran and elsewhere in the world dispel desertification as a factor for warming temperatures (Kosmos & Danalatos, 1994; Soltani & Soltani, 2008; White et al., 2009; Blanc, 2012). However, its role in suppressing temperature increases, or even decreasing temperatures at a local scale should be taken into account, particularly in an arid region prone to desertification.

2.3.5.3 El Niño Southern Oscillation (ENSO)

A third climatic driver responsible for inducing increasing climate variability in Iran is that of the ENSO. Whilst not located in the Pacific equatorial region, there is a relatively strong negative relationship between the Southern Oscillation Index (SOI) and rainfall in Iran (Nazemosadat & Ghasemi, 2004). The SOI is projected to increase in strength with the latitudinal increase of the ITCZ (Nazemosadat & Cordery, 2000; Nazemosadat & Ghasemi, 2004; Evans, 2009). The effect of the ENSO is greatest in autumn, and lower but still significant for the winter, and is responsible for extremes in rainfall with the potential of drought in La Niña periods and floods in El Niño periods (Nazemosadat & Ghasemi, 2004). El Niño periods are associated with a decrease in the occurrence of drought, and increased intensity of precipitation, especially in the southern regions, whilst La Niña conditions are associated with a low chance of precipitation and the potential for severe autumn drought (Nazemosadat & Ghasemi, 2004).

The strongest relationships between rainfall and the SOI in Iran were found for the southern foothills of the Alborz Mountains, the north-western regions and the central plateau, with very little impact on the remainder of the country (Nazemosadat & Cordery, 2000). Even in these regions for which precipitation quantity and intensity is influenced by ENSO, the associated changes in equatorial pressure have no effect on the pressure or wind systems in Iran (Nazemosadat & Cordery, 2000).

2.3.5.4 Solar Irradiance

The fourth climate driver which contributes to past climate variability and induces greater variability under climate change is the amount of incoming solar radiation (Ashjaee et al., 1993; Samimi, 1994; Ohashi et al., 2011). Driven by non-climate related factors such as the time, date, latitude, altitude and azimuth angle, both the number of sunshine hours and the amount of solar radiation received at ground level are affected by climatic factors such as the amount and density of cloud cover, the percentage water vapour, and air temperature (Ashjaee et al., 1993; Siebert & Ewert, 2012). Consequently, changes in these factors have the ability to cause changes in the radiation received, which impacts on both temperature and evaporation (Ashjaee et al., 1993; Samimi, 1994). With projected changes in rainfall for Iran during the century to follow, it may imply considerable changes in the amount of solar radiation received (Koocheki et al., 2006; Evans, 2009).

2.4 Conclusion

The phenology section of this literature review has highlighted the extent to which the phenological responses of plants and animals to climate are specific at both the species and location level. Consequently, to better realise the extent to which increasing climate variability and ongoing climate change is impacting on a phenological event, the plant or animal species and their ecosystems, it is necessary to study as many species in as many locations as possible. Whilst satellite imagery allows for large regions to be studied, ground level observations are currently more accurate, and as they are recorded at a species scale, are more closely aligned with achieving this goal. Whilst it then is necessary to study tropical and polar regions together with more temperate mid-latitudes, a study aimed at determining the impact of climate variability and change on a species is likely to best achieve this through an initial understanding of the response in a highly seasonal location with little impact from unaccountable factors such as snow melt. Such a study is better suited to perennial fruit trees rather than annual crops, and obtains the most accurate representation of the climate impact if focussed on spring events, particularly flowering. With very few studies having been undertaken on the phenological response of citrus to increasing climate variability and ongoing climate change, and none of a sufficient time period to detect statistically significant relationships, this study would serve to fill this gap in the literature. Furthermore, with phenology studies in Iran only having taken place over the last five years, this study should further contribute to this locational gap in the global compendium of studies.

Chapter 3

STUDY SITE

[3]

3.1 Introduction

This study on the phenological response of citrus flowering to climate variability and change in Iran from 1960 to 2010 focuses specifically on commercial citrus gardens in the cities Gorgan, Kerman and Shiraz. Averages of both climate and flowering dates were provided from each of the gardens in each of these three cities for all five studied citrus types viz. orange, tangerine, sweet lemon, sour lemon and sour orange. This allows for a comparison of response of each citrus type in each city, in addition to between cities. A discussion on the data used, its collection, and the gardens from which they originate, can be found in *Chapter 4*. What follows in this chapter is a description of the greater study region of Iran, and the specific cities of interest, with a particular focus on the contemporary climate, climate variability and climate drivers of these regions.

3.2 The Islamic Republic of Iran

3.2.1 Basic Geography

Iran covers a terrestrial area of 1 648 000km^2, bordering Pakistan and Afghanistan to the west; Turkmenistan, Azerbaijan and Armenia to the north; and Turkey and Iraq to the east (Nazemosadat & Ghasemi, 2004; Farmazi, 2010; Fast, 2010; *Figure 3.1*). Approximately half of this land area is mountainous, with the Zagros Mountain range extending along the west of the country whilst the Alborz Mountains are located in the north, surrounding the interior highlands plateau (Gholipoor, 2008; Mostafa, 2008). Consequently, there is a considerable altitudinal range from -20masl in the Caspian Lowlands to 5860masl in the Alborz Mountains (Mostafa, 2008; Faramazi, 2010; Rasuly et al., 2012). The country borders large water bodies with the Caspian Sea to the north and the Gulf of Oman to the south (Rajendra et al., 2003; Haftlang, 2003; *Figure 3.1*). It is also in relatively close proximity to the Mediterranean Sea to the west, the Black Sea to the north-west, the Red Sea to the south-west and the Arabian Sea to the south (Rajendra et al., 2003; Haftlang, 2003; Kehl, 2009).

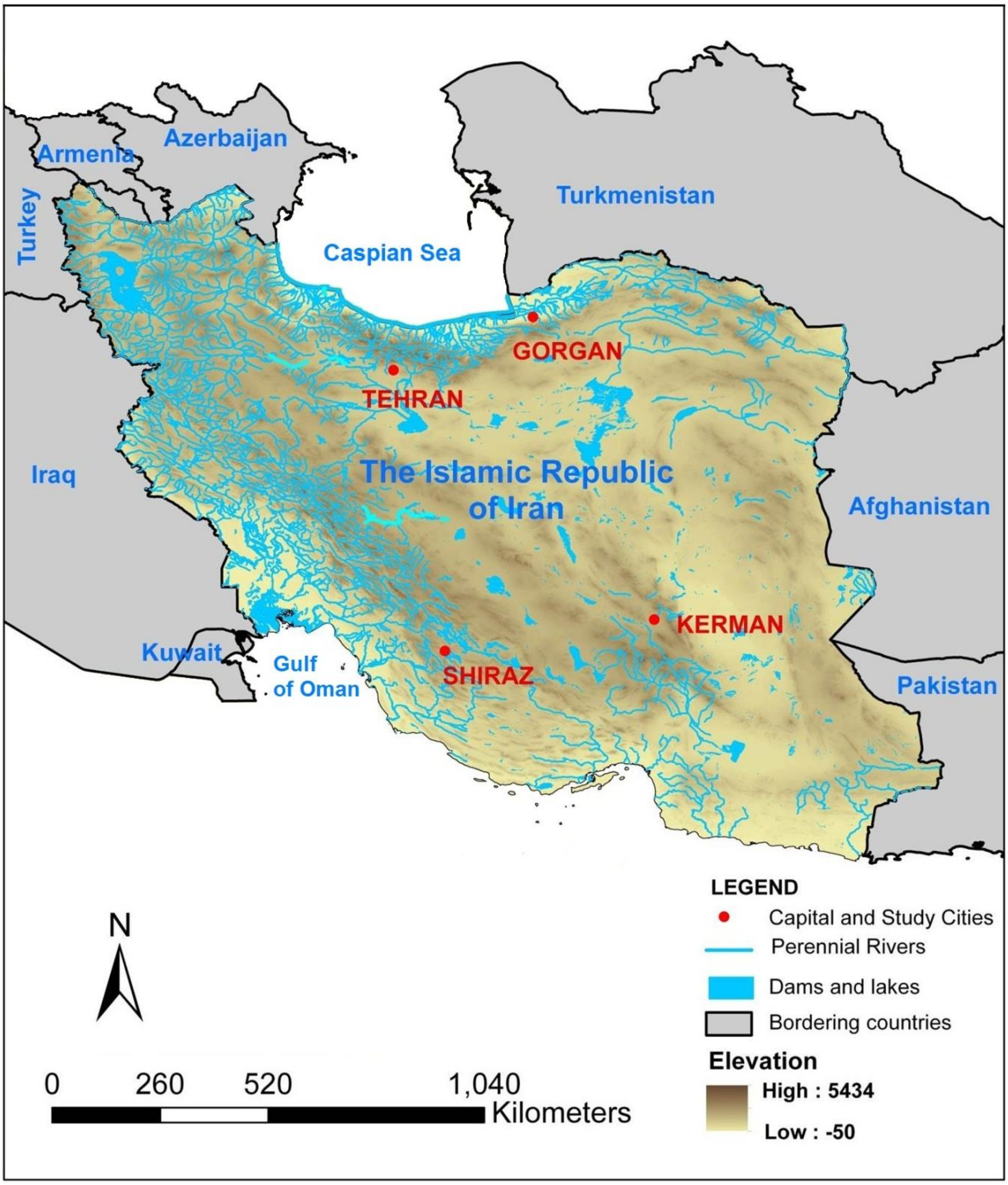

Figure 3.1: Map indicating the location of the three cities which provided citrus flowering and climate data for this study, together with Tehran, the Capital Iran.

This scattered relief, together with the country's position in the Northern Temperate Zone in the mid-latitude belt, results in Iran receiving less than one third of the world annual mean precipitation, and hence being classified as one of the drier regions of the world (Haftlang, 2003; Modarres & Da Silva, 2007; Mostafa, 2008). Despite complex physical geography and considerable climatic variability, the country experiences a predominantly

Mediterranean climate with winter rainfall in all three study cities, governed by the Siberian High, Westerly Depressions and South Westerly Monsoon (Kehl, 2009). The natural vegetation is predominantly thorn and shrub steppe, with little to no vegetation in the desert and high altitude mountainous regions (Rajendra et al., 2003). However the Caspian and Zagros forests have far greater species diversity, including significant populations of elm, maple, oak, walnut, pear and pistachio trees, together with ferns and shrubs (Rajendra et al., 2003).

3.2.2 Climate

Iran can predominantly be categorized as an arid to semi-arid environment, with over 60% of the country experiencing precipitation of less than 50-350mm annually (Modarres & da Silva, 2007; Kehl, 2009; Faramazi, 2010). The dry climate is predominantly the result of a combination of intense solar radiation causing high evaporation rates, dominant north-easterly and north-westerly winds which transport dry air masses across the interior, and the position of the two mountain ranges (Kehl, 2009). These mountains result in the convection of moisture laden air and consequently precipitate out over the Caspian Lowlands, the north-western foothills of the Zagros Mountains, and the northern foothills of the Alborz Mountains (Kehl, 2009). Precipitation varies from over 1800mm over the west Caspian Lowlands to less than 50mm over the eastern inland desert regions (Nazemosadat et al., 2006; Rasuly et al., 2012). Precipitation generally decreases from west to east across the country, with the highest precipitation in the northern Caspian Lowlands where considerable precipitation occurs in both summer and winter (Rajendra et al., 2003). In contrast, and given the lack of moisture over the interior, clear skies prevail across the majority of Iran for most of the year (Rajendra et al., 2003). With a predominantly Mediterranean climate, the rainfall occurs between October and March for 70% of the country, with winter rainfall occurring in light showers (Rajendra et al., 2003; Nazemosadat et al., 2006; Kehl, 2009; Rasuly et al., 2012). While rainfall occurs year round in the Caspian Lowlands, the highest rainfall occurs in late winter to early spring (Rajendra et al., 2003; Nazemosadat et al., 2006).

The north-easterly and north-westerly winds which are responsible for the orographic precipitation on the northern foothills of the Zagros and Alborz Mountains develop in summer as a result of a considerable pressure gradient which develops between the Siberian High located to the north of Iran and the strong heat low over the interior of Iran (Kehl, 2009; Rasuly et al., 2012). From October to April, this is replaced by the predominant westerlies which move south as a result of the shift in the Inter-Tropical Convergence Zone (Kehl, 2009). Inter-annual variability in winter precipitation volume occurs as a result of varying numbers of mid-latitude cyclones reaching the northern Iranian coastline, their strength allowing moisture to progress into the interior (Modarres & Da Silva, 2007). Longer term variability in rainfall can be attributed in part to ENSO cycles, with El Niño years being associated with above average precipitation in the north, and even greater increases in the south, whilst below average precipitation occurs during La Niña years (Nazemosadat et al., 2006).

Temperature in Iran varies considerably, from winter temperatures as low as -20°C to summer temperatures reaching 50°C (Ghasemi & Khalili, 2008). Within the winter months alone, there is up to a 20°C difference between the minimum temperatures in the coldest high altitude alpine regions to the warmer regions in the northern Caspian Lowlands and the lower latitude southern regions (Faramazi, 2010). Temperature differences are largely influenced by the considerable differences in both latitude and altitude across the country, while differences in both seasonal and diurnal ranges are controlled by proximity to moderating water bodies to the north and south of the country. The greatest temperature ranges are found in the inland desert regions where the extremely low humidity prevents heat storage.

Similar to precipitation volumes, winter temperature can be influenced by the number and strength of mid-latitude cyclones reaching Iran. Further variability in temperatures can be explained by large scale forcing mechanisms. Winter temperatures in Iran correlate negatively with both the Atlantic Oscillation (AO) and the North Sea-Caspian Pattern (NCP) for most regions (Ghasemi & Khalili, 2006; Ghasemi & Khalili, 2008). The AO refers to the pressure difference fluctuation between the Arctic base and the mid-latitudes (Ghasemi and

Khalili, 2006). Winter temperatures are negatively correlated with the winter AO for most of Iran, including the three cities in this study (Shiraz: r = -0.49; Kerman: r = -0.49; and Gorgan: r = -0.34), with a positive correlation for the warmest regions of the Caspian Lowlands (Ghasemi and Khalili, 2006). Winter AO accounts for 14-46% of the variability in winter surface temperatures across Iran, while the summer AO statistically explains 25-32% of the variability in winter temperatures (Ghasemi & Khalili, 2006). The NCP, which refers to the 500hPa pressure difference between the North Sea and the Caspian Sea, provides for significant negative correlations with the winter surface temperatures across all regions of Iran, particularly in association with the AO (Ghasemi and Khalili, 2008).

3.2.3 Agriculture

One third of the terrestrial area of Iran is potentially arable farmland, yet far less is actually cultivated due to poor soil, limited water availability, and both minimum and maximum temperature constraints (Gholipoor, 2008; Mostafa, 2008). Currently agriculture comprises 12% of the land use in Iran, covering an area of approximately 123 000km^2, of which 60% is used for cultivating wheat, and a further 27% barley, rice and maize (Atieh Bahar, 2008; Boshrabadi et al., 2008; Faramazi, 2010). Agriculture is responsible for 90% of the freshwater demand in Iran, with the cultivation of cereals responsible for 70% of this agricultural water consumption (Gholipoor, 2008; Faramazi, 2010). This high water demand is predominantly a result of low water efficiency through poor irrigation design, maintenance and operation, together with the negligible cost of water in the country, but is also due to the low water availability with the Caspian lowlands being the only region with sufficient precipitation for non-irrigated agriculture (Rajendra et al., 2003; Faramazi, 2010).

Agriculture currently accounts for 13% of Iran's gross domestic product and 20% of its employed labour (Atieh Bahar, 2008). Whilst the majority of the agricultural sector in Iran is involved in the cultivation of cereals, the country also cultivates pistachio, pomegranate, sugar cane and citrus, predominantly for local consumption (Rajendra et al., 2003; Atieh Bahar, 2008; Boshrabadi et al., 2008). Although Iran is not one of the top world citrus exporters, it is currently ranked 8th in world citrus production, with total yields of 3 500 000 tons in 2009/2010, and an average of 3 533 000 tons for the period 2001-2010 (CGASA, 2011).

3.2.4 Environmental Issues

The greatest environmental concerns in Iran are those of water scarcity and drought (Rajendra et al., 2003; Farmazi, 2010). Iran has very little access to freshwater which, combined with low rainfall and high evaporation rates, results in a critical water shortage. The current annual per-capita water availability for Iran is 2 000m^3, compared with the global mean of 7 000m^3 (Faramazi, 2010; Yaramousi, 2010). Due to increased population growth and the effects of climate change, however, it is forecast to drop to less than 1 500m^3/capita/yr by 2030 (Farmazi, 2010; Parish et al., 2012). Historically, qanāts have been used to transport water into the large urban areas, but more recently dams have been constructed to compliment this system and improve water security (Beckett, 1966; Rajendra et al., 2003). However, where natural droughts occur, not even these qanāts and dams are able to relieve both the household and agricultural water shortages (Rajendra et al., 2003).

An additional environmental concern is the increasing problem of land degradation, which is occurring as a result of the combination of excessive land use and the water shortage (Modarres & da Silva, 2007). A third factor of increasing concern is that of air pollution, particularly in the large urban centres where industry is continuing to grow while personal fossil fuel burning for transport and heating continues (Rajendra et al., 2003).

3.3 Gorgan City

Located in northern Iran, 30km south of the Caspian Sea and at an average altitude of 0 masl, Gorgan is situated in the south Caspian Lowlands, and consequently has a semi-humid, mild Caspian climate (Haftlang, 2003; Asady & Sharifan, 2009; Kehl, 2009). Ranked as the 23rd largest city in Iran, with a population of 343 977 and an area of 40km^2, Gorgan is the smallest of the three study cities. With the highest precipitation volumes in the country, and significant precipitation even in summer, temperature is the limiting factor for agriculture in the Caspian Lowlands. However, whilst Gorgan, located in the east of this region, receives considerably less precipitation than the annual average of over 1 800mm for Anzali Port to the west, it is the warmest city in the region, and hence is well suited to agriculture (Haftlang, 2003; Kehl, 2009). The particularly high temperatures in Gorgan are a consequence of its proximity to both the warm current from the Caspian Sea and the Turkmen Desert to the east (Haftlang, 2003). The high surface temperature influences even the deep level soil temperature in Gorgan, which, together with the direct influence of air temperature on plant species, results in a projected future warming of as little as 1°C resultant in shifts in forest species to altitudes 100m higher (Sharifan et al., 2010). The highest precipitation volumes occur during late winter to early spring, but the proximity to the warm Caspian Sea results in year round high humidity (Haftlang, 2003; Asady & Sharifan, 2009).

3.4 Kerman City

The city of Kerman, located in the north-east of Kerman Province, is situated south-west of central Iran, on the central plateau which forms the Iranian highlands (Boshrabadi et al., 2008; Kehl, 2009). At an altitude of 1 755 masl, typical for that of the central plateau, Kerman is at the highest elevation of the three study cities (Beckett, 1966). The Province of Kerman's location on the central plateau, with the Alborz Mountains blocking the Caspian Sea to the north and the Zagros Mountains obstructing moisture from the Gulf of Oman to the south, results in a very arid climate, with the lowest precipitation in Iran (Beckett, 1966; Haftlang, 2003; Moazallahi & Farpoor, 2009). With the highest rainfall in Kerman Province, Kerman city has a climate which borders on semi-arid, and although associated with considerable rainfall variability, nevertheless has the lowest precipitation of the three cities (Beckett, 1966; Atapour & Aftabi, 2002; Modarres & da Silva, 2007). As is the case for the majority of Iran, the precipitation which does fall, occurs during the winter months (Rajendra et al., 2003; Haftlang, 2003). As a result of the low humidity and the considerable distance from large water bodies which would have a moderating effect, both the diurnal and seasonal temperature ranges are particularly high, with notably hot summers and cold winters (Beckett, 1966; Atapour & Aftabi, 2002; Haftlang, 2003). In addition, Kerman city has the greatest number of freeze days of the three study cities (Boshrabadi et al., 2008). With a population of 621 374 people and an area of 85km^2, Kerman is the 12th largest city in Iran, and the second largest of the three study cities.

3.5 Shiraz City

At an altitude of 1 484masl, Shiraz is located in the south eastern foothills of the Zagros Mountains, in the western region of the Iranian highlands (Kehl, 2009). It is classified as a semi-arid region, with an average of 42 wet days per year and an annual rainfall of approximately 300mm (Modarres & da Silva, 2007; Gholipoor, 2008). With a winter precipitation regime similar to that of Kerman and much of Iran, Shiraz has considerable seasonal climate variation as a result of orographic influences (Haftlang, 2003). The climate is broadly cool and humid for November to March, whilst the spring to autumn months of the year experience a typically desert climate (Shakoor et al., 2008). Shiraz has the warmest temperatures in its region, with a mean annual temperature of 17.8°C, and a temperature profile which can be described as predominantly mild mountainous (Haftlang, 2003; Gholipoor, 2008). Shiraz is the 5th largest city in Iran with a population of 1 549 453 people, and covering an area of 225km^2, which is considerably larger than the other two cities in this study.

3.6 Geographic Summary for the Three Cities

A climatic and geographic summary of the three study cities is presented in *Table 3.1*. There is a 1 755m difference in altitude between Gorgan in the Caspian Lowlands and Kerman in the Iranian Highlands. Gorgan has the highest annual precipitation at 601mm, whilst Kerman has the lowest at 142mm. Whilst Gorgan has the highest average annual temperature, it is only 0.3°C higher than that for Shiraz. With the influence of the moderating effect of the Caspian Sea, Gorgan has the lowest annual average diurnal temperature range, whilst Kerman, located on the Central Plateau, has the largest annual average diurnal temperature range.

Table 3.1: Summary of the geographic and climate statistics for three target cities in Iran.

	Gorgan	Kerman	Shiraz
Co-ordinates	36°50′N	30°17′N	29°37′N
	54°26′E	57°05′E	52°32′E
Altitude	0masl	1 755masl	1 488masl
City area	40km^2	85km^2	225km^2
Population	343 977	621 374	1 549 453
Annual Average Tmin	12.73°C	6.28°C	9.19°C
Annual Average Tmax	22.74°C	24.38°C	25.62°C
Average Annual Temperature	17.7°C	15.3°C	17.4°C
Annual Rainfall	601mm	142mm	305.6mm

Based on the regional temperature and rainfall variation across Iran, the country has been broadly divided into four climatic regions by Ghahraman (2006); Steppe, Desert, Temperate Humid and Cool Humid (*Figure* 3.2). According to these divisions, the city of Kerman would be classified as *Desert*, whilst Gorgan and Shiraz both fall within the classification of *Temperate Humid.*

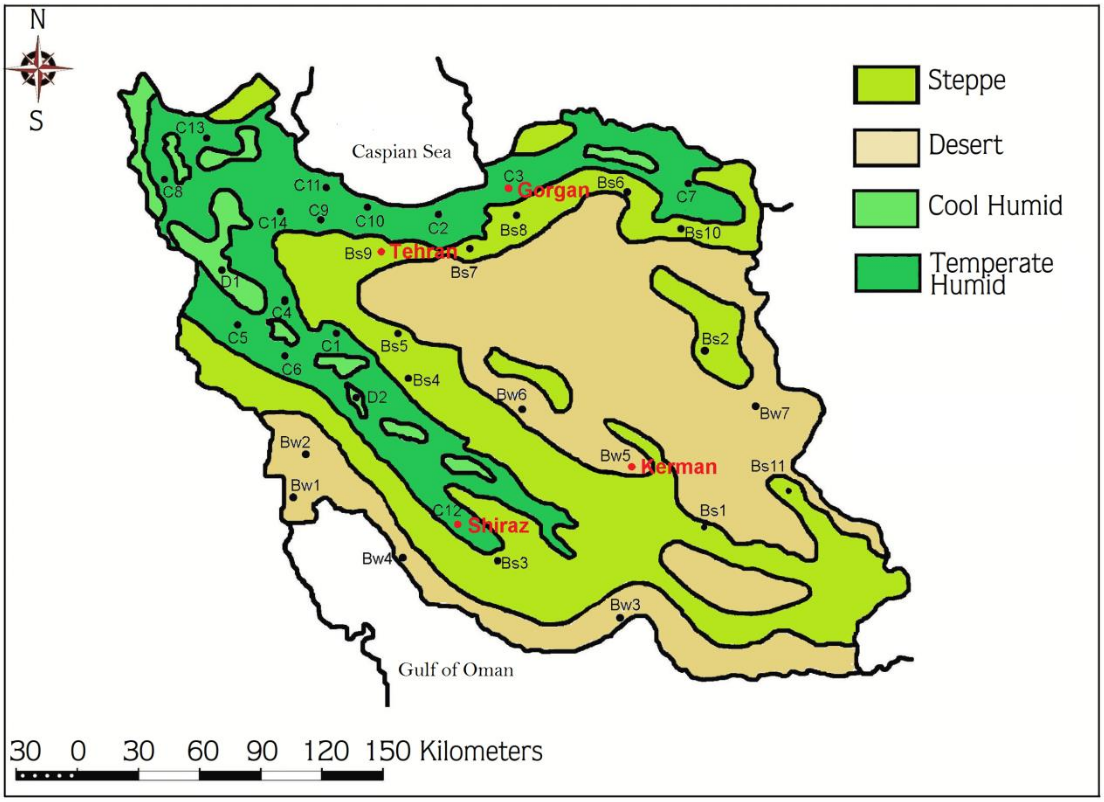

Figure 3.2: Map classifying Iran into four major climate-based biomes. All meteorological stations used in the classification indicated, meteorological stations used in this study highlighted in red (after Ghahraman, 2006).

Chapter 4

DATA & METHODOLOGY

[4]

4.1 Introduction

The broad aim of this study is to contribute to the existing collection of research into the phenological response of plant species to increasing climate variability and ongoing climate change, which are summarised in Table 2.1. The focus is on a species group and region which have received little attention to date, and hence the approach to data acquisition and methodology are largely consistent with this larger body of research. This involves the acquisition of both a phenology and a meteorological dataset which spans a period of at least three decades; statistical analysis of temporal trends of phenological events and climate variables over the study period; and the subsequent analysis of the relationships between these climatic variables and the phenological events, so as to determine the likely associations involved.

This chapter outlines the procedure of data acquisition for this study, followed by information on both the phenological and the climate data which were acquired. This is followed by a discussion on the methodology used to determine these trends and relationships between phenological and climatic variables.

4.2 Data

4.2.1 Data Acquisition

As phenological studies predominantly aim to explore the changes in the timing of annual plant and animal events in response to climate variability and change, they require the analysis of biological records with a comparative dataset of daily weather records for a period of at least 30 years. Consequently, such research comprises desktop statistical studies, and relies on the acquisition of a reliable, continuous record of both phenological events and climate variables spanning a multi-decadal period. Given that daily weather and long-term climate records exist for most regions of the world, extending back to at least the start of the 20th Century, it is rather the absence of long-term phenological records which limits such research.

The scarcity of phenological data, and hence phenology studies, for the Middle East region makes Iran an ideal focus region for climate change and crop response research, provided that suitable data are available. A dataset on the flowering dates of five citrus types for three cities in Iran was acquired through a collaborative project set up between Dr Reza Roshan (University of Golestan, Iran) and Professor Stefan Grab (University of the Witwatersrand, Johannesburg). This 51-year continuous dataset, for three citrus-producing cities, was acquired from the Iranian botanical data collection company Mohit Sabz, whilst climate data (temperature, rainfall and sunshine hours) were obtained for each target city (Gorgan, Kerman and Shiraz) from the Iranian Meteorological Association for the same period. It is fortuitous that these Iranian data are for a robust phenological subject and phase (peak flowering), and cover a sufficient temporal period of greater than 30 years, to facilitate for the study of the flowering dates of deciduous fruit species in three locations.

4.2.1.1 Phenological Data

The phenological data for this study comprise the 85% (peak) bloom dates for each of the five citrus types: orange, tangerine, sweet lemon, sour lemon and sour orange, for the cities of Gorgan, Kerman and Shiraz. These fruit trees, all of which are members of the *Citrus* genus, are a group which includes both species and hybrids (*Table 4.1*). For the purpose of this study, to maintain consistency, these species and hybrids will be referred to commonly as 'citrus types'. Within these species and hybrid groups are numerous varieties, which are particularly adapted to specific micro-climates. Thus whilst all five citrus types are cultivated in each of the gardens in each of the cities, it is likely that each of the gardens cultivate different varieties for at least some of the citrus types. Information of the cultivars for these individual gardens and cities is not available, but the likely differences in cultivars should be considered when comparing results for each of the cities. The sour orange citrus type is cultivated most abundantly, whilst the least abundant is sour lemon (*Roshan, 2012 pers comm)*.

Table 4.1: Scientific name, classification and known cultivars of the five citrus types of interest in this study. Local varieties indicated by an asterisk (after Ebrahimi, 2002; Bitters, 2006).

Common Name	Scientific Name	Classification	Known varieties in Caspian Lowlands	Known varieties in Iranian Plateau
Orange	*Citrus x sinensis*	*Citrus 75eticulate* hybrid	Washington Navel, Thomson, Moro blood, Hamlin, Local seedy*, Marrs	Washington Navel, Moro blood, Local seedy*, Marrs, Valencia
Tangerine	*Citrus x tangerine*	*Citrus 75eticulate* hybrid	Satsuma Owari, Satsuma Wase, Clementine, Younesi, Page	Tancrine, Bam no.1*, Orlando Tangelo, Siahoo*, Clementine, Kinnow
Sweet Lemon	*Citrus limetta*	*Citrus* species	Mediterranean sweet lemon	Mediterranean sweet lemon, Local south*
Sour Lemon	*Citrus x limon*	*Citrus medica* hybrid	Eureka, Lisbon	Eureka, Lisbon
Sour Orange	*Citrus x aurantium*	*Citrus 75eticulate* hybrid	Salustiana	Seville

For the purpose of consistency when making comparisons between phenology studies, the BBCH code is commonly used in the characterization of phenological events; with a value from 0-100 ascribed to each annually repetitive primary event, in order of occurrence and with the grouping of secondary events within segments of 10, such as 60-69 for flowering (van Vliet et al., 2003; Kalbarczyk, 2009; Morisette et al., 2009). The 85% bloom stage for citrus is classified as BBCH 66 (Meier, 2001; Kalbarczyk, 2009). The data for all three cities are currently administered by a private company, Mohit Sabz (trans. *Green Environment*), which took over from the former company, Toseyay Keshavarzy Iran (trans. *Iran Agricultural Development*) in 1990 (*Roshan, 2012 pers comm)*. Mohit Sabz receives records collected by farmers from each of the gardens in these cities, and archives average dates for each city, every year, at their offices in Tehran (*Roshan, 2012 pers comm)*. They act as a small phenological network, collecting and storing data predominantly from three to four government owned gardens in each city (see for example *Figure 4.1*).

Figure 4.1: Photograph of a citrus orchard in 'South of Kerman Garden', Kerman City, Iran (after Adeli, 2011).

The observations in these gardens are made by the farmers responsible for their citrus cultivation, and are conducted every day during the growing period, in either the morning or afternoon. Averaging the data for each city facilitates archiving, and eliminates some of the noise in the dataset which occurs through the different locations of each of the gardens within the city, and from variability resulting from subjective observation (*Roshan, 2012 pers comm)*. The management, size and citrus types cultivated in these gardens have remained consistent over the period of this study. Details of the individual gardens are presented in *Table 4.2*.

Table 4.2: Details of the citrus gardens in Gorgan, Kerman and Shiraz.

City	Garden name	Garden area (m^2)	Location
Gorgan	Baghe Agha Mohammed Khanei	34 439.63	36°50’18”N, 54°25’55”E
	Baghe Tarikhy Gorgan	68 645.82	36°50’36”N, 54°26’28”E
	Baghe Manabe Tabei Gorgan	36 706.25	36°50’15”N, 55°26’05”E
Kerman	South of Kerman Garden	41 229.20	30°16’44”N, 57°04’07”E
	Vakil Abad	24 561.00	30°17’27”N, 57°05’53”E
	Shazdeh	47 427.70	30°01’24”N, 57°16’54”E
Shiraz	Eram Garden	122 908.03	29°38’09”N, 52°31’31”E
	Delgosha Garden	56 407.92	29°37’09”N, 52°34’29”E
	Naranjestan Garden	3 051.60	29°37’44”N, 52°33’30”E
	JahanNama Garden	82 648.52	29°36’28”N, 52°33’09”E

The phenological data are recorded according to the Persian calendar, and are archived in Persian text. These data were translated into English for the years 1960-2008 through the University of Golestan, under the supervision of Dr Roshan, and the dates converted to the Gregorian calendar. The data were then checked to ensure that no obvious errors in translation had occurred. For the years 2009-2010, the data presented had been translated to English, but the flowering dates were provided in Persian Calendar days. Conversion to the Gregorian calendar for these two years was undertaken manually through the comparison of each date from Persian and Gregorian calendars. Finally, dates were converted to Julian Dates (JD) – the day of the year starting from the first of January, for ease in statistical analysis. The conversion of the Gregorian dates to the Julian Date of the year, was undertaken through the use of “Day of Year (DOY)” tables for leap years and non-leap years, such as that published by NASA (Gordo & Sanz, 2006; Kempler, 2011; Luedeling & Gassner, 2012).

4.2.1.2 Meteorological Data

Daily weather records for the period 1960-2010 constitute the climate data for this study and were recorded at weather stations in each of the three cities within a maximum distance of 15km from each of the gardens (*Roshan, 2012 pers comm)*. The data are collected, stored and distributed by the Iranian Meteorological Association, and are provided in English and in Gregorian calendar format, thus requiring no translation. The data include continuous daily maximum and minimum temperatures (T_{max} and T_{min} respectively), and daily precipitation data for 1960-2010. Data also include daily counts of sunshine hours, although these are only continuous for all cities from 1980. Whilst information on dew point temperature and air pressure are available for some of the years, this record is incomplete, and hence of little value to the study. Daily values, and the monthly and annual averages of T_{max}, T_{min}, precipitation and sunshine hours were separated from the incomplete pressure and humidity data and transferred from the ASCII text format into *Microsoft Excel* files to ensure consistent file types for later importing into the requisite statistical programmes. Details of the meteorological stations for each of the cities are summarized in Table 4.3.

Table 4.3: Details of the weather stations in Gorgan, Kerman and Shiraz.

City	Location	Altitude (masl)	Maximum Distance from Garden (km)
Gorgan	36°54’ N, 54°24’E	0	7.7
Kerman	30°15’ N, 56°58’E	1753.8	13
Shiraz	29°32’ N, 52°36’E	1484.0	12.4

4.2.2 Data Limitations

With data from only two sources, both of which form registered data collection agencies, a far greater chance of consistency is ensured than from collection of data directly from individual farms or gardens. With direct accountability for the quality of these data, Mohit Sabz and their predecessor have a great incentive both to ensure consistency in data collection, and to check the data for errors before archiving. Pooling and averaging data from the orchards of the three to four gardens per city ensures that any issues in the data collection for a particular garden can be easily detected and controlled for. Finally, this system ensures standardization in archiving which would not be possible if archived separately by each orchard.

Where data were missing, particularly in the case of phenology data, these remain as omitted data, rather than being completed by interpolated values which could be misleading due to inter-annual variability in the data. This ensures that no misleading trends are generated through the inclusion of interpolated values (Nordli et al., 2008). Perhaps the greatest potential limitations arise through the process of translating the information from Persian into English, and from the Persian to the Gregorian calendar. Fortunately, this was not required for the meteorological data, which were recorded in the archive system in both English and Persian. For the phenological data, the likelihood of translation errors is minimized as it was undertaken at an academic institution under the supervision of an academic climate researcher involved in the project. Any dates translated incorrectly became clearly apparent as outliers during analysis and were subsequently reviewed.

In phenological studies there is concern as to the correct identification both of species and the correct phenological stage. As the records are taken by farmers in these gardens, there is very little likelihood of incorrect species identification. Using 85% (peak) bloom as the phenological stage of interest, decreases the probability of error considerably, as it is easier to detect than stages such as first or last bloom (Miller-Rushing et al., 2008a).

4.3 Methodology

4.3.1 Initial Data Analysis

Initial data analysis involved determining the average flowering date, per species, and average climate conditions over the 50 year study period, the variability in the data over this period, and the magnitude and direction of any change which occurred for each variable over the period. The statistical analyses required the compilation of phenological and climate datasets using *Microsoft Excel.* These data were then imported into the statistical programmes *InStat,* a biostatistical package which allows for the analysis of correlation, regression and statistical significance; *SPSS,* a package originally developed for the statistical sciences, which allows for multiple regression analysis with a large number of input variables; and *STATA 11,* a high-end statistical package which enables the production of variable summaries and multivariate multiple regression analysis (Motulsky, 2003; Kohler & Kreuter, 2005; Leech et al., 2005).

4.3.1.1 Variables of Interest

The procedures described below were undertaken to determine the mean and distribution of the data; followed by the strength, direction and magnitude of any time trends in phenological and climate variables over the study period.

The phenology data comprise the 85% mean bloom date for each of the five citrus species in each of the three cities. Julian Dates were compiled for each year from 1960-2010 for orange, tangerine, sweet lemon, sour lemon and sour orange, for Gorgan, Kerman and Shiraz. Averages of the flowering dates of each for these species for the period 1960-2010 were calculated, with an analysis of the variance of each of these datasets determined through the statistical "five number summary", of the minimum and maximum values, together with the middle and upper and lower quartile values, described in *section 4.2.1.3* below. Trends in the timing of flowering for each species were then determined for each of the three cities.

The basic climate data constituted daily T_{min} and T_{max}, which refer to the highest and lowest temperatures recorded within a 24 hour period; daily rainfall, which refers to the sum of all rain in that same 24 hour period; and for a portion of the dataset, daily sunshine hours, which refer to the total number of sunshine hours in that 24 hour period. These climatic variables were made available for each of the three study cities. The daily values were averaged to monthly and annual values for each city.

In addition to the analysis of raw climatic data which were provided by the Iranian Meteorological Organisation, further investigation included the comparison of mean conditions and trends over the study period, and a "five number summary" in box-plot form similar to that for the phenology data. In addition, the timing of the first significant rain of each season was explored. For the purpose of this study, the first rain was defined with reference to similar arid regions, as a series of consecutive days of rainfall in which the sum was greater than 10mm, or alternatively a day with greater than 20mm in a month which later experienced further rainfall (Odekunle et al., 2005; Fontaine & Louvet, 2006; Laube et al., 2012). Trends in these onset dates were calculated for each of the three cities, using the same methods. The end date of rainfall is not only considerably more difficult to define in an arid region such as Iran where rainfall occurs intermittently, but is also of little relevance to flowering.

Whilst changes in T_{max} and T_{min} over the study period may potentially have a significant effect on plants, and in particular on their flowering dates, so too can changes, and particularly increases, in the number of days which exceed certain threshold conditions suitable for a particular species or cultivar. These thresholds for citrus plants, and particularly their flowering, were based on values obtained from other studies on temperature thresholds in the *Citrus* genus, such as Mendel (1968), Goldschmidt (1997), Stenzel et al. (2006), Hardy and Khurshid (2007), and Connellan et al. (2010). These studies have minimum temperature thresholds ranging from 12.5°C to 13°C. As the majority of the daily temperature data was recorded to the nearest whole number, thresholds are defined as days with minimum temperatures below 13°C (T_{min} < 13°C) and maximum temperatures exceeding 35°C (T_{max} > 35°C). Consequently, daily temperature data was examined for days which fell into these categories, and monthly sums of days in which T_{max} exceeded 35°C, T_{min} fell below 13°C, or in which both T_{max} and T_{min} fell below 13°C were recorded. These sums of days in which temperatures exceeded threshold conditions for each month were presented, together with annual sums for each threshold. Trends in the numbers of threshold-exceeding days were then calculated for each city.

4.3.1.2 Average values for each variable from 1960-2010

Determining the average conditions for each variable over the time period was undertaken through calculating the arithmetic mean of the sample set. This is a measure of the central tendency of the dataset and is calculated as:

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i$$

(Lomax, 2007; Underhill & Bradfield, 2009)

Where data are missing, as is the case for some of the phenology data, the n value was reduced to the number of available data inputs, and hence an average was calculated on the basis of available data, without any interpolated values included (Underhill & Bradfield, 2009). Means were calculated at both monthly and annual intervals, with the annual averages taken as the mean of the monthly values across the 12 months. These averages were calculated using the biostatistical programme *Instat* (Motulsky, 2003).

4.3.1.3 Variability in each variable between 1960-2010

Whilst the mean provides an estimate of the central tendency of the dataset, it does not convey any information on the range of variability of the data over the study period. As an arithmetic mean is taken as the quotient of the sum of the values by the number of entries, the same output can be given for a set of 20 values clustered close to the mean, or 20 values ranging within 50 or even 500 units of the mean (Underhill & Bradfield, 2009). It is therefore of interest to determine the spread of the data – the symmetry of the data on either side of the mean; how close the upper and lower quartiles lie to the mean; and the existence of any values which are so different to the mean as to be classified as outliers – particularly when comparing data for different species or different cities as is the case in this study (Palaniswamy & Palaniswamy, 2006; Lomax, 2007). This can be done through the presentation of a "five number summary" of the dataset in the form of a box-and-whisker plot. This method involves a plot against a y-axis which contains all the possible values in the dataset; a box for each variable drawn from the lowest to the highest quartile; a line through the box at the median; whiskers (lines) from the box to the extremes; and, where required, an asterisk at the position of an outlier (Lomax, 2007; Sarkar, 2008; Underhill & Bradfield, 2009).

The "five number summary" used relies on the rank of the data from the smallest to the largest value. The median is a second measure of the central tendency of the dataset, and refers to the middle ranked value. It is often similar to the mean value of the dataset, however its value is not affected by the presence of extremes or outliers.

The median is calculated as a rank of:

$$m = \frac{n+1}{2}$$

(Underhill & Bradfield, 2009)

The upper and lower quartiles refer to the numbers which are ranked in the quarter positions – half way between the median and the highest or lowest value in the dataset. Their rank is calculated as:

$$l = \frac{m+1}{2} \text{ (lower quartile)}$$

and

$$u = n - l + 1 \text{ (upper quartile)}$$

(Underhill & Bradfield, 2009)

The extremes refer to the smallest and largest values in the dataset. They have a rank of 1 and n respectively. Outliers refer to values which are significantly different to the bulk of the observations. Whilst outliers may represent genuine observations, they potentially result from error in data collection or input. The timing of outliers was explored to determine whether they coincide with any extremes in climate variables, or climate drivers such as El Niño and volcanic events. These values are defined as observations with values greater than:

$$x_m + 6(x_u - x_m)$$

(Underhill & Bradfield, 2009)

Or observations with values less than:

$$x_m - 6(x_m - x_l)$$

(Underhill & Bradfield, 2009)

These "five number summaries" for T_{max}, T_{min} and precipitation for each of the cities, and for the flowering dates of each of the five citrus species for the three cities, and resultant box-and-whisker plots, were produced using the statistical programme *STATA 11* (Kohler & Kreuter, 2005).

4.3.1.4 Trends in Flowering Dates and Climate Variables

A study into the phenological response of plant flowering to climate variability and change requires that there has been some change in the timing of phenological events and in the intensity of the climatic variables. To determine the strength and direction of any trends in either flowering dates or climatic variables over the study period, correlation analysis was undertaken (Manly, 2009). Correlation analysis determines whether there is a relationship between a dependant (y) and an independent variable (x) (Lomax, 2007; Manly, 2009). In the case of time trends, time acts as the independent variable against which the dependant variable of a phenological event or a climatic variable are related (Manly, 2009). Through determining the correlation coefficient I, a value from -1 to +1, the magnitude and direction of the change of a variable over time can be assessed (Manly, 2009; Underhill & Bradfield, 2009). A correlation coefficient close to 1 or -1 indicates a consistent change in the dependant variable over the time period; negative correlation coefficients indicate that the change is in the direction of an earlier date or to progressively lower temperatures or rainfall over the study period; positive coefficients suggest that flowering dates are occurring increasingly later in the year, or that climatic variables have been for the most part continually increasing over this time period; and a correlation coefficient tending towards 0 suggests that either there is no clear pattern in the data over the time period, or that there has been little or no change (Palaniswamy & Palaniswamy, 2006; Underhill & Bradfield, 2009). To compare the relative magnitude of correlation strength, correlation coefficients in this study are presented as the absolute value, and hence lie between 0 and 1. Information on the direction of the trend will be conveyed in the rate of change. The Pearson correlation coefficient for the time trends in flowering dates and climatic variables was calculated using the statistical package *InStat,* using the following equation:

$$|r| = \left| \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \right|$$

(Manly, 2009; Underhill & Bradfield, 2009)

4.3.1.5 Magnitude of the Change in the Dependant Variable over Time

Once a significant trend in either phenological dates or climate variables over the time period have been demonstrated, it is necessary to determine the rate of change over that period. This was undertaken through regression analysis, whereby the best-fit line is set to the data through minimizing the residuals between each data point and the line (Lomax, 2007; Manly, 2009). Regression analysis provides a mathematical relationship between the independent and dependant variables and provides quantitative information on the rate of change of the dependant variable. It is important to note that there has been significant work dealing with trends in phenological data, and that not only are linear relationships found to dominate, but linear regression models most are able to most closely attribute climate impacts to phenological shifts, and hence are the predominant method used in these studies (Rötzer et al., 2000; Sparks et al., 2000; Hegland et al., 2009; Grab & Craparo, 2011; Keatley & Hudson, 2012; Luedeling & Gassner, 2012). Furthermore, as this study aims to contribute findings to the greater body of phenological research, it is essential to follow the methodology of past well-recognized studies. The best fit line for the data is calculated in the basic form of:

$$y = ax + b$$

(Lomax, 2007; Manly, 2009)

This requires the determination of the values for the constants *a* and *b*. The first step is to determine the magnitude of the y intercept, *b.* This term serves as the error term in the linear regression model, and is calculated as:

$$b = \frac{\sum xy - \frac{\sum x \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

(Manly, 2009; Underhill & Bradfield, 2009)

Having calculated the value for *y* intercept, the coefficient of x can now be calculated. This value indicates the amount by which the dependant variable (phenological date or climatic variable) increases or decreases in response to a one unit increase in the independent variable (in this case a one year passing of time). It is calculated as:

$$a = \frac{\sum y - b \sum x}{n}$$

(Manly, 2009; Underhill & Bradfield, 2009)

The linear regression analyses between single dependant and single independent variables were undertaken using *InStat* (Motulsky, 2003). Results of the linear regression analysis are presented as a change in flowering date per year (d/yr); degree Celsius change in temperature per year (°C/yr); and millimetre change in rainfall per year (mm/yr). With a dataset spanning less than 100 years, decadal shifts can only tentatively be inferred from the regression results.

4.3.1.6 Statistical Significance of Findings

Having calculated the strength and direction of any trends in variables over the time period, together with the amount by which the dependant variable increases or decreases per unit time, it is necessary to determine whether these results are statistically significant. Statistical significance is a measure of the probability that the results obtained could have occurred as a result of coincidence of random sampling (Motulsky, 2003; Manly, 2009). The larger the dataset, the greater the chance that a calculation of a strong correlation accurately reflects an existing strong relationship. However, in the case of a small dataset, the chance of a set of consecutive values increasing by chance rather than as part of a greater pattern is considerably higher (Motulsky, 2003; Underhill & Bradfield, 2009). Thus, high statistical significance occurs in results of strong correlations (high r values), derived from datasets comprising large inputs (Manly, 2009). This provides further incentive to seek continuous datasets which cover as long a period as possible.

The degree of statistical significance is measured by way of the *p value*. This probability value ranges from 0 to 1: the smaller the value, the greater the chance that the result has not occurred as a result of random sampling, and that it is a true indicator of the behaviour of the data over the period studied (Motulsky, 2003; Underhill & Bradfield, 2009). The *p value* tests the null hypothesis that there is no relationship between the dependant and independent variables, or in the case of time trends, that there is no change in the phenological or climate variable over the study period (Manly, 2009). The numerical *p value* is the fraction of all possible results obtained under this assumption, for which there could a relationship as strong, or stronger, than that calculated (Motulsky, 2003). Hence a *p value* of 0.01 means that there is a 1% chance of observing a relationship as strong as that calculated if there is in fact no actual relationship between these two variables, or no change over time (Motulsky, 2003). A *p value* of less than 0.05 rejects this null hypothesis, and thus deems the resultant relationship to be statistically significant (Manly, 2009; Underhill & Bradfield, 2009). The *p values* for this study were calculated using *InStat.*

4.3.2 Comparison of Phenology and Climate Data

Significant time trends do not impart a relationship of causation alone, and it is necessary to determine whether there is a significant relationship between any changes in climatic variables and the changes in the flowering dates of the citrus species. Again, this is undertaken through the use of correlation and regression analysis, although instead of the time period serving as the independent variable against which each of these variables are tested, the flowering dates become the permanent dependant variable against which each of the climatic factors are tested as potential causal independent variables. The correlation coefficient (r), regression equation, and statistical significance (p) were calculated using the methods described in *2.1* for combinations of each of the climate variables (*x)* with each of the five citrus species (*y*), for each of the three cities. The flowering dates of the five citrus types were compared with the climate variables for each of the monthly averages, as well as with the annual averages, and sums.

4.3.2.1 Interpretation of Correlation and Regression Results

Interpretation of the correlation coefficient produced through the analysis of the relationship between the climate and phenological variables is similar to that of time trends. A correlation coefficient closer to 1 suggests a strong relationship between the dependant and independent variable, while the sign of the value indicates the direction of the relationship. A negative correlation coefficient indicates an inverse relationship – that an increase in the independent variable (for example an increase in T_{max}) is associated with a decrease in the dependant variable (a shift in flowering dates to earlier in the year) and vice-versa; a positive correlation coefficient indicates a direct relationship – that increases in the independent variable (for example an increase in rainfall) are associated with an increase in the dependant variable (a shift in flowering dates to later in the year), and vice versa (Manly, 2009; Underhill & Bradfield, 2009).

Assuming a linear relationship, the regression best-fit equation again presents the linear model which best fits the associated data, and again the coefficient of *x* provides a quantifiable measure of the amount of change in the dependant variable, which occurs as a result of a one unit change in the independent variable. However, where previously this referred to the shift in either the phenological or climate variable per year for the time trends, here it refers to the shift in the date of flowering as a result of a one unit change in the climatic variable in question (d/°C temperature; d/mm rainfall; d/td threshold conditions). This allows both for the direct association between climatic variables and the timing of phenological events to be determined, and enables cross study comparison of results without interference from the length or timing of the study period.

An analysis of the statistical significance is the same as that for time trends in the variables – a *p value* smaller than 0.05 deems the correlation and regression results significant, based on the number of variables, the subsequent degrees of freedom, and the strength of the correlation (Manly, 2009; Underhill & Bradfield, 2009).

4.3.2.2 Explanatory Power of the Independent Variable

When associating a dependant variable such as flowering dates with a potentially independent climatic variable, it is of interest to calculate the percentage by which changes in the independent variable account for changes observed in the dependant variable (Palaniswamy & Palaniswamy, 2006; Manly, 2009). This is determined through calculating the coefficient of determination (R^2):

$$R^2 = \frac{b\left(\sum xy - \frac{\sum x \sum y}{n}\right)}{\sum y^2 - \frac{(\sum y)^2}{n}}$$

(Palaniswamy & Palaniswamy, 2006; Underhill & Bradfield, 2009)

This provides an R^2 value of between 0 and 1, which can be converted to, and reported as, a percentage. A value closer to 1 reflects a percentage closer to 100, suggesting that a greater portion of the variability in the dependant variable is explained by concomitant variation in the independent variable (Palaniswamy & Palaniswamy, 2006; Manly, 2009).

4.3.3 Growing Degree Day Analysis

Growing Degree Day (GDD) analysis involves the comparison of the date at which heat units (HU) are accumulated seasonally (approximately from the time of dormancy release), with the flowering date (Stenzel et al., 2006). The theory is that flowering is a plant response to an accumulation of heat, and that shifts in flowering dates may occur not only as a result of a general change in air temperatures, but due also to changes in the length of time required for these heat units to be reached (Stenzel et al., 2006; Hardy & Khurshid, 2007). Flowering dates are thus statistically compared with the HU accumulated by the time of flowering, and also with the date at which 200 HU are accumulated. The threshold count of 200 HU is arbitrary, but follows convention for phenological studies involving flowering dates, and in particular those for the flowering dates of fruit trees, and presents a measure of the rate of seasonal heat accumulation (Hardy & Khurshid, 2007). Thus, to determine whether this hypothesis holds true for the timing of flowering of citrus in Iran over the period 1960-2010, it was first necessary to determine the date at which 200 HU have been accumulated for each city each year and hence flowering period.

Whilst the accumulation of heat units by flowering date, and the date of the accumulation of 200 HU is common across phenology studies, the calculation of the HU requirements differs between plant types (Egea et al., 2003). For citrus cultivars, HU accumulate when mean daily temperatures exceed a base temperature of 13°C (Mendel, 1968; Goldschmidt, 1997; Stenzel et al., 2006; Hardy & Khurshid, 2007). Thus when a day experiences a mean temperature of 14°C, 1 HU is accumulated:

$$HU = \sum_{n}^{d=1} \frac{T_{max}+T_{min}}{2} - 13 \text{ [IF } T_{avg} \geq 13]$$

(Hardy & Khurshid, 2007)

The HU accumulation for a year is thus the sum of the daily average temperatures over 13°C, progressively totalled from 1 January (an approximation of the release of dormancy, which is not a clearly visible stage and hence not recorded, up to the date at which 200 HU are reached (Spano et al., 1999; Stenzel et al., 2006; Hardy & Khurshid, 2007). This date is converted into JD for each year, and trends in the rate of HU accumulation calculated using the methods described previously for climate and phenology variables. Whilst some HU calculations involve the subtraction of HU for days in which the average temperature is below 13°C, these have for the most part been deemed physiologically inaccurate approaches, resulting in confusion where the model is assumed to begin at the base temperature (McMaster & Wilhelm, 1997).

Trends in the timing at which 200 HU are accumulated, and of the HU at flowering are calculated for the period 1960-2010. Thereafter, the relationship between the heat accumulation and the timing of flowering can be explored. This can be undertaken either through comparison of the flowering dates and the HU accumulated by the date of flowering, or the flowering dates and the date at which 200 HU are accumulated. The first method places greater emphasis on the amount of warming that the plant has experienced up to the point of flowering, whereas the second analyses the rate of seasonal heat accumulation. Comparisons were undertaken for each of these two methods against the flowering dates for each of the five species in the three cities, using the correlation, regression and significance indices outlined in *2.1.* To qualitatively analyse patterns in the trends in the HU accumulation, composite time trend plots were produced for each of the three cities.

4.3.4 Multiple Regression Analysis

Whilst the study of the relationships between individual dependant (phenological) and independent (climatic) data allows for an initial understanding of those factors which play a significant role in determining the flowering date and any shifts which may have occurred in flowering dates over time, it is unlikely that one of these factors alone will explain even the majority of the phenological response (Leech et al., 2005; Underhill & Bradfield, 2009). More likely, a combination of climatic factors will act together in determining the flowering date, with changes in all of these factors being potentially responsible for the changes observed in the timing of citrus flowering. This premise is confirmed if the relationships between flowering dates and more than one of the independent climate variables are statistically significant. It then becomes necessary to study the effect that various combinations of independent variables, which alone demonstrate significant relationships, have on flowering dates. As these climatic factors occur simultaneously and are part of greater atmospheric processes, it is unlikely that they will have completely separate effects on the flowering dates, but rather work in conjunction with one another. Their combined effects are therefore not equal to the sum of the coefficients of determination for each of the single driver relationships which are found to be significant (Manly, 2009; Underhill & Bradfield, 2009). A multiple regression model is therefore necessary, in which the relationship between the flowering dates for a species in a particular city is related to more than one independent climate variable. This model, calculated using the package *SPSS* as it allows for a non-limiting number of inputted independent variables (Leech et al., 2005), was developed through determining the best fit linear equation to minimize the residual between each input variable and the regression line, producing a regression model of the form:

$$y = \beta_0 + \ \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots \beta_n x_n + \epsilon$$

(Leech et al., 2005; Manly, 2009)

The strength of the model is determined primarily by the coefficient of variation (R^2) and depends on the degree to which the combination of independent variables can explain the changes in the dependant variable. The coefficient of determination for multiple regression, again a number between 0 and 1, which can later be converted into a percentage explanatory power, is calculated as:

$$R^2 = \frac{\sum(y_{est} - \bar{y})^2}{\sum(y - \bar{y})^2}$$

(Leech et al., 2005; Lomax, 2007)

The strength of the estimate dictates the strength of the model, and consequently the selection of independent variables which together will explain the largest proportion of variability in *y* is necessary. However, the inclusion of surplus factors, particularly where closely related (such as cloud cover and sunshine hours), results in multicollinearity (Leech et al., 2005; Underhill & Bradfield, 2009). Multicollinearity refers to the problem of the inclusion of factors which provide no additional strength to the model (Leech et al., 2005; Underhill & Bradfield, 2009). Whilst multicollinearity has little effect on the explanatory power, it does have an influence on the model accuracy (Gnanadesikan, 1997; Leech et al., 2005). The accuracy of the model is measured by means of the standard error of the estimate term in the *SPSS* output, which is commonly alternately referred to as the standard error of the estimate (Leech et al., 2005; Lomax, 2007). This term, which explores the standard deviation of the error term, is the square root of the sum of the square of the residuals, divided by their degrees of freedom (Leech et al., 2005, Lomax, 2007). This second measure of the strength of the model has no set range of values, but the smaller the value, the smaller the root mean squared error, and hence the greater the accuracy of the model (Leech et al., 2005, Lomax, 2007). It is calculated as:

$$\sigma_{est} = RMSE = \sqrt{\frac{\sum(y - y_{est})^2}{N}}$$

(Leech et al., 2005; Lomax, 2007)

The aim in the development of a best-predictor multiple regression model is to determine the combination of input values which maximise the R^2 value, whilst minimizing σ_{est}.

4.3.4.1 Selection of Independent Variables for Input

For the purpose of this study, individual multiple correlation models were developed for each citrus species' flowering dates, in each of the three cities. The selection of the variables for input into these models first required the identification of driver variables which demonstrated strong, significant correlations individually with the flowering dates of a particular species in a specific city. These included relationships between both the annual average of the independent variable, and those correlations for particular months. To ensure that the strongest possible model was developed, three sets of independent variables were collected for each model – *annual values*, *all significant values* and *generic significant values*.

Annual values involve those annual averages of the independent variables which showed significant correlations with the flowering date of a particular species in each city. All significant values involve all of the independent variables for which significant correlations with the flowering dates of that particular citrus species in that city are found, with monthly averages each taken as separate variables (eg. T_{max} April considered a separate variable to T_{max} May). Where both the annual average and the monthly average for one or more months were found to be significant, as is likely where many months show significant relationships, the collection of monthly terms were selected instead of the annual term, unless the annual term has considerably stronger individual relationships (correlation coefficient at least 0.05 greater than the next highest monthly correlation). A collection of generic significant values is taken as that group of independent variables for a city which demonstrate significant relationships with the flowering dates of all five citrus species, again showing preference for monthly terms over annual terms.

Once a collection of terms for each of the three categories had been determined for each species in each city, multiple regression analyses were undertaken to determine which of these collections of independent variables demonstrates the greatest and most accurate explanatory power.

4.3.4.2 Enter and Backward Multiple Regression Methods

For these combinations of variables for each of the five species in each of the three cities, two methods of multiple regression model development were used – the *Enter* method and *Backward* regression. This ensured that the model with the highest explanatory power and greatest accuracy for that set of variables was developed. Output models were compared to determine which had the greatest R^2 and lowest σ_{est} values.

The *Enter* method is the simplest form of multiple regression analysis, whereby all of the specified independent variables are included to form a single linear model relating the combination of this set of values to the change in the dependant variable, and the R^2 and σ_{est} values calculated (Leech et al., 2005). Once this method had been used to determine the explanatory power of the combination of the full set of variables, it is then necessary to determine whether all of these variables are in fact necessary components of the model. As mentioned above, in datasets of a large number of potentially interrelated variables with causal relationships of their own, there is the potential for multicollinearity (Underhill & Bradfield, 2009). Furthermore, whilst an independent variable may show a significant relationship with the dependant variable when studied in isolation, it may potentially not contribute to the full explanatory model of shifts in the behaviour of the dependant variable (Lomax, 2007).

The identification and elimination of unnecessary independent variables, which are potentially detrimental to the predictive strength of the model, was undertaken through running a second method of regression model building – the *Backward* regression method. This method develops a full regression model with all of the specified input independent variables as with the *Enter* method, but then proceeds to eliminate the weakest predictor variable, tests to determine whether this significantly decreases the explanatory power of the model, and if not, proceeds to remove the next weakest predictor variable until only the strong predictor variables remain (Leech et al., 2005). Each of these consecutive models is presented in the output with its respective R^2 and σ_{est} values (Leech et al., 2005). As each independent variable is removed, there may be a slight, if any, decrease in the R^2 value, together with a decrease in the σ_{est} value (Leech et al., 2005; Lomax, 2007).

4.3.4.3 Best Model Selection

Model selection for that particular collection of variables involves a comparison of the output from the *Enter* method, and the various stage outputs of the *Backward* regression. Automatic model selection would result in two models with very different R^2 values – the *Enter* method with all of the inputted values, and the *Backward* regression method with only a few of these values which show the strongest collaborative explanatory power (Lomax, 2007). Manual model selection, however, allows for an intermediary solution – a model which excludes the variables with the weakest explanatory power and which accounts for the greatest effect of multicollinearity, without compromising the explanatory power of the model (Leech et al., 2005, Lomax, 2007). Moving through the list of models created through the *Backward* regression method, a test is made at the elimination of each variable to determine whether the forfeit in the R^2 value was met by a significantly large decrease in the σ_{est} value. This is defined as a change which allows for the R^2 value to remain the same to two decimal places whilst the σ_{est} value drops by at least one decimal place. Thus, a trade-off of a 10% improvement in the accuracy of the model is given in return for a 1% sacrifice in the explanatory power of the model. At that point where the removal of a particular variable results in a greater decrease in the R^2 value, or a lesser decrease in the σ_{est} value, that model is rejected and the previous model favoured.

The *Backward* regression method, together with the procedure outlined for model selection, was undertaken for the collections of all significant values and for the annual values. However, for the collection of generic values, only the *Enter* regression method was used to compare the efficacy of this model between each of the five species in each city. It is then possible to find the best fit explanation of the flowering dates and shifts in flowering dates observed by comparing the selected backwards regression models for the three collections of independent variables, for the flowering dates of each of the five citrus types in each of the three cities.

4.3.5 Multivariate Multiple Regression Analysis

Where there is a collection of datasets which are potentially associated, and which have a common set of explanatory variables, it is possible to develop a combined regression model which simultaneously explores the effect of the common independent variables on the dependant variables. By doing so, the model potentially allows for additional information and explanatory strength to be drawn from these different dependant variables, to better explain the effect that the combination of common independent variables has on each of the dependant variables (Gnanadesikan, 1997; Izenman, 2008). This is arguably the case here, where the flowering dates of each of the five citrus types are potentially related to each other through their genetic similarity and common location, and where a generic set of independent variables has been determined for each city, both with the groupings of significant independent monthly variables common to the five citrus types and the annual averaged variables. It is necessary to first demonstrate whether a significant correlation between the flowering dates of each of the five citrus types exists for each of the three cities. Whilst a strong correlation between flowering dates does not ensure that multivariate multiple regression analysis will contribute additional or improved explanatory power to the model, it is a prerequisite for the selection of multivariate multiple regression analysis as an appropriate tool to model the relationships between climate variables and flowering dates. The pairwise correlation used to developing such correlation matrices is undertaken using the method outlined in *2.1.4,* with the *x* and *y* values arbitrarily selected (Motulsky, 2003).

Provided significant correlations exist between the flowering dates of the five citrus types, it can be justified to then develop multivariate multiple regression models for each city with the flowering dates of the five citrus types forming the multiple dependant variables, whilst the generic independent variables for each city are used as the independent variables. This analysis, computed using *STATA 11,* bases the model on the characteristics of a covariance matrix developed for the collection of dependant and independent variables (Kohler & Kreuter, 2005).

The multivariate multiple regression model then takes the form of a matrix:

$$[y_1 \quad \cdots \quad y_p] = [x_1 \; x_2 \;\; x_3 \;\; \ldots \;\; x_q](\beta_1 \quad \cdots \quad \beta_p) + \varepsilon_{nxp}$$

(Gnanadesikan, 1997; Izenman, 2008)

wherein all columns hold the coefficients for each criterion, with rows for each predictor. The model can be expressed simply as:

$$Y_{nxp} = X_{nxp}.B_{qxp} + \varepsilon_{nxp}$$

(Gnanadesikan, 1997; Izenman, 2008)

Tests for the strength and statistical significance of the multivariate multiple regression model are undertaken through MANOVA, rather than the ANOVA for single and multiple regression, from which the *r*, R^2 and *p values* are calculated. MANOVA investigates variance-covariance between variables to determine i) whether the independent variables have a significant effect on the dependant variables; ii) the nature and extent of the relationship between the independent variables; and iii) the nature and extent of the relationship between the dependant variables (Gnanadesikan, 1997; Izenman, 2008). Where ANOVA studies the sums of squares to determine the root mean squared errors, MANOVA rather studies positive-definite matrices, with the diagonal entries containing the sums of squares for ANOVA and the off-diagonal containing the sums of products (Lomax, 2007; Izenman, 2008). The overall test uses the null hypothesis of H_0: B = 0, where B (as in the above equation) refers to the matrix set of all of the coefficients of all of the independent variables for each of the dependant variable relationships:

$$B = \begin{pmatrix} \beta_{01} & \beta_{02} \\ \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix}$$

(Izenman, 2008)

In this example, B refers to the matrix of coefficients of three independent variables for the two dependant variables studied. However, this does not test hypotheses about subsets of predictors – this involves more complex relationships between the matrix B and matrices including a set of linear combinations of the parameters.

The *STATA 11* output summarizes the results of the MANOVA test, presenting an overall R^2, σ_{est} or Root Mean Squared Error and *p value* for each of the dependant variables (Kohler & Kreuter, 2005). For each of the combinations of dependant and independent variables, the coefficient of *x* is provided, which forms the matrix regression equation for the flowering dates of the five citrus types in response to simultaneous changes in common independent variables (Kohler & Kreuter, 2005). As for the univariate multiple regression analyses, the standard error and the *p value* are also provided.

4.3.6 AIC Values for Model Selection

In addition to the use of the *p values* to determine whether regression models are statistically significant, R^2 values to differentiate between the predictive strength of models and σ_{est} as a measure of model accuracy, the selection of the model which best fits the observed data and hence is most able to predict future changes in that dependant variable can be undertaken through calculating Akaike Information Criterion (AIC) values to each of the models. These form a measure of the likelihood of the estimates, and the comparison of these values for all of the models for each citrus type and each city, allows for that model which returns the lowest AIC value to be selected as the 'best model' (Burnham & Anderson, 2002; Hu, 2007). In a study which aims to most accurately ascribe the climatic drivers of phenological change, a measure of the likelihood of model estimates is an important factor to be considered in addition to the explanatory strength of a mode..

AIC values are calculated as a function of the number of observations (n), the number of parameters in the model (k), and the standard error (σ_{est}) through the following equation:

$$AIC = n * ln\left(\frac{\sigma_{est}}{n}\right) + 2k$$

(Burnham & Anderson, 2002)

It is important to note that these AIC values range from large negative to large positive values, and that it is the difference between the AIC values for comparable models rather than the absolute value which is of importance (Burnham & Anderson, 2002; Hu, 2007). This 'best model' is thus estimated through that criterion to produce variables most similar to the unknown reality which produced those data (Burnham & Anderson, 2002).

Once the univariate and multiple regression models had been developed to explain the flowering dates of each of the five citrus types in each of the three cities, the AIC values for each model were calculated and compared as a tool to facilitate model selection. For the multivariate multiple regression model, AIC values were calculated for each of the citrus types, rather than for the complete model, to enable comparison. Whist emphasis is placed on the potential use of each model for understanding the phenological response of these citrus flowering times to increasing climate variability and ongoing climate change, model preference is given to those which were statistically significant and demonstrated the lowest AIC value, as they are statistically the models which most closely reflect the likely situation.

Chapter 5

RESULTS

[5]

5.1 Introduction

With a location specificity in phenological responses to increasing climate variability and ongoing climate change reported consistently in the literature, together with the considerable climatic differences between the study sites, the phenological and climate data are studied independently. Initial analysis of the data available highlights considerable inter-city variability in both phenology and climate variables for the period 1960-2010. However, within each city very similar trends are observed, particularly for the phenology data in which the timing of flowering of each of the five citrus types demonstrate far greater similarity across the citrus types within a particular city, than between cities for a particular citrus type. Consequently, trends and relationships were assessed for each of the variables first by city, then through inter-city comparison.

5.2 Flowering Dates

5.2.1 Gorgan

Mean annual citrus peak flowering dates (85% bloom) for Gorgan over the study period 1960-2010 range from 132 Julian Days (JD) for orange to 136 JD for sour lemon (*Table 5.1*). This four day range spans 12-16 May in a non-leap year. Mean annual peak flowering dates are calculated as 133 JD (13 May) for tangerine and sweet lemon, and 135 JD (15 May) for sour orange (*Table 5.1, Figure 5.1*). The greatest range in flowering dates of a particular citrus type over the 51-year period is 22 days for sour lemon, from 124-146 JD, whilst the smallest range is 17 days for orange, from 124-141 JD (*Table 5.1, Figure 5.1*). Tangerine has a range of 19 days, and sweet lemon and sour orange a range of 20 days. (*Table 5.1, Figure 5.1*). The earliest flowering date over the study period was for tangerine in 1969, on 122 JD (02 May); whilst the latest flowering date in Gorgan was for sour lemon in 1987, on 148 JD (28 May). Flowering dates in Gorgan demonstrate very slight variance, with coefficients of variation of 0.03 for orange, tangerine and sweet lemon; and 0.04 for sour lemon and sour orange (*Table 5.1*).

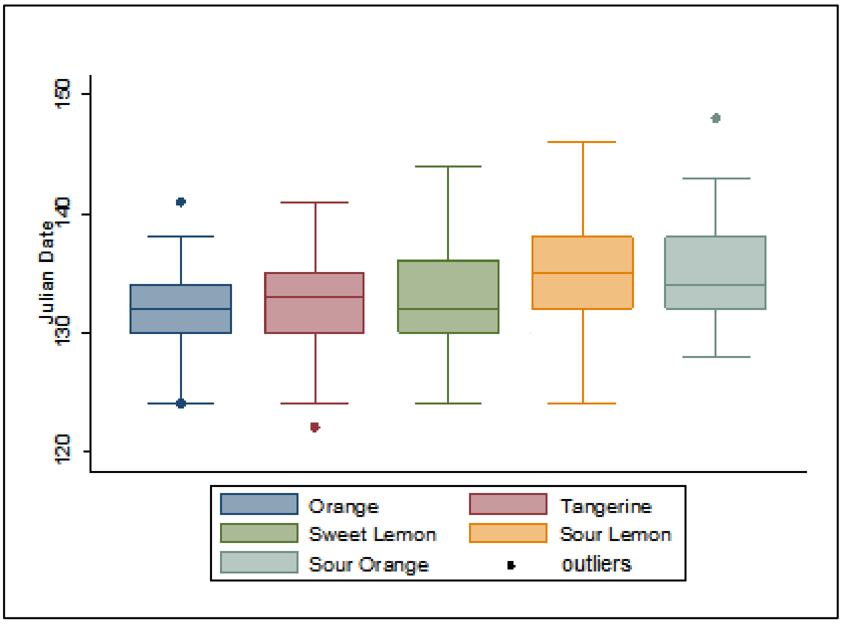

Figure 5.1: Box-and-Whisker Plot demonstrating variability in the flowering dates of citrus for Gorgan over the period 1960-2010.

Over the 51-year study period, significant trends in the flowering dates of citrus in Gorgan are calculated only for orange and tangerine, with weak correlation coefficients of 0.41 ($p = 0.008$) and 0.32 ($p = 0.0352$), respectively (*Table 5.1*). Whilst the trends in the timing of flowering for 1960-2010 are not significant for sweet lemon ($r = 0.24$, $p = 0.1285$), sour lemon ($r = 0.21$, $p = 0.1976$) or sour orange ($r = 0.16$, p = 0.0.3467), all five citrus types demonstrate a shift in flowering dates towards larger JD (later dates) over 1960-2010 (*Table 5.1, Figure 5.2*). These shifts are of a magnitude ranging from 0.05d/yr for sour orange to 0.1d/yr for orange, with shifts of 0.09d/yr for tangerine and 0.07d/yr for sweet lemon and sour orange (*Table 5.1*). This tentatively suggests an average shift of 0.5 days per decade across the five citrus types studied (*Table 5.1*). It is notable that the differences in the rates of change of flowering dates of each of the citrus types results in a convergence of trends over the period 1960-2010. This convergence results in a shift towards common flowering dates for sour orange and sour lemon, and for orange, tangerine and sweet lemon. The magnitude of the trends would suggest a convergence of the flowering dates of all five citrus types within the 21st Century, with trendline equations calculating convergent flowering dates for orange and sour orange by the year 2076.

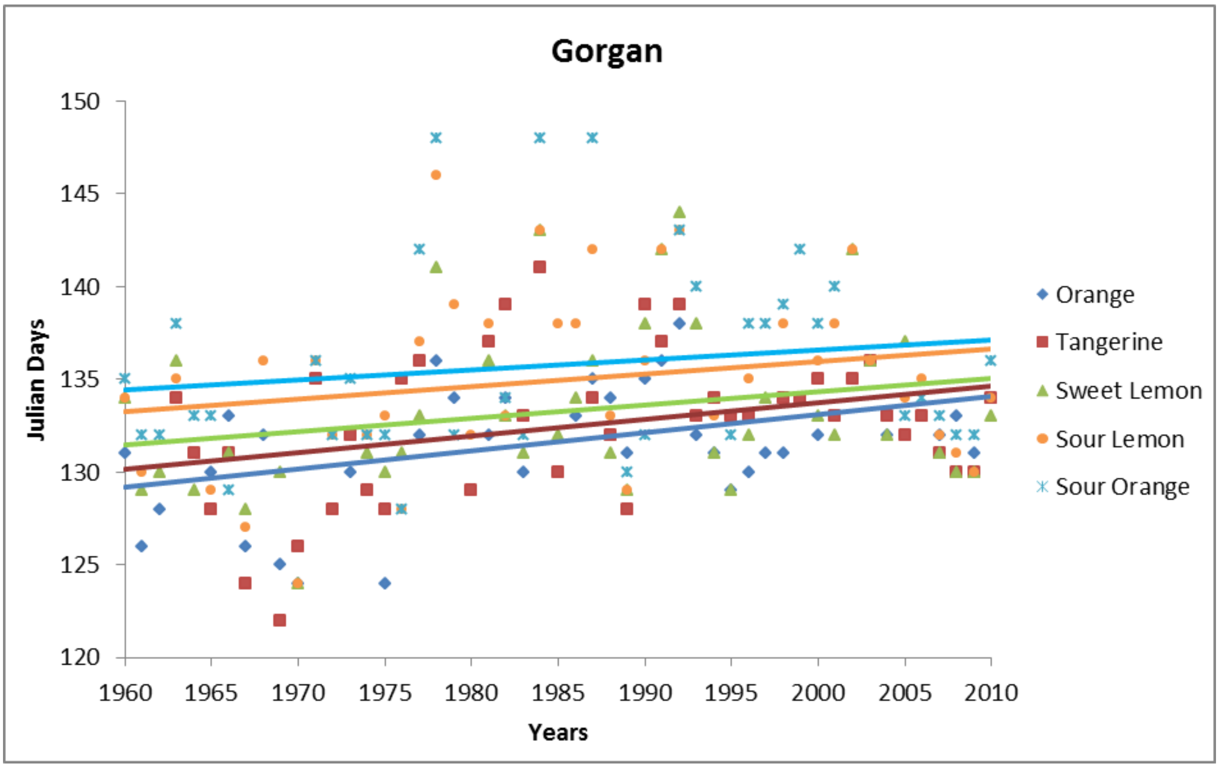

Figure 5.2: Time trends in the flowering dates of the five citrus types for Gorgan, 1960-2010.

5.2.2 Kerman

Citrus peak flowering occurs a month and a half (approximately 50 days) earlier in Kerman than in Gorgan. The mean flowering dates for Kerman over the period 1960-2010 range from 82 JD (23 March) for sour orange to 90 JD (31 March) for sour lemon (*Table 5.1*). Mean flowering for orange and tangerine are at 87 JD (28 March), whilst the mean flowering date for sweet lemon is at 89 JD (30 March) (*Table 5.1*). The greatest range in flowering dates for a particular citrus type over this period is 23 days for sweet lemon, between 77-100 JD (18 March to 10 April); and the smallest range of 18 days for orange, from 77-95 JD (18 March to 05 April) (*Table 5.1, Figure 5.3*). The earliest citrus flowering date for Kerman over the 51-year study period was 77 JD (18 March), which occurred in 2000 and 2009 for orange; in 2008, 2009 and 2010 for tangerine; and in 2009 for sweet lemon. The latest peak flowering date was at 100 JD (10 April) in 1986 for sweet lemon; and in 1986 and 1992 for sour lemon. Variance is slightly greater than for Gorgan, with coefficients of variation of 0.06 for orange, tangerine and sour lemon; 0.07 for sweet lemon and 0.08 for sour orange (*Table 5.1*).

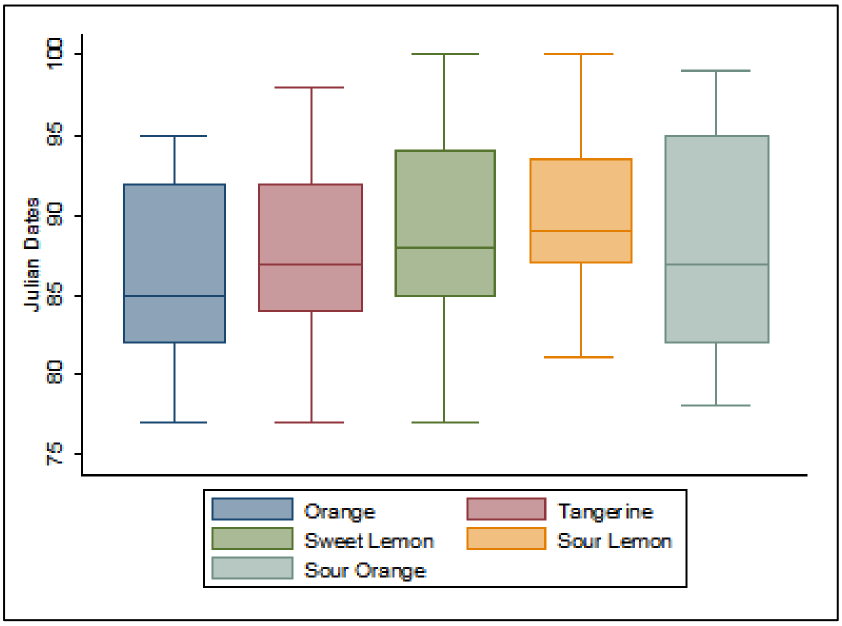

Figure 5.3: Box-and-Whisker Plot demonstrating variability in the flowering dates of citrus for Kerman over the period 1960-2010.

Significant negative trends in the timing of citrus flowering over the period 1960-2010 are exhibited for all five citrus types, indicating a shift in flowering time to earlier in the year (*Table 5.1, Figure 5.4*). These trends are moderately strong, with correlation coefficients ranging from 0.33 (p = 0.0313) for orange to 0.45 (p = 0.0038) for sour lemon; and 0.36 (p = 0.0186) for sour orange, 0.38 (p = 0.0150) for tangerine, and 0.41 (p = 0.0038) for sweet lemon (*Table 5.1*). These shifts to earlier flowering times are 0.12d/yr for orange to 0.17d/yr for sweet lemon and sour orange; with shifts of 0.15d/yr for tangerine and 0.16d/yr for sour lemon (*Table 5.1*). This tentatively suggests an average shift towards earlier flowering of 1 day per decade for the pooled group of the five citrus types (*Table 5.1*). For Kerman, the convergence in flowering date trends exhibited for Gorgan over the period 1960-2010 is apparent for orange, tangerine and sour orange, with convergent flowering dates by 2010. However, for sweet lemon and sour lemon there is a divergence in trends over the study period, from a common intercept with the y-axis at 94 JD in 1960.

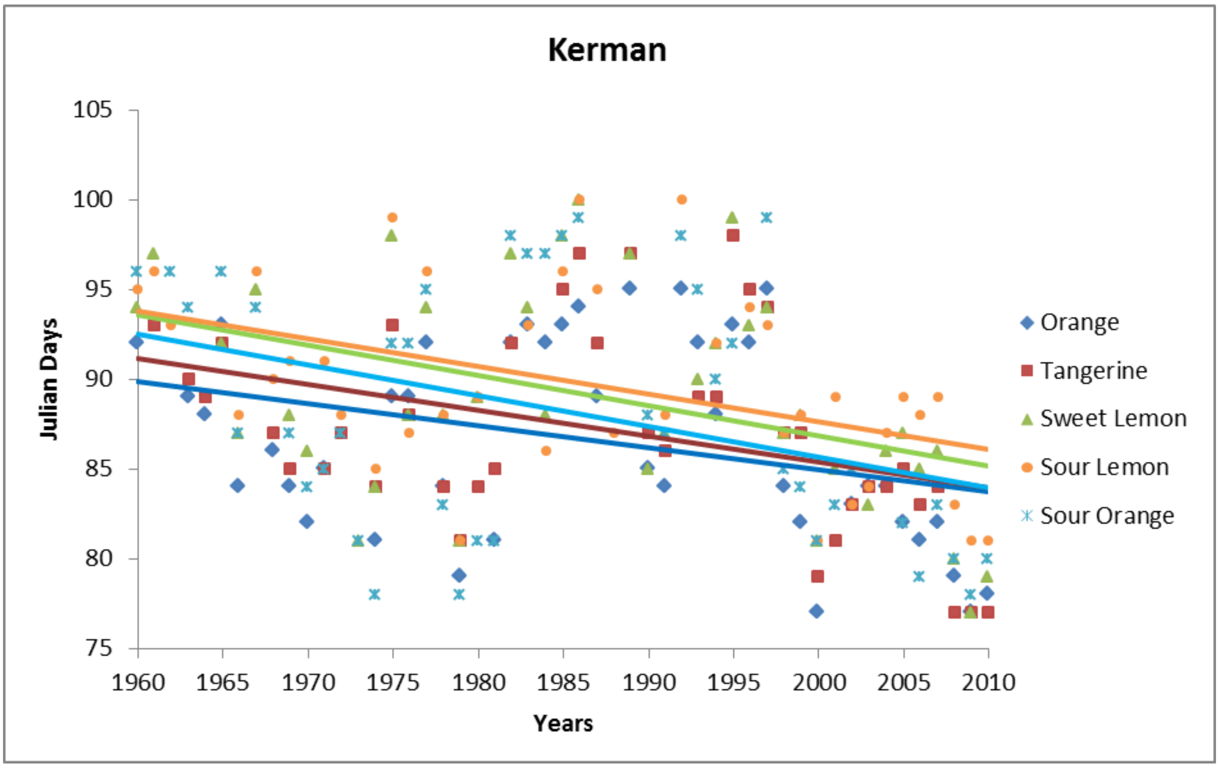

Figure 5.4: Time trends for the flowering dates of the five citrus types for Kerman, 1960-2010.

5.2.3 Shiraz

Mean annual flowering dates for Shiraz spanning the period of 1960-2010 are similar to those for Kerman, ranging from 90 JD (31 March) for orange to 93 JD (03 April) for sour lemon and sour orange (*Table 5.1*). Tangerine has a mean annual flowering date of 91 JD (01 April) over this period, whilst sweet lemon has a mean annual flowering date of 92 JD (02 April) (*Table 5.1*). Flowering dates within each of the citrus types has a considerable range in Shiraz, reaching a maximum 36 days, from 70-106 JD for sweet lemon (11 March to 16 April) and a minimum of 33 days, from 71-104 JD (12 March to 14 April) for orange and tangerine (*Figure 5.1, Table 5.1*). The latest flowering date in Shiraz was for sour orange at 107 JD, which occurred in 1961, 1965 and 1976. The earliest flowering date was for sweet lemon at 70 JD in 2009. Flowering dates in Shiraz demonstrate the largest variance for the three cities, with coefficients of variance of 0.11 for orange, tangerine, sour lemon and sour orange, and 0.12 for sweet lemon (*Table 5.1*).

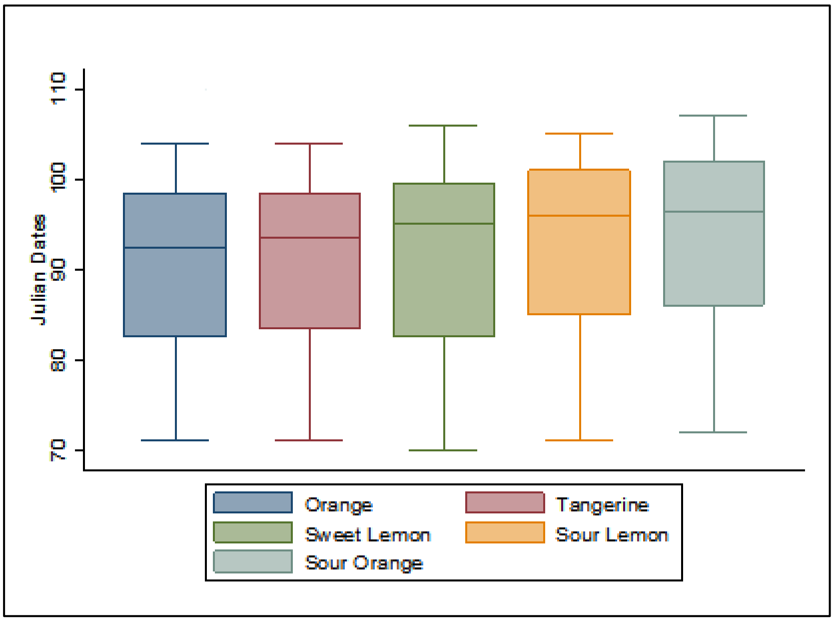

Figure 5.5: Box-and-Whisker Plot demonstrating variability in the flowering dates of citrus for Shiraz over the period 1960-2010.

The timing of flowering in Shiraz over the period 1960-2010 indicates a strong advancing trend towards earlier in the year, with statistically significant time trends for changes in flowering dates for all five citrus types (*Figure 5.6*). These time trends vary slightly across citrus types, with correlation coefficients of 0.84 ($p < 0.0001$) for sour lemon to 0.91 ($p < 0.0001$) for sour orange (*Table 5.1*). The remaining three citrus types had time trend strengths similar to that for sour orange, with correlation coefficients for the period 1960-2010 of 0.88 ($p < 0.0001$) for tangerine and 0.89 ($p < 0.0001$) for orange and sweet lemon (*Table 5.1*). These time trends amount to shifts in flowering time to earlier dates by between 0.56d/yr for sour lemon and 0.65d/yr for sweet lemon (*Table 5.1*). Flowering times for tangerine, sour orange and orange have shifted by 0.60-0.62d/yr (*Table 5.1*). This tentatively amounts to a six day per decade advancement of flowering dates over the period 1960-2010 across all five citrus types (*Table 5.1*). Whilst for Gorgan and Kerman there are clear patterns of convergence and divergence in flowering date trends, the same is not true for Shiraz. For sour lemon and sour orange, flowering date trends converge in 1990, and thereafter maintain their rate of change and diverge. Trends in tangerine and orange flowering dates diverge from a common intercept at 106JD in 1960, whilst tangerine and sweet lemon trends converge by 2010. There is no clear indication of the trends of all five citrus types converging toward a common flowering date within the early 21st Century.

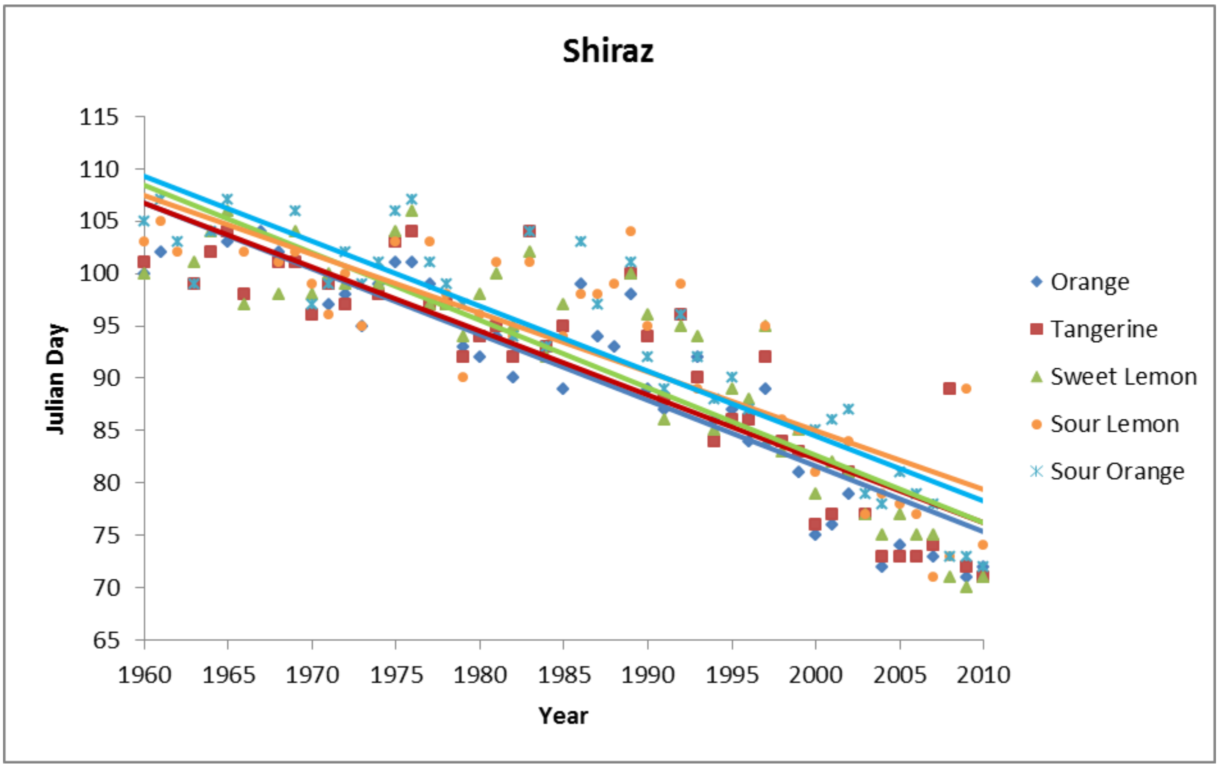

Figure 5.6: Time trends for the flowering dates of the five citrus types for Shiraz, 1960-2010.

5.2.4 Summary

For the period of study (1960-2010), there are statistically significant trends in the advancement of citrus flowering dates for all five citrus types in Kerman and Shiraz. For Gorgan, significant trends to delayed flowering dates were observed only for orange (r = 0.41, p = 0.008) and tangerine (r = 0.32, p = 0.0352) (*Table 5.1*). For Shiraz, both the strongest time trend correlations across all five citrus types (r = -0.84, p < 0.0001 to -0.91, p < 0.0001), in addition to the largest change over the study period with an average shift of 0.6d/yr earlier are demonstrated (*Table 5.1*). Flowering dates of the five citrus types for Gorgan not only have the weakest correlations of the three sites (r = 1592, p = 0.0669 to 0.4086, p = 0.0352), but also demonstrate the smallest change over the period (0.05d/yr), from between 129-135 JD in 1960 to 130-140 JD by 2010 (*Table 5.1*). Notably, this is a shift of flowering dates to later, rather than earlier in the year (*Table 5.1, Figure 5.2*). Shiraz and Kerman both demonstrate significant trends towards earlier flowering (*Figures 5.4, 5.6*), with Kerman having weaker correlation strengths across all five citrus types and less extreme changes over time, advancing by approximately 0.1d/yr between 92-97 JD in 1960 to 76-81 JD by 2010 (*Table 5.1*).

Whilst the range in absolute dates for 1960 and 2010 remains relatively constant for the three cities, the patterns of convergence in flowering date trends are of interest. The convergence of flowering dates of citrus types in a particular city to a common date would suggest an increased effect of local environmental factors in determining the timing of flowering. However, as with Kerman and Shiraz, there are also divergent trends, which may be a function of the rate of change, driven by climate and increasing climate variability, rather than a change in biological processes. In particular, the divergent trends for sour lemon and sour orange in Shiraz would indicate that these convergent trends could well be followed by a divergence as the rate of change remains relatively constant. Should the plants be responding in greater proportions to local climate factors than their intrinsic controls, the trends for all five citrus types in each city would likely be similar in magnitude and direction due to the common climatic conditions those plants would be exposed to. Whilst a linear trendline does not change in direction, an analysis of the individual phenological data for each of the cities does not indicate any clear pattern of increased occurrence of flowering date overlap in more recent years.

The inter-city variability in the flowering dates both within each of the five citrus groups, and across them, was considerably greater than the variability between citrus types within each city. The mean flowering dates for all of the five citrus types in Gorgan for the period 1960-2010 occur in mid-May. For Kerman, the mean flowering date for the five citrus types occurs at the end of March, whilst flowering occurs between late March and early April in Shiraz. The variability in average flowering dates between citrus types for each city has a maximum range of seven days, which occurs for Kerman. The inter-city variability is much greater for all citrus types, with a maximum range of 54 days for sour lemon.

Table 5.1: Summary statistics on the flowering dates of the five citrus types for the period 1960-2010 in the Iranian cities of Gorgan, Kerman and Shiraz. Significant correlations indicated by a single asterisk, particularly strong correlations (r ≥ 0.7) indicated by a double asterisk.

Flowering Dates	Orange	Tangerine	Sweet Lemon	Sour Lemon	Sour Orange	Pooled
Gorgan						
Average	132	133	133	135	136	134
Range	17	19	20	22	20	18.7
Variance	0.03	0.03	0.03	0.04	0.04	0.03
Sample size (n)	41	43	41	40	37	37
Change over time (d/yr)	0.10	0.09	0.07	0.07	0.05	0.05
Strength of trend (r)	*0.41	*0.32	0.24	0.21	0.16	*0.31
Kerman						
Average	87	87	89	90	82	88
Range	18	21	23	19	21	20
Variance	0.06	0.06	0.07	0.06	0.08	0.06
Sample size (n)	43	40	40	40	42	40
Change over time (d/yr)	-0.12	-0.15	-0.17	-0.16	-0.17	-0.1
Strength of trend (r)	*-0.33	*-0.38	*-0.41	*-0.45	*-0.36	*-0.37
Shiraz						
Average	90	91	91	93	93	92
Range	33	33	36	34	35	33
Variance	0.11	0.11	0.12	0.11	0.11	0.11
Sample size (n)	44	44	44	39	42	39
Change over time (d/yr)	-0.63	-0.61	-0.65	-0.56	-0.62	-0.60
Strength of trend (r)	**-0.89	**-0.88	**-0.89	**-0.84	**-0.91	**-0.91

5.3 Climate Variables

5.3.1 Annual T_{max}, T_{min} and Precipitation

5.3.1.1 Gorgan

Located in the Caspian Lowlands, Gorgan receives relatively high rainfall in what is a semi-arid to arid country, with mean annual precipitation of 583.2mm over the period of 1960-2010 (*Table 5.2, Figure 5.10*). Mean annual precipitation over this period has a range of 567.6mm, from 314.6mm in 2008 to 882.2mm in 1962 (*Table 5.2, Figure 5.10*). Over the study period, there has been a shift towards less rainfall relative to the mean for that period, with annual rainfall over the period 2006-2010 falling considerably below the 51-year average (*Figure 5.7*). The mean annual maximum temperature for Gorgan for the study period is calculated as 22.93°C, with a 4.58°C range from 20.47°C in 1969 to 25.04°C in 2010 (*Table 5.2, Figure 5.8*). There has been a non-significant increase towards above average annual T_{max} over this period, with the annual T_{max} for nine of the years from 2001-2010 situated above the 51-year average (*Figure 5.7*). There is a 10.24°C range between the average annual T_{max} and T_{min} for Gorgan. Average annual minimum temperatures are averaged for the study period as 12.69°C, with a 4.26°C range from 10.23°C in 1964 to 14.48°C in 1981 (*Table 5.2, Figure 5.9*). There is no significant trend in the number of years with average annual temperatures above or below the study period average (*Figure 5.7*). As expected from the considerable range, the variance in the average precipitation over the period was considerably greater than that of either T_{min} or T_{max}, with coefficients of variance of 0.21 for precipitation, and 0.04 and 0.06 for T_{max} and T_{min} respectively (*Table 5.2*).

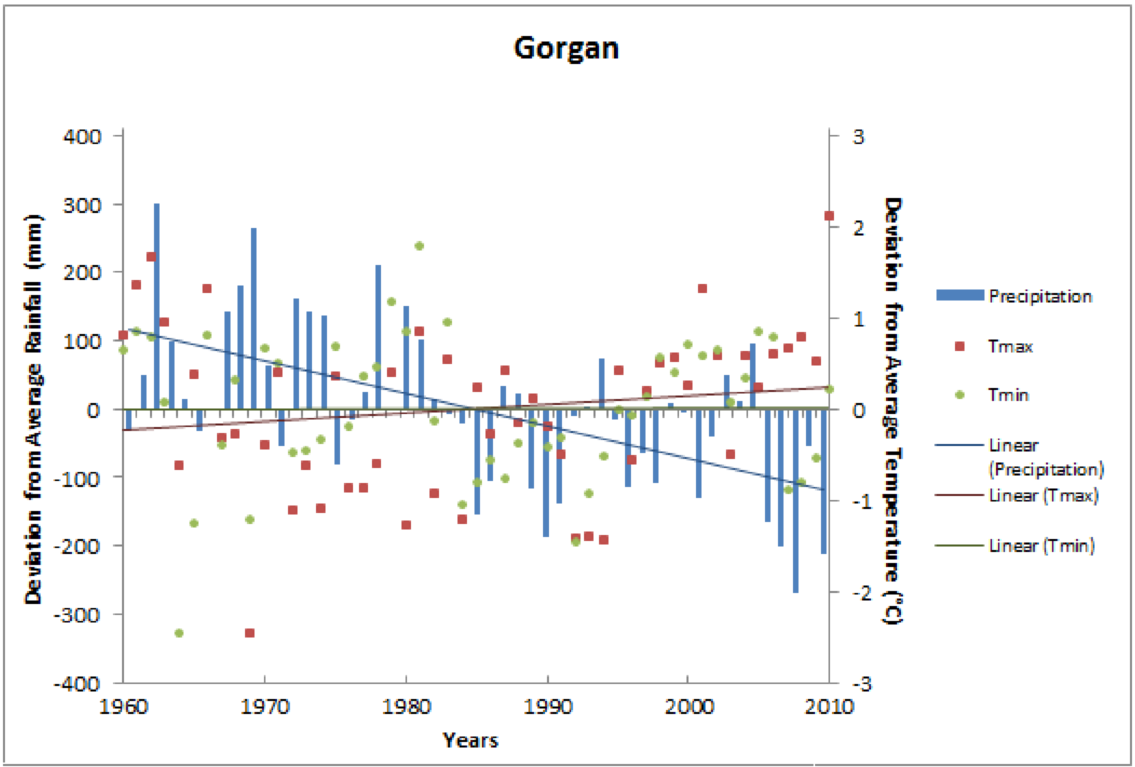

Figure 5.7: Deviation of annual average T_{max}, T_{min} and precipitation from the 1960-2010 average for Gorgan.

As expected from the considerable shift over the study period from above average to below average mean annual rainfall for Gorgan, a significant negative trend exists for mean annual rainfall, with a correlation coefficient of 0.57 ($p < 0.0001$) (*Table 5.2, Figure 5.10*). This trend equates to a decrease in annual average rainfall of 4.69mm/yr and tentatively 47mm/decade over the study period (*Table 5.2*). In contrast, insignificant trends are demonstrated for annual average T_{max} and T_{min} over the period of 1960-2010 (*Figures 5.8,* 5.9). With a correlation coefficient of 0.15, T_{max} demonstrates a shift toward higher temperatures of 0.01°C/yr; whilst T_{min} demonstrates no discernible trend for this period 1960-2010 (*Table 5.2, Figures 5.8, 5.9*). In both instances, time trend correlations are too weak to infer shifts at a decadal scale.

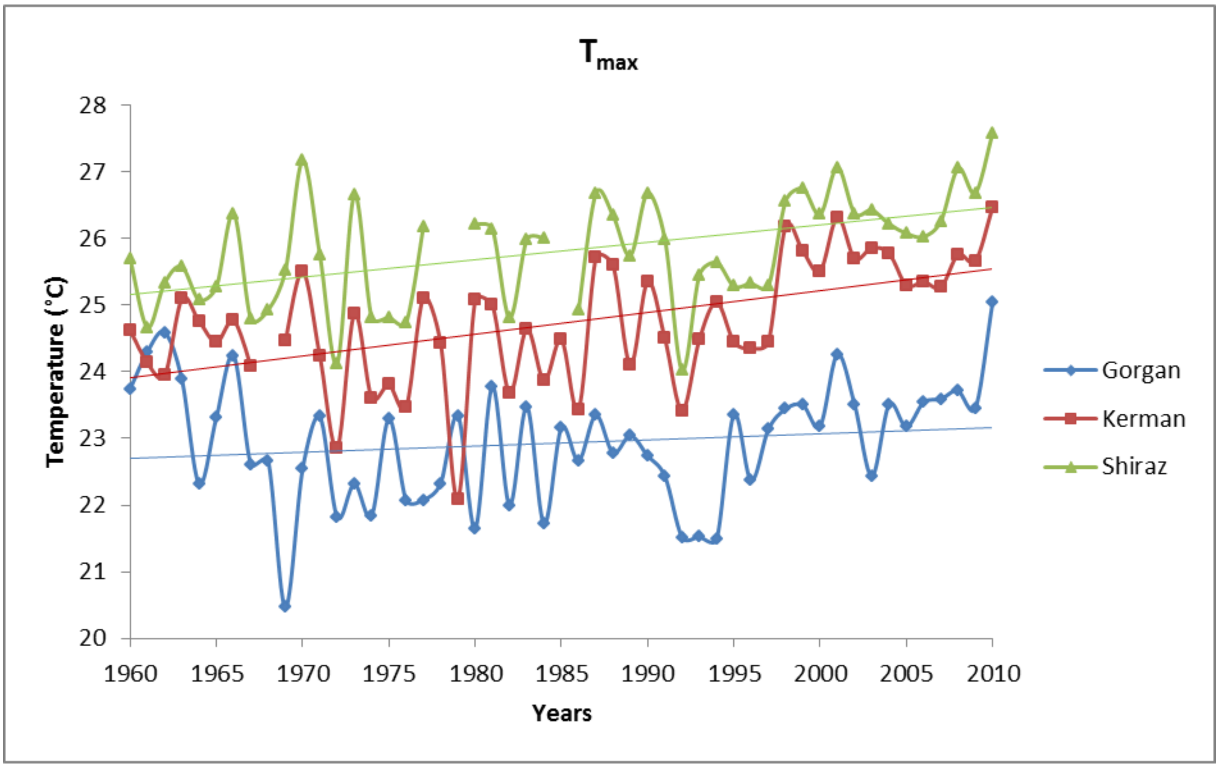

Figure 5.8: Annual T_{max} trends for Gorgan, Kerman and Shiraz from 1960-2010.

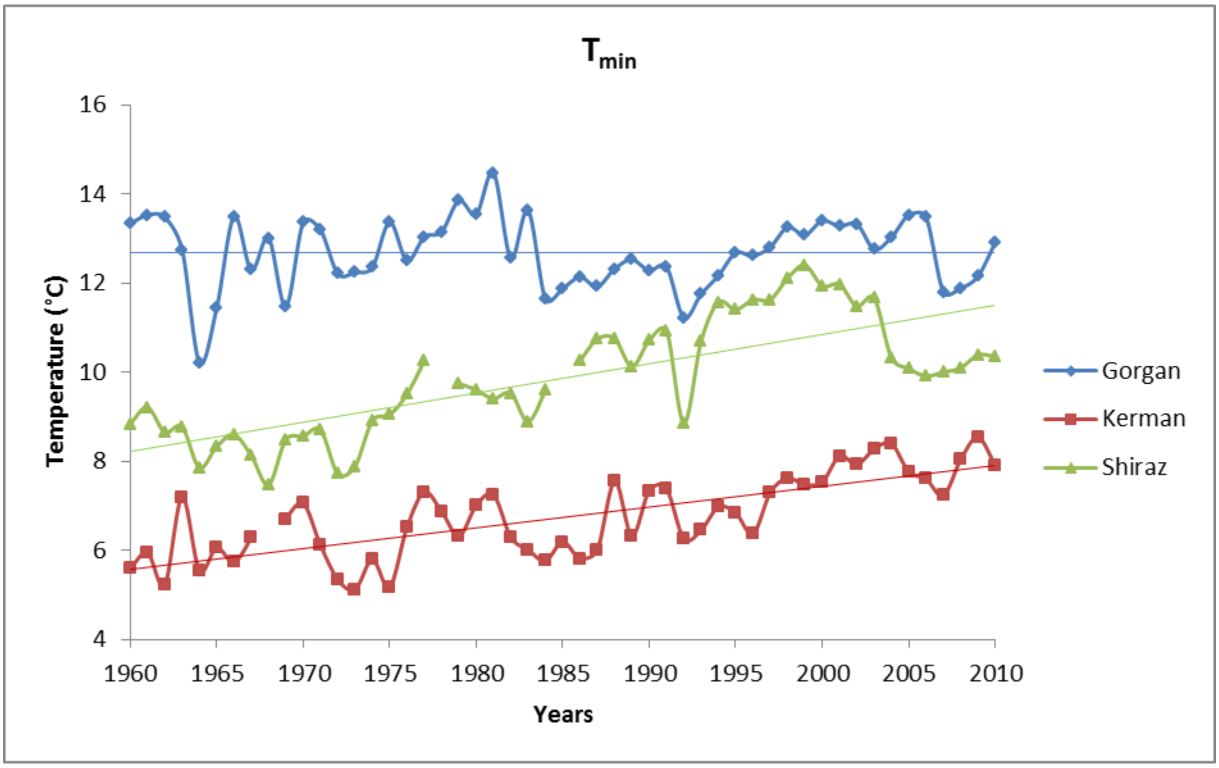

Figure 5.9: Annual T_{min} trends for Gorgan, Kerman and Shiraz from 1960-2010.

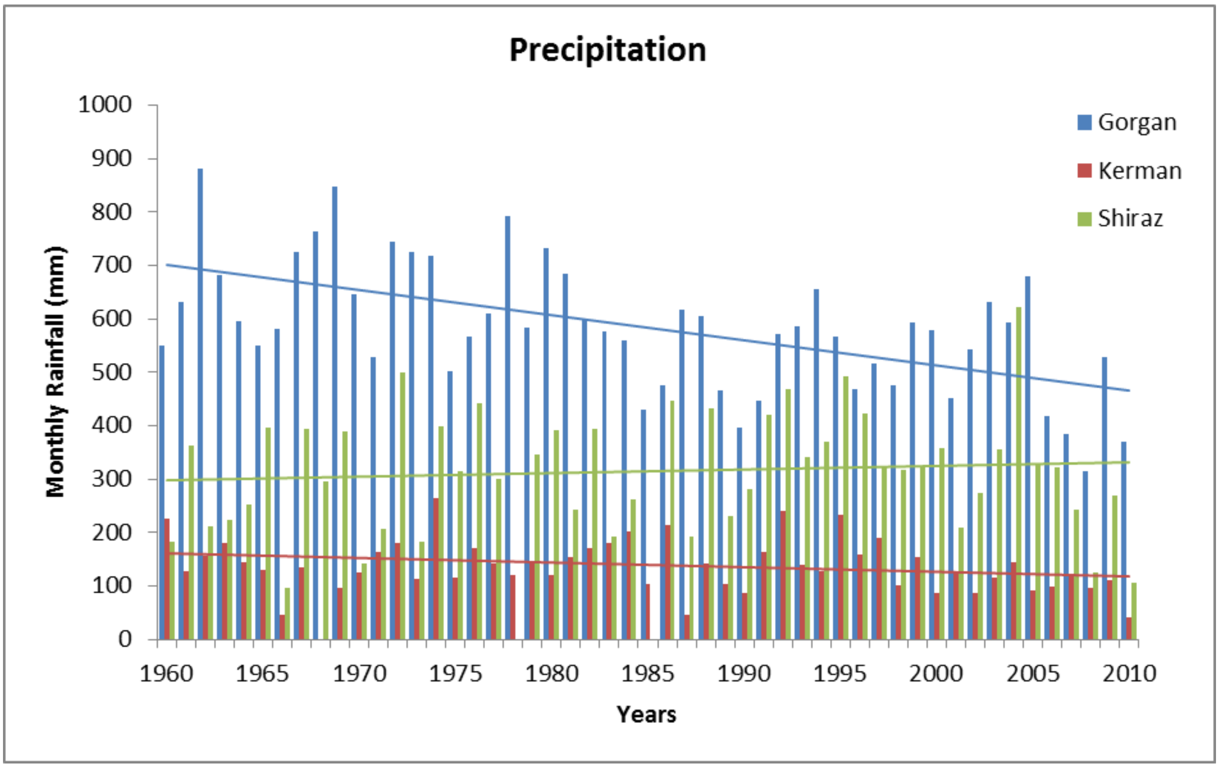

Figure 5.10: Annual precipitation trends for Gorgan, Kerman and Shiraz from 1960-2010.

5.3.1.2 Kerman

Kerman is located in the arid central Iranian Plateau, and hence has a low mean annual precipitation of 138.75mm for the period 1960-2010 (*Table 5.2, Figure 5.15*). This precipitation demonstrates a considerable range (222.78mm), from 40.82mm in 2010 to 263.6mm in 1974 (*Table 5.2, Figure 5.15*). There has been a small shift from the number of years with above average rainfall, to those with below average rainfall, with the annual rainfall for the past decade, with the exception of 2004, falling below the 1960-2010 average (*Figure 5.11*). The annual average T_{max} and T_{min} range for Kerman is considerable (17.99°C) on account of regional aridity. The annual average T_{max} for the study period is 24.74°C, with a 4.38°C range from a lowest recorded annual maximum temperature of 22.09°C in 1979 to a high of 26.47°C in 2010 (*Table 5.2, Figure 5.13*). There has been an increase in the number of years where annual T_{max} is higher than the study period average, with the seven warmest years all having occurred since 1998 (*Figure 5.11*). Kerman has the lowest annual average T_{min} of the three study cities (6.75°C), with a 3.42°C range from 5.13°C in 1973 to 8.54°C in 2009 (*Table 5.2, Figure 5.14*). A strong shift from below average to above average conditions is observed for T_{min}, with all years since 1997 demonstrating above average temperatures; and with the exception of 1963 and 1970, all years from 1960 to 1976 experienced below average temperatures (*Figure 5.11*). Variance in the average climatic conditions calculated for this period differ considerably, from coefficients of variance of 0.04 for T_{max}, 0.14 for T_{min}, and 0.35 for precipitation (*Table 5.2*).

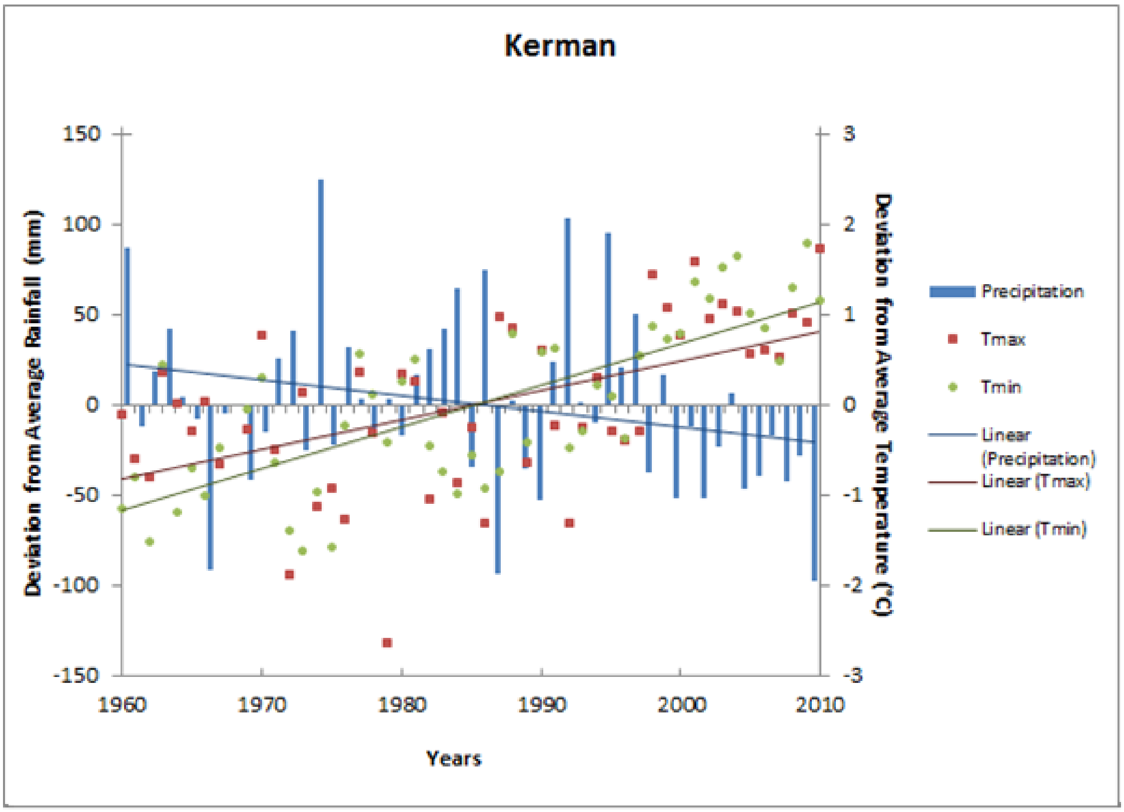

Figure 5.11: Deviation in annual average T_{max}, T_{min} and precipitation from the 1960-2010 average for Kerman.

For the period 1960-2010, significant year-on-year trends are demonstrated for T_{max} and T_{min} in Kerman, with marginally insignificant trends for precipitation. The most significant trend, with a correlation coefficient of 0.74 ($p < 0.0001$), is an increasing T_{min} (*Table 5.2, Figure 5.14*). This equates to an increase in annual average minimum temperatures of 0.05°C/yr, tentatively an increase of 0.5°C/decade (*Table 5.2*). The significant trend ($r = 0.54$, $p < 0.0001$) in T_{max} equates to an increase similar in magnitude of that of T_{min}, at 0.03°C/yr (*Table 5.2, Figure 5.13*). Whilst trends in precipitation are not quite statistically significant ($r = 0.26$, $p = 0.0663$), they reflect a 0.26mm/yr decrease in rainfall (*Table 5.2, Figure 5.15*).

5.3.1.3 Shiraz

Located at the foot of the Zagros Mountains, with a semi-arid climate, Shiraz receives more precipitation than Kerman, with a 51-year mean annual precipitation of 314.35mm (*Table 5.2, Figure 5.15*). This encompasses a substantial 525.60mm range in rainfall, from 96.3mm in 1966 to 621.9mm in 2004 (*Table 5.2, Figure 5.15*). There has been a marginal shift from years with below average rainfall to those with above average rainfall, yet the most recent four years experienced rainfall considerably below the long-term average (*Figure 5.12*). The difference between the average annual T_{max} and T_{min} is slightly lower (15.94°C) than that of Kerman, possibly due to the slightly more humid conditions. The average annual T_{max} for the period is 25.82°C, with a 3.56°C range from 24.02°C in 1992 to 27.58°C in 2010 (*Table 5.2, Figure 5.13*). There has been an increase in the number of years in which T_{max} exceeds the average temperature for 1960-2010, with all T_{max} temperatures for all years after 1998 surpassing the T_{max} average (*Figure 5.12*). The 51-year mean annual T_{min} is 9.88°C, with a 4.93°C range from 7.48°C in 1968 to 12.41°C in 1999 (*Table 5.2, Figure 5.14*). There has been a considerable shift towards mean annual minimum temperatures exceeding the long-term average, with an above average annual T_{min} for all years from 1994-2010 whilst the years 1960-1976 all recorded below average mean annual T_{min} values (*Figure 5.12*). The variance in the mean for each of these climate variables is very similar to that of Kerman, with coefficients of variance of 0.03 for T_{max}; 0.13 for T_{min}; and 0.36 for precipitation (*Table 5.2*).

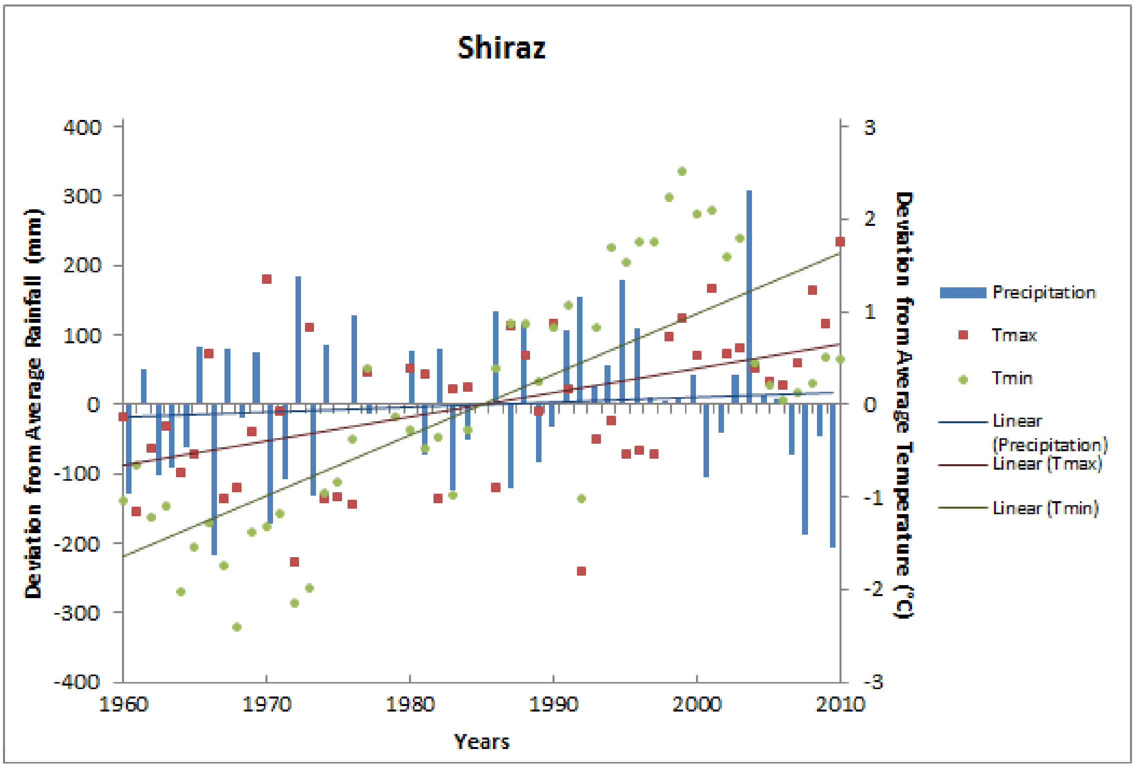

Figure 5.12: Deviation in annual average T_{max}, T_{min} and precipitation from the 1960-2010 average for Shiraz.

With the considerable shift in annual T_{min} to above the 51-year average, the highly significant trends in year-to-year change in annual T_{min} were expected. This trend, with a correlation coefficient of 0.76 ($p < 0.0001$), equates to a minimum temperature increase of 0.07°C/yr, tentatively an increase of 0.7°C per decade (*Table 5.2, Figure 5.9*). Whilst still significant, the 0.3°C/yr increase in annual T_{max} over the study period had a weaker time trend correlation, with a correlation coefficient of 0.48 ($p = 0.0005$) (*Table 5.2, Figure 5.8*). Trends in precipitation over the period 1960-2010 were extremely poor with a correlation coefficient of 0.09 ($p = 0.5270$) (*Table 5.2, Figure 5.10*). Consequently, it is tentatively suggested that precipitation in Shiraz has increased by 0.68mm/yr over the period 1960-2010 (*Table 5.2, Figure 5.10*).

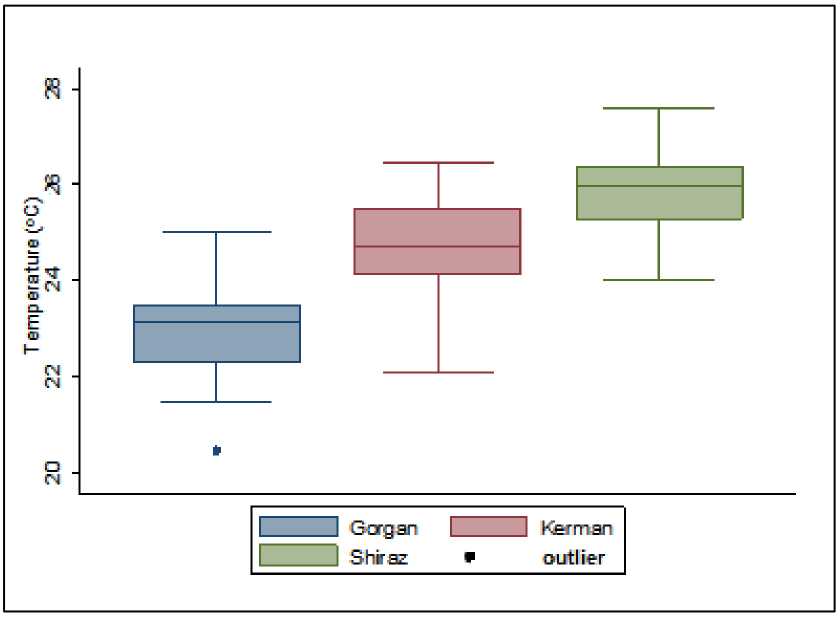

Figure 5.13: Box-and-Whisker Plot demonstrating inter-city variability in T_{max} over the period 1960-2010.

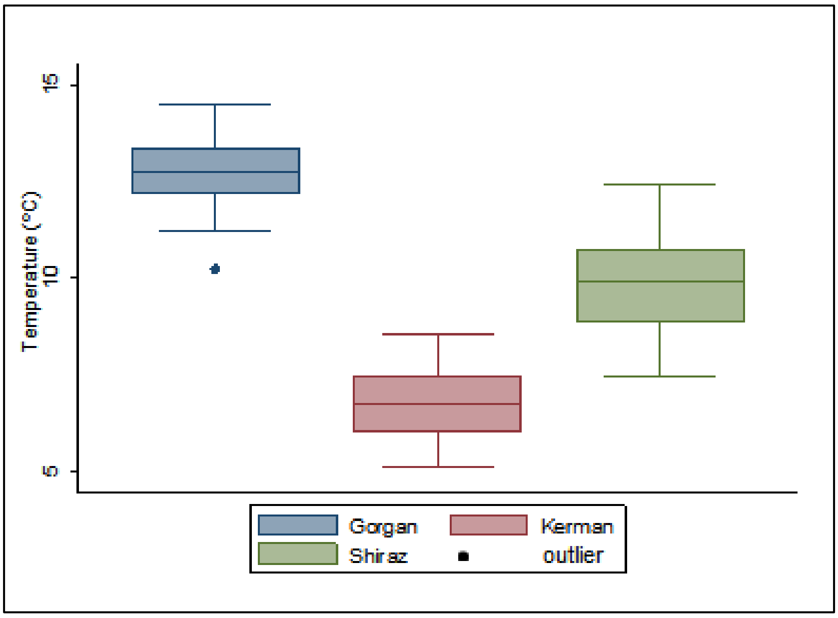

Figure 5.14: Box-and-Whisker Plot demonstrating the inter-city variability in T_{min} over the period 1960-2010.

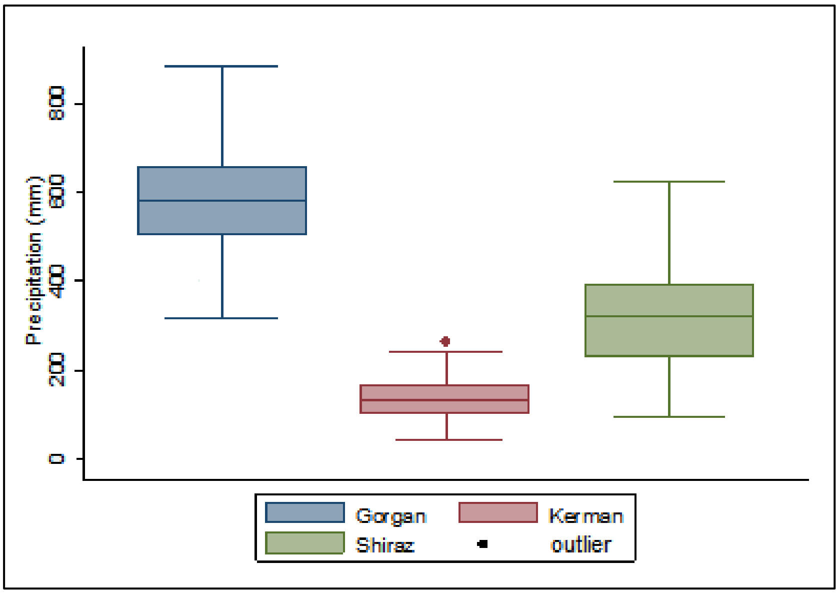

Figure 5.15: Box-and-Whisker Plot demonstrating the inter-city variability in precipitation over the period 1960-2010.

5.3.1.4 Summary

Whilst the average annual T_{max} for the three cities are similar, with only a 3°C range, there are substantial differences between the minimum temperatures (6°C range) and mean annual precipitation (444mm) (*Table 5.2*). Gorgan has the highest rainfall, at 583mm/yr averaged for the study period, and the lowest average annual diurnal temperature range of 10°C (*Table 5.2*). Kerman experienced the lowest rainfall (138.74mm/yr) of the three cities over the study period, but recorded the largest diurnal temperature range (18°C) (*Table 5.2*).

Significant time trends are demonstrated for T_{max} and T_{min} in Kerman and Shiraz, and are particularly strong for T_{min} ($r = 0.7428$, $p < 0.0001$ and 0.7628, $p < 0.0001$ respectively). Whilst Gorgan displays particularly weak time trends for T_{max} and T_{min}, there is a significant correlation for precipitation change ($r = -0.5728$, $p < 0.0001$) (*Table 5.2*). These equate to changes in T_{max} of 0.03°C/yr for both Kerman and Shiraz, and T_{min} changes of 0.05 and 0.07°C/yr for Kerman and Shiraz respectively, and decreasing precipitation of 4.69mm/yr for Gorgan (*Table 5.2*). Gorgan recorded the highest annual precipitation of the three cities, whilst Shiraz and Kerman have both higher T_{max} and lower T_{min}, and hence greater diurnal temperature ranges, than Gorgan (*Tables 5.1, 5.2*).

Table 5.2: Annual averages from 1960-2010 for the T_{max}, $T_{min,}$ and annual Precipitation totals. Statistically significant correlations indicated by an asterisk, particularly strong correlations (r ≥0.7) indicated by a double asterisk.

Annual Climate			
	T_{max}	T_{min}	Precipitation
Gorgan			
Average	22.93	12.69	583.20
Range	4.58	4.26	567.60
Variance	0.04	0.06	0.21
Sample size (n)	51	51	51
Change over time (°C or mm/yr)	0.01	0.00	-4.69
Strength of trend (r)	0.15	0.01	*-0.57
Kerman			
Average	24.74	6.75	138.75
Range	4.38	3.42	222.78
Variance	0.04	0.14	0.35
Sample size (n)	50	50	50
Change over time (°C or mm/yr)	0.03	0.05	-0.86
Strength of trend (r)	*0.54	**0.74	-0.26
Shiraz			
Average	25.82	9.88	314.35
Range	3.56	4.93	525.60
Variance	0.03	0.13	0.36
Sample size (n)	48	49	49
Change over time (°C or mm/yr)	0.03	0.07	0.68
Strength of trend (r)	*0.48	**0.76	0.09

5.3.2 Monthly T_{max}, T_{min} and Precipitation

5.3.2.1 Gorgan

Gorgan displays a clear winter rainfall peak, although significant year-long rainfall is experienced throughout the study period. Minimum rainfall is averaged for the period 1960-2010 at 18.3mm in July, with slightly higher rainfall in August at 25.98mm and June at 28.92mm (*Table 5.3, Figure 5.16*). The highest monthly rainfall averaged over this period is for March (79.39mm), followed by November (67.99mm) and October (61.51mm) (*Table 5.3, Figure 5.16*). The greatest range in monthly precipitation is 368.2mm for January, with 12mm in 2003 and 380.2mm in 1962, whilst the smallest range of 98.1mm captures the difference between 10.7mm precipitation in February 2004 to 108.8mm in February 1978 (*Table 5.3*). Averaged for 1960-2010, the highest mean maximum temperature occurs in August (32.79°C), followed by July (32.77°C) (*Table 5.3, Figure 5.16*). The lowest mean T_{max} (12.29°C) occurs in January (*Table 5.2*), contributing to a 20.5°C seasonal range in $T_{max.}$ The largest inter-annual range in monthly T_{max} is demonstrated for January, with a 12.3°C difference between the 6.1°C recorded in 1977 and the 18.4°C recorded in 1966, followed by a 12.2°C range for April, between 17.6°C (1969) and 29.8°C (1987). The month with the highest T_{min} averaged over the study period, with a peak of 22.95°C, is July (*Table 5.3, Figure 5.16*), and just marginally higher than August (22.91°C) (*Table 5.3*). The lowest mean T_{min} is calculated for January (3.02°C), but low temperatures (3.70°C) continue into February (*Table 5.3, Figure 5.16*). The largest monthly difference between T_{max} and T_{min} is 11.59°C for May (T_{max} of 26.97°C and T_{min} of 15.38°C); the smallest range of 9.27°C occurs in January (T_{max} = 12.29°C, T_{min} = 3.02°C).

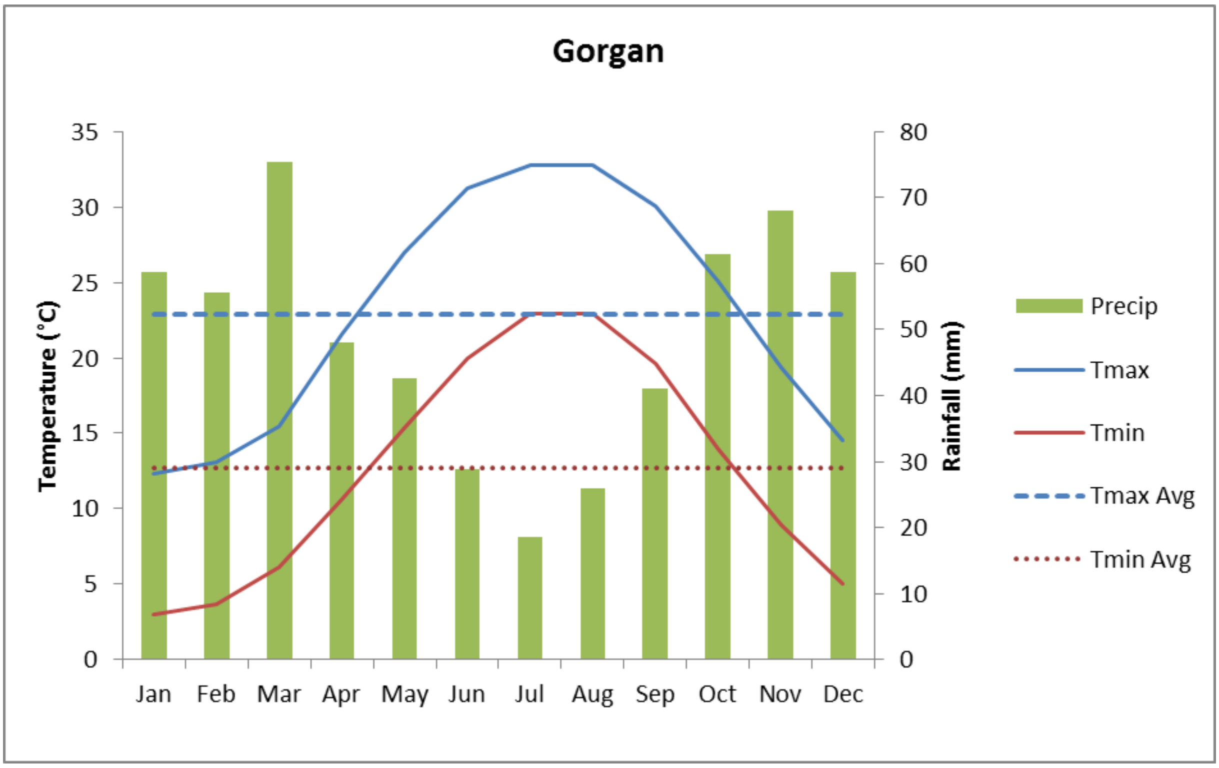

Figure 5.16: Monthly temperature and rainfall distributions for Gorgan, averaged from 1960-2010.

Whilst annual trends in precipitation are statistically significant for Gorgan, only March (r = 0.46, p = 0.0008) and October (r = 0.33, p = 0.0172) demonstrate significant trends in monthly precipitation (*Table 5.3*). These trends equate to monthly decreases in rainfall over the study period of 0.85mm/yr for March and 0.93mm/yr for October (*Table 5.3*). The weakest trends in monthly precipitation are calculated for February (r = 0.05, p = 0.7127) and November (r = 0.06, p = 0.6838) (*Table 5.3*), and reflect statistically insignificant decreases in rainfall over the period, tentatively to the magnitude of 0.09mm/yr and 0.16mm/yr, respectively. Significant trends in monthly averages of T_{min} are recorded for the coldest months of July and August, with correlation coefficients of 0.35 (p = 0.0132) and 0.33 (p = 0.0166), respectively (*Table 5.3*). These trends suggest monthly T_{min} increases of 0.02°C/yr for both months (*Table 5.3*). The weakest trends in monthly T_{min} are demonstrated for February (r = 0.05, p = 0.7057), tentatively suggesting decreasing temperatures in the magnitude of 0.01°C/yr (*Table 5.3*). There are no months with statistically significant trends in monthly $T_{max,}$ although strong correlations are reported for August (r = 0.25, p = 0.0733), September (r = 0.25, p = 0.0808) and October (r = 0.27, p = 0.0537) (*Table 5.3*). January, May, November and December tentatively indicate decreases in year-on-year T_{max} over the study period of up to 0.01°C/yr, whilst the remaining months suggest temperature increases of up to 0.04°C/yr (*Table 5.3*).

5.3.2.2 Kerman

The winter rainfall pattern which dominates Iran is even more extreme in Kerman, with almost no rainfall in the summer months of June to September (*Figure 5.17*). The lowest monthly rainfall is for September, with an average of 0.33mm for the period 1960-2010, and with only nine of the 51 years recording any rainfall (*Table 5.3, Figure 5.17*). For all of the months of the year, there is at least one year over the period 1960-2010 in which all months recorded no precipitation. The highest rainfall averaged over the study period is for March (31.71mm), although the highest monthly rainfall (108.4mm) was for February 1999 (*Table 5.3, Figure 5.17*). The highest monthly T_{max} averaged for the study period is calculated at 35.89°C for July, followed by 34.98°C for June and 34.35°C for August (*Table 5.3, Figure 5.17*). The lowest average T_{max} (12.27°C) is experienced in January (*Table 5.3, Figure 5.17*). The largest range in monthly T_{max} is calculated for December, from 9.4°C in 1964 to 21.6°C in 1998, with the lowest range of 4.8°C in July (*Table 5.3*). The 17.57°C peak in T_{min}, averaged over the study period is recorded in July, with the lowest T_{min} average recorded in January (-3.45°C) (*Table 5.3, Figure 5.17*). The range in monthly T_{min} is considerably greater for October through February (7.9°C to 9.7°C difference) than for the remainder of the year (4.3°C to 7.5°C difference) (*Table 5.3*). The largest difference (21.04°C) between monthly T_{max} and T_{min} is calculated from the 10.31°C T_{min} and 31.35°C T_{max} for September; and the lowest for March with a 15.30°C difference between the 3.59°C T_{min} and the 14.87°C T_{max}.

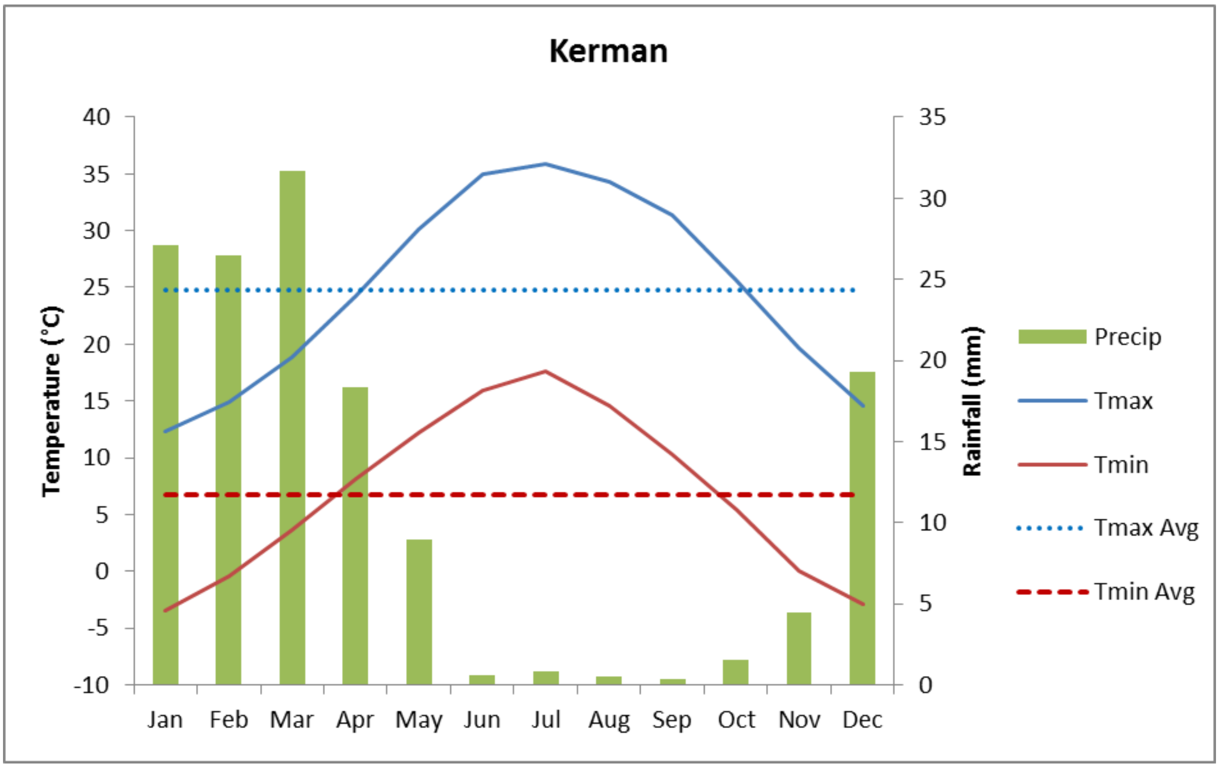

Figure 5.17: Monthly temperature and rainfall distributions for Kerman, averaged from 1960-2010.

As expected from the poor annual precipitation trend correlations, there are no months in which significant trends in precipitation occurred for the period 1960-2010 in Kerman. The strongest of these correlations for monthly precipitation are for April and July, with correlation coefficients of 0.27 ($p = 0.0594$) and 0.24 ($p = 0.0947$), respectively (*Table 5.3*). Tentatively, it can be surmised that rainfall has increased over the study period for June, October and December, but decreased in the remaining months (*Table 5.3*). In contrast, trends in monthly T_{min} are significant for all months except March ($r = 0.20$, $p = 0.1250$) (*Table 5.3*). The strongest time trend correlations were for May ($r = 0.53$, $p < 0.0001$) and December ($r = 0.55$, $p < 0.0001$), representing increases in T_{min} of 0.04°C/yr and 0.09°C/yr over the study period, respectively (*Table 5.3*). The strength of time trends for the remaining months ranged from 0.29 ($p = 0.0468$) for February to 0.5 ($p = 0.0002$) for November, which equate to increases in T_{min} of between 0.03°C/yr and 0.08°C/yr (*Table 5.3*). Five months demonstrate significant time trends in monthly T_{max} over the study period, ranging between correlation coefficients of 0.29 ($p = 0.0418$) for November and 0.50 ($p = 0.0002$) for April (*Table 5.3*). There is considerable variation in the strength of the non-significant time trends, from extremely weak 0.1 ($p = 0.9294$) for January to nearly significant 0.27 ($p = 0.0559$) for

March (*Table 5.3*). Time trends for all months indicate increases in T_{max} over the study period, tentatively ranging in magnitude from 0.001°C/yr for January to 0.07 for April (*Table 5.3*). For those months with significant time trends, increased temperatures of 0.03°C/yr (July and September) to 0.07°C/yr (April) are calculated (*Table 5.3*).

5.3.2.3 Shiraz

Shiraz demonstrates the most defined winter rainfall pattern, with zero precipitation averaged for the months of June and September over the period 1960-2010, and minimal precipitation of 0.75mm and 0.86mm for remaining summer months of July and August, respectively (*Figure 5.18*). The highest rainfall occurs in January, with an average of 84.47mm (*Table 5.3, Figure 5.17*). March through December record zero rainfall counts for at least one year during the study period, with the mid to late winter months of January and February never experiencing zero rainfall. The highest monthly rainfall over the study period of 324.5mm occurred in January 1965. There is a peak in average T_{max} for the month of July (38.1°C), followed by August (37.25°C) (*Table 5.3, Figure 5.18*). The lowest monthly T_{max} (12.19°C) averaged for the study period is in January (*Table 5.3, Figure 5.18*). The highest monthly average temperature recorded for the study period was 40.1°C in July 1997. The highest monthly T_{min} averaged for the 51-year period was also for July (20.68°C), followed by August (19.60°C). The lowest monthly T_{min} values averaged for the study period are for January (0.03°C) (*Table 5.3, Figure 5.18*), with the lowest averaged monthly temperature (3.9°C) in January 1973. The largest monthly range is 18.82°C between 33.81°C T_{max} and 14.99°C T_{min} for September, whilst the smallest range is 12.16°C between 0.03°C T_{min} and 12.19°C T_{max} in January.

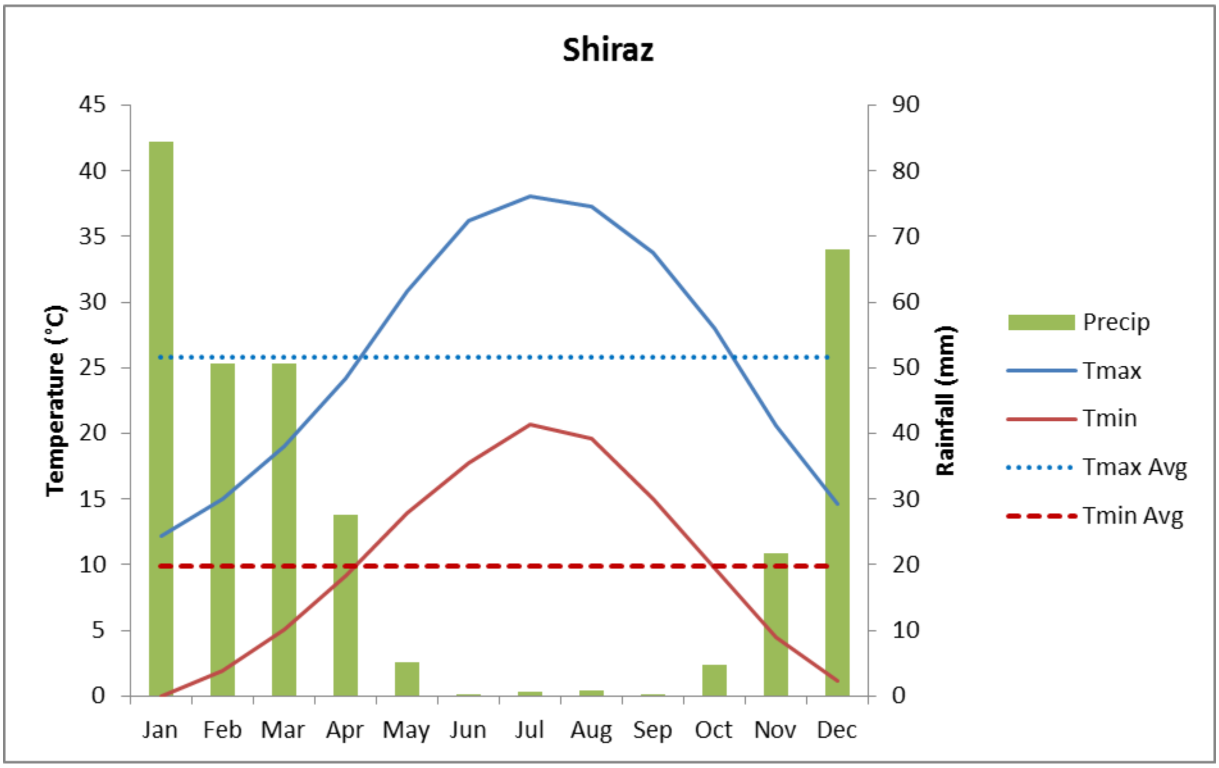

Figure 5.18: Monthly temperature and rainfall distributions for Shiraz, averaged from 1960-2010.

As with Kerman, records from Shiraz reveal months with statistically significant shifts in precipitation over the period 1960-2010. The strongest time trends are calculated for April, August and September, with correlation coefficients of 0.28 ($p = 0.0509$), 0.20 ($p = 0.1517$), and 0.24 ($p = 0.0925$), respectively (*Table 5.3*). These non-significant time trends tentatively suggest a decrease in rainfall for April by 0.52mm/yr, but increases in rainfall for August and September by 0.20mm/yr and 0.24mm/yr, respectively (*Table 5.3*). Trends of decreasing rainfall are recorded for May, July and October, but with increasing rainfall over the 51-year period calculated for the remaining months (*Table 5.3*). By contrast, there are significant trends in T_{min} for all months, ranging in strength $r = 0.31$ ($p = 0.0256$) for January to $r = 0.74$ ($p < 0.0001$) for June (*Table 5.3*). Particularly strong T_{min} time trend correlations are calculated for April through October, with correlation coefficients greater than 0.7 ($p < 0.0001$) for April, May, June and August (*Table 5.3*). These equate to increases in T_{min} of between 0.07°C/yr for June and July and 0.09°C/yr for October (*Table 5.3*). The weaker trends observed for the winter months of November through March suggest increases in T_{min} ranging from 0.08°C/yr for January to 0.70°C/yr for December (*Table 5.3*). Trends in monthly T_{max} over the study period for Shiraz were not significant for all months, but are significant for the summer months of April through October, where the strongest trends in T_{min} are demonstrated. These significant trends in T_{max} ranged in strength from r = 0.34 (p = 0.0155) for September and October, to r = 0.49 (p = 0.0003) for July (*Table 5.3*). These suggest increases in monthly T_{max} over the study period of between 0.02°C/yr for September, October and June, and 0.06°C/yr for April (*Table 5.3*). Trends for those winter months which were not statistically significant suggest increases in T_{max} in the range of 0.03°C/yr for January to 0.07°C/yr for November (*Table 5.3*).

5.3.2.4 Summary

The three cities of Gorgan, Kerman and Shiraz all experience winter rainfall, and similar intra-annual temperature ranges of approximately 20-25°C for both T_{max} and T_{min}. Peak temperatures for all three cities are experienced in July, whilst minimum rainfall is recorded for June. Maximum rainfall occurs in March for Gorgan and Kerman (32 and 35mm respectively), and in January for Shiraz (42mm). Gorgan is subject to the lowest seasonality, having the highest out-of-season rainfall (a minimum of 19mm in June) and the lowest intra-annual temperature variation (20°C for both T_{min} and T_{max}). The statistically significant trends in T_{min} for Gorgan are considerably smaller than those for Shiraz and Kerman, with an increase of 0.02°C/yr for both July and August.

For Shiraz, those months with significant trends indicate an increase in T_{min} of between 0.03°C/yr and 0.09°C/yr over the period 1960-2010. Kerman exhibits similar increases of 0.03-0.08 °C/yr for the same 51-year period. Lower year-on-year increases in monthly T_{max} are recorded for this period, ranging from 0.03-0.07°C/yr for Kerman, and 0.02-0.06°C/yr for Shiraz. Statistically significant decreases in monthly precipitation for Gorgan are of the magnitude of 0.85-0.93mm/yr for March and October, respectively.

Table 5.3: Monthly trends in T_{max}, $T_{min,}$ and Precipitation for Gorgan, Kerman and Shiraz, over the period 1960-2010. Significant correlations are indicated by an asterisk, correlations with r ≥ 0.7 indicated by a double asterisk.

Monthly Climate	Gorgan T_{max}	Gorgan T_{min}	Gorgan Precip	Kerman T_{max}	Kerman T_{min}	Kerman Precip	Shiraz T_{max}	Shiraz T_{min}	Shiraz Precip
January									
Mean	12.29	3.02	58.78	12.27	-3.50	27.07	12.19	0.03	84.47
Range	12.3	10.4	368.2	10.7	9.6	97.5	9.8	6.7	321.5
Variance	0.22	0.69	0.90	0.17	-0.58	0.73	0.17	43.79	0.77
Sample size (n)	51	51	51	50	50	50	51	51	51
Change over time (°C or mm/yr)	-0.01	-0.02	-0.83	0.00	0.04	-0.20	0.01	0.03	0.08
Strength of trend (r)	-0.06	-0.16	-0.23	0.01	*0.32	-0.15	0.05	*0.31	0.02
February									
Mean	13.10	3.70	55.66	14.87	-0.48	26.46	15.03	1.93	50.7
Range	10.9	7.6	98.1	10.8	8.2	108.4	9.4	6.6	156.6
Variance	0.19	0.49	0.45	0.15	-3.93	0.91	0.14	0.77	0.79
Sample size (n)	51	51	51	50	50	50	49	50	50
Change over time (°C or mm/yr)	0.00	-0.01	-0.09	0.03	0.08	-0.23	0.02	0.05	0.14
Strength of trend (r)	0.02	-0.05	-0.05	0.19	*0.28	-0.14	0.13	*0.45	0.05
March									
Mean	15.42	6.14	75.39	18.89	3.59	31.71	19.02	5.09	50.56
Range	21.7	5.7	113.2	10	5.5	99	9.8	4.7	188.6
Variance	0.21	0.23	0.37	0.12	0.39	0.67	0.12	0.24	0.80
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.04	0.01	-0.85	0.04	0.02	-0.21	0.03	0.05	0.14
Strength of trend (r)	0.18	0.12	*-0.46	0.27	0.20	-0.14	0.19	*0.56	0.05
April									
Mean	21.61	10.65	48.03	24.28	8.13	18.32	24.20	9.18	27.66
Range	12.20	6.5	104	8.6	4.9	98	8.2	7.3	169.9
Variance	0.11	0.14	0.50	0.08	0.14	0.97	0.08	0.17	1.01
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.01	-0.01	-0.34	0.07	0.03	-0.32	0.06	0.08	-0.52
Strength of trend (r)	0.05	-0.05	-0.21	*0.50	*0.42	-0.27	*0.44	**0.72	-0.28
May									
Mean	26.97	15.38	42.60	30.13	12.24	8.96	30.87	13.95	5.124
Range	8.9	5.4	165.7	8.3	4.3	65	7.4	6.8	52.5
Variance	0.06	0.08	0.73	0.06	0.09	1.57	0.05	0.12	2.05
Sample size (n)	51	51	51	51	51	51	50	50	50
Change over time (°C or mm/yr)	-0.01	-0.02	-0.36	0.05	0.04	-0.16	0.04	0.08	-0.08
Strength of trend (r)	-0.12	-0.21	-0.17	*0.39	*0.53	-0.17	*0.37	**0.72	-0.12
June									
Mean	31.21	19.97	28.92	34.98	15.97	0.60	36.25	17.79	0.25
Range	8.7	4.7	139.9	5.7	6.5	7.8	3.5	6.3	6.2
Variance	0.06	0.05	0.92	0.03	0.10	2.68	0.03	0.08	4.07
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.01	0.01	-0.33	0.01	0.04	0.00	0.02	0.07	0.00
Strength of trend (r)	0.09	0.14	-0.19	0.17	*0.37	0.01	*0.38	**0.74	0.05

	Gorgan			Kerman			Shiraz		
	T_{max}	T_{min}	Precip	T_{max}	T_{min}	Precip	T_{max}	T_{min}	Precip
July									
Mean	32.77	22.95	18.53	35.86	17.57	0.81	38.10	20.68	0.72
Range	6.7	4.2	104.8	4.8	6.9	18	4.2	6.6	18
Variance	0.05	0.04	1.14	0.04	0.10	3.69	0.03	0.08	3.84
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.01	0.02	-0.34	0.03	0.05	-0.05	0.03	0.07	-0.02
Strength of trend (r)	0.08	*0.35	-0.24	*0.31	*0.40	-0.24	*0.49	**0.68	-0.12
August									
Mean	32.79	22.91	25.98	34.35	14.53	0.49	37.25	19.60	0.86
Range	6.3	4.4	103.2	6.6	7.3	7.4	4.3	6.9	22.5
Variance	0.05	0.05	0.90	0.04	0.11	2.93	0.03	0.08	4.07
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.03	0.02	-0.29	0.03	0.04	-0.05	0.03	0.08	0.05
Strength of trend (r)	0.25	*0.33	-0.18	0.27	*0.32	-0.06	*0.37	**0.71	0.20
September									
Mean	30.08	19.61	41.04	31.35	10.31	0.33	33.81	14.99	0.01
Range	6.6	5	119.3	5.7	7.5	6	4.3	5.9	0.11
Variance	0.05	0.06	0.63	0.04	0.18	3.31	0.03	0.11	4.04
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.03	0.02	0.18	0.03	0.05	-0.002	0.02	0.08	0.00
Strength of trend (r)	0.25	0.21	0.10	*0.33	*0.37	-0.02	*0.34	**0.67	0.24
October									
Mean	25.08	13.96	61.51	25.62	5.48	1.51	27.97	9.75	4.74
Range	9	6.7	231.6	21.7	7.9	23.9	4.5	7.9	73
Variance	0.08	0.12	0.68	0.12	0.37	2.88	0.04	0.39	2.58
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	0.03	0.01	-0.93	0.04	0.06	0.04	0.02	0.09	0.00
Strength of trend (r)	0.27	0.10	*-0.33	0.20	*0.45	0.13	*0.34	**0.98	0.00
November									
Mean	19.38	8.90	67.99	19.61	0.05	4.43	20.55	4.48	21.65
Range	8.4	6.9	152	7.7	9.7	31	7.4	7.4	138.3
Variance	0.10	0.17	0.60	0.09	40.64	1.73	0.09	0.39	1.54
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	-0.01	-0.01	-0.16	0.04	0.07	-0.01	-0.01	0.07	0.16
Strength of trend (r)	-0.08	-0.14	-0.06	*0.29	*0.50	-0.01	0.10	*0.59	0.07
December									
Mean	14.51	5.06	58.78	14.52	-2.95	19.29	14.63	0.12	68.08
Range	9.4	7.9	128.9	12.2	-0.77	94.2	10.6	9	305.2
Variance	0.14	0.37	0.50	0.16	0.14	1.13	0.15	1.68	0.96
Sample size (n)	51	51	51	51	51	51	51	51	51
Change over time (°C or mm/yr)	-0.01	-0.02	-0.35	0.03	0.09	0.21	0.02	0.06	0.70
Strength of trend (r)	-0.10	-0.19	-0.18	0.22	*0.56	0.14	0.02	*0.45	0.16

5.3.3 Seasonal and Pre-flowering Averages

Averages for T_{max}, T_{min} and precipitation for the months and seasons preceding flowering do not provide markedly different information to the annual and monthly analyses, and present weaker correlations than those previously established time trends (*Tables 5.2, 5.3, 5.4*). The spring grouping (March and April) reveals the strongest correlations across the most climate variables and cities, and best resembles the monthly and annual results (*Table 5.4*). However, the spring grouping does not capture the significant (albeit very weak) positive trend in Kerman's precipitation that appears when grouping the three months prior to flowering, nor are correlations for Gorgan's precipitation or Kerman's T_{min} during spring as high as those from the average of the 4 months prior to flowering for each city (*Table 5.4*). Neither the three- nor the four-month averages reflect the significant changes in T_{max} for Kerman and Shiraz, as detected from the spring grouping (*Table 5.4*). The seasonal and pre-flowering monthly groupings do not return the more generic observations of the annual averages, nor do they provide the detail of the monthly averages. Seasonal averages are thus excluded from subsequent analyses and interpretation. The seasons of autumn and summer are not considered in this section, or further in this study, as they occur after flowering, any climate trends during these seasons are likely to only have an indirect effect on flowering in the subsequent growing season.

Table 5.4: Strength, significance and magnitude of the seasonal and pre-flowering monthly trends in T_{max}, T_{min} and Precipitation in Gorgan, Kerman and Shiraz from 1960-2010. Significant relationships indicated by an asterisk, correlations with r≥ 0.7 indicated by a double asterisk

Seasonal Climate									
	Gorgan			Kerman			Shiraz		
	T_{max}	T_{min}	Precip	T_{max}	T_{min}	Precip	T_{max}	T_{min}	Precip
3 months prior to flowering									
Mean (°C or mm)	21.33	10.72	55.34	15.42	-0.05	28.29	15.41	2.36	62.13
Range	8.27	4.2	79	7.9	7.23	38.93	7.1	4.83	130.97
Variance	0.07	0.10	0.31	0.11	0.18	0.37	0.10	0.46	0.48
Sample size (n)	153	153	153	151	151	151	151	152	152
Change over time (°C/yr or mm/yr)	0.01	0.00	-0.52	0.02	0.03	-0.20	0.02	0.04	0.11
Strength of trend (r)	0.11	0.06	*0.45	0.16	*0.30	*0.28	0.18	*0.55	0.06
4 months prior to flowering									
Mean (°C or mm)	15.61	5.88	59.47	15.19	-0.77	26.39	15.22	2.06	63.77
Range	7.78	5.7	119.33	7.35	5	39.75	6.83	4.15	123.8
Variance	0.10	0.20	0.29	0.09	-1.47	0.36	0.09	0.54	0.47
Sample size (n)	204	204	204	202	202	202	202	203	203
Change over time (°C or mm/yr)	0.01	-0.01	-0.53	0.02	0.04	-0.17	0.02	0.04	0.32
Strength of trend (r)	0.09	0.07	*0.46	0.23	*0.52	0.21	0.20	*0.58	0.16
Spring									
Mean (°C or mm)	18.52	8.39	61.71	21.58	5.86	25.02	21.61	7.14	39.11
Range	11.85	5.2	80.8	7.4	4.5	71.25	7.9	5.2	104.45
Variance	0.11	0.14	0.32	0.08	0.19	0.57	0.08	0.18	0.60
Sample size (n)	102	102	102	102	102	102	102	102	102
Change over time (°C or mm/yr)	0.02	0.00	-0.06	0.05	0.03	-0.26	0.04	0.06	-0.19
Strength of trend (r)	0.17	0.04	*0.44	*0.45	*0.35	0.27	*0.37	**0.72	0.12
Winter									
Mean (°C/mm)	14.81	5.15	59.53	15.36	-1.68	19.41	15.60	1.90	56.73
Range	7.13	6.43	103.95	5.5	6.1	37.43	5.1	5.53	135.5
Variance	0.10	0.23	0.35	0.08	-0.79	0.42	0.07	0.64	0.46
Sample size (n)	204	204	204	202	202	202	202	203	203
Change over time (°C or mm/yr)	-0.01	-0.02	-0.27	0.02	0.06	-0.07	0.02	0.05	0.23
Strength of trend (r)	0.07	0.19	0.19	*0.26	*0.62	0.13	0.20	*0.61	0.13

5.3.4 Rainfall Onset

Rainfall onset dates, which are defined for this study with reference to the literature for similar arid and desert regions, are outlined in s*ection 4.3.1.1.* A preliminary analysis of changes in the date of seasonal rainfall onset over the period 1960-2010, yields no significant trends for any of the three cities. Correlations were particularly weak, ranging from r = 0.01 (p = 0.9276) for Kerman to 0.22 (p = 0.1153) for Shiraz (*Table 5.5*). These poor correlations equate to negligible changes in the rainfall start date, from a shift to earlier in the year by 0.03d/yr for both Kerman and Shiraz, to a delay of 0.06d/yr for Gorgan (*Table 5.5*). Consequently, as the date for the start of rainfall, which has not been included in any other phenology studies to date, demonstrated poor time-trends for the study period, it is excluded from further analyses and interpretation in this study.

Table 5.5: Trends in the start date of rainfall for Gorgan, Kerman and Shiraz.

Onset of seasonal rainfall			
	Gorgan	Kerman	Shiraz
Mean (d)	261	361	338
Range	60	169	129
Variance	0.79	0.26	0.3
Change over time (d/yr)	0.06	-0.03	-0.03
Strength of trend (r)	0.07	0.01	0.22

5.3.5 Temperature Thresholds

Whilst basic climate variables such as T_{max}, T_{min} and precipitation are often the direct drivers of phenological events, the analysis of the trends in potentially less direct climate drivers such as threshold temperatures can provide insight into the reasons for shifts in flowering dates, particularly during those periods of the year when both the minimum and maximum temperatures fall outside of optimum temperature thresholds. This would include winter months in which both the maximum and minimum daily temperatures fall below the 13°C threshold, and the spring, autumn and summer months during which days with both maximum temperatures above 35°C and minimum temperatures below 13°C occur. For Shiraz and Kerman, no months during the year exceeded both the minimum and maximum temperatures on at least one day. For Gorgan, July and August are the only months for which both thresholds have not been exceeded on the same day throughout the study period.

5.3.5.1 Gorgan

For the period 1960-2010, there is an average annual count of 28.8 days during which T_{max} > 35°C (*Table 5.6*), which is contributed predominately by the summer months of July (9.1 days) and August (8.7 days) (*Table 5.6*). There are no days with T_{max} exceeding 35°C in the mid-winter months of December through February (*Table 5.6*). Considerable inter-annual variability exists within the 50-year study period, with an approximate 25-30 year cycle and amplitude of *ca*. 40 days (*Figure 5.19a*).

The threshold of T_{min} < 13°C is exceeded considerably more frequently than the T_{max} > 35°C threshold, with an average annual count of 183.2 days for the study period (*Table 5.6*). January and December contribute significantly to this annual count, with average counts of 30.8 and 30.5 days, respectively (*Table 5.6*). The only months in which there are no days with T_{min} < 13°C are July and August, in mid-summer (*Table 5.6*). Inter-annual variability is demonstrated for the counts of days below 13°C, with a similar amplitude of approximately 40-50 days, but over a period of only *ca*. 10 years (*Figure 5.19b*). Average counts of days with T_{max} and T_{min} < 13°C are also greater than days with T_{max} exceeding 35°C, with an average annual count of 60 days over the study period (*Table 5.6*). Almost one-third is contributed by an 18.1 average day count for January (*Table 5.6*). In the summer months of June through September there are no days with T_{max} < 13°C (*Table 5.6*). Large inter-annual variability exists for this variable, with cyclical amplitude of up to 80 days over periods of 10-20 years (*Figure 5.19c*). These cycles in the counts of days exceeding threshold conditions are interesting in that they have not been highlighted in the climate literature for Iran (Ghorbani & Soltani, 2003; Gholipoor & Shahsavani, 2008).

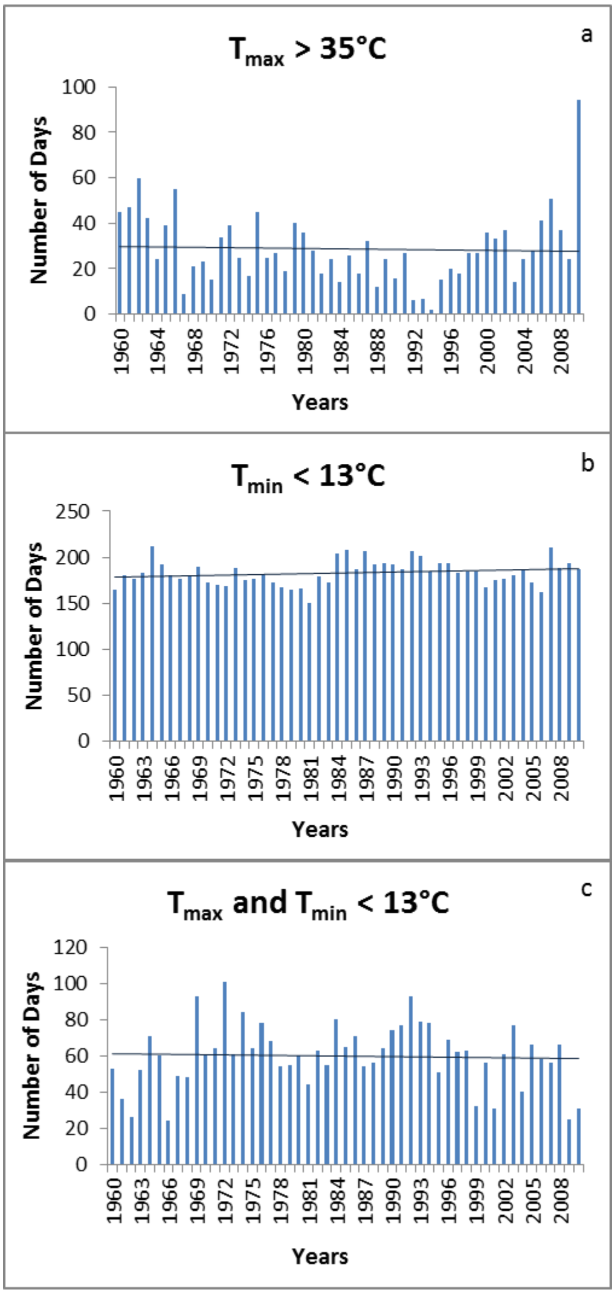

Figure 5.19: Annual counts of days in Gorgan exceeding threshold conditions suitable for citrus flowering, a: T_{max} > 35°C, b: T_{min} < 13°C, c: T_{max} and T_{min} < 13°C.

The strongest trend in counts of days with T_{max} < 35°C is recorded for October, with r = 0.39 (p = 0.0043). Trends for the remaining months range in correlation strength between r = 0.02 (p = 0.8875) for April and r = 0.25 (p = 0.0747) for May (*Table 5.6*). The trend for October tentatively equates to an increase in the count of days with T_{max} > 35°C of 0.02d/yr over the study period (*Table 5.6*). Of the remaining months, a further two suggest increased counts over the study period, six suggest decreased counts, and the remaining three months have consistent counts of 0 days (*Table 5.6*). The strongest trends in the average counts of days with T_{min} < 13°C are for January (r = 0.26, p = 0.0615) and May (r = 0.25, p = 0.0740) (*Table 5.6*). These tentatively suggest an increase in counts of 0.01d/yr and 0.06d/yr over the study period, respectively (*Table 5.6*). For all months, apart from those with zero-counts, the trends tentatively suggest an increased count of days with T_{min} < 13°C (*Table 5.6*). The strongest trends for counts of days in which T_{max} and T_{min} < 13°C are for April (r = 0.24, p = 0.0900) and March (r = 0.23, p = 0.0998) (*Table 5.6*), and tentatively suggest decreases in counts by 0.04d/yr and 0.09d/yr, respectively (*Table 5.6*). Trends of increased counts of days where both thresholds were exceeded are revealed for January, November and December, whilst trends of decreased counts are presented for February, March, April, May and October (*Table 5.6*).

5.3.5.2 Kerman

Kerman has almost double Gorgan's average annual count of days with T_{max} > 35°C, at 58.7 days (*Table 5.6*). This comprises substantial counts for the months of June through August, with average monthly counts of 17.3, 21.4 and 14.5 days, respectively (*Table 5.6*). There are no days during the period November through March where T_{max} > 35°C (*Table 5.6*). Similar to Gorgan, there are considerably more days where T_{min} < 13°C, with an average annual count of 264.2 days (*Table 5.6*). Averaged from 1960-2010, all months experienced at least two days below 13°C, with the lowest counts for July (2.6 days) and June (4.6 days), respectively (*Table 5.6*). Highest monthly counts are recorded for January and December, with 31 days each (*Table 5.6*). The lowest threshold counts for Kerman occur for T_{max} and T_{min} < 13°C; an annual average of 36.4 days for the study period (*Table 5.6*). With no days with T_{max} < 13°C for the summer and autumn months of May through October, the 15.6 day count for January is notable (*Table 5.6*).

There is considerable inter-annual variability in the counts of days in which T_{max} > 35°C, although with poorly defined periodicity (approximately 10 years) and amplitude of approximately 65 days (*Figure 5.20a*). There is considerably less inter-annual variability in the counts of days in which T_{min} < 13°C, and a cyclicity of up to 30% of the mean value (*Figure 5.20b*). The most distinct inter-annual variability is demonstrated for the counts of days in which both T_{max} and T_{min} < 13°C, with a range of 53 days contributing to a mean of only 36.4 days (*Figure 5.20c*).

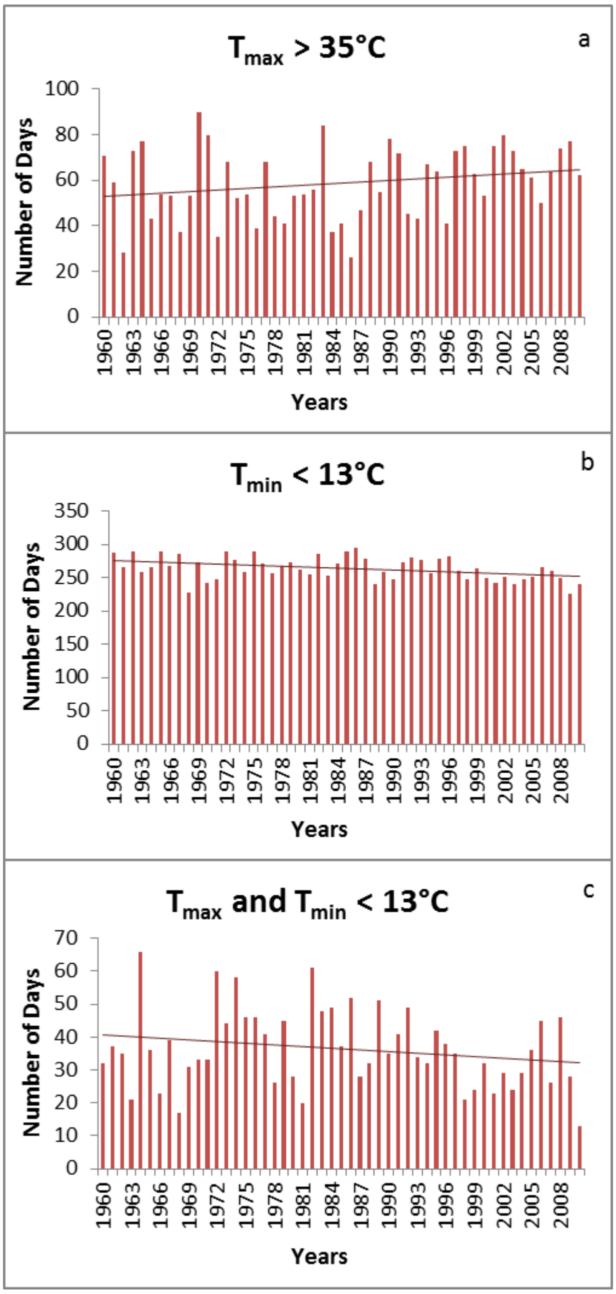

Figure 5.20: Annual counts of days in Kerman exceeding threshold conditions suitable for citrus flowering, a: T_{max} > 35°C, b: T_{min} < 13°C, c: T_{max} and T_{min} < 13°C.

Significant time trends are demonstrated for all threshold groups in Kerman, unlike Gorgan. For counts of days with T_{max} > 35°C, there is a significant increasing trend ($r = 0.29$, $p = 0.0404$) in May, to the order of 0.07d/yr (*Table 5.6*). The remaining months with non-zero counts of days with T_{max} > 35 reveal particularly weak trends, ranging in strength from r =

0.02 (p = 0.8935) for April to r = 0.12 (p = 0.4082) for July (*Table 5.6*). There are more months with statistically significant trends where T_{min} < 13°C, with correlation coefficients ranging from r = 0.29 (p = 0.0395) for April, July and November, to r = 0.38 (p = 0.0055) for May, and r = 0.33 (p = 0.0188) for September (*Table 5.6*). These equate tentatively to decreased counts of 0.13d/yr for September and 0.01d/yr for November (*Table 5.6*). Similar to the trends for T_{max} > 35°C, trends in counts of days with T_{max} and T_{min} < 13°C are statistically significant for only one month – in this case March (*Table 5.6*). With r = 0.33 (p = 0.0200), this trend tentatively suggests a decreased count of -0.05d/yr over the study period (*Table 5.6*). The months of May through October have no days with T_{max} < 13°C. For the remaining months, the weak time trend correlations suggest a decrease in the number of days with T_{max} and T_{min} < 13°C of 0.01-0.05d/yr (*Table 5.6*).

5.3.5.3 Shiraz

Shiraz recorded both the highest count of days where T_{max} > 35°C and where T_{min} < 13°C, but the lowest count of days where both T_{max} and T_{min} < 13°C (*Table 5.6*). A mean annual count for T_{max} > 35°C of 95.2 days is calculated for the period 1960-2010 (*Table 5.6*). With zero-counts recorded for autumn, winter and spring (October through April), this large count is influenced by substantial mean counts for June (22.9 days), July (29.8 days) and August (28.1 days) (*Table 5.6*). By contrast, the annual total count of days with T_{min} < 13°C averaged 22.3 days, with no months recording zero-counts (*Table 5.6*). The highest counts of days with T_{min} < 13℃ are for October (32.5 days), and December, January and March (all with 31 days) (*Table 5.6*). Counts of days with both T_{max} and T_{min} < 13℃ averaged 35.9 days per annum (*Table 5.6*). The bulk of this count comprises a 17.5 day average for January, with the summer months of May through September recording no days with T_{max} < 13°C (*Table 5.6*).

Clear inter-annual variability exists in the counts of days with T_{max} > 35°C, with considerable variability in amplitude (2-60 days) and periodicity (3-8 years) between high and low counts (*Figure 5.21a*). The variability in counts of days with T_{min} < 13°C is considerably smaller, but with a clear trend towards a decrease in annual counts of 0.16d/yr (r = 0.46, p = 0.0007) (*Figure 5.21b*). The greatest inter-annual variability is demonstrated where both T_{max} and

T_{min} < 13°C, with a cycle of approximately 10-12 years and amplitude of 50 days (*Figure 5.21*). Notably, there is less inter-annual variability in the counts of days with both T_{max} and T_{min} < 13°C over the past two decades (*Figure 5.21c*).

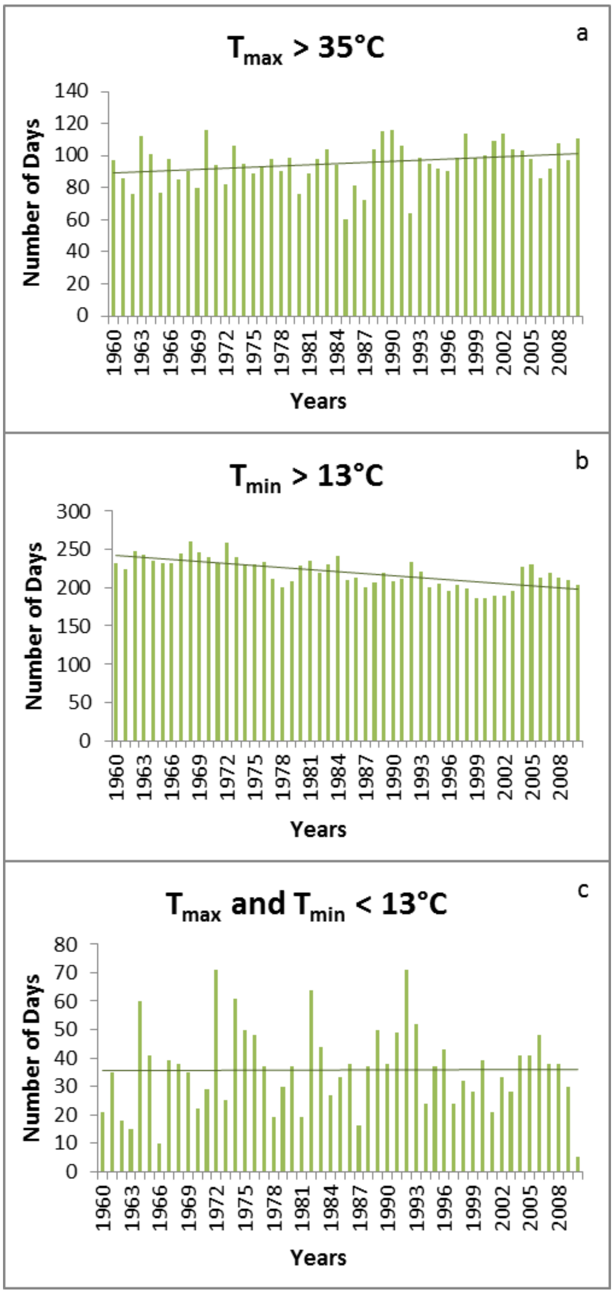

Figure 5.21: Annual counts of days in Shiraz exceeding threshold conditions suitable for citrus flowering, a: T_{max} > 35°C, b: T_{min} < 13°C, c: T_{max} and T_{min} < 13°C.

Unlike Kerman, there are no significant trends in Shiraz for days with T_{max} > 35°C. The strongest trends are for the months of May and August, with correlation coefficients of 0.22

(p= 0.1269) and 0.23 (p = 0.1051), respectively (*Table 5.6*). These trends reflect an increase in the number of days with T_{max} > 35°C of 0.04d/yr and 0.08d/yr respectively (*Table 5.6*). For the remaining months with non-zero counts, correlation strengths range from r = 0.06 (p = 0.6702) for September to r = 0.18 (p = 0.2163) for July (*Table 5.6*). By contrast, six months of the year demonstrate significant trends in the number of days where T_{min} < 13°C, whilst a further two months experience zero counts (*Table 5.6*). Where significant, the strength of the trends range from r = 0.30 (p = 0.0343) for March to r = 0.65 (p < 0.0001) for both May and September (*Table 5.6*). These equate to decreases in the number of days with T_{min} < 13°C, ranging from 0.01d/yr for March, to 0.25d/yr for September and 0.28d/yr for May (*Table 5.6*). July is the only month with a positive trend within this threshold group, albeit with a very slow rate of 0.0001d/yr (*Table 5.6*). No months demonstrate significant trends in the counts of days where both T_{max} and T_{min} fall below 13°C (*Table 5.6*). May through September do not have any days with T_{max} < 13°C throughout the study period. The time trend for days with T_{max} and T_{min} < 13°C with the strongest correlation is April (r = 0.23, p = 0.1012) (*Table 5.6*), tentatively suggesting a decrease of only 0.0004d/yr over the study period. Trends for December and January suggest an increased frequency of extremely cold days (at a rate of 0.01-0.05d/yr), although decreased counts are proposed for the remaining months (*Table 5.6*).

5.3.5.4 Summary

Kerman and Shiraz display significant increases in the annual number of days below 13°C (*Table 5.6*). In addition, Kerman demonstrates a significant increase in the number of days above 35°C in May, and in the numbers of days where both T_{max} and T_{min} fall below 13°C in March (*Table 5.6*). These annual trends in the number of days with T_{min} < 13°C equate to decreases of 0.48d/yr for Kerman, and 0.86d/yr for Shiraz, with monthly trends indicating significant decreasing trends ranging from 0.05-0.15d/yr for Kerman and from 0.01-0.25d/yr for Shiraz, indicating an increase in climate variability (*Table 5.6*).

Table 5.6: Monthly and annual counts of days exceeding thresholds suitable for citrus growth from 1960-2010.

Threshold temperatures	Gorgan			Kerman			Shiraz		
	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C
January									
Mean (d)	0	30.8	18.1	0	31	15.6	0	31	17.5
Range	0	2	29	0	0	30	0	0	31
Variance	0	0.02	0.41	0	0	0.36	0	0	0.42
Change over time (d/yr)	0	0.01	0.03	0	0	-0.04	0	0	0.05
Strength of trend (r)	0	0.26	0.06	0	0	0.10	0	0	0.10
February									
Mean (d)	0	28.0	15.3	0	28.2	7.7	0	28.3	7.3
Range	0	3	24	0	1	20	0	1	24
Variance	0	0.03	0.38	0	0.02	0.59	0	0.02	0.80
Change over time (d/yr)	0	0.01	-0.001	0	-0.001	-0.05	0	-0.002	-0.06
Strength of trend (r)	0	0.16	0	0	0.05	0.17	0	0.05	0.14
March									
Mean (d)	0.1	30.3	11.2	0	30.7	2.7	0	30.8	1.2
Range	2	4	24	0	3	10	0	1	5
Variance	5.28	0.03	0.52	0	0.02	0.90	0	0.01	1.27
Change over time (d/yr)	-0.002	0.01	-0.09	0	-0.01	-0.05	0	-0.01	-0.003
Strength of trend (r)	0.10	0.09	0.23	0	0.27	*0.33	0	*0.30	0.03
April									
Mean (d)	0.4	22.4	2.0	0	26.8	0.3	0	26.1	0.1
Range	2	18	11	1	9	3	0	18	1
Variance	1.78	0.20	1.30	7.14	0.09	2.29	0	0.15	4.04
Change over time (d/yr)	-0.001	0.04	-0.04	0.0002	-0.05	-0.01	0	-0.14	-0.004
Strength of trend (r)	0.02	0.13	0.24	0.02	*0.29	0.26	0	*0.55	0.23
May									
Mean (d)	1.9	4.6	0.1	2.5	17.0	0	3.2	9.7	0
Range	7	12	2	17	22	0	12	23	0
Variance	0.94	0.74	4.30	1.44	0.33	0	1.07	0.67	0
Change over time (d/yr)	-0.03	0.06	-0.001	0.07	-0.15	0	0.04	-0.28	0
Strength of trend (r)	0.25	0.25	0.04	*0.29	*0.38	0	0.22	0.65	0
June									
Mean (d)	5.7	0.1	0	17.3	4.6	0	22.9	0.6	0
Range	26	1	0	29	12	0	30	6	0
Variance	0.85	3.46	0	0.37	0.80	0	0.27	2.39	0
Change over time (d/yr)	-0.04	0.02	0	0.03	-0.05	0	0.06	-0.04	0
Strength of trend (r)	0.11	0.09	0	0.08	0.20	0	0.14	*0.39	0
July									
Mean (d)	9.1	0	0	21.4	2. 6	0	29.8	0	0
Range	30	0	0	31	16	0	7	1	0
Variance	0.72	0	0	0.34	1.36	0	0.06	7.14	0
Change over time (d/yr)	-0.04	0	0	0.06	-0.07	0	0.02	0.001	0
Strength of trend (r)	0.09	0	0	0.12	*0.29	0	0.18	0.08	0

	Gorgan			Kerman			Shiraz		
	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C
August									
Mean (d)	8.7	0	0	14.5	10.5	0	28.1	0	0
Range	27	0	0	30	21	0	28	2	0
Variance	0.82	0	0	0.58	0.54	0	0.19	7.14	0
Change over time (d/yr)	0.04	0	0	0.06	-0.10	0	0.08	-0.002	0
Strength of trend (r)	0.08	0	0	0.11	0.25	0	0.23	0.13	0
September									
Mean (d)	2.5	0.3	0	3.1	22.5	0	11.2	6.8	0
Range	9	5	0	14	21	0	25	20	0
Variance	1.01	2.59	0	1.18	0.25	0	0.46	0.84	0
Change over time (d/yr)	0.01	0.001	0	0.01	-0.13	0	0.02	-0.25	0
Strength of trend (r)	0.05	0.02	0	0.05	*0.33	0	0.06	*0.65	0
October									
Mean (d)	0.4	10.3	0.2	0	30.6	0	0	27.2	0.1
Range	2	25	3	1	5	0	0	14	2
Variance	1.54	0.64	3.34	7.14	0.03	0	0	0.17	5.28
Change over time (d/yr)	0.02	0.03	-0.01	-0.01	-0.02	0	0	-0.17	-0.003
Strength of trend (r)	*0.39	0.07	0.22	0.05	0.26	0	0	*-0.55	0.14
November									
Mean (d)	0.	25.8	2.1	0	29.9	1.4	0	29.9	0.6
Range	1	13	16	0	2	8	0	1	5
Variance	5.00	0.12	1.40	0	0.01	1.49	0	0.01	1.83
Change over time (d/yr)	-0.001	0.01	0.001	0	-0.01	-0.02	0	-0.01	-0.0003
Strength of trend (r)	0.07	0.04	0.01	0	*0.29	0.11	0	*0.41	0
December									
Mean (d)	0	30.5	11	0	31	9.2	0	31	9.4
Range	0	5	28	0	2	26	0	0	25
Variance	0	0.04	0.56	0	0.01	0.64	0	0	0.73
Change over time (d/yr)	0	0.02	0.06	0	-0.001	-0.04	0	0	0.01
Strength of trend (r)	0	0.21	0.15	0	0.02	0.09	0	0	0.02
Annual									
Mean (d)	28.8	183.2	60	58.7	264.2	36.4	95.2	225.3	35.9
Range	92	62	77	64	69	53	56	74	66
Variance	0.55	0.07	0.29	0.26	0.07	0.33	0.14	0.09	0.41
Change over time (d/yr)	-0.05	0.18	-0.05	0.24	-0.48	-0.17	0.24	-0.86	0.01
Strength of trend (r)	0.05	0.19	0.05	0.23	*0.41	0.21	0.27	*0.46	0.01

5.3.6 Sunshine Hours

Data on the number of daily sunshine hours are not available for the full study period, but do cover the requisite 30 years for phenological studies. Consequently trends in the number of sunshine hours were considered in addition to standard climatic variables related to temperature and rainfall. Sunshine hours can be influenced through the duration of cloud cover, making it necessary to examine the relationship between sunshine hours and rainfall.

5.3.6.1 Gorgan

Averaged for the years in which data are available, 1976 and from 1982-2008, there is a mean annual sum of 2148.73 sunshine hours for Gorgan (*Table 5.7*). This has a range of 898.7 hours, from a minimum of 1552.5 hours in 1976 to a maximum 2451.2 hours in 1999 (*Table 5.7, Figure 5.22*). The month with the highest total is August, with 227.82 hours, and a 190.5 hour range from 123.8 hours in 1990 to 314.3 hours in 2006 (*Table 5.7*). The least sunny month, on average, is February, with 130.15 hours and a 104.8 hour range between 80 hours in 2003 and 184.8 hours in 2001 (*Table 5.7*). For 1982-2008, where a complete data series exists, there appears to be a roughly 10 year cyclic variability in the annual sunshine hours, with an amplitude of approximately 400 hours (*Figure 5.22*).

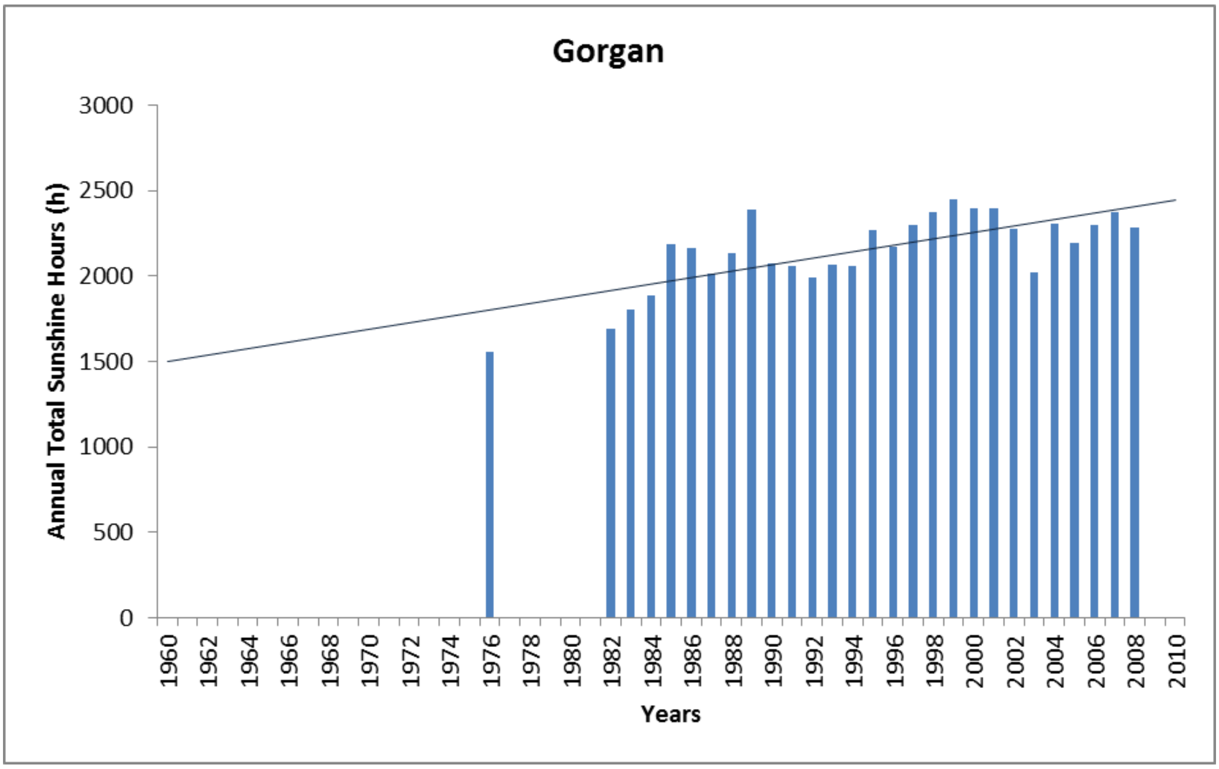

Figure 5.22: Annual total daily sunshine hours for Gorgan.

Over the most recent 28 years, there has been a highly significant trend toward increasing sunshine hours. With a correlation coefficient of 0.73 ($p < 0.0001$), this convincingly equates to an increase of 19.01h/yr for this period (*Table 5.7*). Significant trends towards increasing sunshine hours exist for seven months, ranging in strength from 0.37 ($p = 0.0455$) for July to 0.53 ($p = 0.0033$) for October (*Table 5.7*). For these months, trends equate to increases in sunshine hours of between 2.39h/yr for July and 1.21-1.51h/yr for January and October (*Table 5.7*). Four months have significant inverse relationships between the number of sunshine hours and rainfall, ranging in correlation strength from 0.38 ($p = 0.0457$) for April and October to 0.5 ($p = 0.0033$) for February (*Table 5.7*). Whilst the remaining months have statistically weaker trends, ranging in strength from 0.02 ($p = 0.597$) for March to 0.31 ($p = 0.0748$) for May and June, they too indicate an inverse relationship (*Table 5.7*), suggesting that a decrease in rainfall is associated with a decrease in cloud cover, and hence an increase in sunshine hours for these months.

5.3.6.2 Kerman

Kerman has a longer dataset for sunshine hours than Gorgan, covering 40 years during the period 1960-2010. However, gaps in the data are frequent, with the longest continuous dataset covering 1996-2008 (*Figure 5.23*). There is an average annual total of 3220.53 sunshine hours, almost 50% greater than that for Gorgan (*Table 5.7*), which is to be expected given the location on the arid Iranian Plateau. This annual average has a range of 589.3 sunshine hours from 2857.1 hours in 1982 to 3446.4 hours in 2000 (*Table 5.7, Figure 5.23*). The most sunny month is August at 337.5 sunshine hours, with a 144.2 hour range between the 234.1 hours recorded in 1967 to the 378.3 hours recorded in 2000 (*Table 5.7*). The least sunny month is January, at 195.64 hours, with a 164.9 sunshine hour range from 111.6 hours in 1977 to 276.5 hours in 1987 (*Table 5.7*). There is low inter-annual variability in the annual total sunshine hours for Kerman, with no evident cyclical pattern (*Figure 5.23*).

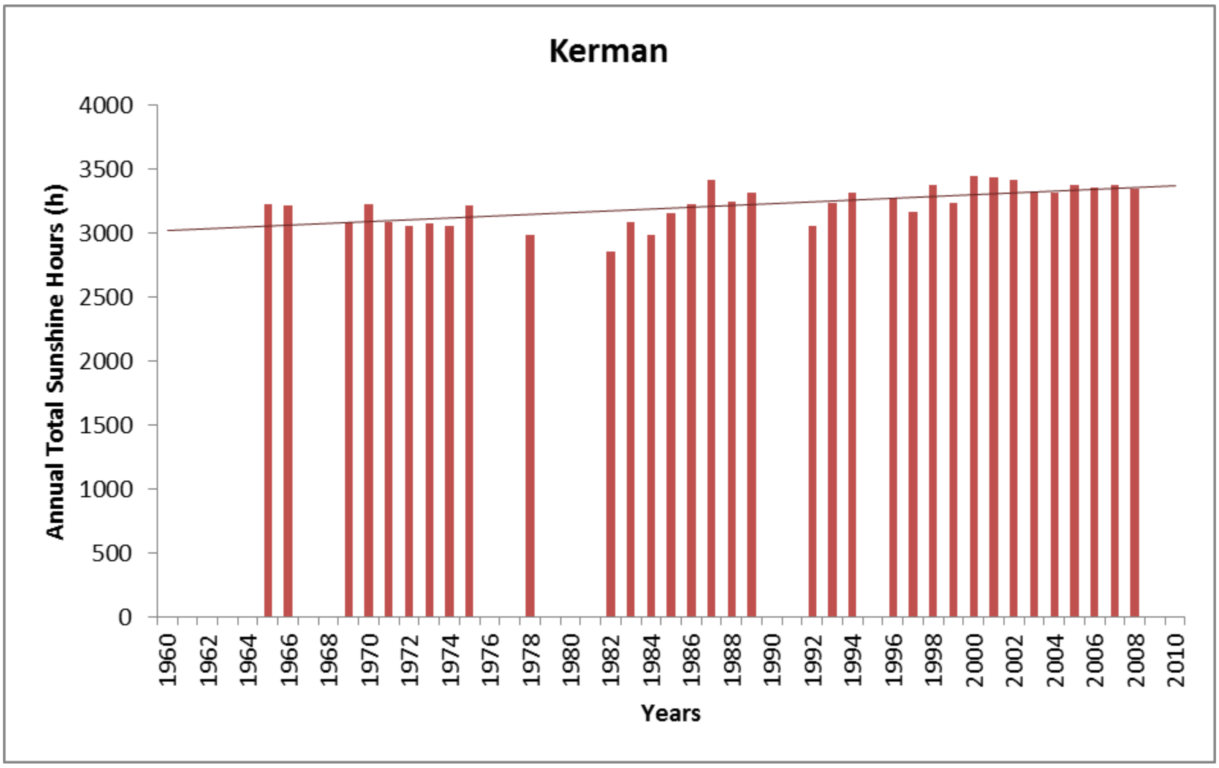

Figure 5.23: Annual total daily sunshine hours for Kerman.

As for Gorgan, there is a statistically significant positive time trend in the annual number of sunshine hours for Kerman. With a correlation coefficient of 0.64 ($p < 0.0001$), this equates to an increase of 7.09h/yr (*Table 5.7*). Significant trends in monthly total sunshine hours are found for only five months, ranging from $r = 0.32$ ($p = 0.0352$) for October to $r = 0.66$ ($p < 0.0001$) for April (*Table 5.7*). These months suggest increases equivalent to between 1.05h/yr for October and 0.5h/yr for September (*Table 5.7*). As for Gorgan, even those months without significant trends suggest increasing sunshine hours over time (*Table 5.7*). Significant inverse relationships between the number of sunshine hours and the total monthly rainfall are recorded for seven months, ranging in strength from correlation coefficients of 0.33 ($p = 0.0382$) for May to a particularly strong 0.68 ($p = 0.0050$) for January (*Table 5.7*). As for Gorgan, there is no significant trend in the relationship between the annual total of sunshine hours and annual total rainfall for Kerman (*Table 5.7*).

5.3.6.3 Shiraz

Shiraz has the greatest annual total daily sunshine hours for the three study cities, with an average of 3355.34 hours (*Table 5.7*). These averages are recorded from the largest dataset, which spans 45 years with a four-year gap from 1977-1981 (*Figure 5.24*). The range of 499.3 sunshine hours represents the difference between the 3075.4 hour total recorded in 1969 to the 3574.7 hour total for 2001 (*Table 5.7*). The sunniest month is June at 357.20 hours, and a 61.1 sunshine hour range between 313.7 hours in 1971 to 374.8 hour in 1960 (*Table 5.7*). The month with the lowest total sunshine is January with 214.09 hours and a 150.2 hour difference between the minimum monthly total of 130 hours in 1965 and the maximum of 280.2 in 1963 (*Table 5.7*). Despite having the lowest variance (0.04) Shiraz demonstrates the greatest inter-annual variability in total sunshine hours, as indicated by the 452.3 range from the annual sums of 3057.4 for 1969 and 3527.7 for 1970. Similar to Kerman, this inter-annual variability presents no clear cyclical patterns (*Figure 5.24*).

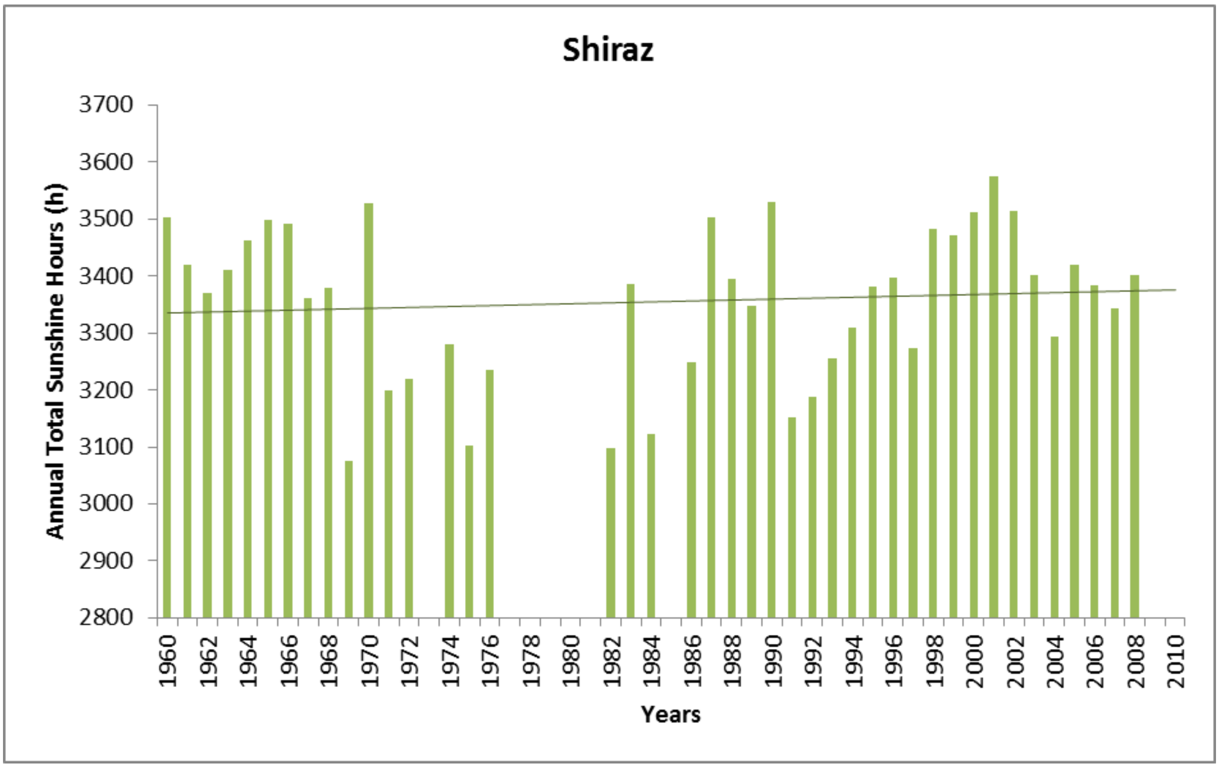

Figure 5.24: Annual total daily sunshine hours for Shiraz.

The annual trend in the total daily sunshine hours is statistically insignificant, with a very weak correlation coefficient of 0.09 (p = 0.5603) (*Table 5.7*). This is expected from the considerable inter-annual variability in the annual total sunshine hours, and the contrast with the other two cities is notable (*Table 5.7, Figure 5.24*). April and September demonstrate significant monthly trends in total daily sunshine hours, with relatively weak correlation coefficients of r = 0.38 (p = 0.0099) and r = 0.34 (p = 0.0222), respectively. These tentatively suggest increases in sunshine hours of 0.7h/yr (April) and -0.26h/yr (September) (*Table 5.7*). Five months (June, July and October to December) indicate decreases in monthly total sunshine hours, whereas the remaining months have trends suggesting an increase in sunshine hours consistent with the findings for Gorgan and Kerman (*Table 5.7*). In further contrast to Gorgan and Kerman, there is a significant relationship between annual total sunshine hours and annual rainfall for Shiraz (r = 0.41, p = 0.0054) (*Table 5.7*). Nine months demonstrate significant relationships between sunshine hours and rainfall, varying in strength between r = 0.29 (p = 0.0415) for May and r = 0.67 (p = 0.0002) for November (*Table 5.7*).

5.3.6.4 Summary

Whilst data on sunshine hours are not available for the entire study period, trends in annual totals for available years are statistically significant for Gorgan and Kerman with correlation coefficients of r = 0.73 (p < 0.0001) and r = 0.64 (p < 0.0001) respectively (*Table 5.7*). Notably, very poor annual trends are calculated for Shiraz, with r = 0.09 (p = 0.5603), and with significant monthly trends for only April and September, with correlation coefficients of r = 0.38 (p = 0.0099) and 0.34 (p = 0.0222) respectively (*Table 5.7*). These are two of the seven months which have significant trends for Kerman, but also two of the four months which did not have significant trends for Gorgan. This is notable as Shiraz has the most complete and continuous sunshine hour record. However, even considering correlations with a *p value* of 0.025 or less (where r = 0.4 or higher), there are still sufficient months with significant trends for Kerman and Gorgan, and thus the chance of their trends being coincidental is small. Consequently, it would appear that there are differences in the climatic conditions responsible for the differing trends between cities. These significant monthly trends reflect substantial changes in the number of sunshine hours, ranging from 0.67-3.84h/yr for Gorgan; 0.16-1.77h/yr for Kerman; and -0.26h/yr for Shiraz (*Table 5.7*).

Table 5.7: Trends in sunshine hours for Gorgan, Kerman and Shiraz, 1960-2010. Significant results indicated by an asterisk; correlations with r ≥ 0.7 indicated by a double asterisk.

Sunshine Hours	Gorgan	Kerman	Shiraz
January			
Mean (h)	138.58	195.64	214.09
Range	116.2	164.9	150.2
Variance	0.17	0.19	0.16
Sample size (n)	30	40	45
Change over time (h/yr)	1.21	0.48	0.05
Strength of trend (r)	*0.48	0.17	0.03
Correlation with rainfall (r)	*-0.39	*-0.68	*-0.54
February			
Mean (h)	130.15	200.04	218.45
Range	104.8	135.7	91.4
Variance	0.22	0.16	0.11
Sample size (n)	30	39	45
Change over time (h/yr)	1.33	0.71	0.01
Strength of trend (r)	*0.43	0.30	0.01
Correlation with rainfall (r)	*-0.50	*-0.58	*-0.63
March			
Mean (h)	135.58	221.00	241.31
Range	140.7	142.1	152.4
Variance	0.29	0.16	0.14
Sample size (n)	31	41	45
Change over time (h/yr)	1.87	0.80	0.24
Strength of trend (r)	*0.45	0.30	0.11
Correlation with rainfall (r)	-0.02	*-0.64	*-0.61
April			
Mean (h)	163.31	237.63	253.51
Range	154.8	164.1	122.9
Variance	0.25	0.15	0.11
Sample size (n)	30	42	45
Change over time (h/yr)	0.84	1.77	0.70
Strength of trend (r)	0.19	*0.66	*0.38
Correlation with rainfall (r)	*-0.38	*-0.50	*-0.59
May			
Mean (h)	207.28	297.36	329.73
Range	158.3	186.8	121.3
Variance	0.21	0.12	0.08
Sample size (n)	29	41	44
Change over time (h/yr)	2.50	0.89	0.30
Strength of trend (r)	*0.51	*0.33	0.18
Correlation with rainfall (r)	-0.31	*-0.33	*-0.29
June			
Mean (h)	221.69	323.54	357.20
Range	174.8	82.5	61.1
Variance	0.20	0.07	0.04
Sample size (n)	28	40	44
Change over time (h/yr)	2.01	0.40	-0.09
Strength of trend (r)	*0.39	0.23	0.10
Correlation with rainfall (r)	-0.31	-0.06	0.19

	Gorgan	Kerman	Shiraz
July			
Mean (h)	220.56	337.16	342.28
Range	220.8	91.5	83.6
Variance	0.25	0.07	0.05
Sample size (n)	29	39	45
Change over time (h/yr)	2.39	0.69	-0.16
Strength of trend (r)	*0.37	*0.42	0.15
Correlation with rainfall (r)	-0.03	-0.16	-0.27
August			
Mean (h)	227.82	337.75	334.13
Range	190.5	144.2	64
Variance	0.25	0.09	0.05
Sample size (n)	29	42	45
Change over time (h/yr)	3.84	1.21	0.21
Strength of trend (r)	0.59	0.52	0.21
Correlation with rainfall (r)	-0.26	-0.35	0.03
September			
Mean (h)	199.77	309.77	315.88
Range	164.6	62.3	47.4
Variance	0.17	0.05	0.04
Sample size (n)	29	41	44
Change over time (h/yr)	1.27	0.50	-0.26
Strength of trend (r)	0.33	*0.41	*0.34
Correlation with rainfall (r)	-0.07	-0.26	*-0.32
October			
Mean (h)	197.60	283.34	297.74
Range	108.3	198.4	112.9
Variance	0.13	0.15	0.07
Sample size (n)	29	43	44
Change over time (h/yr)	1.51	1.05	-0.11
Strength of trend (r)	*0.53	*0.32	0.08
Correlation with rainfall (r)	*-0.38	-0.12	*-0.48
November			
Mean (h)	152.69	240.38	238.54
Range	140.9	116.4	113.7
Variance	0.19	0.13	0.14
Sample size (n)	30	43	44
Change over time (h/yr)	1.10	0.20	-0.10
Strength of trend (r)	0.34	0.08	0.05
Correlation with rainfall (r)	-0.11	*-0.58	*-0.67
December			
Mean (h)	133.06	204.34	216.58
Range	70	174.7	123.1
Variance	0.15	0.19	0.14
Sample size (n)	31	42	45
Change over time (h/yr)	0.67	0.16	-0.05
Strength of trend (r)	0.32	0.06	0.03
Correlation with rainfall (r)	-0.09	*-0.59	*-0.64
Annual			
Mean (h)	2148.73	3220.53	3355.34
Range	898.7	589.3	499.3
Variance	0.10	0.05	0.04
Sample size (n)	28	34	42
Change over time (h/yr)	19.01	7.09	0.81
Strength of trend (r)	**0.73	*0.64	0.09
Correlation with rainfall (r)	-0.13	-0.23	*-0.41

Testing the correlation of sunshine hours with rainfall, the significant results found for Shiraz are unexpected, as the city displayed poor rainfall trends but strong sunshine trends over time. This suggests some inter-annual variability in both sunshine hours and rainfall, resulting from fluctuations in cloud cover, rather than the majority of precipitation occurring in short lived storms. While annual correlations between rainfall and sunshine are not significant for Gorgan and Kerman, the two cities had four and eight months respectively displaying significant correlations, suggesting a more intra-annual association between rainfall, and the related cloud cover, and the number of sunshine hours.

5.4 Relationship between flowering dates and climatic factors

5.4.1 Flowering Dates and Annual Averages of Climate Variables

Correlation analyses for the flowering dates of the five different citrus types and the annual averages for T_{max}, $T_{min,}$ and precipitation for Gorgan all demonstrate poor, statistically insignificant relationships, and with considerable variation between the citrus types. Correlation coefficients for the relationship between peak flowering dates and T_{max} range from r = 0.06 (p = 0.7064) for sour lemon to r = 0.26 (p = 0.1279) for sour orange; with r = 0.02 (p = 0.9125) for sour lemon and r = 0.22 (p = 0.1585) for orange (*Table 5.8*). Relationships between the flowering dates and precipitation are slightly stronger, ranging from r = 0.02 (p = 0.8874) for sour lemon to r = 0.30 (p = 0.0528) for tangerine (*Table 5.8*). These inverse relationships with precipitation equate to a delay in flowering dates in response to precipitation increases of up to 0.01d/mm, whilst a positive relationship for sour orange indicates a similar magnitude of delay in flowering dates in response to an increase in precipitation of 0.01d/mm. Whilst the strength of these relationships is consistent with the time trends in the climate variables, the variability between citrus types is surprising given the similar trends in flowering dates over the study period.

By contrast, significant relationships for Kerman are found between all the basic climatic variables and the flowering dates for each citrus type. The strongest correlations exist for the relationship between flowering dates and annual average T_{min}, with correlation coefficients ranging from r = 0.46 (p = 0.0020) for sour orange to r = 0.61 (p < 0.0001) for tangerine (*Table 5.8*). These relationships equate to advances in flowering dates in response to warming T_{min} of 3.15d/°C for sour lemon to 3.93d/°C for tangerine (*Table 5.8*). These strong relationships can be expected given the strong T_{min} trends calculated for Kerman (*Table 5.2*). Relationships between the flowering dates of the five citrus types and T_{max} range in strength from $r = 0.35$ ($p = 0.0295$) for sour lemon to 0.59 ($p < 0.0001$) for sweet lemon, which equate to advances in flowering dates in response to temperature increases, of 1.85d/°C for sour orange and 3.08d/°C for sweet lemon (*Table 5.8*). The weakest relationships exist between flowering dates and precipitation, with correlation strengths ranging from $r = 0.32$ ($p = 0.0448$) for sour lemon to 0.46 ($p = 0.0020$) for orange (*Table 5.8*). Statistically insignificant relationships between flowering dates and precipitation tentatively indicate advances in flowering dates in response to increased precipitation, ranging from 0.03d/mm for sour lemon to 0.06d/mm for sour orange (*Table 5.8*).

The strongest relationships for flowering dates in Shiraz are with mean annual T_{min}. These relationships are even stronger than those for Kerman, ranging from $r = 0.53$ ($p = 0.0386$) for sour lemon to $r = 0.67$ ($p < 0.0001$) for tangerine, and equating to advances in flowering dates in response to warming of between 4.34d/°C (sour lemon) and 5.47d/°C (sour orange) (*Table 5.8*). This too is expected, given the very strong time trends for T_{min} in Shiraz. Strong correlations are calculated for flowering dates and T_{max} in Shiraz, ranging from $r = 0.50$ ($p = 0.0018$) for sour lemon to $r = 0.60$ ($p < 0.0001$) for orange, equating to advances in flowering dates in response to warming of 6.14d/°C and 7.45d/°C respectively. In contrast to Kerman, relationships precipitation and peak flowering dates are insignificant for all citrus types in Shiraz, with correlation coefficients ranging from $r = 0.01$ ($p = 0.9396$) for sour lemon to $r = 0.08$ ($p = 0.6287$) for tangerine and sour orange (*Table 5.8*).

Comparing the results between citrus types across cities, the lowest correlation between flowering dates and the annual average of any climatic variable is found for sour lemon, in 8/9 cases. In 1/3 of cases the strongest correlation is for orange, followed by tangerine and sour lemon, in 2/9 cases each (*Table 5.8*). In all cases where orange does not demonstrate the strongest correlation with climatic variables, it has the second highest correlation.

Flowering dates for sour orange demonstrate the greatest variability in correlation strength, ranging from highest to lowest across the three cities.

As expected from the poor time trends (*Table 5.5*), there are no significant relationships between rainfall start and flowering dates for any citrus type in any of the three cities. Of these weak relationships, the strongest are for Gorgan, with correlation coefficients of r = 0.05 (p = 0.7717) for orange to r = 0.25 (p = 0.1133) for sour lemon (*Table 5.8*). With no significant trends or relationships with flowering dates, rainfall onset is thus excluded from subsequent analyses and interpretation.

Table 5.8: Correlation between flowering dates for the five citrus types and the annual climate variables, including date of rainfall onset, for Gorgan, Kerman and Shiraz, 1960-2010. Significant relationships are highlighted by an asterisk.

Flowering and Annual Climate Averages						
	Orange	Tangerine	Sweet Lemon	Sour Lemon	Sour Orange	Pooled
Gorgan						
T_{max} (r)	0.13	0.07	0.21	0.06	0.26	0.03
Change (d/°C)	-0.49	+0.62	-0.98	-0.35	-1.48	-0.13
T_{min} (r)	0.22	0.12	0.08	0.02	0.13	0.01
Change (d/°C)	-1.06	+0.59	-0.43	+0.12	-0.86	+0.04
Precipitation (r)	0.28	0.30	0.05	0.02	0.13	0.18
Change (d/mm)	-0.01	-0.01	-0.002	-0.001	+0.01	-0.01
Rainfall onset (r)	0.05	0.17	0.14	0.25	0.24	0.17
Change (d/d)	0.01	-0.05	-0.05	-0.09	-0.09	-0.05
Kerman						
T_{max} (r)	*0.45	*0.43	*0.59	*0.35	*0.40	*0.46
Change (d/°C)	-2.78	-2.48	-3.08	-1.85	-2.96	-2.76
T_{min} (r)	*0.57	*0.61	*0.52	*0.56	*0.47	*0.52
Change (d/°C)	-3.66	-3.93	-3.52	-3.15	-3.65	-3.19
Precipitation (r)	*0.46	*0.38	*0.41	*0.32	*0.45	*0.42
Change (d/mm)	+0.05	+0.05	+0.05	+0.03	+0.06	+0.05
Rainfall onset (r)	0.17	0.10	0.10	0.08	0.01	0.09
Change (d/d)	-0.03	-0.02	-0.02	-0.02	0	-0.02
Shiraz						
T_{max} (r)	*0.60	*0.54	*0.59	*0.50	*0.59	*0.58
Change (d/°C)	-7.45	-6.99	-7.86	-6.14	-7.41	-7.05
T_{min} (r)	*0.65	*0.67	*0.62	*0.53	*0.62	*0.66
Change (d/°C)	-5.27	-5.32	-5.10	-4.34	-5.47	-5.04
Precipitation (r)	0.06	0.08	0.04	0.01	0.08	0.01
Change (d/mm)	+0.01	-0.01	+0.01	-0.01	+0.01	+0.01
Rainfall onset (r)	0.22	0.27	0.15	0.01	0.09	0.15
Change (d/d)	0.11	0.07	0.05	0.01	0.03	0.05

5.4.1.1 Flowering Dates and Monthly T_{max} Averages

Whilst the annual and monthly time trends for T_{max} in Gorgan are weak, significant correlations are demonstrated between the flowering dates of the five citrus types and T_{max} for May, with correlation coefficients ranging from r = 0.43 (p = 0.0075) for sour orange to r = 0.73 (p < 0.0001) for orange and r = 0.75 (p < 0.0001) for sweet lemon (*Table 5.9*). Considering that mean flowering for Gorgan occurs in mid-May, this suggests a particularly important role of T_{max} in the few weeks preceding flowering. Significant results are also found for the relationship between the flowering dates of sour orange and the November T_{max} average, with r = 0.43 (p = 0.0080) (*Table 5.9*). Sweet lemon flowering dates, which demonstrate the strongest correlation with annual T_{max} of any of the citrus types, display a range in correlation strengths for the relationship with monthly T_{max} from 0.04 (p = 0.8279) for April to 0.75 (p < 0.0001) for May. Sour lemon flowering, which has the weakest relationship with annual T_{max}, has relationships with monthly T_{max} ranging from r = 0.05 (p = 0.7405) for March to 0.57 (p = 0.0001) for May (*Table 5.9*).

Kerman, which has significant annual trends for T_{max}, together with significant monthly trends for five months of the year, only has significant relationships between T_{max} and flowering for the five citrus types in March, April and May. April demonstrates the strongest correlations between T_{max} and the flowering for all citrus types, ranging from r = 0.56 (p = 0.0002) for sour lemon to r = 0.62 (p < 0.0001) for orange. From the timing of these significant relationships, a significant driving influence of T_{max} in the month prior to flowering can again be inferred (*Table 5.9*). Sweet lemon, which demonstrates the strongest correlation with annual T_{max}, has variability in the strength of monthly correlations from r = 0.09 (p = 0.6029) for January to 0.59 (p < 0.0001) for April. Sour lemon, which has the weakest correlation between flowering dates and annual T_{max} of any of the citrus types, has a range in the strength of monthly T_{max} correlations from 0.02 (p = 0.9004) for February to 0.56 (p = 0.0002) for April (*Table 5.9*). Variability in the strength of correlations is stronger between months than between citrus types, even where monthly correlations are significant, which suggests a strong intra-annual variability in the association between T_{max} and flowering dates.

Table 5.9: Strength of the relationship between T_{max} averaged for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk; relationships with a correlation coefficient greater than 0.7 highlighted by a double asterisk.

Flowering and monthly average T_{max}						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.12	0.24	0.12	0.10	0.05	0.16
February	0.09	0.18	0.14	0.07	0.03	0.08
March	0.11	0.11	0.12	0.05	0.07	0.07
April	0.11	0.15	0.04	0.13	0.28	0.16
May	**0.73	*0.50	**0.75	*0.57	*0.43	*0.60
June	0.14	0.15	0.20	0.10	0.25	0.17
July	0.08	0.12	0.11	0.09	0.13	0.11
August	0.09	0.14	0.23	0.16	0.29	0.15
September	0.24	0.25	0.20	0.27	0.07	0.28
October	0.20	0.07	0.24	0.09	0.23	0.15
November	0.09	0.10	0.25	0.28	0.43	0.26
December	0.23	0.13	0.25	0.12	0.08	0.16
Kerman						
January	0.09	0.05	0.09	0.11	0.10	0.03
February	0.21	0.22	0.28	0.02	0.10	0.16
March	*0.46	*0.56	*0.48	*0.38	*0.40	*0.45
April	*0.62	*0.57	*0.59	*0.56	*0.61	*0.64
May	*0.48	*0.45	*0.47	*0.37	*0.43	*0.46
June	0.10	0.26	0.20	0.18	0.14	0.23
July	0.18	0.21	0.18	0.15	0.15	0.20
August	0.10	0.17	0.15	0.21	0.08	0.17
September	0.15	0.04	0.16	0.22	0.22	0.14
October	0.13	0.08	0.12	0.16	0.13	0.12
November	0.04	0.08	0.14	0.14	0.18	0.13
December	0.27	0.21	0.29	0.15	0.24	0.24
Shiraz						
January	0.20	0.20	0.19	0.06	0.27	0.17
February	*0.37	*0.35	*0.37	0.24	0.28	*0.29
March	*0.35	*0.30	*0.39	*0.37	*0.38	*0.34
April	*0.53	*0.46	*0.46	*0.49	*0.48	*0.52
May	*0.45	*0.40	*0.41	*0.24	*0.34	*0.37
June	*0.39	0.24	*0.31	*0.39	*0.33	*0.36
July	*0.41	*0.41	*0.42	*0.39	*0.45	*0.41
August	*0.44	0.25	0.26	0.18	*0.40	*0.34
September	*0.30	0.22	0.27	0.24	0.25	0.26
October	*0.35	*0.37	*0.38	*0.37	*0.33	*0.35
November	0.14	0.03	0.04	0.10	0.10	0.13
December	0.03	0.09	0.10	0.07	0.09	0.11

Shiraz, which has the strongest correlations between annual T_{max} and the flowering dates of each of the five citrus types for any of the cities, also demonstrates the greatest number of months with significant trends in T_{max}. For all citrus types, there are significant relationships between peak flowering and T_{max} for March, April, May and October. The strongest correlations are for April, ranging from r = 0.46 (p = 0.0019) for tangerine and sweet lemon to r = 0.53 (p = 0.0002) for orange (*Table 5.9*). However, with mean flowering occurring in late March here, there is a less compelling argument that T_{max} is a direct driver of flowering dates. Each citrus type had at least six months for which there are significant correlations between flowering dates and T_{max}, ranging from February to August, and October. Tangerine is the only citrus type for which June temperatures are not significant, with r = 0.24 (p = 0.1255) (*Table 5.9*). One final observation is that whilst the correlations between annual T_{max} and flowering dates are stronger for Shiraz than Kerman, the maximum correlation coefficients for the monthly correlations are higher for Kerman than Shiraz. This is consistent with Kerman, demonstrating stronger annual and monthly trends in T_{max} than Shiraz.

5.4.1.2 Flowering Dates and Monthly T_{min} Averages

Reported previously, no significant annual T_{min} trends are observed for Gorgan (*Table 5.2, Figure 5.9*). Similarly, there are no significant correlations between the flowering dates for any citrus type and annual T_{min}. However, some significant monthly correlations do exist between flowering dates and monthly T_{min} for individual citrus types. Orange and sweet lemon demonstrate statistically significant relationships with T_{min} for May, with correlation coefficients of 0.54 (p = 0.0003) and 0.44 (p = 0.0043), respectively (*Table 5.10*). Sweet lemon additionally has a significant relationship with June T_{min} (r = 0.31, p = 0.0478) (*Table 5.10*). Orange flowering dates are calculated as having a statistically significant relationship with December T_{min}, with r = 0.31 (p = 0.0453), whilst tangerine flowering correlates significantly (r = 0.30, p = 0.0475) with January T_{min} (*Table 5.10*). Sour lemon and sour orange have no months with significant relationships between their flowering dates and T_{min}, with correlation strengths for sour lemon ranging from 0 for July to 0.25 (p = 0.1137) for May; and correlation strengths for sour orange ranging from 0 for April to 0.30 (p = 0.0280) for May (*Table 5.10*). The strongest relationships with T_{min} across all of the citrus types are for May, with considerable variability between citrus type demonstrated by correlation coefficients ranging from $r = 0.10$ ($p = 0.5182$) for tangerine to $r = 0.54$ ($p = 0.0003$) for orange (*Table 5.10*).

In Kerman, considerably more months have significant relationships between flowering date of each citrus type and monthly averages of T_{min}. These relationships are considerably stronger than those for Gorgan, with correlation coefficients ranging from $r = 0.32$ ($p = 0.0388$) for sour orange flowering dates and July T_{min}, to $r = 0.73$ ($p < 0.0001$) for tangerine flowering dates and April T_{min} (*Table 5.10*). March, April, May and September demonstrate significant relationships between T_{min} and flowering dates for all citrus types, ranging in strength from $r = 0.34$ ($p = 0.0332$) for tangerine in September, to $r = 0.73$ ($p < 0.0001$) for tangerine in April (*Table 5.10*). Similar to T_{max}, the strong correlations for April T_{min} in particular, are likely as a result of the close proximity to peak flowering in May. Unlike Gorgan, there is minimal variability between the correlation strengths of the different citrus types, except for January where $r = 0.02$ ($p = 0.9072$) for sweet lemon and $r = 0.34$ ($p = 0.0326$) for sour lemon (*Table 5.10*).

Correlation between monthly T_{min} and all citrus flowering dates for Shiraz demonstrate strong, significant correlations for nine months, ranging from February through December (*Table 5.10*). Similar to the relationships between T_{max} and flowering dates, on average, the strongest relationships are for April, followed by May and June. Sour lemon flowering dates have significantly weaker relationships with monthly T_{min} than the other citrus types, with correlation coefficients for April ranging from $r = 0.35$ ($p < 0.0001$) for sour lemon to $r = 0.70$ ($p < 0.0001$) for orange (*Table 5.10*). While variations of this magnitude do not exist in other months, sour lemon consistently demonstrates the weakest relationships between flowering dates and monthly T_{min}. Similar to Kerman, the mid-winter months of December and January have particularly weak relationships between flowering dates and monthly T_{min}, with correlation coefficients ranging from $r = 0.06$ ($p = 0.7736$) for sour lemon to $r = 0.33$ ($p = 0.0302$) for tangerine flowering dates and December T_{min}; and from $r = 0.18$ ($p = 0.2680$) for sour lemon to $r = 0.28$ ($p = 0.0709$) for tangerine and January T_{min} (*Table 5.10*).

Table 5.10: Strength of the relationship between T_{min} averaged for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk; relationships with a correlation coefficient greater than 0.7 highlighted by a double asterisk.

Flowering and monthly average T_{min}						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.04	*0.30	0.19	0.20	0.15	0.21
February	0.08	0.24	0.05	0.14	0.08	0.12
March	0.12	0.03	0.09	0.08	0.13	0.04
April	0.09	0.18	0.03	0.05	0	0.08
May	*0.54	0.10	*0.44	0.25	0.30	*0.31
June	0.28	0.12	*0.31	0.16	0.28	0.22
July	0.02	0.21	0.10	0	0.25	0.07
August	0.11	0.12	0.04	0.04	0.11	0.01
September	0.03	0.17	0.14	0.11	0.20	0.16
October	0.01	0.06	0.14	0.03	0.17	0.07
November	0.12	0.04	0.12	0.10	0.20	0.13
December	*0.31	0.22	0.23	0.11	0.09	0.21
Kerman						
January	0.21	0.20	0.02	*0.34	0.04	0.09
February	*0.39	0.30	*0.39	0.30	0.24	*0.32
March	*0.44	*0.41	*0.40	*0.43	*0.47	*0.44
April	**0.70	**0.73	*0.67	*0.68	*0.67	**0.72
May	*0.65	*0.66	*0.60	*0.51	*0.58	*0.59
June	0.30	*0.37	*0.32	*0.37	*0.34	*0.36
July	0.29	0.24	0.27	*0.28	*0.32	*0.31
August	0.29	*0.36	*0.37	*0.37	0.23	*0.34
September	*0.37	*0.34	*0.45	*0.41	*0.41	*0.36
October	0.21	0.25	0.23	0.30	0.15	0.21
November	0.04	0.08	0.05	0.05	0.05	0.03
December	0.08	0.25	0.10	0.15	0.09	0.11
Shiraz						
January	0.26	0.28	0.21	0.18	0.22	*0.28
February	*0.62	*0.58	*0.48	*0.51	*0.50	*0.54
March	*0.52	*0.53	*0.49	*0.45	*0.49	*0.53
April	**0.70	**0.70	*0.65	*0.35	*0.66	**0.71
May	*0.65	*0.64	*0.62	*0.50	*0.57	*0.62
June	*0.65	*0.62	*0.58	*0.54	*0.63	*0.65
July	*0.54	*0.56	*0.53	*0.49	*0.58	*0.57
August	*0.57	*0.53	*0.50	*0.43	*0.57	*0.57
September	*0.52	*0.54	*0.53	*0.44	*0.51	*0.54
October	*0.53	*0.60	*0.55	*0.47	*0.54	*0.57
November	*0.34	*0.42	*0.40	*0.26	*0.38	*0.40
December	0.28	*0.33	0.27	*0.06	0.22	*0.32

5.4.1.3 Flowering Dates and Monthly Precipitation Averages

For Gorgan, the relationships between monthly total precipitation and the flowering dates for the five citrus types are significant in only a few cases. Sweet lemon flowering dates have significant relationships with precipitation for February, May and September, with the strongest relationship for May ($r = 0.52$, $p = 0.0004$) (*Table 5.11*). For orange flowering dates, May rainfall has similarly strong correlations, with $r = 0.43$ ($p = 0.0053$). A significant relationship also exists for October ($r = 0.34$, $p = 0.0320$) (*Table 5.11*). Strong May correlations between flowering and precipitation are consistent with those seen for T_{min} and T_{max}. Tangerine flowering dates demonstrate a significant relationship with precipitation only for December with a correlation coefficient of 0.31 ($p = 0.0421$), whilst flowering dates for sour lemon and sour orange demonstrate no significant correlations with monthly precipitation totals (*Table 5.11*). These patterns of significant correlation are partly consistent with the monthly trends in significant precipitation, which highlight March and October.

Kerman is the only city where there are significant relationships between mean annual precipitation and flowering dates of all citrus types. The flowering dates of four citrus types demonstrate significant relationships with monthly precipitation, but for a maximum of two months. These are relationships between orange peak flowering dates and March and April precipitation, with correlation coefficients of $r = 0.33$ ($p = 0.0294$) and $r = 0.34$ ($p = 0.0279$) respectively; sweet lemon and April precipitation, with $r = 0.32$ ($p = 0.0429$); sour lemon flowering dates for April and August precipitation, with correlation coefficients of $r = 0.34$ ($p = 0.0329$) and $r = 0.35$ ($p = 0.0282$) respectively; and sour orange and April precipitation with the strongest correlation coefficient of $r = 0.39$ ($p = 0.0101$) (*Table 5.11*). Flowering dates of tangerine display no significant relationships with monthly precipitation. Similar to T_{max} and T_{min}, the strongest correlations across citrus type are for April, although for precipitation, they range in strength from the relatively weak, statistically insignificant correlation coefficient of $r = 0.25$ ($p = 0.1242$) for tangerine, to the stronger, significant correlation strength of $r = 0.39$ ($p = 0.0101$) for sour orange (*Table 5.11*).

Table 5.11: Strength of the relationship between precipitation averaged for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk; relationships with a correlation coefficient greater than 0.7 highlighted by a double asterisk.

Flowering and monthly average precipitation						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.24	0.17	0.19	0.09	0.07	0.20
February	0.30	0.01	*0.32	0.30	0.22	0.24
March	0.25	0.15	0.21	0.26	0.19	0.25
April	0.08	0.03	0.02	0.17	0.18	0.03
May	*0.43	0.21	*0.52	0.30	0.29	*0.31
June	0.17	0.06	0.11	0.14	0.28	0.09
July	0.1	0.12	0.25	0.22	0.02	0.16
August	0.10	0.13	0.29	0.14	0.28	0.17
September	0.24	0.23	*0.39	0.27	0.05	0.24
October	*0.34	0.25	0.21	0.23	0.15	0.21
November	0.11	0.10	0.01	0.01	0.02	0.08
December	0.02	*0.31	0.09	0.07	0.16	0.13
Kerman						
January	0.07	0.02	0.03	0.05	0.05	0.05
February	0.03	0.05	0.08	0.06	0.02	0.01
March	*0.33	0.28	0.21	0.17	0.15	0.20
April	*0.34	0.25	*0.32	*0.34	*0.39	*0.36
May	0.25	0.25	0.24	0.25	0.18	0.27
June	0.10	0.18	0.17	0.01	0.02	0.08
July	0.16	0.04	0.11	0.13	0.19	0.14
August	0.20	0.12	0.20	*0.35	0.24	0.22
September	0.16	0.08	0.19	0.11	0.21	0.22
October	0.14	0.23	0.20	0.12	0.11	0.11
November	0.07	0.08	0.15	0.09	0.15	0.09
December	0.26	0.12	0.16	0.16	0.24	0.20
Shiraz						
January	0.03	0.02	0.04	0.20	0.04	0.04
February	0.01	0.01	0.07	0.11	0.04	0.01
March	0.09	0.03	0.08	0.14	0.09	0.02
April	0.26	0.15	0.18	0.26	0.27	0.26
May	0.26	0.22	0.23	0.27	0.19	0.18
June	0.03	0.06	0.03	0.08	0.03	0.08
July	0.10	0.12	0.15	0.01	0.15	0.10
August	0.18	0.17	0.15	0.23	0.18	0.18
September	0.15	0.19	0.21	0.16	0.23	0.21
October	0.13	0.09	0.04	0.12	0.05	0.05
November	0.04	0.28	0.25	0.09	0.15	0.06
December	0.09	0.11	0.05	0.01	0.07	0.07

Given the lack of significant trends in both annual and monthly precipitation for Shiraz, and the poor relationships between annual precipitation and the flowering dates of the five citrus types, there are no months with significant relationships. Correlation strengths have a minimum of r = 0.01 (p = 0.9445) for the relationships between rainfall in February and flowering dates for orange and tangerine, as well as between rainfall in July and December and flowering dates for sour lemon (*Table 5.11*). The maximum correlation coefficient (r =0.28, p = 0.0648) exists for the relationship between November rainfall and the flowering dates of tangerine (*Table 5.11*). There is no significant variability between the responses of different citrus types, and variation between the strength of monthly relationships is limited to an order of 0.02.

5.4.2 Flowering Dates and Annual Climate Threshold Counts

The only significant relationship between flowering dates and total days exceeding threshold conditions suitable for citrus flowering for Gorgan is a weak correlation between the flowering of sweet lemon and the counts of days where T_{max} and T_{min} < 13°C (r = 0.33, p = 0.0331) (*Table 5.12*). This relationship tentatively suggests a delay in flowering by 0.08d per increase in days with T_{max} and T_{min} < 13°C (*Table 5.12*). Insignificant relationships are found for counts of days with T_{max} > 35°C, with correlation coefficients ranging from r = 0.08 (p = 0.6184) for sour lemon to 0.29 (p = 0.0866) for sour orange (*Table 5.12*). Similarly, no significant relationships exist for days with only T_{min} < 13°C. There is significant variability between citrus types in the strength of relationships across all three threshold groups, with the relationships between flowering dates and counts of days with T_{max} and T_{min} < 13°C varying in strength from r = 0.03 (p = 0.8596) for tangerine to r = 0.33 (p = 0.0331) for sweet lemon (*Table 5.12*). Averaged threshold conditions reveal significant variability between citrus types, ranging from r = 0.19 for sour orange to 0.06 for tangerine (*Table 5.12*).

Kerman demonstrates a far greater number of significant relationships between the flowering dates of the citrus types and counts of numbers of days exceeding thresholds. Total days with T_{min} < 13°C are statistically significantly associated with the flowering dates of all five citrus types, with strong correlations ranging r = 0.60 (p < 0.0001) for sour orange to 0.66 (p < 0.0001) for sweet lemon (*Table 5.12*). This relationship suggests a delay in flowering across the citrus types by 0.13d per increase in days with T_{min} < 13°C for sour lemon (*Table 5.12*), and by 0.22d for sweet lemon. Counts of days with T_{max} and T_{min} < 13°C also have significant relationships with four of the citrus types, with the exception of sour lemon ($r = 0.26$, $p = 0.1010$) (*Table 5.12*). These statistically significant relationships suggest an advance in flowering in response to a decrease in the number of days with T_{max} and T_{min} < 13°C of between 0.15d/td (tangerine) and 0.19d/td (sour orange) (*Table 5.12*). In addition, tangerine flowering dates have a significant relationship with days over 35°C, with a correlation coefficient of 0.32 ($p = 0.0419$), which equates to an advance in flowering dates of 0.12d/td in response to an increase in days with T_{max} > 35°C (*Table 5.12*). There is considerably less variability between citrus types in the correlation strength for each of the threshold variables than for Gorgan.

In contrast, none of the relationships between flowering dates and days with T_{max} and T_{min} < 13°C are significant for Shiraz. However, days with T_{min} < 13°C demonstrate significant relationships with flowering in all five citrus types, with correlation coefficients ranging from $r = 0.39$ ($p = 0.0118$) for sour orange to $r = 0.48$ ($p = 0.0022$) for sour lemon, which equate to advances in flowering dates of 0.09d/td and 0.26d/td respectively, in response to a decrease in days with T_{min} < 13°C (*Table 5.12*). Orange and sour orange have significant relationships with the counts of days with T_{max} > 35°C, with $r = 0.37$ ($p = 0.0147$) and $r = 0.34$ ($p = 0.0285$), respectively (*Table 5.12*). These statistically significant relationships equate to advances in flowering dates of 0.29-0.30d/td in response to increases in days with T_{max} > 35°C (*Table 5.12*). Whilst there is similarity in correlation strength across the five citrus types for days with T_{max} > 35°C and days with T_{min} < 13°C, there is considerable variability in the correlation strengths between citrus types for days with T_{max} and T_{min} < 13°C, from $r = 0.04$ ($p = 0.8327$) for sour lemon to $r = 0.21$ ($p = 0.1821$) for tangerine (*Table 5.12*).

In comparison to the basic climatic variables, there is considerable variation in the strength of correlation between the counts of days exceeding threshold temperatures and the flowering dates of each of the citrus types, with no citrus type exhibiting either the strongest or weakest correlations in more than three instances. There is no citrus type which consistently responds more or less to these threshold count variables than the others, and inter-city variations appear to be far stronger determinants of climate response than the citrus type. Notably, there are inverse relationships between flowering dates and counts of days with T_{max} > 35°C for all five citrus types in all three cities, whereas both flowering dates and counts of days with T_{min} < 13°C and flowering dates and counts of days with T_{max} and T_{min} < 13°C demonstrate positive relationships. The predominance of significant relationships with counts of days with T_{min} < 13°C (and those with T_{max} and T_{min} < 13°C) confirms the importance of this minimum temperature threshold in ensuring temperatures warm enough for the induction of flowering, as less days with temperatures below this threshold are associated with earlier flowering dates. The 35°C maximum temperature threshold is more crucial to the success of the fruit yield than flowering. Furthermore, as temperatures exceeding this threshold seldom occur in the spring flowering period, it only affects flowering dates indirectly through its effect on the plant's health.

Table 5.12: Correlation between flowering dates of each of the five citrus types and the annual sums of days exceeding temperature thresholds for Gorgan, Kerman and Shiraz from 1960-2010. Significant relationships are highlighted by an asterisk.

Flowering and annual counts of days exceeding citrus threshold temperatures						
	Orange	Tangerine	Sweet Lemon	Sour Lemon	Sour Orange	Pooled
Gorgan						
T_{max} > 35°C (r)	0.12	0.10	0.14	0.08	0.29	0.12
Change (d/td)	-0.02	-0.03	-0.04	-0.02	-0.09	-0.03
T_{min} <13°C (r)	0.25	0.05	0.08	0.09	0.20	0.09
Change (d/td)	+0.07	+0.01	+0.03	+0.03	+0.08	+0.03
T_{max} & T_{min} < 13°C (r)	0.20	0.03	*0.33	0.13	0.09	0.11
Change (d/td)	+0.04	+0.01	+0.08	+0.04	+0.03	+0.05
Kerman						
T_{max} > 35°C (r)	0.26	*0.32	0.28	0.25	0.25	*0.31
Change (d/td)	-0.09	-0.12	-0.12	-0.09	-0.11	-0.11
T_{min} <13°C (r)	*0.61	*0.65	*0.66	*0.61	*0.60	*0.62
Change (d/td)	+0.20	+0.21	+0.24	+0.18	+0.25	+0.20
T_{max} & T_{min} < 13°C (r)	*0.40	*0.34	*0.39	0.26	*0.31	*0.34
Change (d/td)	+0.18	+0.15	+0.22	+0.13	+0.19	+0.16
Shiraz						
T_{max} > 35°C (r)	*0.37	0.25	0.30	0.30	*0.34	*0.33
Change (d/td)	-0.30	-0.20	-0.25	-0.22	-0.29	-0.25
T_{min} <13°C (r)	*0.40	*0.42	*0.41	*0.48	*0.39	*0.41
Change (d/td)	+0.09	+0.09	+0.10	+0.26	+0.09	+0.09
T_{max} & T_{min} < 13°C (r)	0.18	0.21	0.20	0.04	0.20	0.15
Change (d/td)	+0.13	+0.14	+0.14	+0.02	+0.14	+0.10

5.4.2.1 Flowering Dates and Monthly Counts of Days above 35°C

Whilst the correlations between the flowering dates of each of the citrus types and the annual counts of days with T_{max} > 35°C for Gorgan are weak, significant trends occur in May across four citrus types, ranging in strength from r = 0.41 (p = 0.0089) for sour lemon to r = 0.50 (p = 0.0008) for orange (*Table 5.13*). The exception is sour orange, with r = 0.13 (p = 0.4600), and a significant monthly correlation for March (r = 0.36, p = 0.0275) (*Table 5.13*). There are no further statistically significant relationships. Unlike the relationships between flowering dates and annual counts of days with T_{max} > 35°C, variability between citrus types is low between monthly correlations.

Kerman demonstrates significant relationships between total days with T_{max} > 35°C in May and flowering dates of all five citrus types, ranging in strength from r = 0.44 (p = 0.0037) for sour orange to r = 0.55 (p = 0.0002) for orange (*Table 5.13*). These correlation coefficients are slightly stronger than those for Gorgan, yet not as strong as the relationships between peak flowering dates and monthly T_{max} and T_{min} for Kerman. Notably, no other months demonstrate statistically significant relationships. Similar to Gorgan, there is little variability between citrus types in the strength of relationships, but rather considerable variability between months. This is accentuated by zero count days where T_{max} > 35°C for a number of months from autumn through spring (*Table 5.13*).

Shiraz has the weakest relationships between counts of days with Tmax > 35°C and the flowering dates of all five citrus types. Significant relationships only exist between days with T_{max} > 35°C in August and the flowering dates of orange, sweet lemon and sour orange, with relatively weak correlation coefficients of 0.31 (p = 0.0440), 0.30 (p = 0.0468), and 0.34 (p = 0.0266), respectively (*Table 5.13*). In contrast to Gorgan and Kerman, these significant relationships occur considerably later in the year, and do not coincide with peak flowering in April, but rather with the fruit development phenophase. However, similar to Kerman, there is little variability in correlation strength between citrus types, with a maximum difference in correlation coefficients of only 0.01 for flowering dates of tangerine and sour lemon and

August counts of T_{max} > 13°C. The considerable monthly variation in correlation strengths is again contributed by multiple (seven) months with zero-counts (*Table 5.13*).

Table 5.13: Strength of the relationship between the counts of days with T_{max} > 35°C for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk.

Flowering and monthly counts of days with T_{max} > 35°C						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0.10	0.14	0.11	0.23	*0.36	0.24
April	0.23	0.20	0.10	0.13	0.19	0.17
May	*0.50	*0.43	*0.47	*0.41	0.13	*0.41
June	0.18	0.17	0.14	0.07	0.13	0.16
July	0.04	0.10	0.12	0.09	0.16	0.08
August	0.16	0.06	0.20	0.11	0.28	0.10
September	0.07	0.09	0.12	0.01	0.20	0.05
October	0.11	0.01	0.08	0.05	0.24	0.07
November	0.08	0.18	0.10	0.17	0.12	0.10
December	0	0	0	0	0	0
Kerman						
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	0	0	0	0
April	0.07	0.14	0	0.16	0	0.09
May	*0.55	*0.54	*0.50	*0.51	*0.44	*0.49
June	0.12	0.20	0.19	0.19	0.19	0.22
July	0.19	0.15	0.11	0.07	0.16	0.16
August	0	0.13	0.05	0.11	0.01	0.09
September	0.05	0.16	0.07	0.15	0.03	0.06
October	0	0.09	0	0.02	0.16	0.07
November	0	0	0	0	0	0
December	0	0	0	0	0	0
Shiraz						
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	0	0	0	0
April	0	0	0	0	0	0
May	0.20	0.18	0.21	0.08	0.27	0.21
June	0.16	0.10	0.19	0.21	0.13	0.18
July	0.23	0.17	0.13	0.11	0.17	0.16
August	*0.31	0.28	*0.30	0.30	*0.34	*0.31
September	0.17	0.10	0.09	0.11	0.08	0.09
October	0	0	0	0	0	0
November	0	0	0	0	0	0
December	0	0	0	0	0	0

5.4.2.2 Flowering Dates and Monthly Counts of Days with T_{min} below 13°C

Significant relationships between flowering date and the number of days with $T_{min} < 13$°C for all citrus types in Gorgan exist for only three citrus types, fewer than for days with $T_{max} >$ 35°C. There is overlap in May for orange and sweet lemon, but not for sour orange in November. These relationships have relatively weak correlation coefficients; orange at $r = 0.46$ ($p = 0.0025$) and weaker relationships for sweet lemon and sour orange with $r = 0.34$ ($p = 0.0291$) and $r = 0.35$ ($p = 0.0353$), respectively (*Table 5.14*). Relationships for the flowering dates of tangerine and sour lemon are insignificant, with maximum correlation coefficients of 0.13 ($p = 0.3912$) for tangerine and 0.19 ($p = 0.2322$) for sour lemon (*Table 5.14*). There is considerable variability between the responses of citrus types, ranging from $r = 0.46$ ($p = 0.0025$) for orange to $r = 0.10$ ($p = 0.5292$) for tangerine in May (*Table 5.14*).

For April, May and September there are significant relationships for Kerman between days with $T_{min} < 13$°C and flowering dates across all citrus groups, being particularly strong for April with correlation coefficients ranging from 0.68 ($p < 0.0001$) for tangerine to 0.71 ($p < 0.0001$) for orange and sour orange (*Table 5.14*). Each citrus type has at least five months for which there are significant relationships, with sour lemon demonstrating significant relationships for the seven consecutive months from April to October. These range in strength from 0.31 ($p = 0.0483$) for September to 0.69 ($p < 0.0001$) for April (*Table 5.14*). For all citrus types there is a zero correlation coefficient for January, since all days have minimum temperatures below 13°C. Kerman has a considerably higher number of significant relationships between days with $T_{min} < 13$°C and flowering dates of all citrus types than either Gorgan's counts of days with $T_{min} < 13$°C or Kerman's days with $T_{max} > 35$°C.

Table 5.14: Strength of the relationship between the counts of days with T_{min} < 13°C for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk, correlations stronger that 0.7 indicated by a double asterisk.

Flowering and monthly counts of days with T_{min} < 13°C						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.01	0.04	0.07	0.07	0.04	0.05
February	0.15	0.02	0.01	0.09	0.04	0.06
March	0.26	0.08	0	0.05	0.13	0.03
April	0.09	0.11	0.03	0.04	0.02	0.01
May	*0.46	0.10	*0.34	0.19	0.28	0.26
June	0.02	0.07	0.10	0.14	0.07	0.08
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0.01	0.05	0.10	0.05	0.09	0.01
October	0.07	0.07	0.07	0.02	0.11	0.03
November	0.13	0.13	0.11	0.17	*0.35	0.19
December	0.11	0.03	0	0.04	0.05	0.05
Kerman						
January	0	0	0	0	0	0
February	0.20	0.07	0.06	0.01	0.13	0.05
March	0.25	0.22	0.30	0.27	*0.36	*0.30
April	**0.71	*0.68	*0.69	*0.69	**0.71	**0.70
May	*0.57	*0.56	*0.52	*0.46	*0.55	*0.49
June	0.14	0.23	0.21	*0.33	0.20	0.25
July	*0.32	0.29	*0.40	*0.35	*0.39	*0.34
August	0.18	0.30	0.29	*0.31	0.13	0.26
September	*0.34	*0.34	*0.40	*0.31	*0.36	*0.34
October	0.29	*0.33	0.31	*0.40	0.17	*0.28
November	0.28	0.31	*0.33	0.28	0.23	*0.28
December	0.07	0.14	0	0.16	0	0.09
Shiraz						
January	0	0	0	0	0	0
February	0.08	0.15	0.06	0.02	0.01	0.04
March	0.27	0.29	0.25	0.11	*0.40	0.27
April	*0.60	*0.60	*0.56	*0.48	*0.50	*0.58
May	*0.58	*0.58	*0.56	*0.43	*0.51	*0.55
June	*0.41	0.29	0.25	0.23	0.29	*0.32
July	0.03	0.01	0.04	0.06	0.02	0.02
August	0.12	0.10	0.11	0.12	0.13	0.10
September	*0.47	*0.49	*0.50	*0.41	*0.48	*0.51
October	0.24	0.25	0.26	*0.37	0.25	0.24
November	*0.38	*0.33	*0.43	*0.39	*0.48	*0.41
December	0	0	0	0	0	0

Significant relationships are demonstrated between days with T_{min} < 13°C and flowering dates across all citrus types in Shiraz for the months of April, May, September and

November. The highest correlations are recorded for April and May, with correlation coefficients ranging from $r = 0.48$ ($p = 0.0021$) to $r = 0.60$ ($p < 0.0001$) and from $r = 0.43$ ($p = 0.0073$) to $r = 0.59$ ($p < 0.0001$), respectively (*Table 5.14*). In addition, orange flowering dates have significant relationships with days in June where $T_{min} < 13°C$, with $r = 0.41$ ($p = 0.0065$); sour lemon for October, with $r = 0.37$ ($p = 0.0215$); and sour orange for March, with $r = 0.40$ ($p = 0.0084$) (*Table 5.14*). Despite this, variation between citrus types is largely insignificant. As for Kerman, all citrus types have correlation coefficients of zero for January and December since all days in these months have $T_{min} < 13°C$. Similar to relationships between flowering dates and counts of days with $T_{max} > 35°C$, the relationships of days with $T_{min} < 13°C$ for Shiraz are significant for fewer months than Kerman.

5.4.2.3 Flowering Dates and Monthly Counts of Days with T_{min} and T_{max} below 13°C

Gorgan, Kerman and Shiraz all have only a few months with significant relationships between the flowering dates of each of the five citrus types and the number of days with both T_{min} and $T_{max} < 13°C$. For Gorgan, these include the month of December for orange, with $r = 0.37$ ($p = 0.0187$); tangerine, with $r = 0.34$ ($p = 0.0272$); and sweet lemon, with the strongest correlation ($r = 0.42$, $p = 0.0067$) (*Table 5.15*). Significant relationships exist for sweet lemon in May, with $r = 0.39$ ($p = 0.0128$); sour lemon, with $r = 0.42$ ($p = 0.0078$); and sour orange with $r = 0.39$ ($p = 0.0165$) (*Table 5.15*). Sweet lemon flowering dates demonstrate the highest number of months with significant relationships with days where T_{max} and $T_{min} < 13°C$, and the strongest correlations ranging from $r = 0.05$ ($p = 0.7657$) for October to $r = 0.42$ ($p = 0.0067$) for December (*Table 5.15*). For the summer months of June through September there are no days where $T_{max} < 13°C$, and hence zero correlation values. There is significant variation between citrus types in the strength of correlations.

Table 5.15: Strength of the relationship between the counts of days with both T_{max} and T_{min} < 13°C for each month and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations are indicated by an asterisk.

Flowering and monthly counts of days with T_{max} and T_{min} < 13°C						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.01	0.10	0.02	0.02	0.07	0.05
February	0.21	0.05	0.25	0.01	0.04	0.04
March	0.01	0.08	0.12	0.03	0.10	0.03
April	0.18	0.28	0.08	0.13	0.07	0.19
May	0.19	0.04	*0.39	*0.42	*0.39	0.26
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	0.01	0.06	0.05	0.17	0.03	0.04
November	0.13	0.21	*0.38	0.30	0.23	0.26
December	*0.37	*0.34	*0.42	0.22	0.13	*0.32
Kerman						
January	0.15	0.04	0.06	0.14	0.04	0.03
February	0.29	*0.33	*0.37	0.07	0.17	0.24
March	0.28	*0.32	0.25	0.24	0.25	0.26
April	0.17	0.01	0.25	*0.35	0.27	*0.31
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	0	0	0	0	0	0
November	0.16	*0.32	0.23	0.23	0.23	0.25
December	0.25	0.20	0.27	0.11	*0.31	0.22
Shiraz						
January	0.06	0.05	0.05	0.07	0.14	0.02
February	*0.40	*0.37	*0.35	0.24	0.28	*0.31
March	0.26	0.28	0.26	0.27	0.29	0.22
April	0.17	0.26	0.24	0.26	0.29	0.26
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	0.20	0.16	0.16	0.22	0.19	0.16
November	0.05	0.10	0.02	0.10	0.04	0
December	0.06	0.03	0.04	0.13	0.01	0.03

For Kerman, the months in which significant relationships occur is even more disperse than for Gorgan, with significant relationships in February for tangerine and sweet lemon, with r = 0.33 (p = 0.0399) and r = 0.37 (p = 0.0181) respectively; March for tangerine, with r = 0.32

(p = 0.0448); April for sour lemon, with r = 0.35 (p = 0.0250); and December for sour orange, with r = 0.31 (p = 0.0484) (*Table 5.15*). Whilst tangerine demonstrates the highest number of months with significant relationships (albeit only 2); the strongest relationships are for sour lemon flowering dates and the counts of days where T_{max} and T_{min} < 13°C in April, with r = 0.35 (p = 0.0250) (*Table 5.15*). As for Gorgan, the summer months of May through October have no days with T_{max} < 13°C. Again, considerable variation in the strength of relationships between citrus types is demonstrated.

Shiraz once again has the least number of cases of significant correlations between flowering dates and days where T_{max} and T_{min} < 13°C, with only three citrus types indicating any significant relationships. These relationships between the counts of days with both T_{max} and T_{min} < 13°C and flowering dates are significant for orange, tangerine and sweet lemon, all for the month of February. With correlation strengths of r = 0.35 (p = 0.0241) to r = 0.40 (p = 0.0083) for sweet lemon and orange respectively, these relationships are stronger than any of those for Kerman (*Table 5.15*). The summer months of May to September similarly have correlation coefficients of zero on account of there being no days with T_{max} < 13°C. There is also notably less variation between citrus types for these relationships.

5.4.3 Flowering Dates and Annual Sunshine Hours

Despite the strong time trends in annual sunshine hours for Gorgan and Kerman (r = 0.73, p < 0.0001 and r = 0.64, p < 0.0001 respectively) (*Table 5.7*), few significant relationships exist between annual sunshine hours and the flowering dates for each of the five citrus types in the three cities. For Gorgan, significant relationships exist for orange and tangerine, with r = 0.43 (p = 0.0373) and r = 0.53 (p = 0.0058) respectively; whilst for Kerman significant relationships exist for orange and sour orange, with r = 0.41 (p = 0.0264) and r = 0.42 (p = 0.0263) respectively (*Table 5.16*). These significant correlations suggest quantified inverse relationships of a 0.01 day shift toward earlier flowering for each one hour increase in annual sunshine hours for Gorgan, and a shift earlier of 0.02 d/h for Kerman (*Table 5.16*). Shiraz, which demonstrates very weak trends in annual sunshine hours (r = 0.09, p = 0.5603) (*Table 5.7*), has no significant relationships between sunshine hours and the flowering dates for any of the citrus types. Sweet lemon and sour lemon demonstrate no significant relationships with sunshine hours for any of the cities. The weakest correlation exists for the relationship between annual sunshine hours and sour lemon flowering dates for Gorgan, with r = 0.03 (p = 0.9097) (*Table 5.16*). Whilst the strongest correlation is for tangerine flowering dates in Gorgan (r = 0.53, p = 0.0058), which equates to an advanced flowering of -0.01d/h, the set of relationships with the strongest correlations are for orange, with an average correlation coefficient 0.06 greater than the strongest city average, and equating to -0.01 to -0.02d/h (*Table 5.16*).

Table 5.16: Relationship between the flowering dates of each of the five citrus types and the annual total sunshine hours for Gorgan, Kerman and Shiraz, 1960-2010. Significant results are indicated by an asterisk.

Flowering and annual total daily sunshine hours						
	Orange	Tangerine	Sweet Lemon	Sour Lemon	Sour Orange	Pooled
Gorgan						
Sunshine hours (r)	*0.43	*0.53	0.21	0.03	0.07	0.13
Relationship (d/h)	-0.01	-0.01	-0.01	+0.01	+0.01	-0.01
Kerman						
Sunshine hours (r)	*0.41	0.27	0.31	0.28	*0.42	0.33
Relationship (d/h)	-0.02	-0.01	-0.01	-0.01	-0.02	-0.01
Shiraz						
Sunshine hours (r)	0.31	0.26	0.26	0.21	0.18	0.21
Relationship (d/h)	-0.02	-0.02	0.02	0.02	0.01	-0.02

5.4.3.1 *Flowering Dates and Monthly Sunshine Hours*

Relationships between monthly sunshine hours and the flowering dates of the five citrus types for Gorgan are weak for sour lemon and sour orange, with no significant relationships for any month. There are, however, significant relationships for the month of February for orange, tangerine and sweet lemon, with correlation coefficients ranging from 0.39 (p = 0.0477) for sweet lemon to 0.53 (p = 0.0057) for orange (*Table 5.17*). Tangerine, which has the strongest relationship with Gorgan's annual sunshine hours, also has the strongest monthly relationships, with a correlation coefficient of 0.54 (p = 0.0039) for August, and statistically significant relationships for March and May (*Table 5.17*). For most months, there is significant variability between citrus types in the strength of correlation, with the greatest variation for the month of August with correlation coefficients ranging from 0.03 ($p = 0.9100$) for sour orange to 0.54 ($p = 0.0039$) for tangerine (*Table 5.17*). This resembles the patterns observed in the annual relationships (*Table 5.16*). The timing of the significant relationships with sunshine hours is relatively consistent with the three vegetative flushes that citrus grown in the temperate Northern hemisphere experience. As this is the phenological phase which most directly relies on sunshine for photosynthesis, and is the phase which ensures that sufficient nutrients are available to support flowering, it is biologically valid.

For Kerman there is considerably greater conformity between citrus types than Gorgan in their response to sunshine hours. Significant relationships are found for all five citrus types for the month of March, and for all types except sweet lemon in May, which has a correlation coefficient of 0.32 ($p = 0.0733$) (*Table 5.17*). For April, significant relationships are also demonstrated for orange and sour orange, with correlation coefficients of 0.36 ($p = 0.0296$) and 0.34 ($p = 0.0493$) respectively (*Table 5.17*). Surprisingly, given the lack of significant relationships for sour orange in Gorgan, Kerman has significant relationships between sunshine hours and the flowering dates of sour orange for four months (March, April, May and December). The strongest correlation is for tangerine in March with a correlation coefficient of $r = 0.51$ ($p = 0.0027$), whilst the strongest correlations are for the flowering dates of orange, with a range from $r = 0.36$ ($p = 0.0296$) to $r = 0.44$ ($p = 0.0068$) for April and March respectively (*Table 5.17*). For Kerman, these months for which relationships between sunshine hours and flowering are significant, are less closely aligned with the timing of leaf flushes, but rather with the period of flowering. This suggests a more direct role of the photoperiod in determining flowering time. This is of interest, as Kerman is the most arid of the three study cities, and receives little year round precipitation. Any fluctuations in the sunshine hours are likely more strongly governed by day length than by cloud cover.

Table 5.17: Strength of the relationship between monthly totals of daily sunshine hours and the flowering dates of the five citrus types in each of the three cities for the period 1960-2010. Statistically significant correlations indicated by an asterisk.

Flowering and monthly total daily sunshine hours						
Correlation strength (r)	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
January	0.09	0.22	0.07	0.11	0.17	0.05
February	*0.53	*0.51	*0.39	0.19	0.35	0.35
March	0.35	*0.40	0.26	0.19	0.34	0.29
April	0.13	0.25	0.17	0.09	0.02	0.15
May	0.32	*0.47	0.24	0.12	0.04	0.22
June	0.01	0.20	0.17	0.31	0.31	0.20
July	0.07	0.06	0.19	0.32	*0.44	0.29
August	0.20	*0.54	0.26	0.17	0.03	0.20
September	0.08	0.11	0.06	0.10	0.26	0.07
October	0.10	0.21	0.05	0.07	0.04	0.01
November	0.34	0.26	0.24	0.20	0.38	0.28
December	0.08	0	0.22	0.05	0.04	0.03
Kerman						
January	0.01	0.21	0.15	0.04	0.07	0.05
February	0.01	0.11	0.07	0.08	0.10	0.03
March	*0.44	*0.51	*0.36	*0.41	*0.36	*0.38
April	*0.36	0.31	0.34	0.32	*0.34	0.30
May	*0.44	*0.37	0.32	*0.46	*0.41	0.42
June	0.20	0.04	0.11	0.16	0.23	0.17
July	0.12	0.04	0.02	0.02	0.13	0.10
August	0.19	0	0.21	0.28	0.30	0.24
September	0.09	0.19	0.09	0.08	0.06	0.10
October	0.07	0.08	0.10	0.01	0.02	0.06
November	0.15	0.01	0.19	0.06	0.24	0.17
December	0.26	0.02	0.17	0.10	*0.39	0.22
Shiraz						
January	0.17	0.22	0.24	0.07	0.23	0.13
February	0.01	0.01	0.09	0.02	0.10	0.05
March	*0.35	0.24	0.30	0.28	0.32	0.23
April	*0.44	*0.34	*0.34	*0.35	*0.35	*0.39
May	0.31	*0.34	0.30	0.21	0.15	0.22
June	0.11	0.01	0.06	0.17	0.22	0.14
July	0.10	0.13	0.29	0.31	0.26	0.21
August	*0.37	*0.41	*0.35	*0.44	0.29	*0.32
September	0.26	0.29	*0.42	0.33	*0.36	*0.33
October	0.05	0	0.01	0.04	0.14	0.03
November	0.12	0.02	0.04	0.01	0.08	0.04
December	0.07	0.02	0.03	0.19	0.02	0.03

Despite there being no significant time trends in the sunshine hours for Shiraz (*Table 5.7, Figure 5.24*), this city has the highest number of significant relationships between monthly sunshine and flowering dates. There are significant relationships for all citrus types for April, and significant correlations for all but sour orange for August, with r = 0.29 (p = 0.0797) (*Table 5.17*). Both sour orange and sweet lemon have significant relationships for September, with correlation coefficients of 0.36 (p = 0.0314) and 0.42 (p = 0.0084) respectively; whilst orange has a significant relationship for March, with r = 0.35 (p = 0.0321); and tangerine for May, with r = 0.34 (p = 0.0375) (*Table 5.17*). The monthly sunshine and flowering date correlations are not as strong as those for Kerman and Shiraz. There is considerably smaller variation in correlation strength between citrus types in Shiraz than in the other two cities. Similar to Gorgan, the timing of the significant relationships between sunshine hours and flowering dates is more consistently aligned with the leaf flushes. However, the considerable variability in the months that demonstrate significant relationships with flowering dates between citrus types is notable, particularly given the similar flowering dates of the five citrus types for Shiraz (*Figure 5.6*).

5.5 Analysis of Growing Degree Days

Growing Degree Day (GDD) analysis involves studying the rate at which heat units are accumulated. For citrus, heat units (HU) are accumulated once the threshold temperature of 13°C has been reached. Thus heat unit sums are taken for all days in which T_{avg} > 13°C as the cumulative sum of all daily average temperatures greater than 13°C. In phenology, it is possible that either the rate of heat accumulation up to the time of flowering, or the seasonal rate of heat accumulation, are associated with, and are drivers of, the timing of phenophasic events (Spano et al., 1999; Arora & Boer, 2005). It is likely that the seasonal rate of heat accumulation, rather than heat accumulation up to the time of flowering, is more closely related to the flowering dates given that this study worked with peak, rather than first, flowering. It is therefore of initial interest to determine whether rate of heat accumulation by the date of flowering is equivalent to the seasonal rate of heat accumulation, defined by the date at which 200 HU are accumulated.

5.5.1 Julian Date of 200 HU and HU at Date of Flowering

5.5.1.1 Trends in HU at Time of Flowering and of JD at 200 HU

Although significant results are recorded for all three cities when analysing trends in the JD at which 200 HU have been accumulated, considerably stronger trends are found for Kerman and Shiraz, with correlation coefficients of r = 0.59 ($p < 0.0001$) and 0.66 ($p < 0.0001$) respectively (*Table 5.18*). These trends are associated with shifts in the JD of 200 HU accumulation for Kerman and Shiraz of 0.33d/yr and 0.38d/yr earlier respectively, whilst Gorgan has a more moderate trend to 0.16d/yr later (*Table 5.18*).

Table 5.18: Trends in the Julian Dates at the accumulation of 200 HU and the HU at flowering time for each of the five citrus types, together with the relationships between the JD at 200 HU accumulation and the HU at flowering for each of the five citrus types for Gorgan, Kerman and Shiraz from 1960-2010. Significant results indicated by an asterisk, correlations stronger than 0.7 indicated by a double asterisk.

Association between JD at 200 HU and HU at time of flowering							
	JD 200 HU	HU Orange	HU Tangerine	HU Sweet lemon	HU Sour lemon	HU Sour orange	HU Pooled
Gorgan							
Trend (JD/yr or HU/yr)	*0.29	0.13	0.05	0.16	0.19	0.11	0.10
Relationship (HU/JD)		**0.89	**0.87	**0.80	**0.80	**0.73	**0.85
Kerman							
Trend (JD/yr or HU/yr)	*0.59	0.10	0.12	0.30	0.25	0.08	0.10
Relationship (HU/JD)		*0.45	*0.39	*0.50	*0.51	0.26	*0.39
Shiraz							
Trend (JD/yr or HU/yr)	*0.66	*0.37	*0.47	*0.47	*0.40	*0.50	*0.45
Relationship (HU/JD)		0.03	0.03	0.04	0.09	0.02	0.02

Trends in the HU accumulated by the time of flowering are not nearly as strong, and are significant only for Shiraz, where correlation coefficients range from 0.37 ($p = 0.0143$) for orange to 0.50 ($p = 0.0008$) for sour orange (*Table 5.18*). Trends in accumulated HU at flowering range from r = 0.05 ($p = 0.7553$) for tangerine to r = 0.11 ($p = 0.2434$) for sour orange in Gorgan; and from r = 0.08 ($p = 0.6139$) for sour orange to r = 0.30 ($p = 0.0628$) for sweet lemon in Kerman (*Table 5.18*). Whilst there is variability between the responses of the different citrus types, none consistently exhibits either greater or lesser trends in heat unit accumulation at flowering across cities.

Graphic presentation of these data highlights the extreme inter-annual variability in both the JD at which 200 HU are accumulated for each city, and also in the HU accumulated by the time of flowering, which contributes to explaining the weak correlation values for the time trends (*Table 5.18, Figures 5.25, 5.26, 5.27*). Interestingly, the pattern of peaks in the JD at which 200 HU are accumulated is mirrored by lows in the heat units at the time of flowering, and vice versa. This means that in years in which it takes longer for 200 HU to be accumulated, flowering occurs at considerably lower heat unit accumulations, implying no relationship between heat units and flowering. Gorgan has the greatest inter-annual variation in both trends in the JD at 200 HU, and in the heat units at flowering. Kerman has less extreme inter-annual variability, but a considerably less regulated inter-annual pattern in the JD at 200 HU than Shiraz. However, Kerman and Shiraz exhibit similar patterns in the inter-annual HU patterns at the time of flowering.

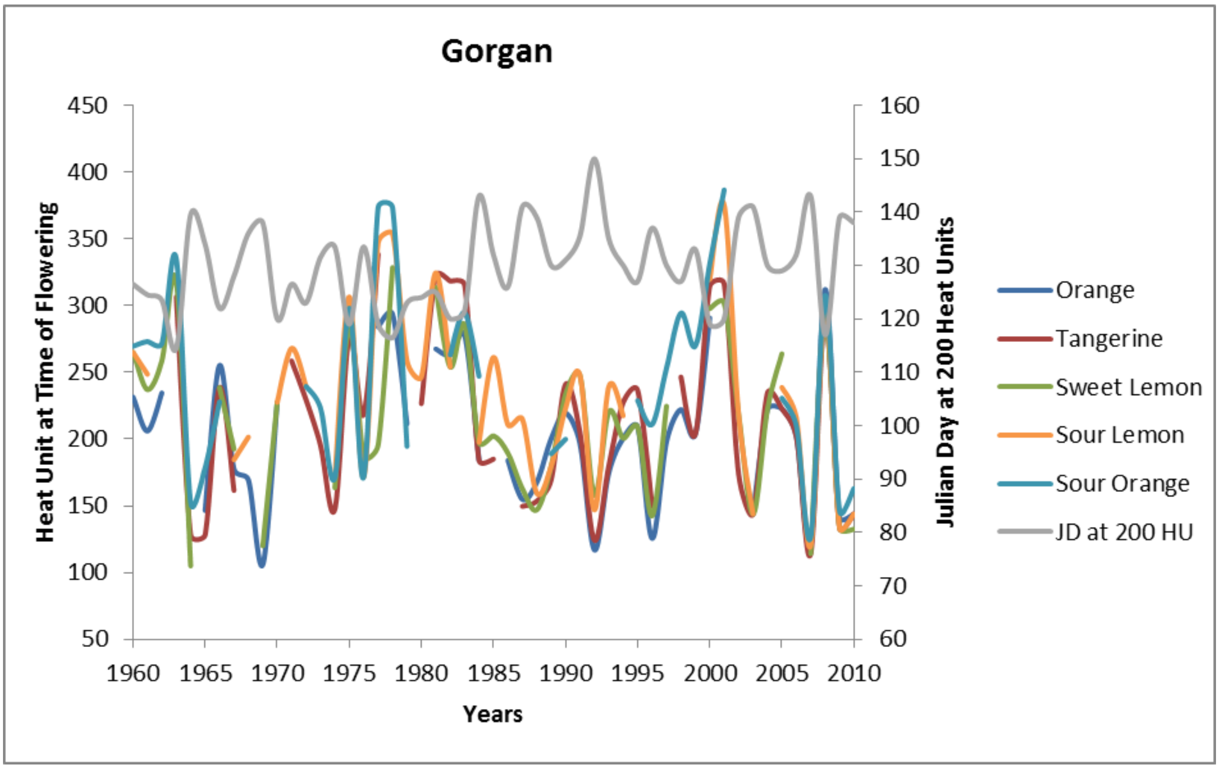

Figure 5.25: Trends in the accumulation of 200 HU and the HU at flowering time for each of the five citrus types for Gorgan, 1960-2010.

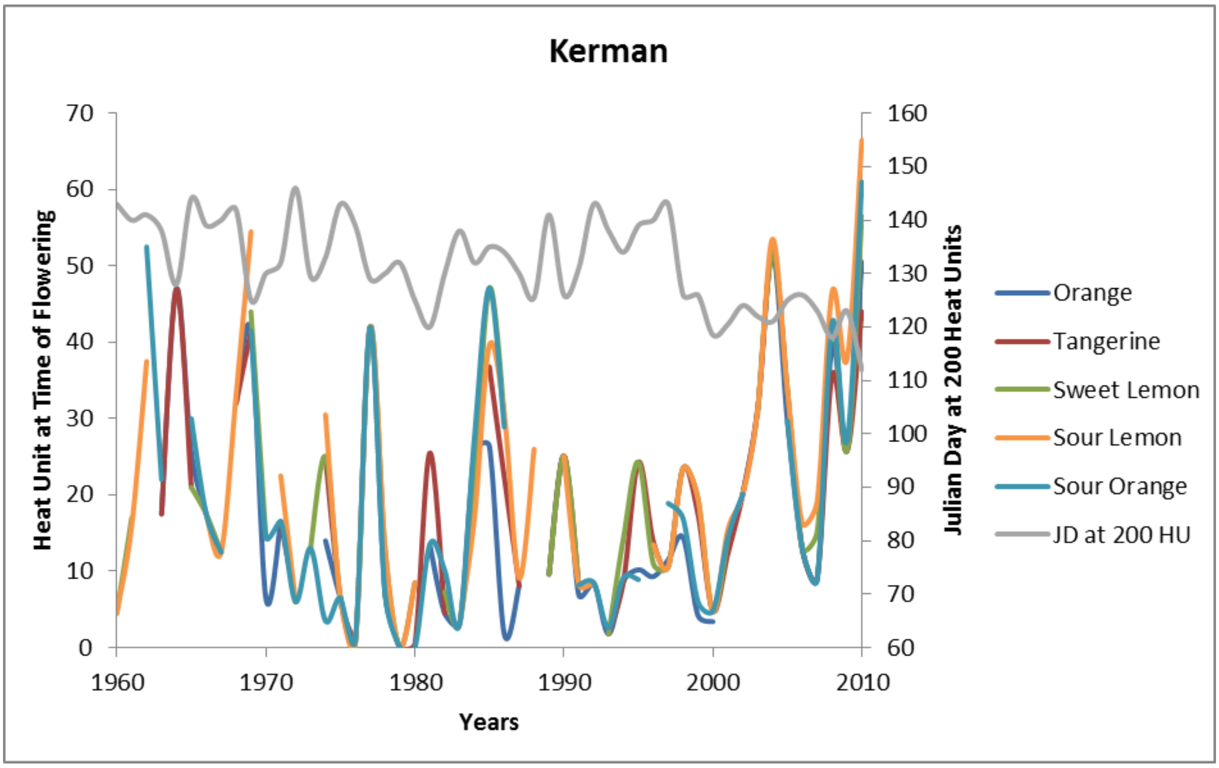

Figure 5.26: Trends in the accumulation of 200 HU and the HU at flowering time for each of the five citrus types for Kerman, 1960-2010.

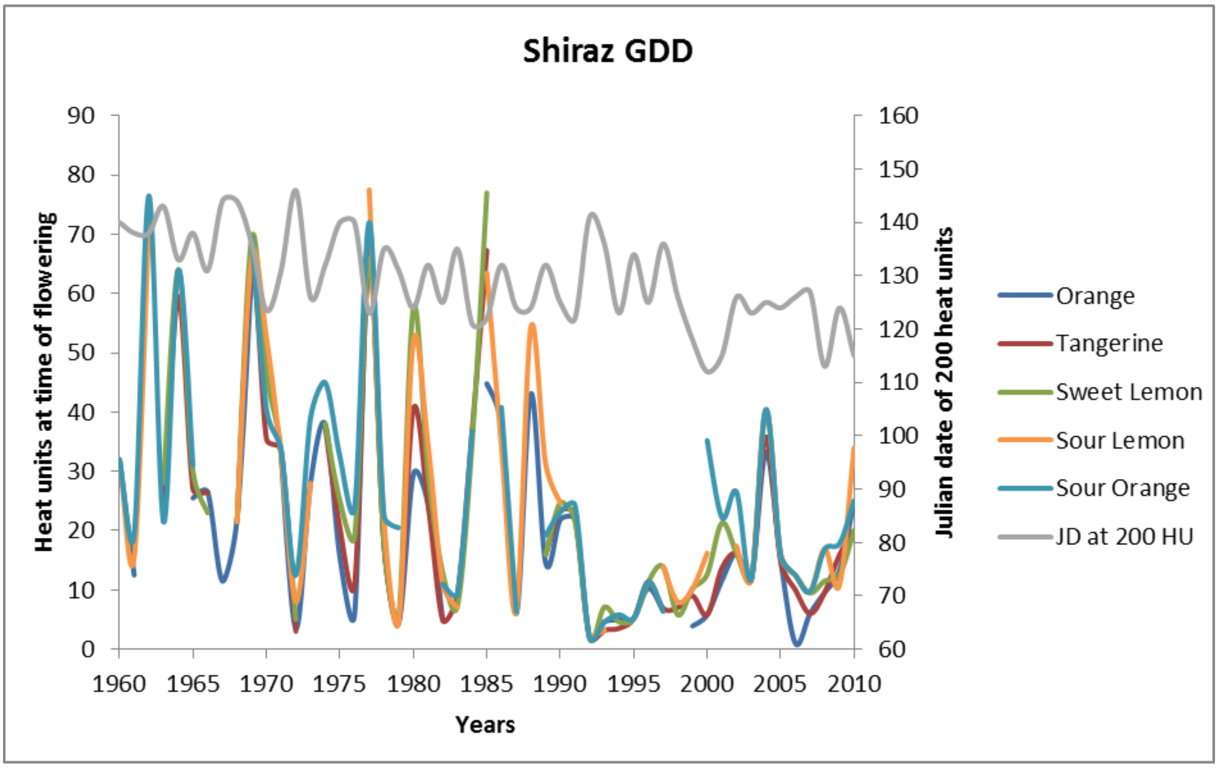

Figure 5.27: Trends in the accumulation of 200 HU and the HU at flowering time for each of the five citrus types for Shiraz, 1960-2010.

5.5.1.2 Relationships between HU at Time of Flowering and JD at 200 HU

Despite the poor time trends (*Table 5.18, Figure 5.25*), relationships between the HU at the time of flowering and the JD at which 200 HU have been accumulated are very strong across all citrus groups for Gorgan. Correlation coefficients range from $r = 0.73$ ($p < 0.0001$) for sour orange to $r = 0.89$ ($p < 0.0001$) for orange (*Table 5.19*). These strong correlations coefficients, however, are associated with an inverse relationship, implying that where 200 HU are accumulated earlier in the year, flowering occurs at a higher HU accumulation, and where 200 HU are accumulated earlier in the year flowering occurs at a lower HU accumulation (*Figure 5.28*). This indicates a poor association between the amount of heat accumulated by the time of flowering, and the heat accumulation rate for the season. Consequently, the rate of seasonal heat accumulation is of greater importance to flowering time than the absolute heat units accumulated for floral induction. It suggests that flowering time is not driven directly by the accumulation of 200 HU, despite the statistically significant association.

By contrast, relationships for Shiraz are particularly weak, with insignificant correlations indicated by $r = 0.02$ ($p = 0.8990$) for sour orange to $r = 0.09$ ($p = 0.6052$) for sour lemon (*Table 5.19, Figure 5.30*). Whilst Kerman demonstrates significant relationships for all citrus types except for sour orange, the relationships are not nearly as strong as those for Gorgan, with correlation coefficients of the significant relationships ranging from $r = 0.39$ ($p = 0.0139$) for tangerine to $r = 0.51$ ($p = 0.0007$) for sour lemon (*Table 5.19, Figure 5.29*). Sour orange consistently has the weakest relationships for each city, with correlation coefficients of 0.73 ($p < 0.0001$) for Gorgan, 0.26 ($p = 0.0044$) for Kerman and 0.02 ($p = 0.8990$) for Shiraz. However, no single citrus type consistently demonstrates the strongest relationships (*Table 5.19*). Gorgan and Shiraz exhibit low variability between the results of the different citrus types, whereas for Kerman correlation coefficients differ by 0.24.

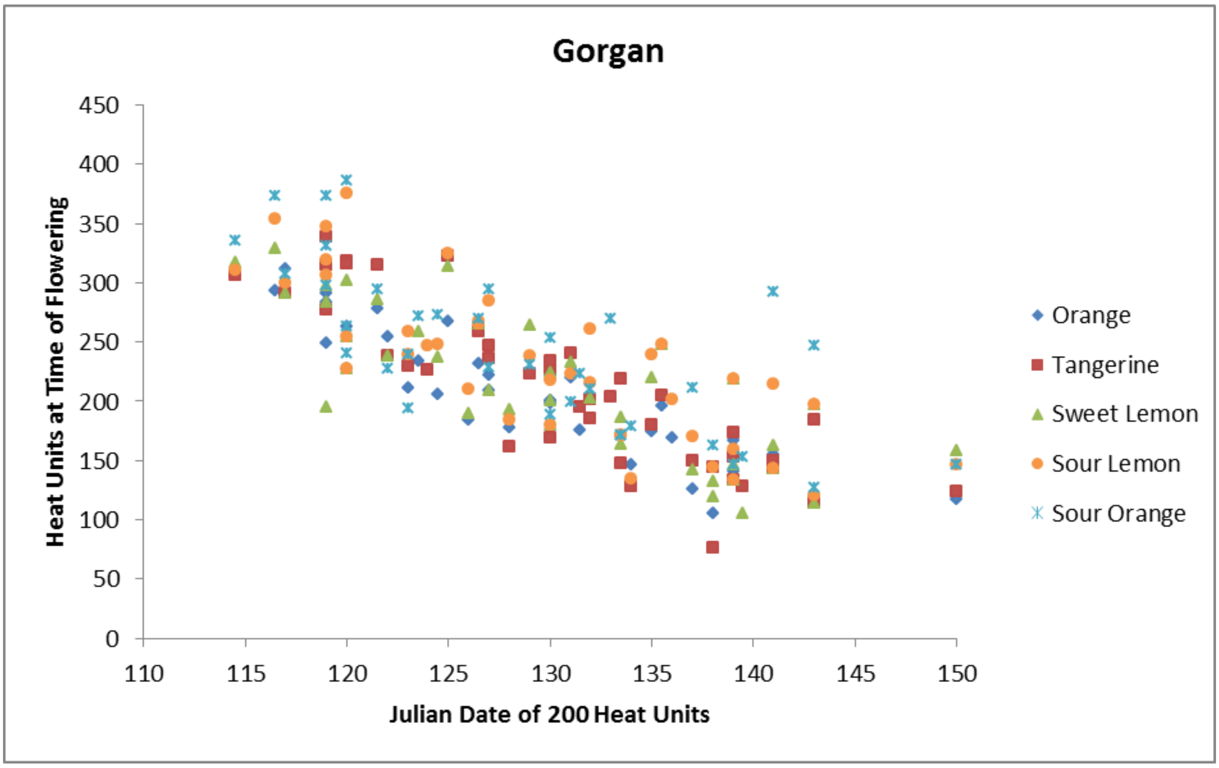

Figure 5.28: Correlation between the JD at which 200 HU are accumulated and the HU accumulated at the time of flowering of each of the five citrus types for Gorgan.

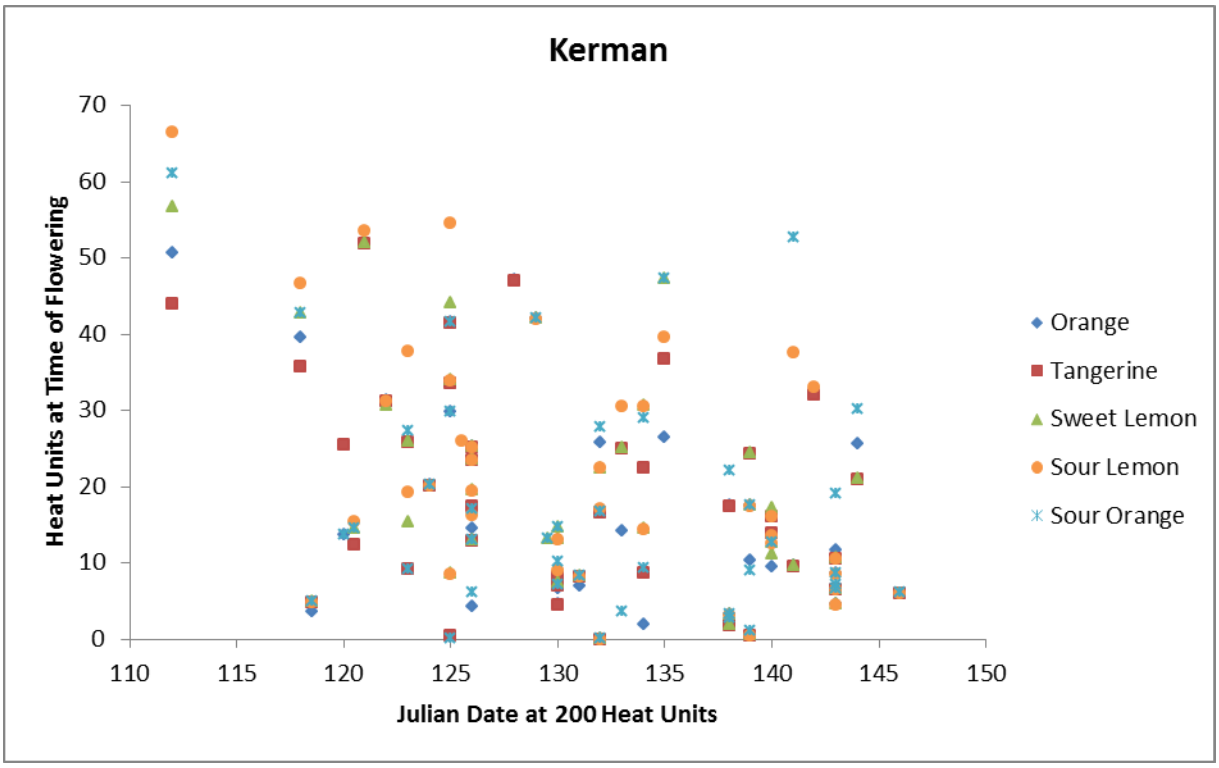

Figure 5.29: Correlation between the JD at which 200 HU are accumulated and the HU accumulated at the time of flowering of each of the five citrus types for Kerman.

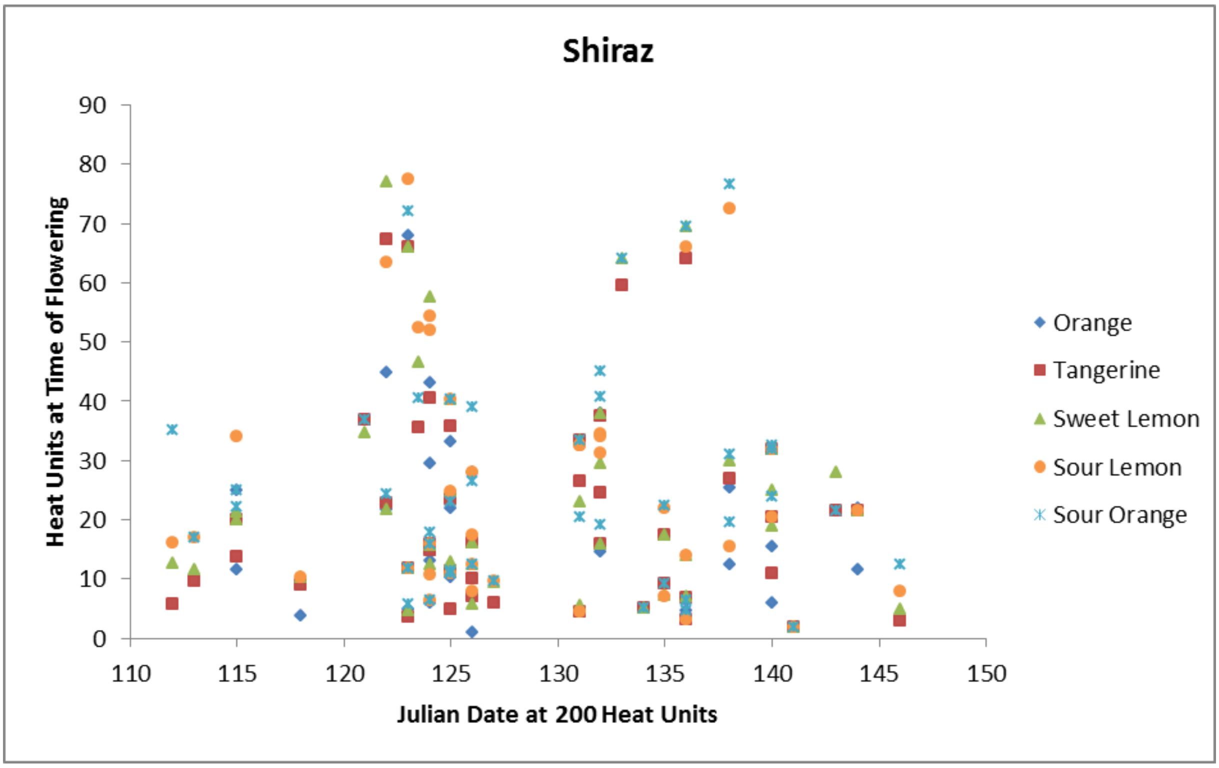

Figure 5.30: Correlation between the JD at which 200 HU are accumulated and the HU accumulated at the time of flowering of each of the five citrus types for Shiraz.

Whilst strong correlations exist for Gorgan ($r = 0.89$, $p < 0.0001$), their implication of the timing of flowering and the poor relationship between the seasonal rate of heat accumulation and the heat accumulation by the date of flowering necessitates the individual analysis of the relationship between flowering dates and HU accumulated by flowering, and the Julian Date at which 200 HU are accumulated.

5.5.2 Julian Date of Flowering and HU at Flowering

The relationships between flowering dates and the heat accumulation at the time of flowering are relatively weak across all five citrus types in Gorgan, with a statistically significant relationship found only for sour orange ($r = 0.45$, $p = 0.0025$) (*Table 5.19*). The weak relationships support later flowering where a greater number of heat units are accumulated, and earlier flowering where fewer heat units are accumulated (*Figure 5.31*). This would suggest that flowering dates are driven directly by the heat accumulation which occurs by the time of flowering, rather than by the satisfaction of a minimal heat unit accumulation threshold. However, as this study analyses peak rather than first flowering dates, it would be unlikely that the heat units accumulated by the time of peak flowering act as a primary trigger.

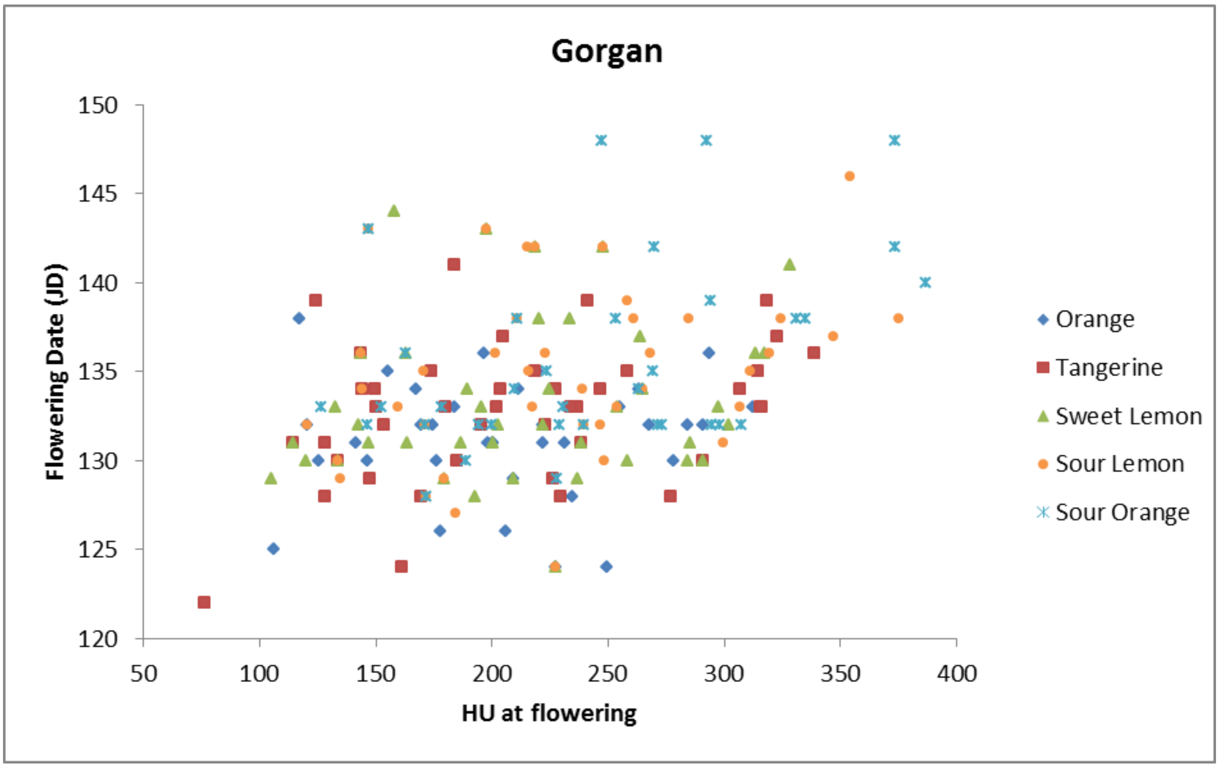

Figure 5.31: Relationship between the flowering date and the HU accumulated at the time of flowering of each of the five citrus types for Gorgan.

For Kerman and Shiraz, the relationship between flowering dates and the HU at flowering are even weaker, with no statistically significant relationships (*Table 5.19*). For both cities, flowering occurs across a large range of heat accumulation sums, including a zero HU (*Figures 5.32, 5.33*). The poor association here strengthens the argument that the heat accumulation at the date of peak flowering is not a primary driver of its timing. The prevalence of flowering occurring at a date associated with the accumulation of between 0-30 HU for the inland cities of Kerman and Shiraz can be explained by their considerably colder winter temperatures experienced early in the Gregorian year, with very few days experiencing the requisite 13°C for HU accumulation. For Gorgan, flowering is more common between 110-130 HU. This is due both to the later flowering dates in Gorgan, facilitating a greater time period for heat units to be accumulated, but also the warmer winter conditions in this city. This suggests that citrus, when grown in these harsher climatic conditions, have lower heat accumulation thresholds. However, as the count of days which exceed 13°C is significantly related with the flowering dates of the five citrus types for Kerman and Shiraz (*Table 5.14*), it is perhaps more feasible that the heat accumulated at the time of flowering is not related to the time by which 200 HU are accumulated. This is not unlikely, as HU are calculated only for days in which the threshold temperature is met, and hence will accumulate far more rapidly once mean temperatures meet the threshold conditions. As the heat accumulation by flowering does vary considerably for Kerman and Shiraz, and is greater for later flowering in Gorgan, peak flowering for the five citrus types in Iran is not driven by a particular accumulation of heat. Flowering appears to occur on dates unrelated to the heat accumulated by them. The between flowering dates and the HU at the time of flowering, can hence be eliminated from further analysis.

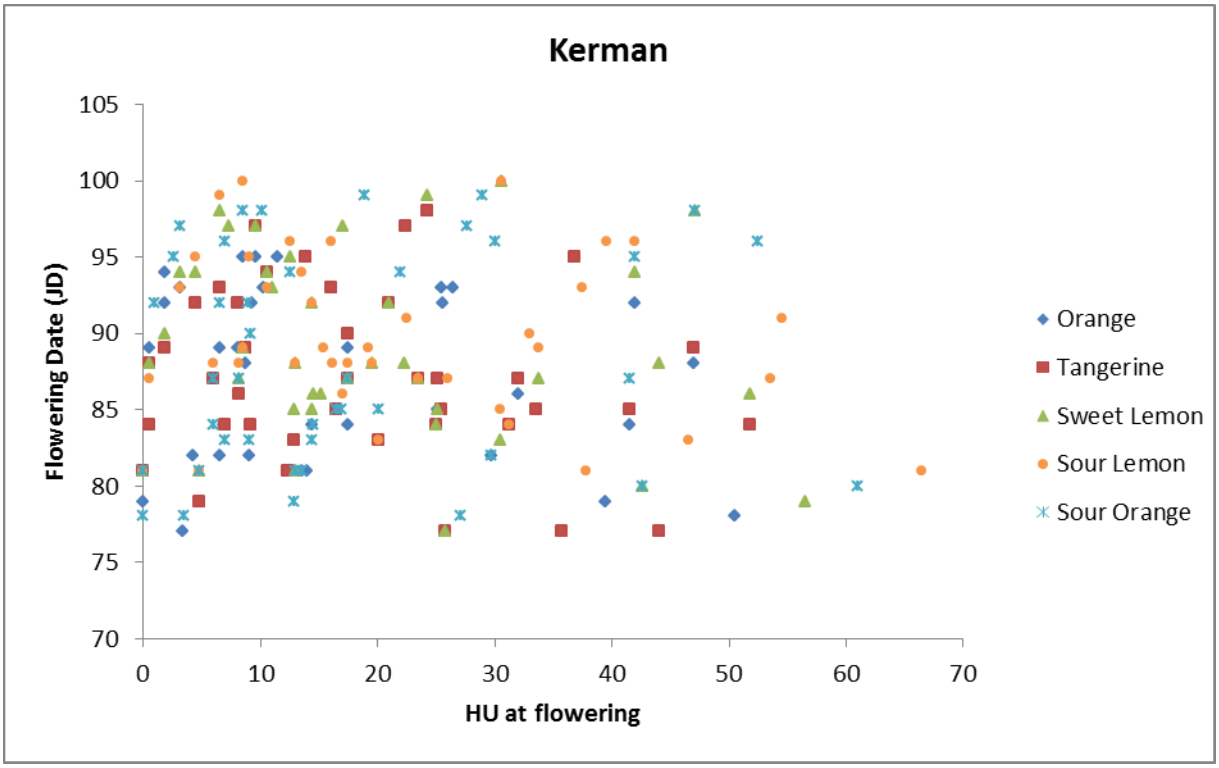

Figure 5.32: Relationship between the flowering date and the HU accumulated at the time of flowering of each of the five citrus types for Kerman.

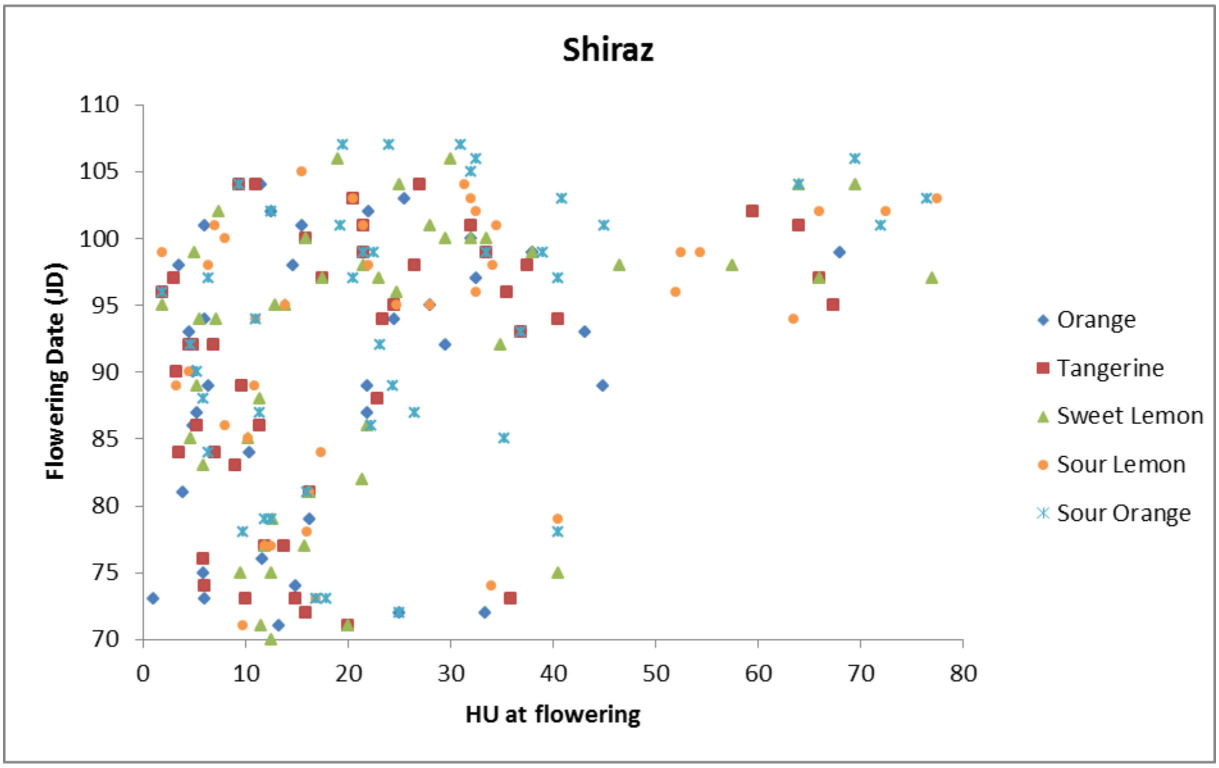

Figure 5.33: Relationship between the flowering date and the HU accumulated at the time of flowering of each of the five citrus types for Shiraz.

The relationship between the flowering date of the five citrus types and the heat units at the time of their flowering for each of the cities is too weak to be considered a significant driver of peak flowering dates. It will thus be excluded from further analysis. However, it remains necessary to test the strength of the relationship between flowering dates and the seasonal rate of heat accumulation, defined as the JD at which 200 HU are accumulated.

5.5.3 Julian Date of 200 Heat Units and Julian Date of Flowering

The relationships between the JD at which 200 HU are accumulated and those of flowering are significant across a greater number of citrus types and in more cities than the relationships between the flowering date and the HU at flowering. Shiraz has no citrus types with significant relationships between flowering date and the HU at flowering time, yet strong significant relationships exist here across all citrus types, with correlation coefficients ranging from $r = 0.65$ ($p < 0.0001$) for sour lemon to 0.70 ($p < 0.0001$) for orange (*Table 5.19*). Kerman has even stronger relationships across all citrus types, with correlation coefficients ranging from 0.64 ($p < 0.0001$) for sour lemon to 0.76 ($p < 0.0001$) for orange

(*Table 5.19*). For Gorgan, there is no consistent improvement in correlation strength, and those improvements observed are of a lesser magnitude than observed for Kerman and Shiraz (*Table 5.19*). Whilst stronger relationships are recorded for the relationship between flowering dates and 200 HU than for flowering dates and HU at flowering for orange, sweet lemon and the pooled flowering dates, the latter demonstrate stronger relationships for tangerine, sour lemon and sour orange. Notable is the statistically significant relationship between sour orange flowering dates and HU at flowering (*Table 5.19*), whereas a relatively weak relationship is demonstrated for sour orange flowering dates and JD at 200 HU (*Table 5.19*). Across all citrus types, and when pooled, there is a stronger correlation between the flowering date and 200 HU than between flowering date and HU at flowering, and so it remains justified to exclude the HU at flowering, and instead consider the JD at which 200 HU are accumulated. The stronger correlations for the rate of accumulation of 200 HU indicate a seasonal impact of the rate of warming, rather than the absolute heat accumulated by a plant, in fulfilling the requirements for the break of dormancy and induction of flowering. These differences are notable, and together with the relatively weak strength of the relationship between flowering dates and the JD at 200 HU, suggest that the accumulation of heat is not a particularly strong driver of flowering dates in Gorgan. This argument is strengthened by the poor relationships between flowering dates and annual T_{max} and T_{min}.

When inspecting data graphically, no unidirectional change in the JD of flowering is apparent despite considerable increase in the JD at 200 heat units (*Figure 5.34*). There is a discontinuity in the JD at which 200 HU are accumulated between 144-150 JD, representing 23-29 May, which coincides with the period directly following flowering for Gorgan. As the date of the accumulation of 200 HU is dependent on the rate of warming, the gap in the absolute dates is likely caused by a period of higher temperatures in early May, followed by a return to the previous rate of warming. Such an increase in temperatures in early May could possibly result in the induction of flowering and hence determine the mid-May flowering dates. The statistically significant relationships between flowering dates and T_{max} for May would support this (*Table 5.9*). Interesting then, are the relatively late flowering dates of between 137-144 which coincide with the very late timing of 200 HU accumulation by 151 JD. As a result of the variability in the behaviour of the response of the timing of flowering to the timing of the accumulation of 200 HU, the relationship is statistically insignificant, with poor correlation values (*Table 5.19*), and unresponsive fluctuation in the JD of flowering. This is perhaps because the JD of flowering demonstrates the least significant time trend for Gorgan (*Table 5.1, Figure 5.2*).

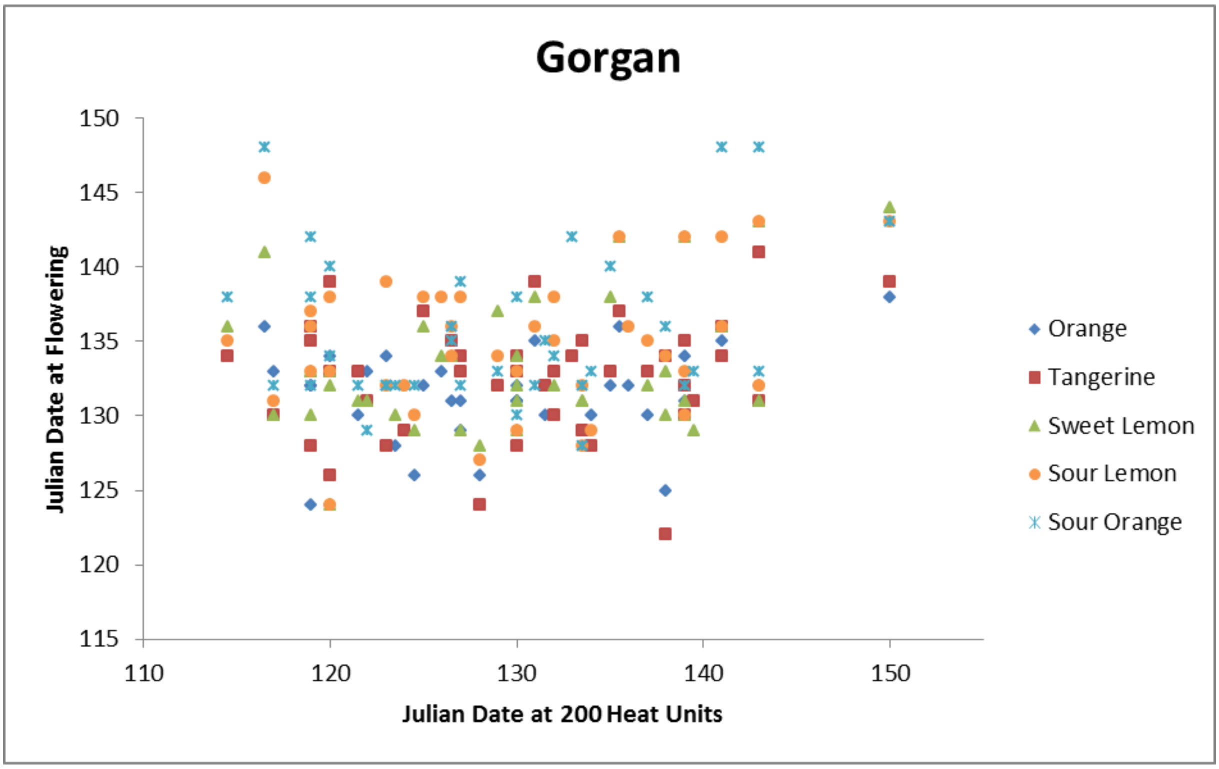

Figure 5.34: Correlation between the JD at which 200 HU are accumulated and the JD at which each of the five citrus types flower for Gorgan from 1960-2010.

Visual representation of the relationships for Kerman and Shiraz indicates strong positive relationships between the timing of flowering and the JD at 200 HU (*Figures 5.35, 5.36*). These statistically significant relationships indicate that the earlier the date at which 200 HU are accumulated, the earlier the timing of flowering. This would imply that the date at which 200 HU are accumulated is a more direct determinant of flowering dates, than the poorly associated heat units accumulated by the time of flowering (*Figures 5.32, 5.33*). A discontinuity for Shiraz is evident between 130 and 135 JD for the accumulation of 200 HU, and a second less extreme discontinuity at 120 days (*Figure 5.36*). However, Kerman has an almost continuous spread of dates for both flowering and the accumulation of 200 HU, with only two discontinuities between 113-117 and 136-138 days (*Figure 5.35*). Similar to Gorgan, these discontinuities in dates at which 200 HU are accumulated suggest brief fluctuations in the rate of temperature accumulation. This results in changes in the rate at which the chilling requirements for the break of dormancy, and heat requirements for floral induction, are fulfilled. It is notable that between these two discontinuities for both Kerman and Shiraz, the greatest variability in flowering dates occurs. The climatic conditions associated with the accumulation of 200 HU between these discontinuities would thus likely result in a greater variation in the timing of the break of dormancy and induction of flowering.

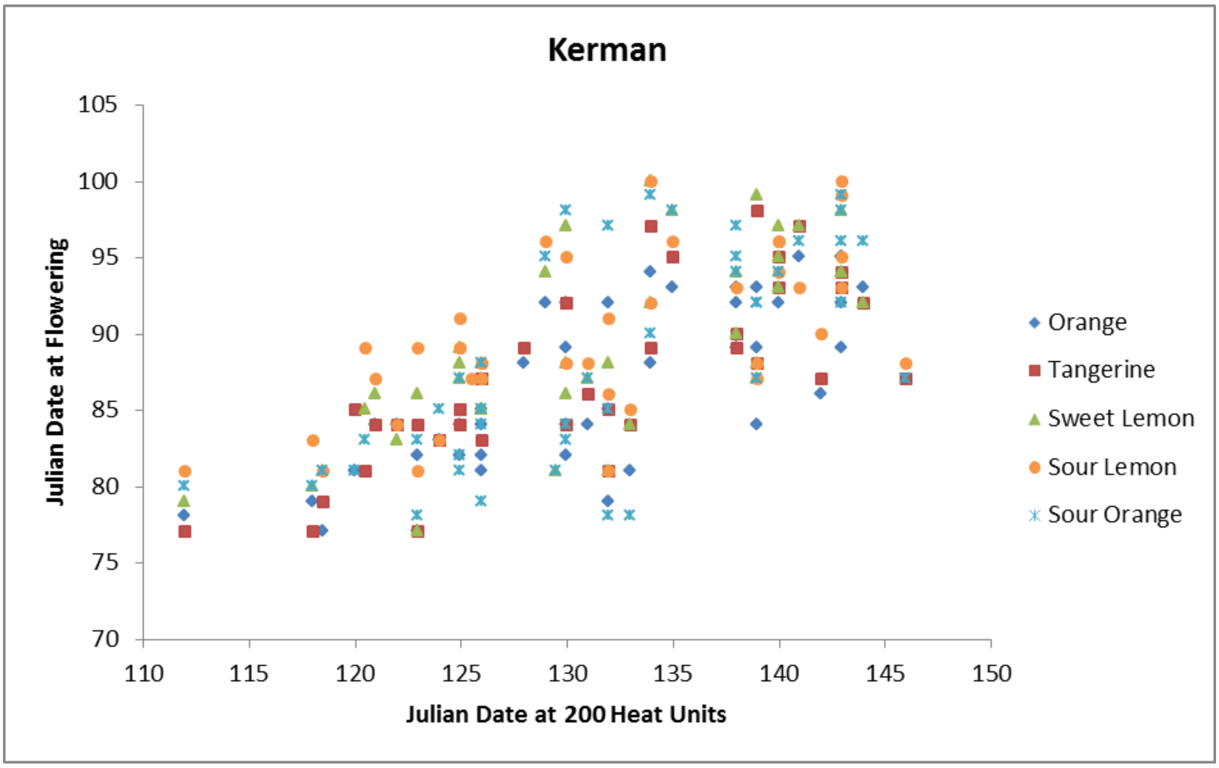

Figure 5.35: Correlation between the JD at which 200 HU are accumulated and the JD at which each of the five citrus types flower for Kerman from 1960-2010.

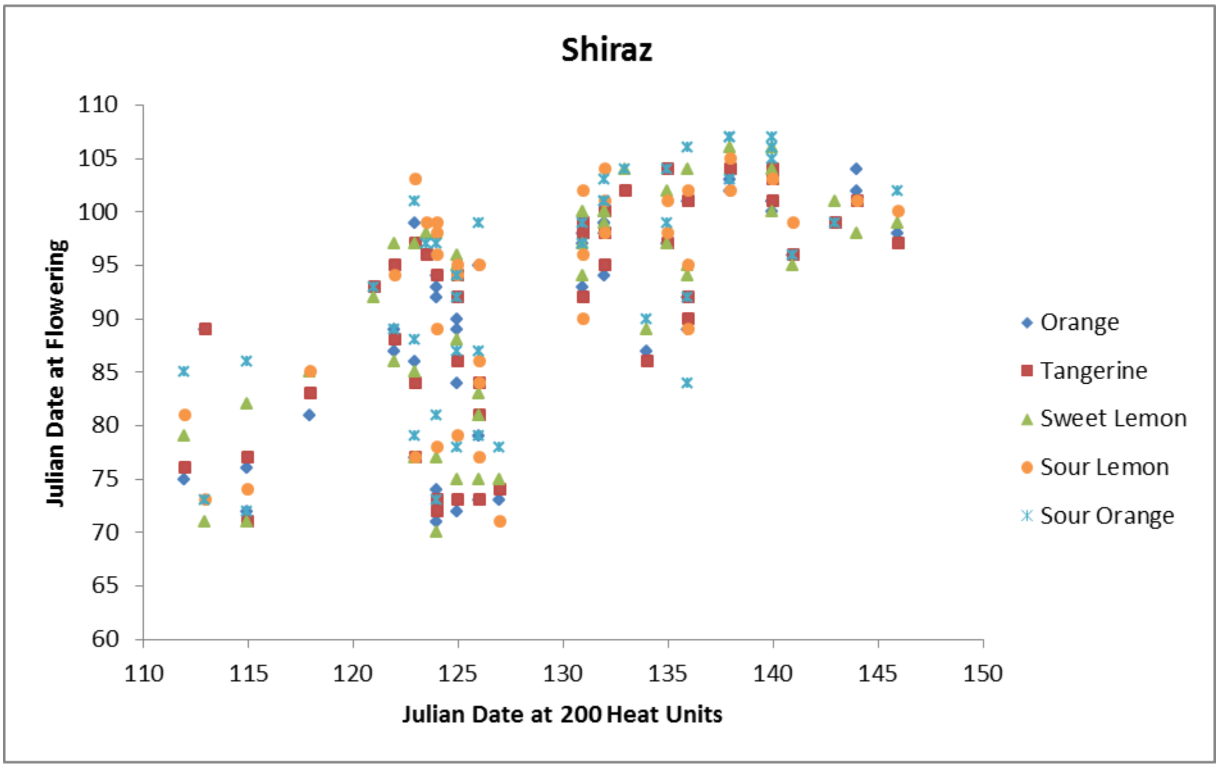

Figure 5.36: Correlation between the JD at which 200 HU are accumulated and the JD at which each of the five citrus types flower for Shiraz from 1960-2010.

This analysis of the relationship between the JD at which 200 HU are accumulated and the JD at which flowering occurs, returns considerably stronger results than the relationships between the flowering date and HU at flowering. Whilst the absolute temperatures at flowering would appear to be a considerably stronger determinant of flowering date than the HU accumulated by the time of flowering, the time required for the accumulation of 200 HU is still relevant. The JD at which 200 HU are accumulated will thus remain in consideration for all three cities in this study as a potential driver of flowering in all citrus types.

As HU are the sum of degrees Celsius temperatures accumulated from daily mean temperatures of 13°C or more, analysis of the relationship between flowering dates and HU at flowering highlights the significant number of cases where flowering occurs before mean daily temperatures exceed 13°C in Kerman and Shiraz (*Figures 5.32, 5.33*). As both Kerman and Shiraz demonstrated statistically significant relationships between flowering dates of the five citrus types and counts of days with T_{min} < 13°, with Kerman further demonstrating significant relationships for the flowering dates of all of the citrus types except for sour lemon with counts of days with T_{max} and T_{min} < 13°C (*Table 5.12*), there is maintained interest in the accumulation of heat above this threshold. These positive relationships between the flowering dates of the five citrus types and days with T_{min} < 13°C presented in *Table 5.12* indicate that an increase in days with temperatures below this threshold delays flowering. The positive relationships between the JD at which 200 HU are accumulated and the JD of flowering for Kerman and Shiraz present a consistent pattern – the earlier the date at which 200 HU are accumulated, the earlier the flowering date. Thus, whilst HU accumulation by flowering is of little relevance, the rate at which warming occurs, and the heat above these threshold temperatures, both of which describe the ambient climate conditions in the time surrounding flowering are of importance. Although the count of days with T_{min} < 13°C and with T_{max} and T_{min} < 13°C is an important driver both in fulfilling the chilling requirements of the flower, and subsequently in delaying the induction of flowering as it prevents sufficient warming, so too are the absolute temperatures and their accumulation above this threshold, as it is a more direct driver of the timing of floral induction and ultimately flowering, both of which require warming.

Table 5.19: Relationships between the flowering date of the five citrus types and the HU at their flowering, and between the flowering date and JD of accumulation of 200 HU for Gorgan, Kerman and Shiraz from 1960-2010. Significant results indicated by an asterisk, correlations stronger than 0.7 indicated by a double asterisk.

Association between JD at flowering and HU at flowering; JD at 200 HU						
	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange	Pooled
Gorgan						
$JD_{flowering}/HU_{flowering}$ (r)	0.04	0.34	0.17	0.32	*0.45	0.05
$JD_{flowering}/JD_{200HU}$ (r)	*0.39	0.16	*0.32	0.19	0.19	0.22
Kerman						
$JD_{flowering}/HU_{flowering}$ (r)	0.23	0.17	0.17	0.19	0.12	0.05
$JD_{flowering}/JD_{200HU}$ (r)	**0.76	**0.75	**0.72	*0.64	**0.70	**0.74
Shiraz						
$JD_{flowering}/HU_{flowering}$ (r)	0.31	0.36	0.39	0.35	0.40	0.26
$JD_{flowering}/JD_{200HU}$ (r)	**0.70	*0.66	*0.69	*0.65	*0.69	**0.70

5.6 Multiple Regression Analysis

Many climate factors demonstrate significant relationships with the flowering dates of the five citrus groups, across the cities of Gorgan, Kerman and Shiraz (summarised in *Table 5.20*). It is likely that these factors are acting in combination to drive both the annual dates of peak flowering, in addition to the observed shifts in flowering dates over the 51-year period. Multiple regression analysis allows for the effects of combinations of driving factors to be studied simultaneously, in this instance to develop a more complete, inclusive model explaining shifts in the timing of peak flowering. As per the methods chapter, three different groups of variables are used as input: i) All variables which demonstrate significant relationships with that particular citrus type in that particular city; ii) the annual average of all significant factors; and iii) a generic set of variables for each city derived from those variables which are common across all citrus types.

Whilst *Stepwise*, *Backward* and *Enter* regression analyses were all undertaken, the *Backward* regression provides the most favourable trade-off between the highest R value and the lowest standard error possible, and hence the lowest potential collinearity. Results of the *Backward* regression are presented together with the results of the *Enter* method to demonstrate changes in model strength where the potential for collinearity is ignored. The outcomes of the *Stepwise* Regression analysis are not presented here, as they ultimately present the same model as the *Backward* regression analysis. In the case of the generic model, all factors are included using the *Enter* method to maintain the generic set of variables. AIC values for all models are presented to allow for the comparison of models including all significant factors, annually averaged factors, and factors generic to the five citrus types across each of the cities, and between the models developed through the *Enter* and *Backward* regression methods.

Table 5.20: Climate variables which demonstrate statistically significant individual relationships with peak flowering for each of the citrus types and in each of the cities.

Individually Significant Factors				LEGEND
	Gorgan	Kerman	Shiraz	
Orange	T_{max} May T_{min} May, Dec *Precipitation* May, Oct T_{max} *>35°C* May T_{min} *<13°C* May T_{max} & T_{min} *<13°C* Dec *Sunshine* **Ann** *200 HU*	T_{max} **Ann**, Mar, Apr, May T_{min} **Ann**, Feb, Mar, Apr, May, Sep *Precipitation* **Ann**, Mar, Apr T_{max} *>35°C* May T_{min} *<13°C* **Ann**, Apr, May, Jul, Sep T_{max} & T_{min} *<13°C* **Ann** *Sunshine* **Ann**, Mar, Apr, May *200HU*	T_{max} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Oct T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sept, Oct, Nov T_{max} *>35°C* **Ann**, Aug T_{min} *<13°C* **Ann**, Apr, May, Jun, Sep, Nov T_{max} & T_{min} *<13°C* Feb *Sunshine* Mar, Apr, Aug *200 HU*	Annual variables Variables for month directly after flowering Variables for month directly preceding flowering Variables for month of flowering Variables for all other months
Tangerine	T_{max} May T_{min} Jan *Precipitation* Dec T_{max} *>35°C* May T_{max} & T_{min} *<13°C* Dec *Sunshine* **Ann**, Feb, Mar *200 HU*	T_{max} **Ann**, Mar, Apr, May T_{min} **Ann**, Mar, Apr, May, Jun, Aug, Sep *Precipitation* **Ann** T_{max} *>35°C* **Ann**, May T_{min} *<13°C* **Ann**, Apr, May, Sep, Oct T_{max} & T_{min} *<13°C* **Ann**, Feb, Mar, Apr, May *Sunshine* Mar, May *200 HU*	T_{max} **Ann**, Feb, Mar, Apr, May, Jul, Oct T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec T_{min} *<13°C* **Ann**, Apr, May, Sep, Nov T_{max} & T_{min} *<13°C* Feb *Sunshine* Apr, May, Aug *200 HU*	
Sweet Lemon	T_{max} May T_{min} May, Jun *Precipitation* Feb, Mar, Sep T_{max} *>35°C* May T_{min} *<13°C* May T_{max} & T_{min} *<13°C* **Ann**, May, Nov, Dec *Sunshine* Feb *200 HU*	T_{max} **Ann**, Mar, Apr, May T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Aug, Sep *Precipitation* **Ann**, Apr T_{max} *>35°C* May T_{min} *<13°C* **Ann**, Apr, May, Jul, Sep, Nov T_{max} & T_{min} *<13°C* **Ann**, Feb *Sunshine* Mar *200 HU*	T_{max} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Oct T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov T_{max} *>35°C* Aug T_{min} *<13°C* **Ann**, Apr, May, Sep, Nov T_{max} & T_{min} *<13°C* Feb *Sunshine* Apr, Aug, Sep *200 HU*	
Sour Lemon	T_{max} May T_{max} *>35°C* May T_{max} & T_{min} *<13°C* May *200 HU*	T_{max} **Ann**, Mar, Apr, May T_{min} **Ann**, Jan, Mar, Apr, May, Jun, Jul, Aug, Sep *Precipitation* **Ann**, Apr, May T_{max} *>35°C* May T_{min} *<13°C* **Ann**, Aug, Sep, Oct T_{max} & T_{min} < 3°C Apr *Sunshine* Mar, May *200 HU*	T_{max} **Ann**, Mar, Apr, May, Jun, Jul, Oct T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct T_{min} *<13°C* **Ann**, Apr, May, Sep, Oct, Nov *Sunshine* Apr, Aug *200 HU*	
Sour Orange	T_{max} May T_{max} *> 35°C* Mar T_{min} *<13°C* Nov T_{max} & T_{min} *<13°C* May *200 HU*	T_{max} **Ann**, Mar, Apr, May, Dec T_{min} **Ann**, Mar, Apr, May, Jun, Jul, Sep *Precipitation* **Ann**, Apr T_{max} >35°C May T_{min} <13°C **Ann**, Mar, Apr, May, Jul, Oct T_{max} & T_{min} *<13°C* **Ann**, Dec *Sunshine* **Ann**, Mar, Apr, May, Dec *200 HU*	T_{max} **Ann**, Mar, Apr, May, Jun, Jul, Aug, Oct T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov T_{max} *>35°C* **Ann**, Aug T_{min} *<13°C* **Ann**, Mar, Apr, May, Sep, Nov *Sunshine* Apr, Sep *200 HU*	
Pooled	T_{max} May T_{min} May *Precipitation* May T_{max} *>35°C* May T_{max} & T_{min} *<13°C* Dec *200 HU*	T_{max} **Ann**, Mar, Apr, May T_{min} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep *Precipitation* **Ann**, Apr T_{max} *>35°C* **Ann**, May T_{min} *<13°C* **Ann**, Mar, Apr, May, Jul, Sep, Nov T_{max} & T_{min} *<13°C* **Ann**, Apr *Sunshine* Mar, May *200 HU*	T_{max} **Ann**, Feb, Mar, Apr, May, Jun, Jul, Aug, Oct T_{min} **Ann**, Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec T_{max} >35°C **Ann**, Aug T_{min} <13°C **Ann**, Apr, May, Jun, Sep, Nov T_{max} & T_{min} <13°C Feb Sunshine Apr, Aug, Sep *200 HU*	

5.6.1 Inclusion of all significant factors

For Gorgan, the inclusion of all significant factors (*Table 5.20*) yields models which explain high percentages of the variation in flowering dates with low standard errors for orange, tangerine and sweet lemon (R^2 = 86.9%, 80.3% and 76% respectively) (*Table 5.21*). Whilst still significant, the models for sour lemon and sour orange have markedly lower explanatory power, with almost doubled values for the standard error. To reduce the standard error only fractionally, significant decreases in the correlation coefficient, and hence the explanatory power of the model, would need to be incurred (*Table 5.21*). The *Backward* regression models for Gorgan result in the elimination of up to four variables, from the original 10-15 variables inputted.

Multiple regression analyses for Kerman demonstrate higher explanatory strength than Gorgan in modelling the shifts in flowering dates for all citrus types, ranging from 75.2% for sweet lemon to 89.5% for both sour lemon and sour orange (*Table 5.21*). Notably, sour lemon and sour orange, which demonstrate the weakest explanatory models for Gorgan, have the strongest models for Kerman, and with the lowest standard error exhibited for sour lemon (*Table 5.21*). This resembles the analysis of the JD at which 200 HU are accumulated and the JD of flowering where sour lemon and sour orange demonstrate poor relationships for Gorgan, but strong relationships for Kerman and Shiraz (*Table 5.19*). Standard error values are also significantly higher than for Gorgan, but through the elimination of statistically unnecessary factors using *Backward* regression, can be reduced to decrease the AIC values without significantly forfeiting model strength (*Table 5.21*).

Table 5.21: Strength and accuracy of multiple regression outputs using both the *Enter* and *Backward* methods for each of the five citrus types in each of the three cities where all significant factors are inputted. Statistically significant models are indicated with an asterisk, models which are able to explain 70% or more of the variation in flowering dates are indicated by a double asterisk.

Multiple regression analysis where all significant factors for each citrus type are inputted					
	R^2	Standard error	Significance (p)	Factors Excluded	AIC values
Gorgan					
Enter Method					
Orange	**0.869	1.214	<0.0001	0	-170.25
Tangerine	**0.803	1.726	< 0.0001	0	-147.15
Sweet lemon	**0.760	2.945	0.015	0	-114.04
Sour lemon	*0.366	4.023	0.003	0	-119.53
Sour orange	*0.399	4.356	0.006	0	-113.47
Pooled	*0.402	3.214	0.001	0	-126.98
Backward Method					
Orange	**0.903	1.042	< 0.0001	3	-180.43
Tangerine	**0.801	1.653	< 0.0001	3	-156.89
Sweet lemon	**0.755	2.697	0.001	4	-127.92
Sour lemon	*0.366	4.023	0.003	0	-119.53
Sour orange	*0.399	4.356	0.006	0	-113.47
Pooled	*0.402	3.178	< 0.0001	2	-131.86
Kerman					
Enter Method					
Orange	**0.856	3.481	0.019	0	-83.76
Tangerine	**0.852	3.455	0.026	0	-74.05
Sweet lemon	**0.752	4.513	0.107	0	-84.73
Sour lemon	**0.895	2.793	0.006	0	-125.02
Sour orange	**0.895	4.278	0.034	0	-55.97
Pooled	**0.782	3.857	0.019	0	-92.36
Backward Method					
Orange	**0.922	2.672	0.001	4	-102.40
Tangerine	**0.874	3.186	0.006	5	-99.43
Sweet lemon	**0.903	2.284	> 0.0001	12	-130.40
Sour lemon	**0.972	1.385	> 0.0001	5	-143.91
Sour orange	**0.943	3.159	0.003	6	-93.86
Pooled	**0.931	2.316	> 0.0001	4	-107.69
Shiraz					
Enter Method					
Orange	**0.960	4.796	0.011	0	-58.80
Tangerine	**0.812	7.921	0.081	0	-44.34
Sweet lemon	**0.933	5.589	0.010	0	-60.27
Sour lemon	**0.869	7.299	0.112	0	-38.05
Sour orange	**0.893	6.488	0.029	0	-40.57
Pooled	**0.859	6.825	0.033	0	-37.05
Backward Method					
Orange	**0.976	3.137	> 0.0001	6	-88.22
Tangerine	**0.859	6.163	0.001	5	-63.78
Sweet lemon	**0.951	4.389	> 0.0001	4	-75.09
Sour lemon	**0.886	5.585	0.001	7	-72.80
Sour orange	**0.893	4.708	> 0.0001	12	-85.51
Pooled	**0.858	5.530	> 0.0001	8	-65.30

The strongest set of explanatory models exist for Shiraz, accounting for at least 80% of the observed variability in flowering dates of each of the five citrus types, with coefficients of determination ranging from 0.812 for tangerine to 0.960 for orange (*Table 5.21*). Whilst standard errors are high, they can likewise be reduced through the elimination of unnecessary factors using *Backward* regression, which results in a decrease in the AIC difference (Δ_i) of between 15 and 45. For both Kerman and Shiraz, the probability of the inclusion of unnecessary factors, and potential resultant collinearity, is heightened due to the large number of input variables. This is because of the stronger individual relationships that exist with peak flowering, in which variables across months demonstrate significant individual results. For both Kerman and Shiraz, the process of *Backward* regression eliminates between four and 13 factors out of the 25-30 factors originally inputted in the *Enter* regression model (*Table 5.21*).

5.6.2 Inclusion of Variables Common to All Citrus Types

To compare the effects of including variables in multiple regression models, factors common to all five citrus groups need to be considered. The first approach is through including only the annual averages of variables, so eliminating the variability between the months which demonstrate significant relationships with different citrus types (*Tables 5.8-5.17*). The second is to include those variables which are common across all five citrus groups for a particular city, here allowing for monthly averages of variables only where they are common across type.

5.6.2.1 Inclusion of Annual Averaged Variables

The substitution of annual averages of variables in place of variables for specific months which demonstrate significant individual relationships with flowering date presents a reduction in the strength of the model across all five citrus types in Gorgan, Kerman and Shiraz (*Tables 5.21, 5.22*). For Gorgan, this decrease in explanatory power is of the magnitude of decreased coefficients of determination between 0.1-0.4, and associated with an increase in the standard error in both the *Enter* and *Backward* regression outputs (*Tables*

5.21, 5.22). The unfavourable difference in AIC values between those models which inputted all of the individually significant variables and those which input only significant annual averages is as much as 30 (*Tables 5.21, 5.22*). *Backward* regression analysis for models inputting annual averages removed up to four of the potential eight variables with little change in the explanatory power of the models, suggesting few annual variables have a significant direct impact on flowering dates (*Table 5.22*). This supports the findings for the individual correlations between flowering dates and annual averages of climate variables (*Tables 5.8, 5.12, 5.16*).

Whilst the substitution of monthly for annual variables for Kerman demonstrates an, albeit smaller, decrease in explanatory power and an increase in the standard error similar to Gorgan, a lower AIC value is calculated, which indicates this as the more accurate predictive model (*Table 5.22*). The result of this substitution decreases the coefficients of determination of up to 0.2, but improve the AIC values with decreases of up to 40 (*Tables 5.21, 5.22*). The less extreme reduction in the coefficient of determination for Kerman, relative to Gorgan, is expected as more months of the year were included in the original analysis, thus more closely reflecting the annual averages. For both Gorgan and Kerman, the weakest model strength is for those explaining changes in the flowering dates of sour lemon and sour orange (*Table 5.22*). Whilst for Gorgan this is similar to models which inputted all individually significant factors, for Kerman it contradicts the comparative strengths of these previous models (*Tables 5.21, 5.22*). The elimination of up to three of the maximum 10 factors through *Backward* regression models for Kerman serves to decrease the standard error in some cases, with minimal impact on explanatory power (*Table 5.22*).

Table 5.22: Multiple regression analysis for the flowering dates of each of the five citrus types for Gorgan, Kerman and Shiraz inputting all annually averaged variables through the *Enter* and *Backward* methods. Significant results are indicated by an asterisk, models which are able to explain at least 70% of the variation in flowering dates indicated by a double asterisk.

Multiple regression analysis where all significant annually averaged variables are inputted					
	R^2	Standard error	Significance (p)	Factors Excluded	AIC value
Gorgan					
Enter Method					
Orange	*0.530	2.280	0.079	0	-140.49
Tangerine	*0.387	2.780	0.153	0	-130.38
Sweet lemon	*0.507	3.814	0.084	0	-114.25
Sour lemon	0.182	4.968	0.836	0	-100.77
Sour orange	0.267	6.188	0.800	0	-89.57
Pooled	0.285	3.392	0.468	0	-120.23
Backward Method					
Orange	*0.530	2.280	0.079	0	-140.49
Tangerine	*0.436	2.582	0.017	3	-140.15
Sweet lemon	*0.504	3.524	0.010	3	-124.28
Sour lemon	0.220	4.657	0.618	2	-108.07
Sour orange	0.265	5.365	0.155	4	-104.85
Pooled	0.281	3.172	0.090	3	-129.65
Kerman					
Enter Method					
Orange	**0.723	3.241	> 0.0001	0	-122.55
Tangerine	**0.734	3.262	> 0.0001	0	-122.22
Sweet lemon	*0.651	4.001	> 0.0001	0	-111.81
Sour lemon	*0.623	3.690	> 0.0001	0	-115.94
Sour orange	*0.587	5.000	> 0.0001	0	-100.44
Pooled	*0.668	3.519	> 0.0001	0	-118.36
Backward Method					
Orange	**0.719	3.124	> 0.0001	3	-130.43
Tangerine	**0.731	3.137	> 0.0001	3	-130.22
Sweet lemon	*0.650	3.885	> 0.0001	2	-117.31
Sour lemon	*0.618	3.539	> 0.0001	3	-124.07
Sour orange	*0.585	4.797	>0.0001	3	-108.56
Pooled	*0.664	3.451	> 0.0001	2	-123.35
Shiraz					
Enter Method					
Orange	*0.668	6.980	> 0.0001	0	-83.43
Tangerine	**0.748	6.026	> 0.0001	0	-90.92
Sweet lemon	**0.735	6.369	> 0.0001	0	-88.10
Sour lemon	*0.612	7.566	0.003	0	-79.32
Sour orange	*0.650	7.023	> 0.0001	0	-83.11
Pooled	*0.658	6.562	> 0.0001	0	-86.58
Backward Method					
Orange	*0.664	6.783	> 0.0001	2	-88.89
Tangerine	**0.748	6.026	> 0.0001	0	-90.92
Sweet lemon	**0.733	6.261	> 0.0001	1	-90.97
Sour lemon	*0.608	7.266	> 0.0001	2	-85.38
Sour orange	*0.648	6.797	> 0.0001	2	-88.78
Pooled	*0.650	6.449	> 0.0001	2	-91.46

The substitution of annual values for Shiraz results in a considerable decrease in the coefficients of determination (up to 0.3) and hence the explanatory power of the models, together with an increase in the standard error (up to 3) (*Tables 5.21, 5.22*). The elimination of up to three variables, where possible through *Backward* regression, does not significantly decrease the standard error (*Table 5.22*). However, AIC values for those models inputting annually averaged variables are considerably lower than those for the models inputting monthly significant variables, indicating a more accurate attribution of cause for the variability in flowering dates over the study period (*Tables 5.21, 5.22*). Again, the weakest explanatory strength is for sour lemon and sour orange, suggesting a consistent response between citrus types across the three cities. However, the decreases in explanatory power and increases in standard errors make these generic models unsuitable in representing the driving factors of these changes in flowering dates in Shiraz (*Tables 5.21, 5.22*).

5.6.2.2 Inclusion of Variables Common to All Citrus Types

Substituting variables that have significant relationships common to all five citrus types yields significantly stronger coefficients of determination than the models with annually averaged variables for Gorgan, Kerman and Shiraz (*Tables 5.22, 5.23*). Although not as strong as those models including the factors significant to each individual citrus type, these models differ from the former by as little as 1% (*Tables 5.21, 5.23*). For Gorgan the inclusion of these generic factors demonstrates the weakest explanatory power for sour lemon and sour orange, with the strongest correlation for orange (*Table 5.23*). Whilst for the most part slightly higher, the standard errors are not limiting, with AIC values relatively similar to those for the first set of models (*Tables 5.21, 5.23*). Similarly for Kerman, the decreases in explanatory power and increase in standard error are not limiting, and are associated with very similar AIC values to those models which include all of the variables that demonstrate significant relationships with the flowering dates of each citrus type (*Tables 5.21, 5.23*). Notably, for the first multiple regression models for Kerman, the strongest coefficients of determination are for sour lemon and sour orange (R^2 = 89.5% for both using the *Enter* method, 97.2% and 94.3% respectively using the *Backward* method) (*Table 5.20*), but in both the generic and annual models, tangerine demonstrates the greatest model strength (R^2 = 73.1% for both *Enter* and *Backward* annual models, R^2 = 84.1% for the generic model)

(*Tables 5.21, 5.22*). Sour lemon remains the second strongest model (*Table 5.23*). For Shiraz, the decreases in the explanatory power of the models are non-limiting, yet the increases in the standard error are of concern, and result in higher AIC values than for the annual models and the models inputting all significant factors developed through the *Backward* regression method (*Table 5.21, 5.23*).

Table 5.23: Multiple regression analysis for the flowering dates of each of the five citrus types for Gorgan, Kerman and Shiraz, including all variables that are generic to all types in each city through the *Enter* and *Backward* regression methods. Significant results are indicated with an asterisk, models which explain at least 70% of the variability in flowering dates indicated by a double asterisk.

Multiple regression analysis where all variables generic to the five citrus types are included					
	R^2	Standard error	Significance (p)	Factors Excluded	AIC values
Gorgan					
Enter Method					
Orange	**0.859	1.254	> 0.0001	0	-168.98
Tangerine	**0.735	1.947	0.001	0	-146.54
Sweet lemon	**0.753	2.708	0.001	0	-129.72
Sour lemon	*0.399	4.387	0.459	0	-105.11
Sour orange	*0.417	5.765	0.573	0	-91.18
Pooled	*0.621	2.476	0.008	0	-134.28
Kerman					
Enter Method					
Orange	**0.808	3.373	0.003	0	-100.52
Tangerine	**0.841	3.190	0.005	0	-103.36
Sweet lemon	**0.767	4.159	0.040	0	-89.83
Sour lemon	**0.823	3.205	0.009	0	-103.12
Sour orange	**0.806	4.471	0.009	0	-86.15
Pooled	**0.757	3.572	0.002	0	-97.59
Shiraz					
Enter Method					
Orange	**0.863	6.256	0.005	0	-61.01
Tangerine	**0.798	7.636	0.040	0	-50.85
Sweet lemon	**0.790	8.008	0.048	0	-48.42
Sour lemon	**0.729	9.883	0.465	0	-37.69
Sour orange	**0.854	6.235	0.004	0	-61.18
Pooled	**0.771	6.845	0.005	0	-56.42

5.6.3 Comparison of Model Properties for Citrus Types and Cities

The relative explanatory strength of each of the models for the three cities and five citrus types has been presented, but no analysis has been made as to those variables which were included in the *Backward* regression models, nor the similarities between those variables for the different cities and citrus types. As this study aims to investigate the effect that climate variables have on the timing of flowering, this is essential. The complete *Enter* and *Backward* regression models developed for this study using each of the groups of input variables are presented in *Appendix 1.* Information on those variables included in these models and the direction of their influence within the *Backward* regression models is presented in *Table 5.24*. These models, in which all individually significant variables are inputted, present both the highest explanatory power and accuracy, but also are the most location and species specific and hence most relevant to a phenological study.

Notable are the considerable differences between the factors included and the direction of their influence not only between cities, but also between citrus types. Some of the difference in the factors included in the *Backward* regression models can be expected from the differences in the input variables. However, there is considerable difference in the factors which were excluded through *Backward* regression analysis, and hence the final models present various groups of climate variables which are largely unique to each citrus type and each city (*Table 5.20*). For example, in Gorgan, T_{min} variables for at least one month are inputted into the multiple regression models for orange, tangerine and sweet lemon, yet in the final models, only the model for tangerine includes a T_{min} variable (*Tables 5.20, 5.24*). The differences in the input variables alone indicate considerable differences between the climate factors which drive the timing and shifts in the timing of flowering dates of each of the five citrus types both within and between the three cities. The differences between the driving forces for flowering dates between the three cities are to be expected, given both the differences in the shifts in flowering dates in each of the cities over the study period, and their geographic and climatic differences. However, as the flowering dates of the five citrus types in each of the cities occur at very similar times, and demonstrate equivalent rates in their shifts over time, it would be expected that they would have the same or very similar sets of driving forces.

Table 5.24: Direction of variables present in the multiple regression models developed using the *Backward* method, inputting those variables which demonstrate individual significant relationships with the flowering dates of each citrus type and in each city. Signs are listed in order of months which they represent.

Backward regression model inputting all individually significant factors

	T_{max}	T_{min}	Precipitation	Sunshine hours	T_{max} > 35°C	T_{min} < 13°C	T_{max} & T_{min} < 13°C	200 HU
GORGAN								
Orange	-		+	-/+	+	+	+	-
Tangerine	-	+	-	-/+/ -	+			-
Sweet Lemon	-		+/+/-	+	-	-	+/+	+
Sour Lemon	-				-		+	+
Sour Orange	-				+	+	+	+
KERMAN								
Orange	-/+/+	-/+/-/-/-/-/+	-/+/+	+/+/+/-	-	+/-/+/-		+
Tangerine	+/+/+	-/-/-/-/+		-/-/+	-/-	+/+/-/-	+/-	+
Sweet Lemon	-/+	-/-/-/-/-/-/-/+	+		-	+		
Sour Lemon	-/-/+	-/+/-/-/-/+/-	+/-/+	+/-	+	+/-		-
Sour Orange	-/+/-/-/+	-/-/-/-	+/+	+/-	-	+/+/-/+/-/-	-/+	-
SHIRAZ								
Orange	+/-/+/+/+/-/-/-	-/+/-/+/-/+/+/-		+/-/-	+	-/-/-/-	+	+
Tangerine	-/-/+	+/+/+/+/+/+/+/+/+		+/-/-		-/-/-/+/-	+	+
Sweet Lemon	+/+/+/-/+	+/+/+/+/+/+/+/+/+/+			+	-/-/-/+/-	+/+/-/-	+
Sour Lemon	-/+/+/-/+/+	+/+/+/+/+/+		-/-		+/+/-/-/-		+
Sour Orange	+/+/-	+/+/+/+/+/+		-/-	+	+/-/+/-/-		+

Legend:
Annual variables
Variables for month directly preceding flowering
Variables for all other months
Variables for month directly after flowering
Variables for month of flowering

Consistency in the direction of response of driving forces across citrus types is only exhibited for T_{max} in Gorgan (negative) and 200 HU in Shiraz (positive) (*Table 5.24*). For Shiraz, orange, sweet lemon and sour orange include a positive impact of T_{max} > 35°C in their models, and with the exception of orange, all citrus types are impacted positively by T_{min} (*Table 5.24*). Whilst the models for sour lemon and sour orange in Shiraz contain the same number of terms for the months before and after flowering and those of the remainder of the year, the months of these variables differ. Furthermore, the development of these models using *Backward* regression result in models for Gorgan which include very few variables. Whilst few variables demonstrate individually significant relationships with flowering dates in Gorgan, this further emphasizes the differences in phenological response for Gorgan in comparison to Kerman and Shiraz. Despite there being very few variables remaining in the models for Gorgan, they differ considerably between citrus types. It thus appears that whilst there is considerable similarity in the timing and shifts in timing of flowering of each of the five citrus types within the three cities, this is occurring largely through each citrus type having a unique set of driving climate factors which induce, and control the timing of, flowering. However, when analysing the driving forces of each of the citrus types in each of the cities, there is considerably less similarity. This suggests differences in the adaptation strategies of each of the citrus types to the climate conditions of each of the cities through selective breeding, in order to facilitate flowering at a time which ensures the most productive fruit yield. These differences in the driving climatic factors and their direction highlight genetic differences in the five citrus types, in addition to potential extremes of morphological and behavioural plasticity emerging from this selective breeding, which until now, have been largely overlooked in this study.

Despite the considerable differences in the variables which comprise the multiple regression models and the direction of their influence, there is similarity in the months that these variables are effective. Across all citrus types in Gorgan and Kerman, most of the variables are for the month of flowering, those directly preceding or following flowering, or the annual average (*Table 5.24*). For Gorgan, these four groups of time periods account for 50-100% of the variables included in models for each citrus type, comprising 75% of the variables for orange and 100% of the variables for sour lemon (*Table 5.24*). In Kerman, with a far greater number of variables included in each of the models, those covering the four time periods account for between 62-86% of the variables (*Table 5.24*). Shiraz, by contrast, has models which include a greater percentage of variables for months not associated with flowering. Variables for flowering associated months for Shiraz range from between 36-59%, with less than half the variables falling within the four groups for tangerine and sweet lemon (*Table 5.24*). This would imply that the timing and shifts in the timing of flowering for Gorgan and Kerman are best modelled by a large collection of climate variables that act on the flower during the flowering period, and as a consequence would act directly on flowering mechanisms such as the break from dormancy and induction of flowering. By contrast, the timing and shifts in timing of flowering in Shiraz are best modelled by climate factors that act throughout the year, with equal to greater proportions of variables for months outside of the flowering period. This would suggest a less direct driving force, with these factors rather driving plant phenological phases such as root and vegetative growth, and the onset of dormancy, all of which indirectly drive flowering dates. Notable is that in many cases for Shiraz, variables for the months directly preceding and following flowering are included in the model, but not the month of flowering, which would support such a hypothesis.

Whilst some predictive strength and accuracy of the regression models is lost when substituting factors that demonstrate statistically significant independent relationships with the flowering dates of each of the citrus types in each of the cities with the generic variables, the statistical significance of these generic models suggests that these variables too, may be important. The generic models for each city are more similar to what was expected, considering the similarity of and shifts in flowering dates for each of the citrus types within each city, and the locational differences in climate, particularly if climate is to drive these changes. For the purpose of adaptation to continued climate variability and change, such generic models allow for an improved understanding of the broad-scale effects that changes in those climate variables are likely to have on this group of citrus species in Iran, although their value can extend to varieties not studied here. Further, these models highlight the importance of studying the flowering dates within each of the cities, as the differences in models reflect the impact of the regional climatic conditions However, the initial set of multiple regression analyses containing all individually significant factors provide higher resolution information for each citrus type in each city, which is of value in selecting between citrus types for planting to maintain successful citrus yields in future years.

5.6.4 Multivariate Multiple Regression Analysis

Where there is a set of factors that are significantly related to the various dependant variables, such as for the annually significant and generically significant variables highlighted for each city in this study, it is possible to perform a multivariate multiple regression analysis in which all dependant variables are placed into one model with each of the generic independent variables. For this study, this involves including each of the five citrus types into a model for each city using a city-specific set of generic independent variables. Both the annually averaged independent variables and the month-specific variables which formed the generic model per citrus type are potential candidates for a multivariate multiple regression model for each city. Provided there is sufficient correlation between the flowering dates for each citrus type, their simultaneous analysis would theoretically strengthen the percentage explanation of the variability of the flowering dates of each of the five citrus types, and hence improve both the strength and accuracy of the model.

It is thus necessary to first determine whether there are any significant relationships in flowering dates between the various citrus types for each city. As could expected, given both the common location and genetic similarities of the citrus type, as well as their similarities in time trends for each of the cities (*Figures 5.2, 5.4, 5.6*), the relationships between all five citrus types in all three cities are statistically significant (*Table 5.25*). Flowering dates are most similar between the five citrus types for Kerman and Shiraz, with Gorgan demonstrating relatively weak associations between the flowering dates of sour orange and orange, and sour orange and tangerine (*Table 5.25*). There is no pair of citrus types that consistently exhibits either the highest or lowest correlations of all possible pairs, with the relative strengths of the correlations of the various combinations of citrus types being location dependant (*Table 5.25*). With significant relationships for all pair-wise combinations (*Table 5.25*), the development of multivariate multiple regression matrix models is justified.

Table 5.25: Cross-correlation between the flowering dates of each of the five citrus types for Gorgan, Kerman and Shiraz from 1960-2010. Significant results indicated by an asterisk, correlations with r > 0.7 indicated by a double asterisk.

	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange
Orange	1				
Tangerine	**0.79	1			
Sweet lemon	**0.79	**0.79	1		
Sour lemon	*0.67	**0.73	**0.86	1	
Sour orange	*0.61	*0.60	*0.66	**0.92	1

	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange
Orange	1				
Tangerine	**0.95	1			
Sweet lemon	**0.93	**0.97	1		
Sour lemon	**0.87	**0.92	**0.97	1	
Sour orange	**0.97	**0.91	**0.89	**0.83	1

	Orange	Tangerine	Sweet lemon	Sour lemon	Sour orange
Orange	1				
Tangerine	**0.99	1			
Sweet lemon	**0.92	**0.94	1		
Sour lemon	**0.87	**0.88	**0.92	1	
Sour orange	**0.90	**0.90	**0.95	**0.90	1

5.6.4.1 Multivariate Multiple Regression Model with Citrus Type Generic Variables

The development of a multivariate multiple regression model using the generic variables is only possible for Gorgan, as for Kerman and Shiraz there are too many independent variables (*Tables 5.20, 5.24*) to allow for a robust model in which there are sufficient degrees of freedom. The multivariate multiple regression model developed for Gorgan demonstrates a substantially higher percentage explanatory power for the flowering dates of each of the five citrus types than the individual multiple regression models for each citrus type developed using the same set of generic variables. For this multivariate multiple regression model, coefficients of determination range from R^2 = 0.770 for sour orange to R^2 = 0.990 for tangerine, whereas the independent multiple regression models demonstrate a range from R^2 = 0.399 to R^2 = 0.859 (*Tables 5.23, 5.26*). Standard errors are slightly higher for the multivariate multiple regression model than for the univariate models, suggesting a slight loss in model accuracy (*Tables 5.23, 5.26*). Notable, however, are the considerably higher AIC values, and the lack of statistical significance of the multivariate models (*Table*

5.23, 5.26). This is because the multivariate multiple regression models can only include observations (in the case of this study 'years') for which data are complete across all dependant and independent variables. Hence, whilst 51 observations are inputted into the model, only 12 are used in developing the final model. By contrast, the univariate multiple regression model using citrus type generic variables is statistically significant as the majority of the 51 observations are used in each case. Whilst the improved predictive strength of the multivariate multiple regression model is appealing in providing a better understanding of the role of climate factors in shifts in flowering dates, a model which is not statistically significant cannot be used legitimately. Furthermore, considering the species specificity of phenological responses to climate variability and change reported in the literature (*Table 2.1*), and the variability in which citrus type demonstrates the strongest relationships with each of the climate variables for each city, multiple regression models for each of the citrus types using only those climate variables which are most significantly related to the flowering dates are of greater use in understanding the phenological response to climate variability and change.

Table 5.26: Strength, accuracy and significance of the multivariate multiple regression model developed for the independent variables which are generic to the five citrus types for Gorgan.

Multivariate Multiple Regression Model GORGAN GENERIC					
	R^2	Standard Error	Significance (p)	Variables	AIC values
Orange	0.957	1.560	0.180	9	-6.48
Tangerine	0.990	1.032	0.046	9	-11.44
Sweet lemon	0.890	3.898	0.408	9	4.51
Sour lemon	0.768	5.587	0.696	9	8.83
Sour orange	0.770	7.155	0.692	9	11.80

Although of little value on its own, the multivariate multiple regression output highlights notable relationships between climate and flowering dates, particularly when compared with the univariate multiple regression models. The multivariate multiple regression analyses confirm the differences in the direction of the effect of climate variables on the flowering dates of each of the five citrus types (*Figure 5.37*). Despite providing further information on the behaviour of the variables, and the changes in the magnitude of many of the coefficients of the independent variables, the differences in the direction of drivers between citrus types is consistent with the univariate multiple regression models. This further confirms a more intricate relationship between the climate variables and the flowering dates of each of the citrus types, despite their similarities in flowering dates across the study period. This suggests differences in the adaptation of each of the citrus types to the local climate, resulting in flowering within a narrow period of favourable conditions. Although flowering times for each citrus type are variously impacted by the climate variables, the net outcome is flowering over a very similar period across types. This citrus type-specific adaptation is concerning, as a shift in one of these climate variables at a faster rate than the remaining climate variables could disrupt the equilibrium and flowering.

$$
\begin{aligned}
y\begin{bmatrix} orange \\ tangerine \\ sweet\ lemon \\ sour\ lemon \\ sour\ orange \end{bmatrix} &= \begin{bmatrix} -1.611 \\ -4.217 \\ -2.982 \\ -3.948 \\ -3.693 \end{bmatrix} T_{max}(May) + \begin{bmatrix} 2.563 \\ -1.668 \\ 0.078 \\ 5.930 \\ 18.212 \end{bmatrix} T_{min}(May) + \begin{bmatrix} 0.010 \\ -0.113 \\ 0.034 \\ -0.031 \\ 0.001 \end{bmatrix} Precip(May) \\
&+ \begin{bmatrix} -0.019 \\ 0.025 \\ 0.026 \\ 0.003 \\ 0.043 \end{bmatrix} Sun(May) + \begin{bmatrix} 0.665 \\ 0.396 \\ 0.553 \\ 1.688 \\ 2.629 \end{bmatrix} T_{max} > 35°C(May) + \begin{bmatrix} 0.947 \\ -1.469 \\ 0.105 \\ 1.095 \\ 4.139 \end{bmatrix} T_{min} < 13°C(May) \\
&+ \begin{bmatrix} 0.480 \\ -1.273 \\ -0.357 \\ 2.393 \\ 6.337 \end{bmatrix} T_{max}\&T_{min} < 13°C(May) + \begin{bmatrix} 0.080 \\ 0.276 \\ -0.151 \\ 0.062 \\ 0.357 \end{bmatrix} T_{max}\&T_{min} < 13°C(Dec) + \begin{bmatrix} -0.085 \\ 0.240 \\ 0.050 \\ 0.066 \\ 0.043 \end{bmatrix} 200HU \\
&+ \begin{bmatrix} 144.845 \\ 242.863 \\ 199.301 \\ 132.379 \\ -57.474 \end{bmatrix}
\end{aligned}
$$

Figure 5.37: Multivariate multiple regression model for Gorgan with the inclusion of variables which generically demonstrate significant individual relationships with all five citrus types.

5.6.4.2 Multivariate Multiple Regression Model with Annual Climate Variables

Whilst multivariate multiple regression models using all variables which are generic to all citrus types could not be developed for all three cities, models using the annual averages of variables for each city were. Similar to the multivariate multiple regression model for Gorgan using generic variables, the models for all three cities using annually averaged variables demonstrate substantially higher coefficients of variation, and hence predictive strength, than the univariate multiple regression models with the same input (using the *Enter* method) (*Tables 5.22, 5.27*). This supports the premise that by drawing on the similarities in the behaviour of the flowering dates of the individual citrus types, a multivariate model can better explain their simultaneous responses to the independent climate variables to which they are all exposed.

Table 5.27: Strength, accuracy and significance of the multivariate multiple regression models developed for the annual averages of independent variables which are generic to the five citrus types for Gorgan, Kerman and Shiraz respectively. Statistically significant models indicated by means of an asterisk.

Multivariate Multiple Regression Models (Annual Variables)					
	R^2	Standard Error	Significance (p)	Variables	AIC values
Gorgan					
Orange	0.802	2.724	0.399	8	0.21
Tangerine	0.681	4.685	0.645	8	6.71
Sweet lemon	0.860	3.599	0.267	8	3.55
Sour lemon	0.821	4.009	0.358	8	4.84
Sour orange	0.887	4.096	0.203	8	5.10
Kerman					
Orange	*0.827	3.021	0.0027	8	-19.80
Tangerine	*0.900	2.462	0.0002	8	-23.90
Sweet lemon	*0.908	2.569	0.0001	8	-23.04
Sour lemon	*0.732	4.804	0.0229	8	-10.53
Sour orange	*0.850	2.886	0.0014	8	-20.72
Shiraz					
Orange	*0.953	3.184	< 0.0001	8	-18.75
Tangerine	*0.960	3.007	< 0.0001	8	-19.90
Sweet lemon	*0.972	2.654	< 0.0001	8	-22.39
Sour lemon	*0.902	4.557	0.0002	8	-11.58
Sour orange	*0.927	3.987	< 0.0001	8	-14.25

Similar to the multivariate multiple regression model for Gorgan using the generic independent variables, for the models with annually averaged variables the AIC values are considerably higher (*Tables 5.22, 5.27*). This is again due to the small proportion of input-years for which data are complete across all dependant and independent variables, with only 12 years for Gorgan and 20 for Kerman and Shiraz. For Gorgan, this is associated with *p values* too high to yield the model statistically significant, and thus the univariate models for each citrus type using the annually averaged variables should be favoured over this multivariate multiple regression model, despite its stronger explanatory power (*Table 5.27*). However for Kerman and Shiraz in particular, there are sufficient observations to allow for a low enough *p value* for the model to be deemed significant (*Table 5.27*). Whilst the higher AIC values calculated for the multivariate multiple regression models in comparison to those univariate multiple regression models would suggest a preference for the univariate models for each of the citrus types and the annual averages of independent variables in these cities, final model selection must be made on the basis of useability, which given the high explanatory power and depending on the application, may favour this model.

5.7 Key Findings

The mean flowering dates of the five citrus types for the period 1960-2010 are considerably more consistent within each city, than for each citrus type across the three cities of Gorgan, Kerman and Shiraz. Flowering in Gorgan, occurs relatively late in the year with mean flowering dates ranging from 12-16th May. The earliest flowering occurs in Kerman, with mean flowering dates for the five citrus types ranging from 23-31 March. The timing of flowering in Shiraz is more similar to that of Kerman than Gorgan, ranging from 31 March to 03 April. Over the study period, trends in the timing of flowering have differed in direction between late flowering Gorgan and early flowering Kerman and Shiraz. For Gorgan, there is an increasing delay in flowering dates over the 51 year period, with a magnitude of 0.05-0.1d/yr. In Kerman and Shiraz, there has been an advance in flowering dates, with a particularly high rate of change for Shiraz at 0.56-0.6d/yr, and a moderate 0.12-0.17d/yr shift for Kerman. The trends in flowering dates for Kerman and Shiraz are significant across all five citrus types studied, whereas the trends for Gorgan are statistically significant for only orange and tangerine.

There are distinct climatic differences between humid Gorgan, and the more arid cities of Kerman and Shiraz, which are highlighted by mean climatic conditions over the period 1960-2010. Gorgan, which is located in close proximity to the warm Caspian Sea, has the highest mean precipitation, together with the lowest T_{max} and highest T_{min} of the three cities. Kerman, located in the central Iranian Plateau, has the lowest mean precipitation, and the lowest mean $T_{min.}$ Shiraz has a more moderate climate than Kerman, with precipitation and T_{min} values between those of Kerman and Gorgan, but the highest T_{max} of the three cities.

Simultaneous with the flowering date trends of differing directions, are trends in annually averaged climate variables which demonstrate distinct differences between Gorgan and the inland cities of Kerman and Shiraz. Gorgan demonstrates a significant trend of decreased precipitation, but no statistically significant trends in T_{max} or T_{min}. By contrast, Kerman and Shiraz demonstrate significant trends toward increases in both T_{max} and $T_{min,}$ with particularly strong trends for T_{min}, but no significant trends for precipitation. Trends of decreases in annual counts of days with T_{min} < 13° are significant for Kerman and Shiraz, but not for Gorgan. Trends towards increases in the annual number of sunshine hours are significant for Gorgan and weaker for Kerman, but not for Shiraz. These contrasts in the changes in climate variables observed for Kerman and Shiraz compared to those for Gorgan, with differences in concurrent shifts in flowering dates for these cities imply that the changes in climate that occurred over the period 1960-2010 are likely to have driven these flowering date changes.

Analysing the nature of any such relationships between climate variables and flowering dates for each of the citrus types in each of the cities over the period 1960-2010 through individual correlation and regression methods endorses this hypothesis. Kerman demonstrates statistically significant relationships between the flowering dates of the five citrus types and annual mean T_{max}, T_{min}, and precipitation, which equate to advances in flowering dates of 1.85-3.08d/°C (T_{max} increase), 3.15-3.93d/°C (T_{min} increase) and 0.03-0.06d/mm (precipitation decrease). Shiraz demonstrates significant relationships between flowering dates of all citrus types and T_{max} and T_{min} which equate to advances in flowering dates of 6.14-7.86d/°C (T_{max} increase) and 4.34-5.47 (T_{min} increase), but not precipitation. Gorgan, which has the weakest flowering date time-trends for 1960-2010, demonstrates no statistically significant relationships with mean annual climate variables. Gorgan does however demonstrate significant relationships between flowering dates and annual sunshine hours for orange and tangerine, whilst Kerman has significant relationships between sunshine hours and the timing of orange and sour orange flowering. There are no significant relationships between annual sunshine hours and the flowering dates of any of the citrus types for Shiraz. Annual counts of days with T_{min} < 13°C have significant relationships with all of the citrus types for Kerman and Shiraz, but not for Gorgan. The date at which 200 HU are accumulated is significantly related with all flowering dates for Kerman and Shiraz, but not with flowering dates for Gorgan.

An analysis of the relationships between mean monthly climate variables and flowering dates highlights significant relationships with many of the climate variables, for all three cities. The notable exception is monthly precipitation, for which there are no significant relationships with the flowering dates of any of the five citrus types in any month for Shiraz. For Gorgan, the majority of the significant relationships between flowering dates and monthly climate variables are for May, the month in which flowering occurs. For Kerman, significant relationships are found for a broader group of months from March to May, but again include the period in which flowering occurs. The broadest group of significant monthly relationships are for Shiraz, in which the majority of climate variables demonstrate significant relationships with flowering variables for the months of February to November, and with the strongest relationships found for April, coinciding with peak flowering. Within these broad observations for the three cities are additional months across the year for which significant relationships between a monthly climate variable and the flowering date of one citrus type are demonstrated. This highlights differences between the responses of citrus types within a particular city, despite their similar mean flowering dates and trends.

The development of multiple regression models through both manual input variable selection and their step-wise elimination through *Backward* regression, further indicates subtle differences in the factors that drive the flowering dates of each of the citrus types, both within, and between the three cities. Whilst there remains greater similarity in the input variables, and their direction of influence, across the five citrus types within each city, than between them, there is considerable variability in each of the individual models. Despite their differences, the multiple regression equations are able to model the similar flowering dates statistically significantly, and with relatively high accuracy. Furthermore, for Kerman and Shiraz, the models for the flowering dates of each of the five citrus types have largely similar explanatory power. The high explanatory power of these multiple regression models statistically confirms the hypothesis that these flowering dates, and their shifts over the study period, are driven predominantly by climate rather than intrinsic factors.

Chapter 6

DISCUSSION

[6]

6.1 Introduction

The primary aim of this study is to determine the response of citrus flowering dates in the three Iranian cities of Gorgan, Kerman and Shiraz to increasing climate variability and ongoing climate change over the 51-year period of 1960-2010. In so doing, it contributes to the existing body of scientific research on phenological responses to climate change. This discussion critically analyses the results obtained in this study in comparison to results reported from other studies on the response of deciduous fruit tree flowering dates to climate variables. This is followed by a critical assessment of the multivariate models. The extent to which these models, which extend the single variable comparisons used in the majority of phenology studies, are able to improve the explanatory potential and hence the understanding of the drivers responsible for shifts in the timing of flowering is enhanced.

The second section of this discussion explores the likely implications of the identified relationships for the timing of flowering of these citrus types, together with the resultant success of flowering and ultimately crop yields in Iran. Hypotheses of potential future shifts in citrus flowering dates for the 21st century, calculated from both the trends in climate variables over the past 51 years, and downscaled GCM projections for the next century, are presented for Iran.

The final section of this chapter discusses the various limitations in this study, from data collection and language translation, through to statistical restrictions. It further suggests additional causal factors which could not quantitatively be assessed in this study, but which are very likely to have contributed to the observed shifts in flowering dates over the period.

6.2 Analysis of Results

6.2.1 Trends in Flowering Dates

Whilst the flowering dates for the three cities in Iran vary considerably from late March to early May, these are not unusual for citrus phenology (Meier, 2001; Connelan et al., 2010). The considerably greater difference in the timing of flowering between the cities rather than between citrus types, together with the distinct climatic conditions of each of the cities, is an indication that the timing of citrus flowering in this study is driven by environmental rather than intrinsic cues (Tan & Swain, 2006; Connellan et al., 2010). Any shift in flowering dates over a defined period would suggest that there has been some change in those factors responsible for cueing flowering. Given the location-specific mean flowering dates observed in this study, it is likely that an environmental cue is primarily driving flowering of the five citrus types, and hence an environmental cue which has been changing over the 51-year study period.

Of particular interest is the contrasting direction of flowering date shifts for the different Iranian cities over the period 1960-2010. Whilst flowering dates advance for all citrus types in Kerman and Shiraz, flowering dates of the five citrus types in Gorgan are increasingly delayed over the 51 year study period (*Figures 5.2, 5.4, 5.6*). The shifts to earlier flowering dates in Kerman and Shiraz are consistent with the majority of published phenology studies. A global mean advance in spring events across 1700 species by 2.3 days per decade is reported by Parmesan and Yohe (2003); for Japan, Miller-Rushing et al. (2007) report a shift in cherry flowering to earlier in the year; Guédon and Legave (2008) report advances in the date of apple and pear flowering in France and Switzerland of six to eight days for the period 1976-2002; and Nordli et al. (2008) report increasingly earlier budburst for 20 species of fruit trees at four sites in Norway for the period 1971-2005. These trends towards earlier flowering dates mark a shift in the beginning of spring to earlier in the year; in most cases driven by the increases in late winter temperatures such that the climate resembles the former spring conditions (Schwartz & Reiter, 2000; Ahas et al., 2002). This in turn results in any heat requirement for floral induction being met earlier in the year.

Delays in the timing of spring events, and in particular flowering dates, have been reported, although considerably less frequently than advanced phenophases. In a study of 542 plants and 19 animal species in 21 European countries for the period 1971-2000, Menzel et al. (2006c) found that whilst 30% of species demonstrated a significant shift toward earlier spring events, 3% demonstrated shifts towards later dates. Similarly, of the 65 species analysed in a single-site study in Victoria, Australia, Keatley and Hudson (2012) report a delay in first flowering dates of three species over the period 1983-2006. Of greatest relevance to this study are the findings of Ahas et al. (2002), who report similar location specific differences in the timing of phenological events for the same species of hazel, apple, coltsfoot and lilac for the period 1951-1998. An advance of spring events by four weeks across these species is found for Western and Central Europe, whereas spring events of these same species are delayed by up to two weeks in Eastern Europe (Ahas et al., 2002). The contrasting phenologies seen for citrus in Iran between Kerman and Shiraz, with their earlier flowering, and the delayed flowering in Gorgan, mirror these earlier findings for Europe.

It has been argued that the differences between the rates of phenological change within a single species across different locations, which can be as extreme as differences in direction of change, could result from differences in altitude and latitude between the localities (Ruml et al., 2011). In this study, there is far greater similarity in both latitude and altitude for the inland cities of Kerman and Shiraz, which both contrast considerably with Gorgan at its northern coastal position, which would support this theory. However, Parmesan (2007) argues that whilst more marked phenological responses occur at high latitudes due to more extreme changes in climate, latitude explains less than 4% of the variation in the phenological shifts of 203 species studied. It is interesting that it is the late citrus flowering dates in Gorgan which are demonstrating trends towards delayed flowering, whilst the earlier citrus flowering dates in Kerman and Shiraz are advancing to even earlier in the year. Primack et al. (2009a) argue that in warm regions, both late flowering and delays in flowering dates over periods in which temperature increases simultaneously, occur as a result of the fulfilment of chilling requirements becoming difficult in a warmer late winter. The fulfilment of dormancy in citrus requires either a chilling period, or a period of drought. As year-round rainfall occurs in Gorgan, this chilling requirement presents a very plausible explanation for the delayed flowering dates under conditions of climate warming. By contrast, Kerman and Shiraz not only experience cooler winter temperatures than Gorgan, even in the most recent years, but also have arid to semi-arid climates. Thus, the requirements for the fulfilment of dormancy can be achieved through the winter drought, even if temperatures do not drop low enough or remain low enough to fulfil the chilling requirements. In an analysis of spatial differences in the timing of phenophases of fruit trees in Norway, Wielgolaski (2003) recorded earlier flowering dates inland and later flowering dates in coastal regions, as are consistent with the inland regions of Kerman and Shiraz, and the coastal Gorgan in this study. These findings suggest that local and regional climatic factors can act in isolation, or synergistically, to satisfy dormancy requirements of a species and so determine the timing of associated reproductive phenological events. Moreover, the argument is presented that the region and its associated climate, rather than species, determines which climatic variables serve as the greatest determinants of the timing of phenological events.

With trends towards later flowering revealed for the five citrus types in Gorgan in this study, and reported for other species and locations elsewhere, and considering the plausible explanations for such an occurrence, it is surprising that there are so few cases of delayed flowering presented in the phenology literature. Where reported, they comprise the minority of findings against a significantly larger number of cases of advancing flowering dates. It is possible that many studies coincidentally do not include sites or species for which trends to later phenological events exist. However, Menzel et al. (2006c) and Parmesan (2007) argue that the predominance of studies reporting advanced flowering dates may, in part, be a publication bias. Authors selectively report on subjects that demonstrate significant trends in the expected direction, because such results stand a greater likelihood of being published than those of statistically insignificant trends or trends in the opposite direction to the norm. This theory of publication bias presented by Menzel et al. (2006c) is summarized in *Figure 6.1.* A combination of both possible publication and reporting bias, and coincidental sampling of advancing phenophases, most likely explains the scarcity of delayed phenophase results similar to those found in this study. It is however possible that the scarcity of trends towards delayed flowering is simply due to such long term phenological shifts occurring less often under recent climatic conditions. The occurrence of contrasting trends suggests that considerable work needs to be undertaken to understand these differences, particularly where they occur either in the same location across different species, or for the same species across geographically and climatically different locations.

		Climate	
		Change in expected direction	No change / change in unexpected direction
System	Change in expected direction	Most likely to be published, especially when as expected	Likely to be published, explained by other drivers
	No change/ change in unexpected direction	Unlikely to be published, explained by other drivers	Unlikely to be analysed or reported

Figure 6.1: Publication biases in phenological responses to changes in climate (after Menzel et al., 2006c).

6.2.2 Trends in Climatic Variables

There is a notable contrast between trends in the annual climate variables of T_{max}, T_{min} and precipitation for Gorgan and the more climatically similar cities of Kerman and Shiraz. The city of Gorgan demonstrates very weak, statistically insignificant trends in T_{max} and T_{min} for the period 1960-2010, whilst Kerman and Shiraz demonstrate strong, statistically significant increases in T_{max} of 0.03°C/yr, and even stronger increases in T_{min} of 0.05°C/yr to 0.07°C/yr respectively (*Table 5.2*). However, Gorgan demonstrates a statistically significant decrease in precipitation of -4.69mm/yr for the study period, whereas precipitation trends for Kerman and Shiraz are statistically insignificant (*Table 5.2*). This dichotomy is of geographic interest, as Gorgan is located in the humid region of the Caspian lowlands, whilst Kerman and Shiraz are located on the Iranian Plateau with arid to semi-arid climates, but also notable in light of the contrast between the delay in flowering dates for Gorgan, and the advance of this phenological event for Kerman and Shiraz (Rajendra et al., 2003; Kehl, 2009).

Annual counts of days in which temperatures exceed the thresholds suitable for citrus flowering display similarly contrasting trends for the three cities, with patterns from Kerman and Shiraz differing from those for Gorgan. Trends of decreasing counts of days with $T_{min} <$ 13°C over the study period are significant for Kerman and Shiraz, but not for Gorgan, where an insignificant increase in these 'cold' days is revealed (*Table 5.6*). There are relatively strong, although not statistically significant, increases in the number of days with T_{max} > 35°C for Kerman and Shiraz, but a marginal decrease in these 'hot' days for Gorgan over the study period (*Table 5.6*). The results chapter highlights potential cyclic inter-annual patterns in the counts of days in which T_{max} > 35°C, T_{min} < 13°C or T_{max} and T_{min} < 13°C for the three cities. These cycles differ in amplitude and period, both when comparing temperature threshold groups within a city, and between the cities for each threshold group. Furthermore, there is considerable variability within these cycles. To understand the nature and drivers of these cycles better, a dataset covering a longer temporal period would be required, ideally incorporating a greater number of weather stations from discrete geographic localities. However, it can be tentatively suggested that these cycles may occur as a result of a combination of known climate drivers, such as the Atlantic Oscillation (AO) and the North Sea-Caspian Pattern (NCP) that correlate particularly well with winter temperatures in Iran (Ghasemi & Khalili, 2006; Ghasemi & Khalili, 2008), in addition to the position and direction of flow of the 500hPa trough (Alijani, 2002), ENSO (Nazemosadat & Cordery, 2000; Nazemosadat & Ghasemi, 2004), and fluctuations in solar irradiance associated with decadal cycles in sunspot activity (Ohashi et al., 2011). Should the ocean-atmosphere systems of the AO, NCP and ENSO have played a significant role in the period and amplitude of these cycles, they would also likely be a cause of the differences in trends in these counts of days exceeding threshold temperature conditions between the coastal city of Gorgan and the inland Kerman and Shiraz. It should be noted that two studies which coincidentally analysed the frequency of days with T_{max} > 35°C, for weather stations in Gorgan, for periods 1961-2000 (Ghorbani & Soltani, 2003), and 1961-2003 (Gholipoor & Shahsavani, 2008), do not make reference to any cycles in their counts of days with temperatures exceeding this threshold.

Trends in annual total sunshine hours over the study period are similar for Gorgan and Kerman; with both exhibiting statistically significant increases in the number of annual sunshine hours of 0.03h/yr to 0.06h/yr (*Table 5.7*). However, Shiraz reveals a very weak trend towards increasing sunshine hours for the study period (*Table 5.7*). This contrast between Kerman and Shiraz is interesting as they both have a relatively arid climate, and consequently have a similar absence of cloud cover for much of the year (Samimi, 1994;

Faramazi, 2010). It is further notable that humid Gorgan and semi-arid Kerman demonstrate similar trends toward a greater number of annual sunshine hours, despite the heightened potential for cloud cover in Gorgan. It is thus of interest to explore potential drivers of long term changes in sunshine hours for the three cities.

The weak sunshine hour trends for Shiraz suggest a relatively constant amount of cloud cover over Shiraz throughout the study period. Located at the foot of the Zagros Mountains, it is likely that the majority of clouds in Shiraz are formed through orographic processes, resulting from the uplift of moist air advected from the Mediterranean Sea to the south west (Kehl, 2009). As this process is most reliant on consistency in wind direction, the resultant frequency of cloud production is likely to remain more constant than cloud formation through convective processes, which would necessarily be enhanced under any climate warming. Under prolonged periods of climate warming, however, the size of the ITCZ and the position of the pressure cells responsible for the wind production may well change to the point at which the predominant wind direction changes, which would result in changes in sunshine hours in Shiraz. The increase in sunshine hours for Gorgan is most likely associated with a decrease in precipitation in the region. Whilst decreased precipitation can potentially be associated with an increase in non-precipitating, high altitude clouds, the majority of precipitation in the Caspian Lowlands is driven by the passage of mid-latitude cyclones, and hence cloud cover is directly associated with precipitation (Sabziparvar & Shetaee, 2007; Kehl, 2009). Furthermore, as climate warming is associated with the expansion of the ITCZ, it is likely that the number of mid-latitude cyclones passing over the region has changed, and will continue to decrease over time, as the region of tropical air circulation expands, thereby reducing precipitation and cloud cover and consequently increasing the number of sunshine hours. Located at close proximity to the Caspian Sea, ocean-atmosphere drivers such as the NCP, AO and ENSO are likely to control the frequency of precipitation, and hence cloud cover, in Gorgan. For Kerman, where cloud cover and precipitation are driven by convective heating, the increase in both T_{max} and T_{min} has most likely resulted in the occurrence of more extreme, short-lived convective storms, with a low duration of cloud cover (Kehl, 2009). Furthermore, cycles such as the North-Sea Caspian Pattern have been reported to influence the amount of cloud cover across Iran, a pattern which must be compensated for by micro-climatic conditions in Shiraz, but which would likely have a considerable impact on Gorgan due to its proximity to the Caspian Sea (Ghasemi & Khalili).

Trends in annual averages temperature and precipitation for Gorgan are consistent with the literature on climate variability and change in Iran over recent decades. The statistically insignificant trends in annual T_{max} and T_{min} for Gorgan found in this study are supported in reports of climate studies for the periods of 1961-2000 and 1961-2004 by Ghorbani and Soltani (2003) and Gholipoor (2012). The slight increase in T_{max} reflected in these statistically insignificant trends for Gorgan is reported for period 1961-2003 by Gholipoor and Shahsavani (2008). Similarly, the statistically significant decrease in annual precipitation for Gorgan is confirmed by the work of Ghorbani and Soltani (2003). The difference in the magnitude of change in rainfall from the 4.3mm/yr decrease reported by Ghorbani and Soltani (2003) and the 4.9mm/yr decrease presented in this study (*Table 5.2*) can potentially be attributed to differences in the study periods, with the former study analysing precipitation data for the period 1961-2000, whilst this study includes an additional 10 years, with 1960 and 2001-2010 (*Table 5.2*). This would suggest an increasingly rapid decrease in the rainfall for Gorgan over at least the past 10 years. Precipitation trends for the most recent 10, 15 and 20 years of the study period confirm this notion, with negative trends becoming more extreme as earlier years are omitted (*Figure 6.2*). However, the trend for the most recent five years, whilst inherently statistically insignificant due to the low *n value*, and which could potentially have been driven by interannual oscillations, indicates a strong increase in precipitation (*Figure 6.2*). What casts further doubt on this hypothesis, however, is the analysis of the common period of data availability; 1961-2000. Instead of demonstrating a smaller rate of decrease in precipitation than for the full study period, a more rapid decrease in precipitation of 5.2mm/yr is demonstrated (*Figure 6.3*). Again, this in part can be explained by the omission of the data from 1960, which, with a value of 550.6mm, would have reduced the rate of change across the period, highlights the importance of the beginning and end date of precipitation trend analyses, as well as the inverstigation of outliers.

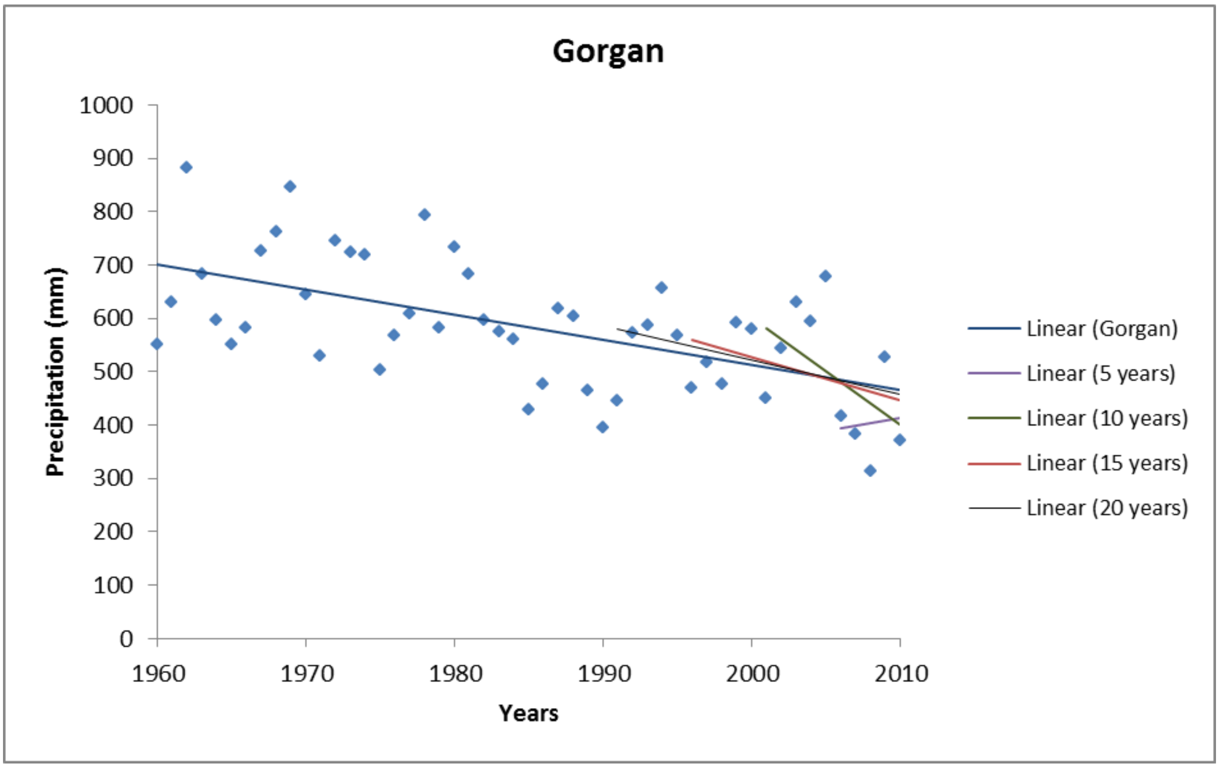

Figure 6.2: Trends in precipitation in Gorgan for the period 1960-2010, together with trends for the most recent 5, 10, 15 and 20 years.

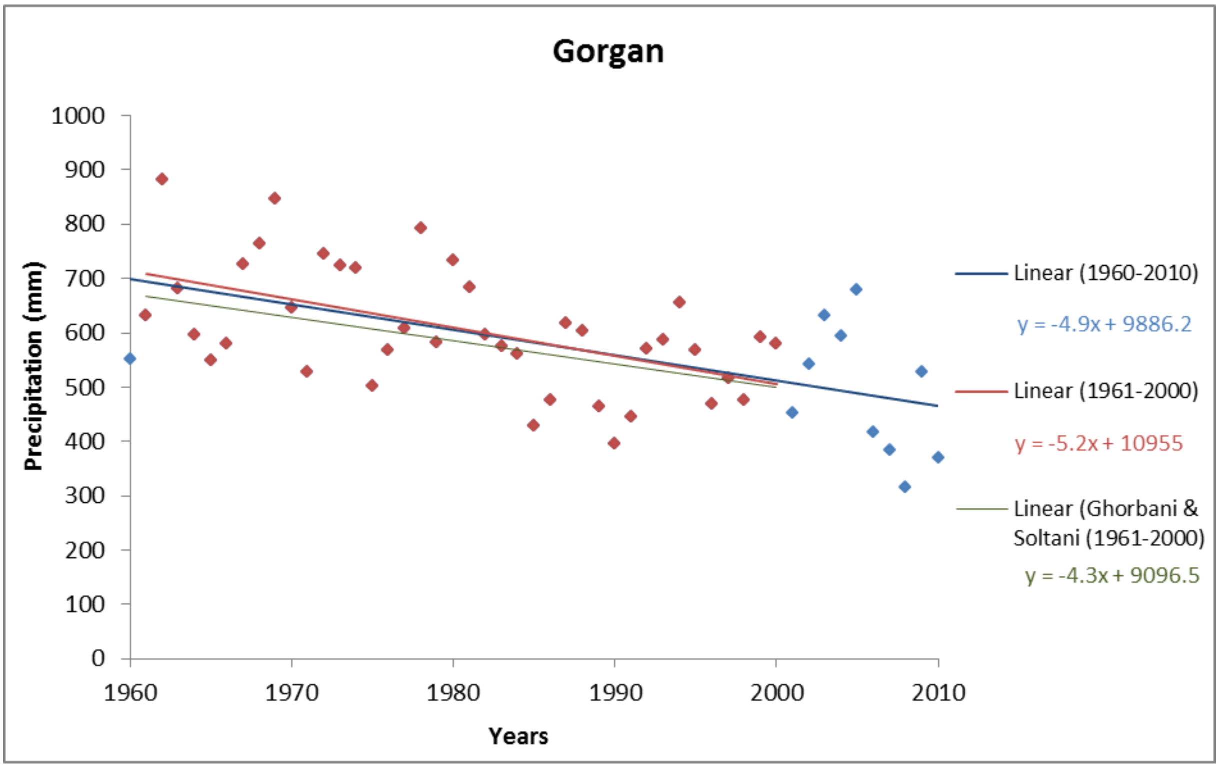

Figure 6.3: Comparison of precipitation trends for Gorgan using the data from this study for the periods 1960-2010 and 1961-2000, plotted in comparison with the -4.3mm/yr trend presented by Ghorbani and Soltani (2003) for 1961-2000.

Trends in monthly averages of climate variables for Gorgan are less consistent with the, albeit contradictory, literature. Gholipoor and Shahsavani (2008) report significant trends in monthly T_{min} for May and August form 1961-2003, whilst Ghorbani and Soltani (2003) report a significant trend in T_{min} for May alone, for the period 1961-2000. The trends in monthly T_{min} calculated in this study are statistically significant for August and July, but not for May (*Table 5.3*). Gholipoor and Shahsavani (2008) present statistically significant increases in the number of days with T_{max} > 35°C for the months of May and August; whilst the earlier work of Ghorbani and Soltani (2003) reports significant trend increases for May and June. By contrast, this study found no months with significant trends in days with T_{max} > 35°C for Gorgan. Whilst May was amongst the months with the strongest trends ($r = 0.39$, $p = 0.0053$), trends for August and June are particularly weak (*Table 5.6*). The inconsistencies in the climate trends for monthly averages across both the literature and this study highlight the importance of the period of study, where the effect of long term climate cycles such as El Niño can impact on averaged variables considerably, depending on whether the study period coincides with the beginning, middle or end of these cycles. Furthermore, it is possible that the climate data used for Gorgan in each of these studies were sourced from different weather stations and hence reflect the effect of a micro topography. However, as none of these studies presents information on the name or position of the weather stations at which the climate data were recorded, this theory cannot be confirmed. While this does limit comparison between studies, and the importance of reporting of weather stations should be noted for furture studies, general climate trends made within a singlecity are unlikely to be vastly different.

Very little research has been published in English on shifts in climate variables for Kerman and Shiraz specifically. A number of studies have, however, analysed shifts in climatic variables across a number of localities in Iran, which include these two cities. Results from 34 Iranian meteorological stations over the period 1968-2002 are reported by Ghahraman (2006), with only 50% of the stations demonstrating trends towards increased T_{avg} and with the least significant trends found for stations with humid climates. This supports the differences measured here between the weak temperature trends for humid Gorgan, and the strong increasing trends for more arid Kerman and Shiraz. Trends in temperature variables averaged for 19 meteorological stations in Iran from 1966-2005 are presented by Tabari and Hosseinzadeh Talaee (2011), reporting the largest change in T_{max} for the month of January (0.823°C/yr); the strongest trend in T_{min} for September (0.343°C/yr); and strong positive T_{min} trends for all stations. Whilst the current study finds strong monthly trends in T_{min} for the cities of Kerman and Shiraz, there are particularly weak trends in T_{min} for Gorgan. This contradiction is likely due to Tabari and Hosseinzadeh Talaee (2011) having study sites only in arid and semi-arid locations in Iran. Furthermore, even for Kerman and Shiraz, which are included in the 19 stations studied by Tabari and Hosseinzadeh Talaee (2011), there are differences in the months for which the strongest trends are recorded: this study records the strongest trends in monthly T_{max} for April in Kerman and Shiraz; whilst strongest trends in T_{min} are demonstrated for December in Kerman, and October for Shiraz, most likely as these are the autumn to winter months. This highlights the extent to which the changes in climate experienced in Iran over the period 1960-2010 are location-specific, which is supported by the considerable differences in temperature trends between cities located in climatically different regions of Iran highlighted by Soltani and Soltani (2008) and Roshan and Grab (2012).

Demonstrating results more consistent with this study, Modarres and Sarhadi (2009) report a significant decrease in precipitation for 67% of 145 meteorological stations across Iran over the period 1951-2000. The greatest decreases in precipitation are reported for the humid north and north western regions of the country, which includes the Gorgan City meteorological station (Modarres & Sarhadi, 2009). A further study for the period 1965-2005, similarly reports that 40% of the 79 Iranian locations studied demonstrate decreasing precipitation, but these decreases are, for the most part, statistically insignificant for semi-arid to arid regions (Raziei et al., 2005).

For the greater Middle Eastern region, the average precipitation trends for recent decades are similar to those for Kerman and Shiraz, with increases in both annual T_{max} and T_{min} over recent decades (Turkes & Sumer, 2004; Smadi, 2006). Similar to Kerman and Shiraz, the average increases in annual T_{min} for the Middle East are occurring at a greater rate than those for T_{max}, which consequently reduces the diurnal temperature range (Turkes & Sumer, 2004; Smadi, 2006). An increase in the number of days with temperatures above the 10th percentile, and a decrease in the number of days with temperatures below the 90th percentile, reported for 15 countries across the Middle East, reflect trends in the number of 'hot' days with T_{max} > 35°C and 'cold' days with T_{min} < 13°C in Kerman and Shiraz (Zhang et al., 2005).

6.2.2.1 Urban Heat Island

Many of the studies for both Iran and the greater Middle Eastern region postulate that the increase in temperatures, and in particular the increase in T_{min} over recent decades, can be largely attributed to the urban heat island effect (Ghahraman, 2006; Soltani & Soltani, 2008; Gholipoor & Sinclair, 2011; Tabari & Talaee, 2011; Tabari et al., 2011). The urban heat island effect refers to the relative warmth of a city compared with the surrounding rural areas, occurring as a result of the modified radiative and heat storage properties of city areas due to changes from natural to artificial surfaces (IPCC, 2007; Zhang et al., 2013). In particular, the change in surfaces from natural vegetation such as grass and trees to tar and concrete in cities significantly increases potential heat storage, and hence increases T_{min} (IPCC, 2007; Zhang et al., 2013). Through changes in the albedo, these artificial surfaces can result in a decrease in the reflectance of insolation, which can result in an increase in low level atmospheric temperatures. Finally, the urban heat island effect may be the consequence of an increase in the direct heating from heat generating sources such as cars, households and manufacturing (IPCC, 2007; Zhang et al., 2013). Should a city increase in area or population over a particular period of time, and hence result in an increase in both the conversion of natural to artificial surfaces and the amount of direct heating, it is possible that this may be responsible for a simultaneous rise in temperatures recorded within that city (Lu et al., 2006; Tabari et al., 2011; Jochner et al., 2012). To determine whether any changes in temperature can be directly attributed to the urban heat island effect, data from adjacent rural areas which cover the same study period are required for comparison (Jochner et al., 2012). Unfortunately these are lacking in Iranian studies (Gholipoor & Sinclair, 2011; Tabari et al., 2011).

As the citrus gardens and weather stations for this study are all located within cities, it is likely that the urban heat island effect is partly responsible for the temperatures that the plants are exposed to, as reflected in the increases in temperatures observed over the period 1960-2010. However, with no data for citrus gardens located outside of these cities, the comparative tests for a direct role of the urban heat island as have been undertaken by Ohashi et al. (2011) for Japan and Jochner et al. (2012) for Germany, are not possible. As the net sizes of the cities of Kerman and Shiraz are considerably larger than Gorgan, and as population growth has been more rapid for Kerman and Shiraz (with a population increase of 130 580 and 186 611 people per decade, respectively) than Gorgan (with a population growth of 68 299 people per decade), it is possible that the urban heat island effect may account for some of the difference between the statistically significant increases in temperatures observed in Kerman and Shiraz, and their absence in Gorgan (Statistical Centre of Iran, 2006, *Figure 6.4*).

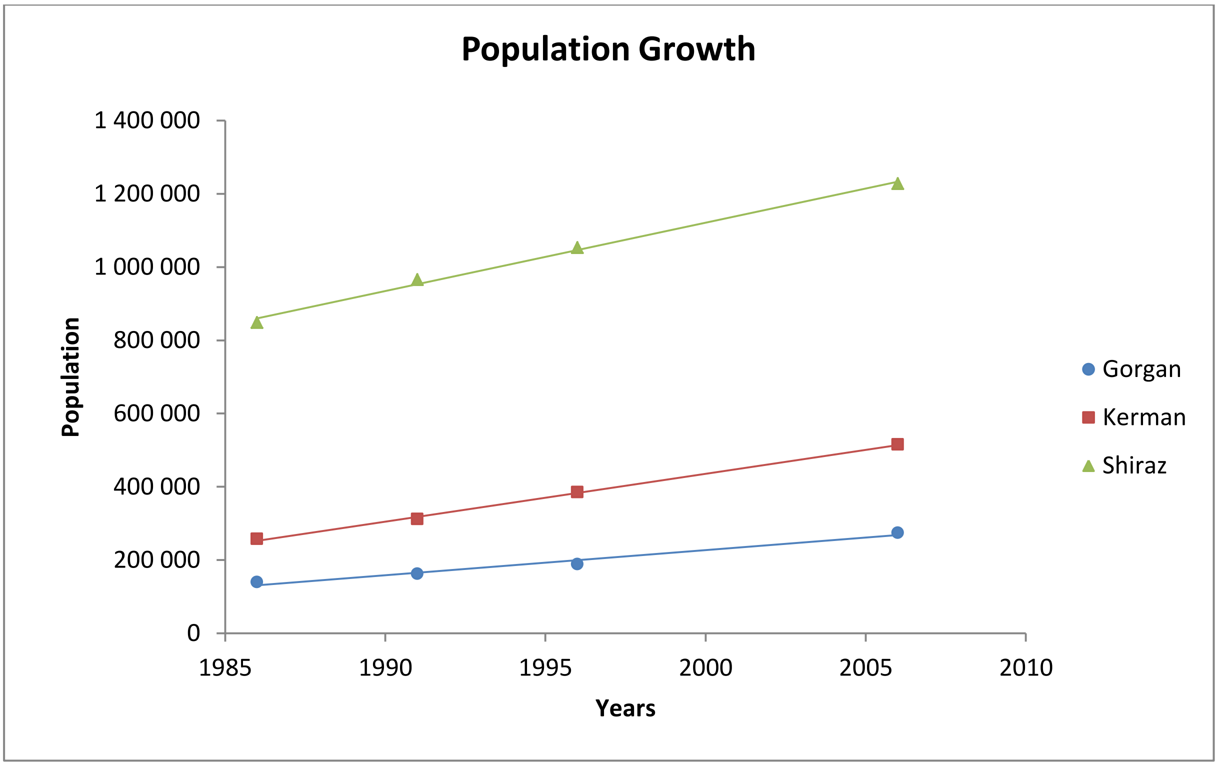

Figure 6.4: Size of population and rate of population growth for Gorgan, Kerman and Shiraz for the period 1985-2006 (after Statistical Centre of Iran, 2006).

Assuming that the urban heat island effect contributed to the increase in temperatures in Kerman and Shiraz over the period 1960-2010, and particularly the considerable increases in T_{min}, it is likely that it is also responsible for the significant decrease in the number of days in which T_{min} < 13°C in Kerman and Shiraz, but not in Gorgan. However, with increases in temperatures also reported for rural locations in both Iran and the greater Middle Eastern region, the urban heat island effect is unlikely to have been responsible for all of the observed warming of up to 0.1°C/yr (Lu et al., 2006; Gholipoor & Sinclair, 2011). With a global mean warming of 0.6°C over the past century, which has been primarily attributed to the increase in anthropogenic atmospheric carbon dioxide levels, it is likely that the larger proportion of the increase in temperatures, and in particular increases in T_{min}, have resulted from broader-scale climate change (Walther et al., 2002; Cleland et al., 2007).

Whilst urban growth and the resultant change in surfaces may potentially have an impact on precipitation through local changes in both uplift dynamics and wind patterns (Zhang et al., 2013), it is more likely that the differences in changes in precipitation observed for the three cities are occurring through factors relating to their geographical location (Nazemosadat et al., 2004; Modarres & da Silva, 2007). Kerman and Shiraz are located in arid to semi-arid regions which currently receive low annual rainfall volumes; hence there is a small margin for annual precipitation to decrease before reaching hyper-aridity. Gorgan has substantial annual rainfall, and hence can potentially experience a much greater quantitative decrease. Furthermore, as the precipitation in Gorgan is driven by the warm Caspian Sea current and the number of mid-latitude cyclones making landfall along the coast, shifts may be driven by changes in the global thermohaline circulation and in shifts in the location and extent of the ITCZ affecting the track-paths of the mid-latitude cyclones (Modarres & da Silva, 2007; Kehl, 2009).

6.2.3 Outliers

Through the calculation of the ‘five number summary’ and resultant production of box-and-whisker plots for the phenology and climate variables, statistical outliers were identified (*Figures 5.1, 5.3, 5.5, 5.13-5.15*). These are values which are significantly different from the bulk of the data observations, and which could occur either through errors in data recording, or which are actual abiotic anomalies. The years in which flowering dates and climate variable outliers occurred are highlighted, together with the outlier value relative to the mean (*Table 6.1)*.

Table 6.1: Year of flowering date and climate variable statistical outliers for Gorgan, Kerman and Shiraz. Outliers which lie above the mean are highlighted in red; below average outliers highlighted in blue. Outliers which coincide with known strong El Niño events are marked by an asterisk.

Statistical outliers for phenology and climate data			
	Recorded value	Median values (1960-2010)	Year
Flowering Dates			
Orange Gorgan	141 JD	132 JD	*1984
Tangerine Gorgan	122 JD	133 JD	1969
Sour Orange Gorgan	148 JD	134 JD	1978
Climate Variables			
T_{max} Gorgan	20.5°C	23°C	1969
T_{min} Gorgan	10.2°C	12.8°C	1964
Precipitation Kerman	263.6mm	132.4mm	*1974

With a study of five different citrus types in three cities over a 51-year period, the overall number of outliers is very small, and indicates highly reliable data both from the citrus gardens and the meteorological stations. Data entries which form statistical outliers are revealed for the flowering dates of orange, tangerine and sour orange in Gorgan (*Table 6.1, Figure 5.1*). For the cities of Kerman and Shiraz, no outliers are found for the flowering dates of any of the five citrus types (*Figures 5.3, 5.5*). Outliers for climate variables are revealed for T_{max} and T_{min} in Gorgan, and for precipitation in Kerman (*Table 6.1, Figures 5.13, 5.14*). The predominance of outliers for Gorgan in both the phenological and climate data suggests either less robust quality standards, both for the gardens and weather station in that city, or a larger margin of variability and a greater influence of climate extremes at that location. The climate and phenological data used here were collected by separate companies, and the phenological data are averaged for three gardens in each city. It is thus unlikely that all of these outliers are a consequence of human error. However, Gorgan is climatically distinct with humid conditions, and differed considerably from Kerman and Shiraz in climate and phenological trends.

All of the outliers, for both phenology and climate variables, occur in the 25 year period from 1964-1988 (*Table 6.1*). With trends towards later flowering dates in Gorgan over the period 1960-2010, it is surprising that the above average outliers do not occur during the more recent past. It is thus likely that these outliers are not driven by the same climate forces responsible for the warming observed over the period 1960-2010. Two strong El Niño events occurred during the 1964-1988 period, one in 1972-1973 and the other in 1982-1983 (Davis, 2001; NCEP 2012). The timing of the earlier El Niño event directly precedes the high precipitation anomaly recorded for Kerman (*Table 6.1*). As El Niño years have been reported to be responsible for precipitation extremes and floods in Iran (Nazemosadat & Ghasemi, 2004), this El Niño event serves as a likely explanation for this outlier. The 1982-1983 El Niño event is followed by the above average outlier for orange flowering dates in Gorgan (*Table 6.1*). With the requirements for the break of dormancy for citrus being either the fulfilment of a period of cooling, or a period of water stress, it is possible that the higher precipitation volumes in an El Niño event may have delayed flowering. However, it is unclear why flowering would not have been delayed for all of the citrus types and in all of the cities (Srivastava et al., 2000). Furthermore, if this is the case, one would expect markedly delayed flowering for Kerman following the precipitation outlier associated with the El Niño event a decade earlier. The greatest concern in attributing El Niño events to these precipitation outliers entirely, is that the strongest El Niño event in recorded history (1997-1998) is not associated with any of the phenology or climate variable outliers for any of the cities (Davis, 2001; NCEP, 2012).

In a study of first flowering dates in Edmonton, Canada, Beaubien and Freeland (2000) report a significant relationship between El Niño and phenology, and notably find a strong negative deviation in first flowering dates for 1993, directly following this strong El Niño year. Whilst this finding presents a contradictory finding to the coincidence of the above average outlier for orange flowering dates in Gorgan and the 1982-1983 El Niño event, it must be noted that the climatic impacts of El Niño events vary regionally (Nazemosadat et al., 2006). In a review paper on the migratory phenology of birds, Gordo (2007) reports that of the few studies which have included El Niño as a potential driver of shifts in migratory behaviour, none report significant relationships. Whilst dissynchrony in the phenological responses of birds and plants resulting from climate variability and change have been discussed in *section 2.1.4.1* (*Literature Review Chapter)*, the scarcity of direct comparisons between the timing of El Niño events and phenological shifts, make it difficult to determine the full nature of its effect (Gordo, 2007). However, as Iran is located within continental Asia, and is surrounded by small seas, it is likely that whilst there would be some effect from El Niño on phenology through its reported effect on rainfall, in years with very strong El Niño events such as 1993 and 1997-1998 there may be a dampening effect from more direct regional climate drivers (Nazemosadat & Cordery, 2000; Nazemosadat & Ghasemi, 2004). One of these regional drivers of climate variability is the AO, with winter temperatures inversely related to the strength of the AO (Ghasemi & Khalili, 2006). For the years 1992-1993 there is an anomalously high AO reported by Ghasemi & Khalili (2006), which would have resulted in below average winter temperatures in Iran. Furthermore, the particularly severe eruption of Mount Pinatubo occurred in 1991, resulted in reported global decreases in temperatures (Grab & Nash, 2010). The argument for the orange flowering outlier following the 1982-1983 El Niño event was owing to a delay in the fulfilment of drought conditions for dormancy. Following the 1992 El Niño, the occurrence of these cold temperatures as a result of the concurrent anomalously high AO and the Pinatubo eruption, would act to fulfil the dormancy requirements despite the lack of drought conditions (Srivastava, 2000). Another regional climate factor, often closely linked with the AO, is the North-Sea Caspian Pattern, which similarly has an inverse relationship with winter temperatures (Ghasemi & Khalili, 2008). Whilst not as extreme as the AO anomaly for the period 1992-1993, there are above average NCP values, which would further influence below average winter temperatures. These cold winter temperatures would allow for the fulfilment of the requirements for dormancy despite the above average rainfall likely associated with the strong El Niño of 1992, and result in relatively average flowering dates.

A second factor which may have been responsible for outliers in climate, and in turn, phenology variables are rapid short-term changes in global temperatures. A decreases in sunspot numbers results in lowered temperatures, with the most notable effect occurring during the Maunder Minimum (NOAA, 2012). However, the effect of sunspot numbers as a driver of the exhibited outliers in this study is that, rather than following the 10-year sunspot cycle (Wilson, 1984), these outliers cluster throughout a single 20-year period in the 51-year dataset. Indeed, these years in which outliers occur are associated with sunspot numbers ranging from very low (1964) to high (1969), with low sunspot numbers for 1974 and 1984, and average sunspot numbers for 1978 (NOAA, 2012). Furthermore, there are no outliers in climate or phenology observations which coincide with sunspot maxima and minima that occur during the period 1990-2010.

A third potential causal factor for the timing of these climate and phenological outliers is the occurrence of large volcanic events (Hansen et al., 1992; Kondrat'ev & Galindo, 1997; Grab & Nash, 2010). The ash from these events becomes trapped in the lower stratosphere, increasing the scattering and reflectance of incoming solar radiation, and hence reducing temperatures (Kondrat'ev & Galindo, 1997). Such an event could potentially result in below average T_{max} and T_{min} outliers, and also delayed flowering dates. However, not only were there no unusually large volcanic eruptions in the years directly preceding 1964 or 1969, but furthermore, if volcanic eruptions were to play a causal role in outlier temperatures or flowering dates, the 1991 eruption of Mount Pinatubo would have necessarily resulted in outliers during the period 1992-1994 (Hansen et al., 1992; Grab & Nash, 2010). Furthermore, any causal effect of either sunspots or volcanic eruptions would have most likely had an impact throughout Iran, rather than on individual cities (Kondrat'ev & Galindo, 1997).

It is interesting to note that the below average T_{max} outlier for Gorgan coincides with the advanced tangerine flowering date outlier for the same city (*Table 6.1*). This is particularly surprising as warmer temperatures are traditionally associated with advanced flowering dates, and indeed there is a statistically significant, positive relationship between mean annual T_{max} and the flowering dates of tangerine in Gorgan (*Table 5.8*). However, this outlier perhaps was responsible for the earlier fulfilment of the chilling requirements of dormancy, and hence earlier flowering (Srivastava et al., 2000). No other climate outliers are contemporaneous with the flowering date outliers.

6.2.4 Relationships between flowering dates and climate variables

6.2.4.1 Individual Regression Analyses

As outlined in the study aims and objectives, the potential to compare the results of this study with the findings reported from other studies on shifts of flowering dates over recent decades, particularly for citrus species, is of value to improve understanding of the global response of plant phenology to climate variability and change. The results presented in this study are thus analysed independently, and then critically compared with those from similar studies.

A phenological study relevant for comparison with this investigation is Gordo and Sanz (2005), which explores the phenological responses of 29 perennial plant species at the Observatori de l'Ebre, near Tortosa City in Spain, to climate variability and change over the period 1943 to 2003. Notably, this data set includes the first flowering dates of orange and lemon trees. As very little work has been undertaken on citrus phenological responses to climate change internationally, and no existing peer reviewed work investigates the flowering response of citrus, these results presented by Gordo and Sanz (2005) provide the only source for direct comparison with, and validation of, the results of this study. With methods consistent with this study, using linear regression to compare annual T_{max} and precipitation with first flowering dates of two citrus types individually, Gordo and Sanz (2005) report an advance in flowering dates for both citrus types, associated with an increase in maximum temperatures over the study period at a rate of 0.31-0.85d/°C. Their study found no clear trends in precipitation over the period 1943-2003, but a positive relationship between precipitation and lemon flowering dates and an inverse relationship for orange. The quantitative relationships presented in this study compared with the work of Gordo and Sanz (2005) are presented in *Table 6.2*.

For the present study, statistically significant relationships between citrus flowering dates and annual T_{max} are found for Kerman and Shiraz. These relationships are quantified by advances in the flowering dates of the five citrus types in response to the increases in T_{max} for Kerman, ranging between 1.85d/°C for sour lemon and 3.08d/°C for sweet lemon (*Table*

5.8*). The response of orange flowering dates to increases in T_{max} is calculated as 2.78d/°C (*Table 5.8*). The relationships for both sour lemon and orange flowering dates in Iran are considerably greater than those reported by Gordo and Sanz (2005) for Spain. The relationships between annual T_{max} and the flowering dates of the five citrus types in Shiraz indicate an even greater advance of flowering dates per 1°C increase in T_{max}, ranging from 6.14d/°C for sour lemon to 7.86d/°C for sweet lemon (*Table 5.8*). Flowering dates for orange are calculated to advance by 7.45d/°C (*Table 5.8*).

Table 6.2: Response of first flowering dates of lemon and orange trees in Spain (Tortosa) for the period 1943-2003 and of peak flowering dates in Iran for the period 1960-2010 (after Gordo & Sanz, 2005).

Phenological response of citrus flowering dates to climate change			
		Annual T_{max}	Annual Precipitation
Citrus limon (sour lemon)			
	Gorgan	-0.35 d/°C	-0.001 d/mm
	Kerman	-1.85 d/°C	+0.03 d/mm
	Shiraz	-6.14 d/°C	-0.1 d/mm
	Tortosa (Gordo & Sanz, 2005)	-0.31 d/°C	+0.12 d/mm
Citrus sinensis (orange)			
	Gorgan	-0.49 d/°C	-0.01 d/mm
	Kerman	-2.78 d/°C	+0.05 d/mm
	Shiraz	-7.45 d/°C	+0.01 d/mm
	Tortosa (Gordo & Sanz, 2005)	-0.85 d/°C	-0.10 d/mm

Whilst relationships between the flowering dates of the five citrus types and T_{max} for Gorgan are not statistically significant, the magnitude of the temperature related shifts is more similar to that reported by Gordo and Sanz (2005). Orange (including *Citrus sinensis*) flowering dates are calculated to advance by 0.49d/°C, whilst sour lemon (including *Citrus limon*) flowering dates advance by 0.35d/°C (*Table 5.8*). This is particularly interesting as, unlike the semi-arid to arid regions of Kerman and Shiraz, Gorgan has a similar humid Mediterranean climate to that of Tortosa, Spain which has a comparable winter rainfall, high humidity and moderate temperatures. Notable is the positive relationship between annual T_{max} and the flowering dates of tangerine recorded for Gorgan. There are inverse relationships for the remaining citrus types in Gorgan, and for the five citrus types in

Kerman and Shiraz. These inverse relationships between T_{max} and flowering dates are similarly demonstrated for both lemon and orange in Spain (Gordo & Sanz, 2005). However, Gordo and Sanz (2005) report positive relationships between T_{max} and flowering dates for six of the 45 plant species studied, and thus this result for tangerine is not completely unprecedented.

Significant relationships between annual precipitation and the peak flowering dates of the five citrus types are only found for Kerman. These relationships equate to a delay in flowering dates ranging from 0.03d/mm for sour lemon to 0.06d/mm for sour orange, and 0.05d/mm for orange (*Table 5.8*). Where considerably stronger responses in flowering dates to increased T_{max} are found for the three Iranian cities relative to Spain, the responses of flowering dates to a 1mm change in precipitation are considerably weaker for Iran. Gordo and Sanz (2005) report an inverse relationship between flowering dates and annual precipitation for orange in Spain, but decreases in rainfall are associated with the advance of flowering dates for all five citrus types in Kerman. Whilst the relationships between flowering dates and annual precipitation are not statistically significant for Gorgan and Shiraz, with maximum shifts in flowering dates of 0.01d/mm, they demonstrate contrasting responses between citrus types (*Table 5.8*). For Gorgan, there is only a positive relationship between flowering dates and precipitation for sour orange, whilst the remaining citrus types demonstrate inverse relationships. There are positive relationships for orange, sweet lemon and sour orange in Shiraz, whilst inverse relationships exist for tangerine and sour lemon. In Spain a positive relationship is demonstrated for lemon and an inverse relationship for orange, whereas the opposite pattern is demonstrated for Shiraz. However, with negligible shifts in the flowering dates calculated in response to precipitation for Shiraz, the direction of the relationship, and its comparison with that for Spain, is not of great significance.

The differences between the results obtained in this study and those presented by Gordo and Sanz (2005) can be explained, at least in part, by the difference in the phenological phases studied. Limitations of the use of first flowering dates, relative to peak or 85% flowering, are discussed in the *Literature Review* chapter, but even if there were no limitations, there are likely to be less than perfect correlations between first flowering dates and peak flowering dates, particularly when analysed over multi-decadal periods as these different phenological events are influenced by slightly different driving forces. A second reason for differences is potentially owing to temporal differences in the study period, as Gordo and Sanz (2005) have worked with a 20-year longer dataset than the current study, extending back to 1943, and which terminates five years prior to the Iranian dataset. With climate forcing mechanisms such as El Niño acting over periods of more than five years, the length and timing of the study period can influence the trends (Ahas et al., 2002). However, these factors are unlikely to explain all of the differences in flowering date responses to climate variability and change observed. Rather, the different responses between the citrus types and cities analysed in this study, and between this study and Tortosa (Gordo and Sanz, 2005), highlight species and location specific phenological responses to climate variability and change.

Whilst the advance in flowering dates in response to a 1°C increase in annual T_{max} calculated for Kerman and Shiraz are considerably higher than those reported by Gordo and Sanz (2005), they are not inconsistent with relationships between the timing of spring phenological events and temperature increases for other species in other regions of the world presented in *Table 2.1*. Advances of fruit tree flowering dates, similar to those of the five citrus types for Kerman of 2-4d/°C, are reported for peach and almond in Beijing with 2.88d/°C and 2.19d/°C respectively (Lu et al., 2006); granny smith apple in Poland with 2.4d/°C (Kalbarczyk, 2009); cherry in Japan with 3-5d/°C (Primack et al., 2009b); and granny smith and golden delicious apple in the Western Cape, South Africa with 4.2d/°C and 2.4d/°C respectively (Grab & Craparo, 2011). The even larger advance of peak flowering dates in Shiraz in response to a 1°C temperature increase of approximately 6-8d/°C is consistent with findings for deciduous trees elsewhere, such as apple in England with 7-9d/°C (Cannell & Smith, 1986); hazel in Slovenia with 8d/°C (Črepinšek & Kajfež-Bogataj, 2006); and beech in Spain with 7.62d/°C (Gordo & Sanz, 2009).

Two of the few studies that address phenological responses of plants to climate change in Iran, model the response of chickpeas at different sowing dates (Gholipoor & Shahsavani, 2008), and use satellite imagery to determine advances in the timing of spring events (Kafaki et al., 2009), respectively. Both highlight the significance of the climate in the spring months preceding and during flowering. This pattern is expected theoretically through the induction of flowering occurring as a result of spring warming following the fulfilment of dormancy conditions. Thereafter, optimal temperatures need to be maintained to prevent the termination of flowering. This necessarily occurs in the months directly preceding and including peak flowering, and can be observed in relationships between T_{max}, T_{min} and precipitation, and the flowering dates of the five citrus types in this study. It is most clearly apparent for Gorgan, where significant relationships exist between the flowering dates of all five citrus types and T_{max} for May, the month of peak citrus flowering (*Table 5.9*). The relationships between the flowering dates for orange and sour orange in Gorgan are similarly statistically significant for T_{min} and precipitation in the month of May (*Table 5.10*).

For Kerman, there are statistically significant relationships between flowering dates of the five citrus types and T_{max} for the months of March, April and May, with the strongest correlations demonstrated for April (*Table 5.9*). In this city, peak flowering of the five citrus types occurs between the last month of March and mid-April. Whilst there are a far greater number of months for which relationships between the flowering dates of the five citrus types and T_{min} are statistically significant, ranging from January through to September, similar to T_{max}, the strongest correlations are for the month of peak flowering, April (*Table 5.10*). There are no significant relationships between monthly precipitation and the flowering dates of tangerine, however for the remaining four citrus types there are significant relationships for April (*Table 5.11*). Shiraz has statistically significant relationships between flowering dates for each of the five citrus types and both T_{max} and T_{min} for the majority of months, and similar to Kerman, the strongest correlations are found for April, the month in which peak flowering in Shiraz occurs (*Tables 5.9, 5.10*). Unlike Gorgan and Kerman, there are no months for which there are significant relationships between the flowering dates of any of the citrus types and precipitation. However, the strongest correlations are found for the month of April. The statistically significant relationships between flowering dates and the climate variables for the month of March in Kerman, and the months of January through March for Shiraz, highlight the importance of these climate variables in ensuring the fulfilment of dormancy conditions, and in inducing flowering.

This study, as with previous studies on phenological responses to climate variability and change, confirms that the temperature and precipitation during the month of flowering are the most closely related to, and hence the likely primary causal factors of, the annual date of peak or onset flowering (Chmielewski & Rötzer, 2002; Menzel et al., 2006a; Kafaki et al., 2009; Grab & Craparo, 2011). The phenological stages in the months directly preceding peak flowering (dormancy, floral induction, bud burst and first flowering), are dependant on the climatic conditions, and for the cities of Kerman and Shiraz this dependence is detected in the significant relationships between peak flowering date and the climate variables.

It is of interest to explore the months for which further significant relationships between these climate variables and flowering dates exist. In most cases, there are strong relationships between climate variables and flowering dates for the months directly following flowering. Peak flowering occurs within optimum period for floral induction, in which temperatures have warmed sufficiently, and rainfall onset has occurred to facilitate flowering. These optimal conditions then persist beyond flowering, serving to expedite fruitset (Connellan et al., 2010). There are, however, a number of months considerably later in the year (August to December), for which there are also statistically significant relationships between climatic conditions and flowering dates. This suggests that climatic conditions throughout the year facilitate the various phenological phases of the plant, such as the vegetative shoots and root growth (*Tables 1.1 & 1.2*), and hence regulate the nutrient and water supply of the plant, which are necessary for the timely release from dormancy and the induction of flowering (Goldschmidt et al., 1985; Srivastava et al., 2000; Luedeling & Gassner, 2012).

The differences in the patterns in the number and distribution of months that demonstrate significant relationships between precipitation and the flowering dates of the five citrus types in the three cities are notable. Most prominent is the difference between Shiraz, in which no months have significant relationships between precipitation and flowering dates, and Gorgan in which precipitation averages for the months of February, May, September, October and December all demonstrate significant relationships for the flowering dates of at least one citrus type (*Table 5.11*). This can be attributed to the use of irrigation in the semi-arid region of Shiraz, whereas the semi-humid Caspian Lowlands in which Gorgan is situated, where precipitation is experienced throughout the year, do not require irrigation for agriculture (Rajendra et al., 2003; Faramazi, 2010). The precipitation volumes for Shiraz would thus be unlikely to have any relationship with flowering dates, as the plants' water requirements are met through irrigation. Kerman, which receives the lowest annual precipitation of the three cities, interestingly demonstrates significant relationships with precipitation for April. However, Kerman receives the highest precipitation within the very arid Kerman Province, and is located at large distances from freshwater bodies, making it likely that in April, the irrigation needs to be supplemented by rainfall, rather than rainfall supplemented by irrigation (Atapour & Aftabi, 2002; Modarres & da Silva, 2007). This in turn would make rainfall rather than irrigation a significant determinant of flowering. This difference in potential climatic driving forces further emphasizes the need to simultaneously analyse different climate variables to determine those which best explain the phenological shifts occurring in each city.

Although there are no statistically significant relationships between the flowering dates of any of the citrus types and annual counts of days with T_{max} > 35°C or with T_{min} < 13°C for Gorgan, there are significant relationships between the flowering dates of four of the citrus types and days with T_{max} > 35°C for May, and significant relationships with the flowering dates of sour orange for March (*Tables 5.12, 5.13*). Similarly, the only significant relationships between days with T_{min} < 13°C and the flowering dates of orange and sweet lemon in Gorgan are for May (*Table 5.14*). The relationship between flowering dates of the five citrus types and annual counts of days in which both T_{max} and T_{min} < 13°C for Gorgan is significant only for sweet lemon. However, significant relationships for monthly counts include November and December for sweet lemon and sour lemon, and May for sour orange (*Table 5.15*). As with the distribution of monthly temperature and precipitation variables, the majority of these significant relationships occur in the month of flowering, and hence can be inferred as likely causal factors of flowering (Spano et al., 1999; De Melo-Abreu et al., 2004; Connellan et al., 2010).

Significant relationships between annual counts of days with T_{max} > 35°C for tangerine, days with T_{min} < 13°C for all five citrus types, and days with T_{max} and T_{min} < 13°C for all citrus types apart from sour lemon, are recorded for Kerman (*Table 5.12*). As in Gorgan, significant relationships with counts of days with T_{max} > 35°C for Kerman exist for May (*Table 5.13*). However, unlike Gorgan, flowering dates in Kerman occur during late March, for which individual month correlations with T_{max} > 35°C are particularly weak. Whilst relationships between flowering dates and counts of days with T_{min} < 13°C are significant for months from March through November, depending on the citrus type, the strongest relationships across all citrus types are demonstrated for April (*Table 5.14*), the month following peak flowering. Counts of days with T_{max} and T_{min} < 13°C have significant relationships with sour lemon for April, tangerine for March, and tangerine and sweet lemon for February (*Table 5.15*). It would thus appear that the counts of days in which T_{min} < 13°C which demonstrate strongest relationships for the month of flowering may indicate a direct causal effect on flowering dates. However, the more generic annual counts of days in which threshold conditions suitable for citrus growth are exceeded are more likely to represent conditions that affect the plant health and nutrient balance throughout the annual plant growth cycles in these two cities, an effect which is not as likely to occur in Gorgan (Mendel, 1968; Srivastava et al., 2000).

For Shiraz, as with Kerman, the relationships between the annual counts of days with T_{min} < 13°C are significant for all five citrus types (*Table 5.12*). Relationships between annual counts of days with T_{max} > 35°C in Shiraz are significant for the flowering dates only of orange and sour orange (*Table 5.12*). There are no citrus types for which there are significant relationships with the annual counts of days with T_{max} and T_{min} < 13°C (*Table 5.12*). Whilst a range of months, extending from March to November, demonstrate significant relationships between counts of days with T_{min} < 13°C and the flowering dates of the five citrus types, the strongest relationships are calculated for April, in which peak flowering occurs (*Table 5.14*). Significant relationships between monthly counts of days with T_{max} > 35°C and the flowering dates of orange, sweet lemon and sour orange are recorded for August, whilst the significant relationships for counts of days with T_{max} and T_{min} < 13°C are significant for orange, tangerine and sweet lemon in February (*Tables 5.13, 5.15*). It can thus be inferred that the number of days with T_{min} < 13°C directly affects the flowering date of the five citrus types, and indirectly affects flowering through its effect on the vegetative phases occurring throughout the spring to autumn seasons. The number of days where T_{max} > 35°C would appear to affect the flowering dates indirectly, through their impact on May fruitset, and consequently on the potential nutrient availability for the following year (Mendel, 1968; Goldschmidt, 1997). With the significant relationships between flowering dates and the number of days in which T_{max} and T_{min} < 13°C calculated for February, this threshold most likely affects flowering dates directly through the chilling requirement for dormancy release, resulting in flowering during the following two months.

For the winter months of November through February, the majority (over 80%) of days during each month experience T_{min} < 13°C in both Kerman and Shiraz (*Table 5.14*). Similarly, in the summer months of June through August over 90% of days in each month experience T_{max} > 35° C (*Table 5.13*). Despite significant relationships for both monthly and annual counts of days exceeding threshold conditions, the prevalent occurrence of 'above' or 'below' threshold days suggests that these thresholds are not critical to the survival of the plants, or to successful fruit yield. This highlights the role of threshold temperatures as an indirect driver of flowering dates. Whilst the plant requires the fulfilment of the temperature and/ or precipitation requirements for the break of dormancy, and thereafter warming to induce budburst and flowering, it would appear that the occurrence of days exceeding threshold temperatures acts either to counter or support these effects, and hence has a secondary role in the advance or delay of flowering (Mendel, 1968; Southwick & Davenport, 1986; Goldschmidt, 1997; Srivastava et al., 2000).

Relationships between the flowering dates of the five citrus types and the monthly total sunshine hours are significant for approximately three periods during the year for the three cities; these include February/March, April/May and August (*Table 5.17*). These periods roughly approximate the timing of the three vegetative flushes of citrus plants, in early spring, mid-summer and autumn (Guardiola, 1997; Tan & Swain, 2006). Increases in sunshine hours are conducive to increased photosynthesis, which in turn allow for plant growth. These significant relationships between flowering dates and leaf flushes represent indirect effects similar to that of the counts of days exceeding threshold conditions for citrus growth. With the exception of Shiraz, there are no particularly strong relationships between the month of flowering of the five citrus types and the monthly counts of sunshine hours, supporting the notion of a much weaker direct effect of sunshine hours on flowering. For Shiraz, there are relationships of a similar strength for August and September as those for April, which could imply that the first leaf flush occurs at a similar time to flowering dates in this city. As the relationships between annual counts of sunshine hours and flowering dates of the five citrus types are weak, with no significant relationships for Shiraz, it would appear that the number of sunshine hours is not a direct determinant of flowering dates.

6.2.4.2 Heat Units

Heat units refer to the temperatures above a base temperature of 13°C accumulated within a spring season, and are of value when determining the cumulative heat to which the plant is exposed, and the seasonal rate of warming (Mendel, 1968; Goldshmidt, 1997; Connellan et al., 2010). When interpreting the results from the growing degree day analysis, it is of interest first to note the patterns in statistical significance of trends in the date by which 200 heat units have been accumulated (ie. the rate of heat accumulation), and the trends in the actual number of heat units which have accumulated by flowering. For all three cities, the trends in the date by which 200 HU are accumulated are significant, ranging from correlation coefficients of 0.29 for Gorgan to 0.66 for Shiraz (*Table 5.18*). Shiraz not only has the strongest trend for the date at which 200 HU are accumulated, but is also the only city for which there are significant trends in the HU accumulated by peak flowering of all five citrus types (*Table 5.18*). Gorgan, which has the weakest trend in the JD at 200 HU, similarly has the weakest trends in the HU accumulated by flowering dates of the five citrus types (*Table 5.18*). Shiraz further demonstrates the strongest trends in advanced flowering dates over the period 1960-2010, whilst Gorgan exhibits the weakest trends in delayed flowering. It is thus unexpected that, when analysing the relationship between the JD at which 200 HU have been accumulated and the HU accumulated by flowering, Shiraz is the only city for which there are no significant relationships across the five citrus types, and that rather the strongest relationships are calculated for Gorgan (*Table 5.18*). This highlights the importance of running correlation and regression analyses for the comparison of factors, rather than simply inferring relationships from common trends, and highlights the complexity of driving factors of flowering dates, preventing a simple association of concurrent climate and phenological trends. When interpreting the inter-annual patterns in the statistically significant trends in both the JD at which 200 HU are accumulated, and the HU at flowering for each of the citrus types for Shiraz (*Figure 5.27),* it is distinct that within these long term trends, there are patterns of peaks in the JD at 200 HU occurring simultaneously with troughs in the HU accumulated by the date of flowering (*Figure 5.27*). This in part explains the particularly weak correlation for Shiraz, as the values for the JD at 200 HU very seldom change in a direction consistent with the HU accumulated by flowering. Moreover, this means that in years when 200 HU are reached by a late JD, flowering will occur at a lower HU accumulation, whereas when 200 HU are reached earlier in the year, flowering will occur at a higher HU accumulation, closer to 200 HU. This would imply that flowering in Shiraz will occur within a day in March, regardless of the rate at which 200 HU are accumulated, and at an HU accumulation which is a function of the distance between the date of flowering and the date of 200 HU accumulation, rather than a target value. For Gorgan and Kerman, there is much stronger alignment in the occurrence of peaks for both trends, particularly after 1970 *(Figure 5.25, 5.26)*. With the correlation analysis determining the extent to which an independent climate variable has the potential to explain the behaviour in the dependent variable, these patterns in the alignment of maximum and minimum conditions necessarily results in the return of strong correlations for Gorgan and Kerman, but not for Shiraz. Despite these strong correlations at Kerman and Gorgan, the inverse relationship between the HU at flowering, and the JD at which 200 HU are accumulated further suggests that flowering occurs at low HU accumulation when 200 HU are reached later in the year, which implies that the rate of HU accumulation up to flowering is poorly associated with the seasonal heat accumulation. Thus, whilst correlation strength is greater than that for Shiraz, the patterns of data association would suggest that there is no direct association between the rate of accumulation of 200 HU, and the HU accumulated by flowering. Regression analyses between the HU accumulated at the time of flowering and the flowering dates are poor, with flowering for Kerman and Shiraz frequently occurring at 0 HU, suggesting that the heat accumulation at flowering is not a strong direct driver of flowering date (Egea et al., 2003).

The relationship between the JD at 200 HU and the flowering dates of the five citrus types for each of the three cities is strongest for Kerman and Shiraz, and weakest for Gorgan. With the exception of the statistically significant correlation between the flowering dates of sour orange and the HU accumulated by flowering for Gorgan (r = 0.45), and the non-significant relationships for tangerine and sour lemon in Gorgan (r = 0.34 and 0.32 respectively), relationships between flowering dates and the JD at which 200 HU are accumulated are stronger than relationships between flowering dates and the HU accumulated by flowering (*Table 5.19*). The implication of these results is that the rate of heat accumulation throughout spring and early summer is a good indicator of the timing of flowering for that season (Stenzel et al., 2006). As citrus require the accumulation of heat to induce flowering once dormancy has been broken, both this result and inference are theoretically consistent (Mendel, 1968; García-Luís et al., 1992). For Gorgan, however, it would appear from the relatively weak correlation between the flowering dates and the JD at 200 HU, and also between flowering dates and the heat units accumulated by flowering, that heat accumulation is a relatively weak indicator of flowering time. This is interesting as in the arid to semi-arid regions of Kerman and Shiraz, precipitation acts to limit both plant growth and flowering, whereas in humid Gorgan, temperature is the more limiting factor, and yet the rate of accumulation of heat units would appear to be a less direct driver of flowering in Gorgan than it is in Kerman and Shiraz. When interpreting the distribution of the relationship between the JD at which 200 HU are accumulated and the JD of flowering for Gorgan, there is a considerable range in JD at which 200 HU are accumulated, which corresponds with very little change and poor trends in the JD of flowering (*Figure 5.33*). This suggests that the date at which 200 HU are reached does not determine the date of flowering, but rather that flowering will occur regardless of the rate of heat accumulation and has the potential to occur at a date with lower heat units. By contrast, the strong relationship between the JD at which 200 HU are accumulated and the JD of flowering in Shiraz is directly proportional, and hence a later date at which 200 HU are accumulated results in later flowering (*Figure 5.35*). The timing of the accumulation of 200 HU in Kerman demonstrates a moderately strong, significant relationship with flowering, which would imply that the rate of accumulation of HU in Kerman may at least serve as an indicator of the likely timing of flowering (*Figure 5.44*).

6.2.4.3 Multiple Regression Analysis

Whilst the merits of each of the multiple regression analyses are discussed later in this chapter, it is of interest to note those factors which are excluded from the multiple regression models using the *Backward* regression method. These models originally input all factors which demonstrated statistically significant individual relationships with the flowering dates for each of the five citrus types and in each of the cities, and the process of *Backwards Regression* eliminated those which, when analysed in conjunction with one another, did not improve the explanatory strength of the model. It would be expected that the elimination of the annual average of climate variables where the significant monthly trends are also included would reduce the effect of collinearity, whilst not decreasing the strength of the model. Indeed, annual averages and sums of at least one climate variable are removed for all the regression analyses for all of the citrus types in Kerman, and similarly for sweet lemon, sour lemon, and sour orange in Shiraz, and for tangerine and sweet lemon in Gorgan (*Table 6.3*). Further, it would be expected that all annual averages and sums would be eliminated before the monthly variables. For monthly variables, those furthest from flowering and which have no obvious indirect association with flowering (such as their coincidence with the timing of one of the leaf flushed, resulting in improved photosynthetic activity), would be expected to have been eliminated before variables for the month of flowering (*Table 6.3*). Whilst a considerable number of variables for the non-flowering months of July through to December are removed in these models, a notably large number of variables were retained for the month directly following flowering (June for Gorgan; May for Kerman and Shiraz).

Unexpected are the number of excluded variables for the months of flowering, in particular T_{max} and T_{min}, which have previously been highlighted as demonstrating strong, statistically significant individual relationships with the flowering dates, and hence as likely determinants of flowering time (*Table 6.3*). The multiple regression models have the highest predictive strength with the lowest root mean squared error and hence the lowest collinearity, when they combine indirect and direct explanatory factors for the months leading up to, but not including, flowering (Badeck et al., 2004; Doi, 2007; Estrella et al., 2007).

Table 6.3: Variables eliminated from the multiple regression models which originally included all variables with significant individual relationships with the flowering dates of the five citrus types in the three cities.

Variables eliminated through *Backward* regression	
Gorgan	
Orange	T_{min} Dec, precipitation Oct, T_{min} May
Tangerine	T_{max} & T_{min} < 13°C Dec, sunshine hours Mar, sunshine hours ann
Sweet Lemon	T_{min} May, T_{min} June, T_{max} & T_{min} < 13°C ann, T_{max} & T_{min} < 13°C May
Sour Lemon	None
Sour Orange	None
Kerman	
Orange	T_{max} May, T_{max} & T_{min} < 13°C ann, T_{min} July, T_{min} < 13°C Sept
Tangerine	T_{max} & T_{min} < 13°C Mar, T_{min} May, T_{max} ann, precipitation ann, T_{min} < 13°c ann
Sweet Lemon	T_{max} May, T_{min} < 13°C ann, T_{max} & T_{min} < 13°C ann, T_{min} < 13°C Apr, 200 HU, T_{min} May, T_{max} & T_{min} < 13°C Feb, T_{min} < 13°C May, T_{max} April, T_{min} < 13°C Nov, T_{min} < 13°C Sept, precipitation ann
Sour Lemon	T_{min} < 13°C ann, T_{max} April, T_{min} Aug, T_{min} ann, T_{min} < 13°C Oct
Sour Orange	T_{min} ann, T_{min} March, sunshine hours Dec, sunshine hours April, T_{min} Jul, sunshine hours May
Shiraz	
Orange	T_{max} May, T_{min} Nov, T_{min} < 13°C Nov, T_{min} Sept, T_{min} < 13°C May, T_{min} Oct
Tangerine	T_{max} Feb, T_{max} Mar, T_{min} Apr, T_{min} Feb, T_{min} Sept
Sweet Lemon	T_{max} ann, T_{min} ann, T_{max} July, T_{max} Mar
Sour Lemon	T_{min} Jul, T_{min} Apr, T_{min} Nov, T_{min} Feb, T_{min} Oct, T_{max} ann, T_{max} July
Sour Orange	T_{max} ann, T_{min} Apr, T_{min} < 13°C Nov, T_{max} Aug, T_{max} Jul, T_{max} Mar, T_{max} Oct, T_{min} Jul, T_{min} Sept, T_{min} Nov, T_{min} Aug, T_{min} Feb.

Variables listed in order of elimination.

Legend:

Annual variables

Variables for month directly after flowering

Variables for month directly preceding flowering

Variables for month of flowering

Variables for all other months

6.2.4 Comparison of Flowering Date Explanatory Models

Throughout this study, numerous regression models have been developed to accurately determine the effect that the available climate variables have had on shifts in flowering dates of the five citrus types during the period 1960-2010. In addition, these models have the potential to project likely flowering dates under continued climatic change. Whilst all of these models only include those variables which individually demonstrate statistically significant relationships with flowering dates, there is considerable difference between models developed through the *Enter* and the *Backward* regression methods. There is also considerable diversity in the strength of the models which included all significant variables, those with the annual average variables, and those which included only those variables which are individually statistically significant across all five citrus types for a particular city. Further difference exists between the explanatory power and standard error of the univariate and multivariate models which either individually or simultaneously include the effects of a set of common independent variables for the five citrus types for each city. All statistically significant models that are able to explain shifts in the flowering dates with a high percentage of explanatory power are of some value in understanding the role which climate variables over the 50 year study period have played in inducing shifts in flowering dates. However, it is of interest to analyse the relative strengths of each of the models developed.

Model selection foremost involves determining which model has both the strongest and most accurate predictive capacity. This first involves determining whether the model is statistically significant. The determination of the *p value*, which is a factor of the correlation coefficient (r) and the number of observations (n), is used to determine the likelihood that such a relationship could have occurred by chance. Any model that is not statistically significant should be excluded. Thereafter, comparison can be made on the basis of the R^2 values of each of the models, which reflect the percentage change in flowering dates explained by the model, and the standard or root mean squared error (RMSE) term (σ_{est}) which describes the standard deviation of the error term, and hence the accuracy, of the model. The third category of comparison is the AIC values which are calculated as a function of the number of observations (n), the standard error (σ_{est}) and the number of parameters in the model (k), for the purpose of model selection. Statistically, the 'best' model is one with a statistically significant *p value* ($p < 0.05$), the highest R^2 value, the lowest σ_{est} value and the lowest AIC value (Burnham & Anderson, 2002; Hu, 2007).

Thereafter model preference is decided more intuitively, based on the extent to which a model meets the requirements for its practical application. For example, a model which includes climate variables at a monthly resolution is of little value where the purpose of the model is to predict future shifts in flowering dates using downscaled GCM projections at an annual resolution. In attempting to determine the exact drivers of changes in the timing of phenological events over a historical period, however, a model which uses only annual climate data is likely to exclude more intricate relationships between flowering dates and their possible climate drivers, in which case models including all individually significant climate variables at both a monthly and annual scale would be preferable (Fitter & Fitter, 2002; Lu et al., 2006; Hegland et al., 2009).

The multivariate multiple regression model was developed to test whether a model which simultaneously incorporated the flowering dates of all five of the citrus types as a combined set of dependant variables, against the group of independent variables which had demonstrated significant individual trends for all of the flowering dates, was able to provide greater predictive strength and accuracy than individual models for each citrus type. The model significant monthly variables for all five citrus types in Gorgan, and the models for all three cities using annually averaged variables, the multivariate multiple regression models demonstrated higher R^2 values across all citrus types than the univariate multiple regression models for each of the five citrus types. However, as the model can only include years for which there are complete observations across all dependant and independent variables, the number of observations (n) decreases from the potential 51 to between 12 and 20. Consequently, many of these multivariate models are statistically insignificant. Those multiple regression models which remain statistically significant (those with annually averaged variables for Kerman and Shiraz) are further limited by the decreased *n value* in the AIC values, which are considerably higher than those for the univariate models. These AIC values highlight a preference for the univariate models over the multivariate approach.

Furthermore, as phenological responses of plants to climate variability and change are location and species dependant, both as reported in the literature and reiterated in this study (Parmesan 2007, *Table 2.1*), a univariate multiple regression model which aims to study the role of climate drivers on each plant type individually is more appropriate.

Model selection is thus restricted to the univariate multiple regression models which were developed for each of the five citrus types in each of the three cities. The generic models were developed to determine a common understanding of the role of those variables which are significant across all five citrus types for each city. Both the generic-variable and annual models facilitated the development and comparison of the multivariate multiple regression models. However, whilst the explanatory power of these generic models is greater than that of the annual models, it is weaker than the more specific models which include all of the factors with individually statistically significant relationships with the flowering of each citrus type. Consequently, outside of their use in the multivariate multiple regression analysis, these generic models offer little practical value as their inclusion of monthly variables make the resolution too fine for climate models, and through including only variables which are common to all citrus types, they exclude the detail for a complete understanding of the more precise drivers of phenological change experienced over the period 1960-2010.

The annual models include all of the annual averages of variables, for which the annual averages demonstrated significant relationships individually with peak flowering dates. Whilst these models do not have particularly strong explanatory power, they are potentially of great value when using GCM projections to project future flowering dates, and when including phenology components in GCM models due to their compatible resolution. Models with annual averages of climate variables have the added advantage of smoothing data gaps of a few of days, and of errors in recording. However, such smoothing accounts for some of the poor explanatory power of the models.

The multiple regression models for each citrus type in each city, which included those variables that demonstrated significant individual relationships for that citrus type in each city, have the strongest explanatory power and greatest accuracy of the three model input groups. This is to be expected as they input all of the variables with the strongest individual relationships, and similar to the nature of phenological responses both in this study and broader phenological literature, are species and location specific (*Table 2.1, Figures 5.2, 5.4, 5.6*). They are thus the most useful in explaining the nature of the relationships between the changes in flowering dates and the simultaneous changes in their explanatory independent climate variables. Whilst the resolution is too fine for use in GCM projections, their detail facilitates agricultural adaptation through a thorough understanding of the interacting roles of multiple changing climate variables.

For those models including all significant annual variables, and all significant monthly variables, both the *Enter* and the *Backward* regression approaches were undertaken. For this study, the process of variable elimination was terminated at that point at which the removal of a variable reduced the R^2 value by more than one decimal point for an improved root mean squared error of two decimal points (a maximum 10% change for a 1% change). The *Enter* method is useful in that it allows for comparison with the simple regression models with each of the individual independent variables, both in determining whether the coefficients have changed, and in presenting the increase in the predictive strength of the single variable model once additional factors have been included. However, for predictive purposes, it is detrimental to have included variables which do not contribute to the predictive strength of the model, but which rather increase the root mean squared error. In order to remove variables which increase the problem of collinearity, the *Backward* method is useful in refining the model. Thus, to achieve both the best understanding of the role that individual variables simultaneously have on flowering, and to ensure the strongest and most accurate explanatory power, both methods are of value. As it is unlikely that any one climate variable will influence the timing of peak flowering in isolation, such multiple regression methods are critical in understanding the relative influence of the multiple climate variables on the flowering of the plant. For citrus in particular, where both precipitation and temperature conditions can result in the release from dormancy and the induction of flowering, the explanation of any changes in flowering dates necessarily requires the simultaneous analysis of the impact of temperature and precipitation variables.

The improved explanatory strength of all of the multiple regression models in comparison to single variable regression supports this theory.

6.3 Implications of Results

6.3.1 Implications of phenological response to climate change

As there is no further phenological information available for the Iranian agricultural gardens, such as the timing of the onset and termination of flowering, the length of the fruiting season, or yield data, it is not possible to quantify the effect that shifts in the timing of peak flowering in the three cities have had on their agricultural success. However, shifts in the timing of any phenological phases which occur simultaneously with environmental and climatic changes, and significant correlations between phenological events and climate variables, suggest that plants are being affected by such changes. Through the modelling of flowering dates for the five citrus types, including both monthly and annual means of T_{max}, T_{min}, precipitation, sunshine hours, counts of days exceeding threshold temperatures and the timing of the accumulation of 200 HU in multiple regression analyses, it is highly likely that the observed changes in climate have, through their cumulative action, directly affected the peak citrus flowering dates in this study.

Given the strength of the combined impact of climatic variables on the flowering dates, the climate variability and change over the 51-year study period has undoubtedly had an effect on the five types of citrus trees in the gardens of Gorgan, Kerman and Shiraz. Further, it is unlikely that these climate changes would have affected only the peak flowering dates and no other phenological stage or yields (Beaubien & Freeland, 2000; Kafaki et al., 2009). However, even if peak flowering were the only phenological phase affected, the timing of peak flowering alone plays a significant role in the potential yields of the crop, and hence these shifts in flowering date have significant implications for crop success (Beaubien & Freeland, 2000; Rigby & Porporato, 2008). Peak flowering too late in the season increases the likelihood of late harvest and early winter frost risk to the fruits (Rigby & Porporato, 2008). The alternative to late fruit maturation after a fixed reproductive period following late peak flowering, is a decrease in the length of the reproductive period with less change in the date of fruit maturing, and hence a decrease in potential yields (Menzel, 2002). Both of these outcomes are of concern to citrus agriculture in Gorgan, where citrus flowering dates already occur later than in Kerman and Shiraz, and are demonstrating trends to continued delays in flowering. Whilst Gorgan does not experience many early winter frost days, the potential for decreases in the growing season is possible and should be monitored.

Peak flowering occurring too early in the year encourages early fruiting, and an increased potential for heat stress and damage to the fruits. The timing of peak flowering has a direct impact on the potential viability of the flowers (Cannell & Smith, 1986; Rosenzweig et al., 1996). Early flowers have a significantly higher likelihood of frost damage and premature flower-fall, whereas late flowers have the increased risk of experiencing temperatures exceeding the 35°C threshold, and hence suffering heat stress and wilting (Cannell & Smith, 1986; Rigby & Porporato, 2008). These are likely to be considerable risks for Shiraz and Kerman, with their early season flowering dates, and trends towards continued advance in flowering. Of greatest concern are the risks for Kerman, as the high aridity results in both a large number of days with frost conditions in late winter, and of temperatures exceeding 35°C throughout summer (*Table 5.6*).

Furthermore, flowering date shifts in either direction result in risks to the success of pollination (Fitter & Fitter, 2002; Hegland et al., 2009). Pollinators, such as bees for citrus, and the plant species with which the plants can cross-pollinate, may not necessarily respond in the same direction, or by the same magnitude, to the climate changes (Fitter & Fitter, 2002; Hegland et al., 2009; Moghadam et al., 2009). Finally, shifts in plant phenology can expose plants to increased threat of pests, particularly where the timing of the application of pesticides has not been adjusted accordingly (Gordo & Sanz, 2005). Thus, whilst the direct impact of climate variability and change on the success of citrus agriculture in these three cities cannot be directly quantified, it is likely that there would have been some impact.

Shifts in the timing of phenological events as a means of adaptation to climate variability and change may also result in changes in annual cycles and growth which are less easy to detect (Porter & Semenov, 2005). These may include changes in the timing and duration of the root growth period, which only occurs in the plant's reproductive dormancy phase, but which is required to ensure that the plant has the strength to hold greater yields, and the potential to absorb greater volumes of soil moisture (Srivastava et al., 2000; Fitter & Fitter, 2002). Climate changes may also induce changes in the timing and development of shoot growth and leaf flushes, which have a direct effect on the photosynthetic productivity of the plant, and hence nutrient availability for fruit production (Arora & Boer, 2005; Tan & Swain, 2006). These phenological shifts are impacted directly by the same climate factors responsible for changes in the timing of peak flowering, but also indirectly through the shifts in timing of flowering, which affects the plant's energy and water balance, and the timing of crop maturity (Stöckli & Vidale, 2004; Arora & Boer, 2005).

The impact of climate variability and change on plant health and crop yields may be mitigated to some extent through the correctional use of irrigation and fertilizer (Barnes & Bengtson, 1968; Tubiello et al., 2007). Provided that there is sufficient water availability, irrigation allows for compensation for precipitation shortages and variability (Tubiello et al., 2007). However, in an arid to semi-arid region which already suffers considerable water shortages, it is unlikely that these gardens will be able to receive sufficient irrigated water to compensate for the current precipitation deficit, or indefinitely. With trends for the period 1960 to 2010 suggesting considerable decreases in precipitation for the two more water-stressed cities of Kerman and Shiraz, which already require irrigation to support agriculture, it is likely that the precipitation deficit for these cities will continue to increase rapidly over future years (Rajendra et al., 2003; Faramazi, 2010; Roshan & Grab, 2012). Furthermore, as demonstrated in *Figure 6.4*, both cities are experiencing considerable population growth, which will compound the water stress (Rajendra et al., 2003; Solomon et al., 2007). In a simulation of the impacts of water shortages on projected future wheat yields, Roshan and Grab (2012) calculate water deficits for wheat producing regions of Iran of 23% by 2050 and 38% by 2100. These water deficits are projected to result in a far greater reliance on irrigation, and given the likelihood that such irrigation may be limited, the threat to wheat yields will be considerable, despite the improvement in the growing season length induced by temperature increases (Roshan and Grab, 2012). This, combined with the projected per capita water availability decrease from the present 2 000m^3 to 500m^3 by 2030, poses a serious challenge to the cultivation of fruit crops suited to Mediterranean mid-latitude and tropical regions, and of relevance to this study, for the continued profitable cultivation of citrus in Shiraz and Kerman (Faramazi, 2010; Yamouri, 2010; Parish et al., 2012).

Fertilization can improve the nitrate and phosphate availability to the plants, and hence potentially improve their reproductive and vegetative growth, but can do little to assist the plant when it experiences climate stress (Nerd et al., 1991; Tubiello et al., 2007). Without preventing the detrimental effects of increasing temperatures which are already detected in the trends toward increased counts of days with T_{max} > 35°C for the three cities over the period 1960-2010 (*Figures 5.19-5.21*), or changes in the number and distribution of daily sunshine hours (*Figures 5.22-5.24*), the improved yields associated with fertilization will not be able to ensure the long term success of these agricultural gardens in Iran (Tubiello et al., 2007).

To maintain successful yields, and ultimately the viability of the citrus trees in these agricultural gardens in Gorgan, Kerman and Shiraz, it is necessary to understand the nature and extent of the effects that climate variability and change over recent decades have had on the plants. Adaptation to the changing climate in Iran to maintain agricultural profitability and food security, will ultimately require a change in the plants farmed in arid cities such as Kerman and Shiraz to species or varieties which are far more resilient to the increased temperatures and water shortages (Rajendra et al., 2003). With continued trends towards unsuitable temperatures and water shortages, citrus farming would at some point need to relocate to regions with both sufficient precipitation and optimal temperatures. This would most likely mean an extension of citrus farming in the Caspian Lowlands extending further west from Gorgan, and the cessation of citrus farming in the inland regions of the Iranian plateau, including Shiraz and Kerman, together with Khorason, Fars and Jiroft (Ebrahimi, 2002). Citrus farming also currently takes place in the Persian Gulf Belt, in the cities of Homozgan and Boushehr, which have a milder and more humid climate than the more arid inland cities (Ebrahimi, 2002). If desalination of seawater became financially viable, citrus farming could potentially continue in this region through irrigation (Ebrahimi, 2002; Rajendra et al., 2003).

6.3.2 Future trends

With the trends in flowering dates for the period 1960-2010 statistically explained by increases in T_{max} and T_{min} over the study period, and increases in days with temperatures above 35°C, and representing a broader phenological response of these citrus types to increasing climate variability and ongoing climate change, under projections of continued climate warming into the mid- and late-21st century, it would be expected that the trends observed for the study period would continue in future decades. At some time, whilst temperatures may continue to increase, the rate at which flowering dates advance or are delayed will necessarily slow down, or flowering will become non-viable, unless simultaneous changes in the conditions which fulfil dormancy and which promote floral induction also occur. Assuming that flowering dates can continue to shift indefinitely and are not limited by secondary factors, the continued trends would mean advanced flowering dates from those observed for 2010 to 22-26 days by 2050, and tentatively 50-59 days by 2100 for Shiraz; and 5-7 days by 2050 and tentatively 11-15 days by 2100 for Kerman. Whilst the trends for Gorgan are considerably weaker over the study period, it is possible that under future warming, there will continue to be a progressive delay in peak flowering dates for the five citrus types at a similar rate, resulting in a shift of 2-4 days by 2050 and 5-9 days by 2100. For the purpose of these tentative projections, it is assumed that the similarities in the response of each of the citrus types to the set of significant climate drivers for each city, will remain in future decades since they varied only marginally over the study period.

6.3.2.1 Flowering Date Projections from GCMs

Downscaled GCM projections for annual T_{max}, T_{min} and precipitation for Gorgan, Kerman and Shiraz were provided by the University of Golestan, Iran. From these GCM projections, very tentative projections on future flowering dates can be made for the 21st century. These are produced using multiple regression models for each of the five citrus types in each of the three cities, based on the flowering dates, T_{max}, T_{min} and precipitation data for the period 1960 to 2010, inputting the GCM projected values for every 10 years from 2020 to 2100 (*Table 6.4*). These projected flowering dates for each of the five citrus types, together with the observed flowering dates for the year 2010, are then graphed to determine the possible nature of future trends. To make use of the annual GCM projections, these regression models do not have as complete an explanatory potential as the more inclusive models of historic flowering which included both monthly climate variables, and counts of days in which threshold temperatures are exceeded which are derived from daily data. These annual GCM projections do not facilitate the counting of days where temperatures exceed threshold conditions, nor growing degree day analyses. Furthermore, there are no projections for future sunshine hours.

Table 6.4: Regression equations for flowering projections using T_{max}, T_{min} and precipitation developed from the data for 1960-2010, with flowering date trends for each of the citrus types in Gorgan, Kerman and Shiraz.

Regression Equations for flowering date projections		
	Trend (1960-2010)	Projection Equation
GORGAN		
Orange	+0.10 d/yr	JD = 156.2 – 0.592(T_{max}) – 0.455(T_{min}) – 0.009(Precipitation)
Tangerine	+0.09 d/yr	JD = 154.56 – 1.269(T_{max}) + 1.282(T_{min}) – 0.016(Precipitation)
Sweet lemon	+0.07 d/yr	JD = 161.98 – 1.488(T_{max}) + 0.692(T_{min}) – 0.006(Precipitation)
Sour lemon	+0.07 d/yr	JD = 148.5 – 0.81(T_{max}) + 0.591(T_{min}) – 0.0004(Precipitation)
Sour orange	+0.05 d/yr	JD = 166.56 – 1.296(T_{max}) – 0.230(T_{min}) + 0.004(Precipitation)
SHIRAZ		
Orange	-0.63 d/yr	JD = 325.33 – 7.701(T_{max}) – 2.818(T_{min}) – 0.027(Precipitation)
Tangerine	-0.61 d/yr	JD = 328.18 – 7.74(T_{max}) – 2.738(T_{min}) – 0.034(Precipitation)
Sweet lemon	-0.65 d/yr	JD = 332.54 – 8.071(T_{max}) – 2.523(T_{min}) – 0.025(Precipitation)
Sour lemon	-0.56 d/yr	JD = 283.5 – 6.236(T_{max}) – 2.313(T_{min}) – 0.021(Precipitation)
Sour orange	-0.62 d/yr	JD = 334.62 – 7.857(T_{max}) – 3.186(T_{min}) – 0.024(Precipitation)

Climate outputs downscaled from the GCM HADCM3 for the cities of Gorgan, Kerman and Shiraz, under scenarios A1B, A2 and B1, are used in the projection of flowering dates. This climate model developed by the Hadley Centre for the 3rd Assessment Report of the IPCC, has a spatial resolution of 2.5° x 3.75°, which in the mid-latitudes approximates to an area of 417km x 278km (Gordon et al. 2000). Downscaling was thus required to improve the spatial resolution for projections for each city. This was undertaken using the climate data provided by the Iranian Meteorological Organization for each of the cities. Climate projections for annual T_{max}, T_{min} and precipitation were then made using the scenarios from the 4th IPCC Assessment Report for which the global projections are summarised in *Table 6.5*. Scenario A1B assumes rapid economic growth, population growth reaching nine billion by 2050 and thereafter declining, and a balanced emphasis on all energy sources (Solomon et al., 2007). Scenario A2 assumes a continually increasing population throughout the 21st century and regionally oriented economic development (Solomon et al., 2007). Scenario B1 assumes population growth up to 2050 and thereafter declining as per A1B, and with a shift to sustainability through renewable clean energy (Solomon et al., 2007).

Table 6.5: Projected global average surface warming from the 4th Assessment Report of the IPCC for scenarios A1B, A2 and B1 (after Solomon et al., 2007).

	Temperature Change (°C at 2090-2099 relative to 1980-1999)	
Case	Best estimate	Likely range
Constant year 2000 concentrations	0.6	0.3-0.9
B1 scenario	1.8	1.1-2.9
A1B scenario	2.8	1.7-4.4
A2 scenario	3.4	2.0-5.4

The accuracy of the downscaled GCM projections provided is questionable, particularly for Kerman, where there is a difference in projected temperatures for all three scenarios by up to 20°C from the 2010 values. The projected temperatures for Gorgan and Shiraz far more closely resemble the observed temperatures for 2010. As there is considerable inter-annual variability in precipitation, the projected precipitation values fall within the range of those observed over the period 1960 to 2010. Consequently, flowering date projections for only Gorgan and Shiraz are presented in *Figures 6.5 and 6.6*. These projections must, however, still be considered with caution. This is in part due to concerns as to the validity of the GCM projections, arising both from to the dated age of the HADCM3 model, and the inconsistencies in the downscaled outputs for Kerman. Further concerns exist as these regression models only include the climate variables for which GCM data is available – T_{max}, T_{min} and precipitation, rather than the complete group of historical climate variables used in this study. However, as the excluded variables are functions of T_{max}, T_{min} and precipitation, and as these three climate variables presented statistically significant individual correlations with the flowering dates of most of the citrus types for at least two cities, these projections are likely to provide an estimate of future peak flowering date trends.

Most notable in the flowering date projections for Gorgan is the variability in the responses of each of the citrus types (Fig 6.5), whereas over the 51-year study period they are largely similar, with all citrus types demonstrating progressive delays in flowering dates (*Figure 5.2*).

This variability is most evident in shifts to advanced flowering for orange and tangerine under A1B and A2 scenarios, and for orange under the B1 scenario (*Figure 6.5*). This is unexpected as these citrus types presented the strongest trends to delayed flowering dates of 0.1d/yr for orange and 0.09d/yr for tangerine over the period 1960 to 2010. Despite having the strongest shift in delayed flowering dates of the five citrus types in Gorgan over the period 1960-2010, orange and tangerine remained the earliest flowering citrus types in 2010. Notable are the anomalous projected dates of 129-130 Julian dates for orange and tangerine, deviating from the remainder of dates of between 131 and 133 JD under all scenarios (*Figure 6.5*). Not only are these anomalies of interest, but furthermore projected for the year 2070 for scenario A1B, 2050 for scenario A2 and 2030 for scenario B1, there is a delay in the occurrence of these outlier flowering dates across scenarios. These anomalies are coincident (and modelled through) the highest projected precipitation and lowest projected T_{max} occurring simultaneously, and highlight an interesting lag in these temperature and precipitation conditions between the scenarios. Projections for sour orange flowering dates demonstrate the largest variation between scenarios, with a small delay for A1B, a slight advance for B1 and a more rapid advance for B2 (*Figure 6.5*). Similar to the observed trends for 1960 to 2010, sweet lemon flowering dates consistently demonstrate minimal change across the three scenarios, which would imply that this citrus type has the greatest likelihood of maintaining profitable yields under continued climate change (*Figure 6.5*). Projections for sour lemon flowering dates most closely resemble the pattern in observed flowering dates over the study period, with a delay in flowering dates across all three scenarios. Should these differences in the trends between citrus types be an accurate projection of future conditions, it would have large implications on the capacity for adaptation as citrus types such sweet lemon may prove to be more robust in resisting climate stress. Those citrus types whose projected flowering is best associated with theoretical high yields, which would need to be determined experimentally, would be best suited for continued cultivation, and could replace those for which the shifts in flowering dates are detrimental to yields. However, as these trends are for the city which has the greatest water availability, this does not provide as great a benefit as it would for Kerman or Shiraz.

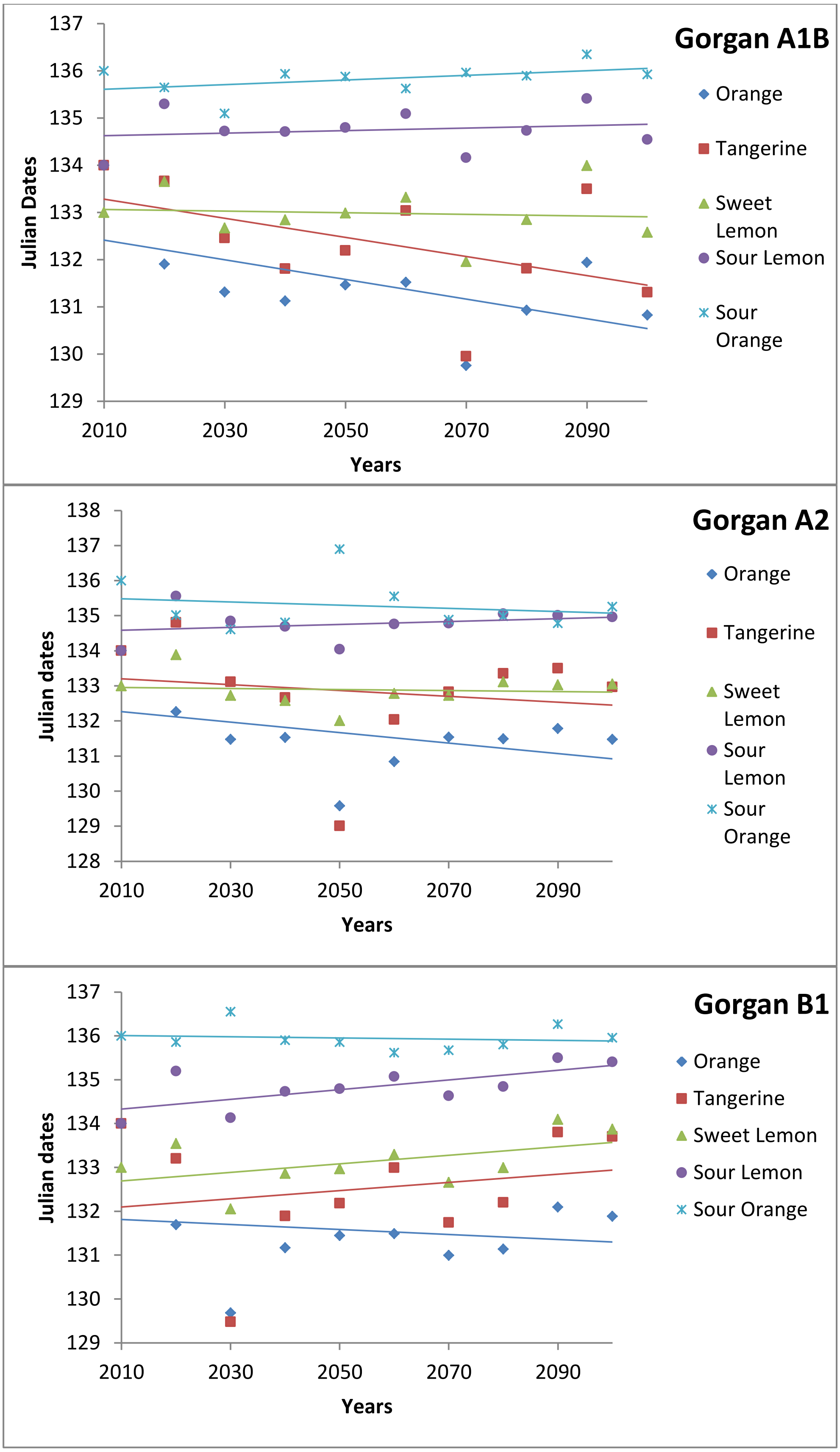

Figure 6.5: Flowering date projections for Gorgan for the 21st century calculated using downscaled temperature and precipitation projections from HADCM3.

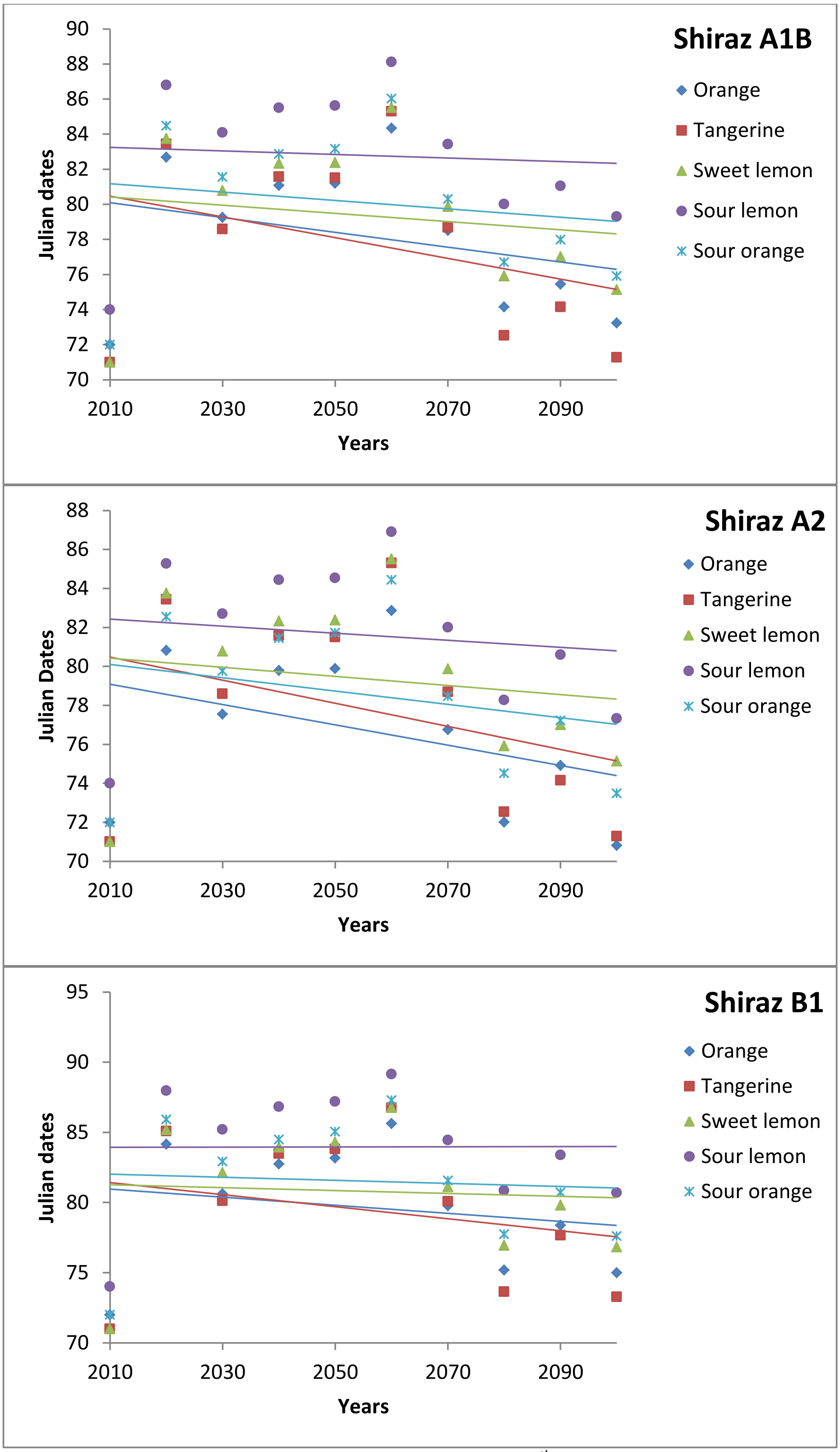

Figure 6.6: Flowering date projections for Shiraz for the 21st century calculated using downscaled temperature and precipitation projections from HADCM3.

Projected flowering date trends in Shiraz for the 21st century are considerably more consistent with the historic trends in observed flowering dates for 1960-2010 than for Gorgan (*Figure 6.6*). For Shiraz, the projections retain similarity between the five citrus types, and in maintaining trends for advancing flowering dates through to the year 2100 (*Figure 6.6*). Whilst the rates of change of flowering dates were very similar between citrus types in the observed record, there is considerable variation in the projected rates (*Figure 6.6*). For all three HADCM3 scenarios, flowering dates for sour lemon are projected to change very little throughout the century. Whilst sour lemon flowering dates demonstrate the least change over the period 1960 to 2010, with a shift to earlier flowering of 0.56d/yr, it is not as negligible a shift as those projected for all five citrus types. In all three scenarios, flowering dates for tangerine are projected to have the largest shift toward earlier flowering dates of the five citrus types (*Figure 6.6*). This is unexpected given that the fastest rate of change (0.65d/yr) over the study period was recorded for sweet lemon, and not tangerine (0.63d/yr). This presents a further inconsistency for sweet lemon flowering date projections under all three scenarios, which decrease only slightly over the century.

A large difference in the range of flowering dates is notable when comparing those observed for the period 1960-2010 and the projected dates for 2020-2100. Whilst peak flowering dates observed for the study period range from approximately 110 JD in 1960 to 70 JD by 2010, the projected flowering dates range from 90 JD in 2020 to 70 JD by 2100. Whilst projected flowering dates continue to advance over the century as they have done over the study period, the dates for the early to mid-century are considerably later in the year than those for the last decade of the observed study period. This is confirmed by observed flowering dates for 2010, which appear anomalously early when compared with the projected flowering dates for the remainder of the century. This suggests that the regression model, or the projected input climate variables, is returning flowering dates too late in the year, as a sudden delay in flowering dates between 2010 and 2020 is unlikely. Furthermore, with a shift in observed flowering dates by 40 JD over the period 1960-2010 and a shift of only 20 JD for the period 2020-2100, the rate of change across all citrus types is considerably larger for the observed record than from model projections. That said, flowering dates cannot advance indefinitely whilst still satisfying the requirements for dormancy and floral induction (Mendel, 1968; Southwick & Davenport, 1986; Srivastava et al., 2000). For viable flowering to continue, the rate of advance would at some point need to slow down. However, the concurrent timing of this delay with the transition from observed to modelled values most likely suggests a bias in the modelled flowering dates.

Whilst it is necessary to regard these projections with caution, it is very likely given the response of flowering dates to climate variability and change over the period 1960-2010, that there will continue to be a shift in flowering dates due to the increased rate of climate warming and precipitation changes expected during the 21st century. It is likely that the flowering dates for Gorgan will not indefinitely shift to later in the year, and these projections highlight that it may be the earlier flowering citrus types (orange and tangerine) which shift to advancing trends sooner, a theory supported by Miller-Rushing et al. (2007). Shifts in flowering dates for the five citrus types for Shiraz of between the 20 days using the projected values and 60 days from the observed data, are likely to have considerable implication for the agricultural success of these crops, through the risk of frost, pests and unsuccessful pollination. The projections thus provide valuable information on the likely future direction and magnitude of trends, particularly when compared with the observed trends for 1960-2010. Such information allows for improved management decisions for adaptation to continued climate variability and change.

6.3.2.2 Frost Risk

What is not captured by these projections is the possible effect of frost. An argument posed in phenological studies is that with an advance in flowering dates comes an increased risk of frost damage both to the flowers and the potential size and quality of yields (Cannelll & Smith, 1986; Inouye, 2008; Rigby & Porporato, 2008). However, this assumes that whilst the flowering date is advancing, the last frost day of the winter-spring season remains unchanged (Cannelll & Smith, 1986). Given that this study, and many which analyse frost effects, find advances in flowering dates to be positively associated with temperature warming, they often do not explore the relationship between warming temperatures and the last frost date, which would be likely to occur increasingly earlier in the season

(Rosenzweig et al., 1996). If the last frost date were to advance at a rate equal to, or greater than, the rate of flowering advancement for Kerman and Shiraz, there would not be increased frost risk. If, however, the last frost date were to advance at a slower rate than flowering dates, or in the case of Gorgan, be delayed at a greater rate than the delay in flowering, there would be some time in the future during which, given a continuation of these trends, frost would become a very high risk both to the flowers and the resultant yields (Rosenzweig et al., 1996).

Trends in the timing of the last frost date of the winter-season demonstrate a delay for Gorgan, and an advance for Kerman and Shiraz for the period 1960-2010. Notably, these frost date trends mimic the direction of trend of flowering dates for these three cities. This is particularly interesting in Gorgan where, whilst not statistically significant, trends to warmer T_{max} and T_{min} are calculated for this period, and yet the delay in frost dates of 0.20d/yr is more rapid than the flowering date delays of 0.07-0.10d/yr (*Table 5.1, Figure 6.7*). Of greatest concern is the very slow advance in the last frost date for Kerman (0.04d/yr), coupled with a relatively rapid advance in flowering dates (0.12-0.17d/yr) *(Table 5.1, Figure 6.8*). Whilst Shiraz demonstrates the most rapid advance in flowering dates (0.56-0.65d/yr), this occurs in association with a slightly less rapid advance in last frost dates (-0.47d/yr) (*Table 5.1, Figure 6.9*).

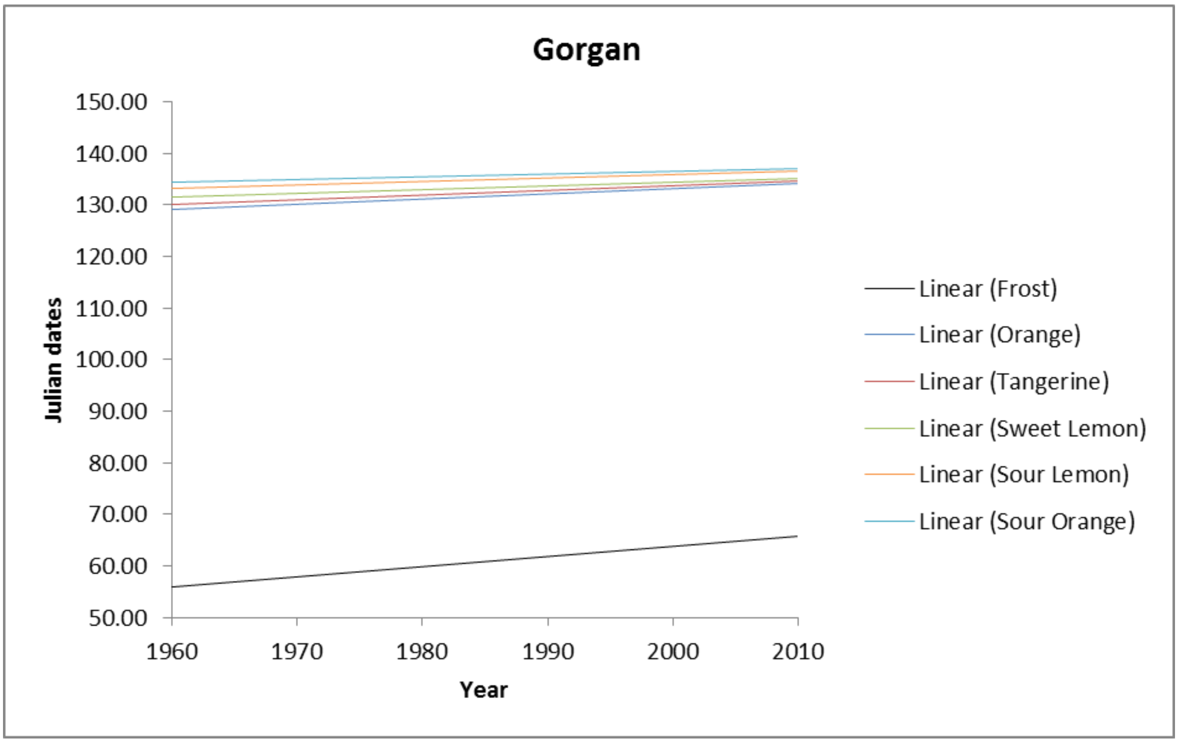

Figure 6.7: Trends in the timing of the last frost date and the flowering dates of the five citrus types for Gorgan over the period 1960-2010.

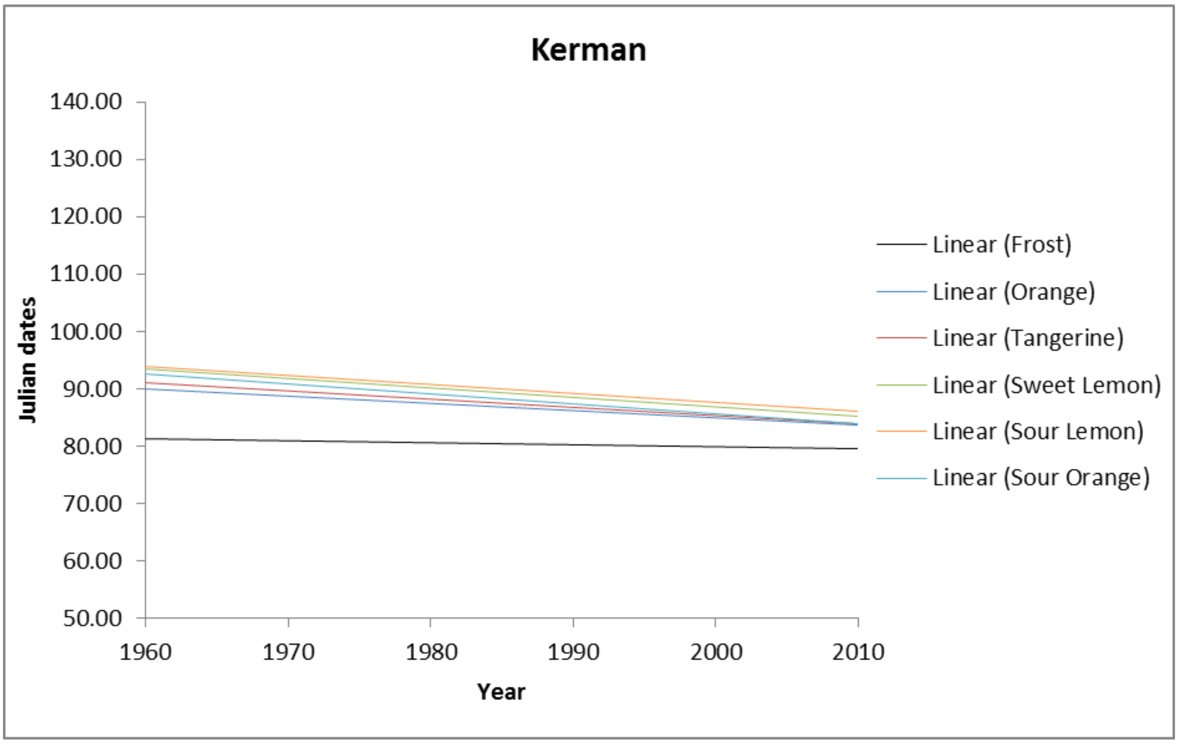

Figure 6.8: Trends in the timing of the last frost date and the flowering dates of the five citrus types for Kerman over the period 1960-2010.

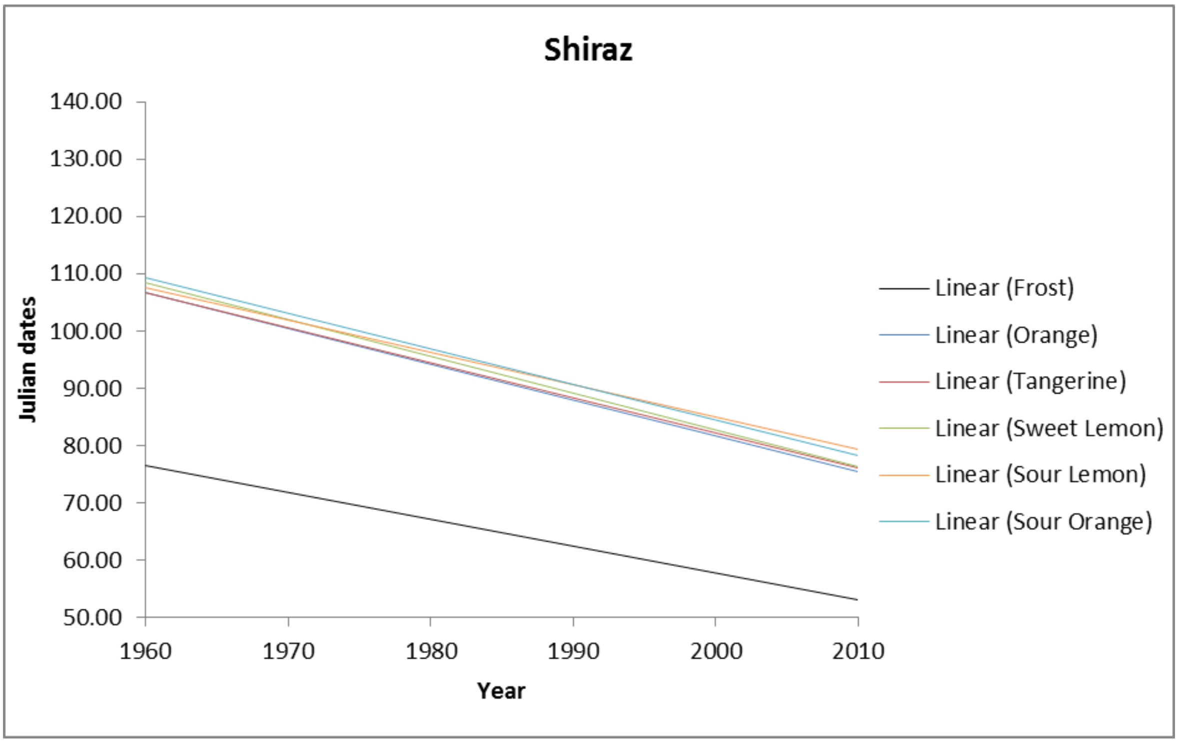

Figure 6.9: Trends in the timing of the last frost date and the flowering dates of the five citrus types for Shiraz over the period 1960-2010.

For Kerman and Shiraz, the advances in frost dates are less rapid than the shifts in flowering dates over the period 1960-2010, and for Gorgan the delays in last frost date are more rapid than the delays in flowering. If these trends for all three cities were to continue into the future, this would necessarily result in a time at which the trends intercept. Thereafter, there would be considerable frost risk to the flowers. However, it must be noted that, particularly for the inland cities of Kerman and Shiraz, which experience very low winter T_{max}, there are already years in which the last frost date occurs after peak flowering (*Table 6.6*). For Kerman, there has been an increase in the number of years in which frost occurs on or after the date of peak flowering for at least one of the citrus types, with 9/15 of the cases of last frost after peak flowering having occurred since 1988 (*Table 6.6*). Furthermore, there has been an increase in the number of days between peak flowering and the subsequent last frost date from 0-3 days in the years prior to 1988, to 0-15 days from 1988-2010 (*Table 6.6*). There has been an increase in the number of citrus types for which peak flowering occurs before the last frost date, with up to three in the years prior to 1988, and up to all five citrus types in the period 1988-2010 (*Table 6.6*). However, the severity of frost is much greater in the 1960s (ranging from -2°C to -5°C), than in the years from 1988-2000, with a peak frost severity of -2.8°C recorded for 1997 (*Table 6.6*). There has been no consistent change in the number of days in which frost conditions occur on or after peak flowering. Whilst the largest count of frost days following peak flowering (4 days) is recorded for 2005, T_{min} reached only -1°C (*Table 6.6*). By contrast, the second highest count of frost days following peak flowering (3 days) recorded for 1968 is associated with a considerably more severe frost with T_{min} reaching -4°C (*Table 6.6*).

The only incidence of last frost occurring after flowering for Shiraz, occurs in 2005 (*Table 6.6*). Notably, this is contemporaneous with the year in which Kerman recorded the highest number of frost days following peak flowering (*Table 6.6*). Despite the 14 day period between peak flowering of tangerine and the last frost day in Shiraz in 2005, only two days recorded frost temperatures on or after peak flowering (*Table 6.6*). Similar to the conditions in Kerman that year, the frost event was mild with T_{min} of 0°C for both days (*Table 6.6*).

Table 6.6: The occurrence of last frost dates on the same day or after the flowering dates of the five citrus types in Gorgan, Kerman and Shiraz.

Last frost dates on the same day or after the flowering date of citrus types.				
Year	Number of citrus types affected	Number of days between peak flowering and subsequent last frost	Maximum severity of frost on/ post peak flowering	Number of frost days on/ post peak flowering of earliest flowering citrus type
Gorgan				
none	-	-	-	-
Kerman				
1966	1	1	-5°C	2
1967	1	0	-2°C	1
1968	2	2	-4°C	3
1972	3	3	0°C	1
1978	3	2	-1°C	1
1983	2	1	-1°C	1
1988	1	7	-1.2°C	1
1990	4	7	0°C	2
1993	2	2	-1.6°C	2
1996	4	6	-1.6°C	1
1997	5	11	-2.8°C	1
2000	1	0	-2°C	1
2005	5	15	-1°C	4
2006	4	6	-0.4°C	2
2008	1	1	-0.8°C	1
Shiraz				
2005	5	14	0°C	2

Thus, whilst statistically significant increases in both T_{max} and T_{min} have been demonstrated for both cities over the period 1960-2010 (*Table 5.1*), the timing of the last day with $T_{min} \leq 0°C$ has changed so marginally that the citrus plants in Kerman, and to a lesser extent in Shiraz, have already been placed at an increasingly higher risk of frost damage to both the flowers and plant health over the study period (*Table 6.6*). However, the warm temperatures would appear to have acted to decrease the severity of these frost events, with T_{min} rarely dropping below -2°C in the days after peak flowering (*Table 6.6*).

The averaged trend lines in *Figures 6.7-6.9* indicate the highest frost risk scenario, with frost risk already confirmed by the occurrence of those late frost events after peak flowering dates over the period 1960-2010 for Kerman and Shiraz. For Gorgan the earliest high frost risk is likely to occur for sour orange which demonstrates the slowest delay in flowering dates, and is calculated for the year 2508. For Shiraz, where the earliest high frost risk is likely to be experienced by sour lemon, the convergence date is similarly outside of the century-end projections, calculated as the year 2280. For Kerman, however, where orange is likely to experience the earliest high frost risk, it falls within the century projections at 2082. This, combined with the occurrence, and trends toward increases in occurrence, of last frost dates after flowering over the period 1960-2010 (*Table 6.6*), the existing water scarcity in this landlocked city, and trends to decreased precipitation over the period 1960-2010 (*Table 5.2, Figure 5.15*), casts a bleak outlook for the future success of citrus farming in Kerman.

As the flowering dates from the projected climate data are quite different from those extrapolated from the 1960-2010 data trends, the future interception of flowering and frost trends should be calculated for the projected flowering dates. For Gorgan, the delay in frost dates recorded over the period 1960-2010 is of even greater concern for the advances in flowering dates projected to the end of the century calculated from GCM models for orange and tangerine under projection A1B; orange, tangerine and sour orange under projection A2; and orange and sour orange under projection B1 (*Figure 6.5*). For orange, which demonstrates advances across all three projections, the intercept with the extrapolated frost trends is calculated at years 2314 for A1B, 2325 for A2 and 2334 for B1. These projected years of intercepts of the trends are far sooner than the extrapolation of the

1960-2010 trends in flowering dates, but are still not within the 21st century projection period. For Shiraz, all citrus types demonstrate trends to advanced flowering in the projections for the 21st century, with tangerine flowering dates demonstrating the most rapid advances under all three scenarios (*Figure 6.6*). From these projected flowering dates, intercepts with the latest frost date trends from 1960-2010 calculate high frost risk for the year 1940 for GCM projection A1B and A2, and 1941 for projection B1. Not only are these dates considerably earlier than those produced by extrapolating both frost and flowering dates from 1960-2010, but the calculated intercept also falls prior to the study period. This could be as only flowering dates were projected using the GCM output, whilst frost dates were extrapolated from the 1960-2010 trends. However, it could also confirm concerns regarding the rate of change projected using these GCM outputs for temperature and precipitation, highlighting a further inconsistency in their output.

6.3.3 Implications for Continued Citrus Farming in Iran

Of the three cities studied, Gorgan's climate is arguably the best suited to citrus cultivation at present, and likely to be the city able to continue to grow citrus successfully in the future under projected climate and environmental change. Whilst there has been a statistically significant decrease in precipitation over the period 1960-2010, sufficient rainfall still occurs for irrigation to be unnecessary. In the unlikely event that precipitation decreases to the point of requiring irrigation in this humid city, the proximity to the Caspian Sea allows for feasible water supply through desalination. Gorgan also demonstrates the longest return period for the interception of frost and flowering date averages using both the extrapolated trends from the 1960-2010 data and the projections using GCM temperature and precipitation outputs. The variability in the rate of change of flowering dates, both over the period 1960-2010 and projected for the 21st century, allow for the preferential growth of the citrus type which best adapts to the changing climate. Whilst the citrus selection would need to be informed by laboratory tests, it could tentatively be suggested that this may be sour orange which is likely to be the last citrus type to experience considerable frost risk, or orange and tangerine which have experienced the least significant change in response to the climate variability and change over the period 1960-2010. The city demonstrates no statistically significant trends in the counts of days exceeding threshold temperatures, but with a strong positive trend in sunshine hours, is likely to facilitate enhanced photosynthetic production and ultimately improve yields.

Kerman, by contrast, appears to be least suited to citrus growth at present, and the most likely city to experience difficulty in cultivating citrus in future decades. With a highly arid climate and considerable distance from water sources, agriculture in Kerman is highly vulnerable to decreases in rainfall. With the lowest precipitation of the three cities, and a decreasing trend, this problem will be exacerbated in future decades. Paired with the 200% population growth in the city over the study period, Kerman is likely to face considerable water shortages. In addition, whilst Kerman demonstrates a statistically significant decrease in days with T_{min} < 13°C, the slow advance in frost days relative to flowering dates will potentially impact negatively on citrus agriculture before the end of the 21st century.

Shiraz, which demonstrated the largest advance in flowering dates over the period 1960-2010, may still be able to cultivate citrus successfully in the decades to come. The rate of advance in frost days, relative to peak flowering, is sufficiently high to prevent considerable frost risk within the 21st century. Shiraz experiences precipitation volumes intermediate to those of Kerman and Gorgan and, with a slight trend toward increased precipitation observed over the study period, is unlikely to face water stress as severe as that for Kerman. Of greatest concern to citrus farming in Shiraz is the trend (although at present statistically insignificant) to increased counts of days above the T_{max} > 35°C threshold. However, as the majority of these days occur after the period of peak flowering, the impact on flower viability with the result on yields is limited as the statistically significant decrease in counts of days with T_{min} < 13°C could compensate.

The considerable variability in the factors which demonstrate statistically significant relationships with, or which are likely to be limiting factors for, the flowering dates of the five citrus types in the three cities in Iran reinforces the location and species specificity of phenological responses to climate variability and change. Given this specificity in both the response to climate variables, and in those climate variables which are the strongest drivers, it is necessary to use statistical methods which incorporate all of these potential drivers simultaneously. Whilst many phenological studies individually analyse the role of temperature, precipitation, and heat units, this study provides evidence for the value in extending this analysis to include all of these factors in multiple regression analyses (Fitter et al., 1995; Keatley et al., 2002). This study further highlights the importance of studying each citrus type in each of the cities individually, rather than using averages across type or city, as this provides a more intricate understanding of the factors responsible for the flowering date of the plant, as well as the changes in flowering dates in response to variability in these climate factors.

6.4 Data and Methodological Limitations

6.4.1 Limitations in Data Collection

Climate data for this study were sourced from three weather stations registered with the Iranian Meteorological Association, which use robust electronic and manual daily weather recording gauges. With little margin for human interpretation, consistency of these data are impacted predominantly by mechanical faults, changes in the system of weather data collection, or human error when dealing with the manual daily recordings. The most likely occurrence of errors would coincide with the time of upgrade from manual to electronic data collection. Where human errors occur, they can often be easily detected and rectified. These most commonly take the form of entries with an extra digit (eg. a temperature reading of 134°C which could be the incorrect entry of 13°C, 34°C or 14°C); digits entered in the reverse order (eg. 71°C instead of 17°C); or the repetition of entries where either it is impossible due to significantly different weather conditions between the two days, or in the case of precipitation the low probability of identical rainfall sums on consecutive days. As it is not possible to determine with complete certainty what the correct value would have been, removing ostensibly incorrect entries is less detrimental to the dataset than the subsequent reduced *n value* (Dale, 2002; Ledneva et al., 2004; Nordli et al., 2008; Underhill & Bradfield, 2009). For this dataset, less than one weather variable was omitted per year in each city, reducing the *n value* by less than 0.3%. The shift from manual to electronic data collection is easily detected in the dataset by the inclusion of a further two decimal points.

No abrupt shifts in the climate variables coincide with this technological shift for each of the cities, but rather there is an improvement in the resolution of the data, which is obscured when averaged to monthly, seasonal and annual indices.

There is a far greater margin for inconsistency in the collection of phenology data, as it involves human judgement and bias, which are likely to change with experience over time and will differ between individuals (Miller-Rushing & Primack, 2008a). Whilst 85% bloom (peak bloom) is one of the most easily identified phenological stages, the exact date at which it is logged to have occurred depends on an individual's perception of the appearance of peak bloom for a particular species or orchard (Fitter et al., 1995; Amano et al., 2010). It is likely that with daily data, there is the potential for considerable variability in the dates recorded for the peak flowering event across orchards (Miller-Rushing et al., 2008a). Averaging the orchards, and also the three to four gardens of which they are components, for each of these cities, corrects for some of the noise in the dataset generated through inconsistencies. There are also likely to be differences between cities since farmers are probably briefed on phenological data collection by different people, especially given their geographic separation.

Whilst it is essential that a phenological dataset span at least three decades in order to infer the effect that climate variability and change are having on the plant species, it does incur inherent limitations in long-term data consistency. Year-on-year consistency relies on an observer identifying the time at which an orchard has the same bloom appearance as the previous year (Miller-Rushing & Primack, 2008a; Amano et al., 2010). This alone is difficult, and requires both memory of the previous year's conditions and consistency in the assessment of the orchard's appearance at particular phenophases (Fitter et al., 1995). This is where the development of experience, whilst bringing observations closer to an absolute 85% bloom, can lead to inconsistency over the period in which an individual makes observations. It is also almost certain that at some time during the 51-year study period one observer would be replaced by another. This subsequent observer will most likely have a different perception of what constitutes peak bloom and have less experience than the replaced observer (Miller-Rushing & Primack, 2008a).

These inconsistencies in phenology data collection are compounded by differences in appearance of each of the five citrus types at the time of 85% bloom, with some species producing a greater total number of flowers than others, or species with larger flowers appearing to be in full bloom earlier (Miller-Rushing & Primack, 2008a; Miller-Rushing et al., 2008a). This is the case for tangerine and orange in this study, with tangerine flowers holding a far greater number of flowers at peak bloom than orange (*Figures 6.10, 6.11*). All of the gardens in each of the three cities cultivate all five of the citrus types studied, but with a predominance of orange trees. Bloom percentage for each species can be difficult to infer, as peak bloom appearance can be markedly different (Ledneva et al., 2004; Miller-Rushing et al., 2008a), and inconsistencies can be eliminated through observations being made by the orchard and garden farmers who, by profession, are familiar with each of the citrus types (Ledneva et al., 2004; Gordo & Sanz, 2009).

Figure 6.10: Appearance of orange tree in peak bloom (after Wittenberg, 2009).

Figure 6.11: Appearance of a tangerine tree in full bloom, with considerably more flowers relative to orange (after Paz, 2012).

The phenology data are centrally managed by a single private company that assumes accountability for the data that it disseminates, thereby placing the onus on this company to ensure that, where possible, these possible data limitations can be accounted for. This, in part, involves communication with data collectors to ensure that they are all working with the same understanding of the appearance of peak flowering for each citrus type. Data management also involves the identification of outlier data entries, the determination of their validity and the detection of periods of sudden change which could be linked to observer bias. This also requires monitoring the data from each orchard and garden to identify any observers who are recording particularly different results as a first step towards improving their training, and the quality of future records. Given that accountability for data integrity resides with the data collection company, and the subsequent checks and balances which they would necessarily have to undertake, these limitations should not have resulted in deleteriously incorrect data.

One situation in which the integrity of both the phenology and climatological data may be compromised is in times of war and civil unrest (Chapman et al., 2005). During periods of conflict, the recording of data which are not essential for immediate human survival is often temporarily suspended to both increase the number of members of society who can fight in the war, and to protect those who are not involved in the conflict (Zurayk, 2011). Furthermore, agriculture often suffers from neglect from the farmers who similarly are required to join armed forces, or who are unable to continue to farm for fear of their safety, and from the destruction of farmland and crops in the cross-fire (Zurayk, 2011). In the years following war, agriculture further suffers through the loss of labour where people have been injured or killed in the conflict (Zurayk, 2011). It is thus not uncommon to find a hiatus in historical agricultural records over periods of conflict (Chapman et al., 2005). Both the 1979 Islamic Revolution in Iran and the Iran-Iraq war which took place from 1980-1988, fall within this study period (Ilias, 2010). Despite the significant impact which these periods of conflict had on the economy of Iran, there are no gaps in climate data coinciding with these events. Whilst there are gaps in the phenology data, these are not consistent across all citrus types in each city for any given year, nor are such gaps larger over periods coinciding with conflict (Ministry of Commerce, 2009; Ilias, 2010). This is perhaps as none of the cities studied form the administrative or business capitals of the country, and thus sufficient focus remained on agricultural management and data collection during these periods. It is therefore concluded that whilst conflict may be a significant factor in ensuring data consistency in countries over periods of war, this has not impacted on the data integrity from these three cities in Iran.

6.4.2 Limitations through Translation

These data are potentially compromised in accuracy through the translation of both dates and notation which was required for such data to be used without proficiency in the Persian language or alphabet. Fortunately, the Iranian Meteorological Organization keeps records of daily weather data in both English and Persian, and thus no translation was required for the use of these data. The phenology data however, were recorded in Persian with the timing of peak flowering archived according to the Persian calendar. Thus, both the translation of the data from Persian to English and the conversion of flowering dates from the Persian calendar to the Gregorian calendar were required before any data analysis could be undertaken. This translation was undertaken at the University of Golestan under the supervision of a climate change researcher, Dr Roshan.

Very little information in the phenology dataset required translating from Persian to English, as the flowering dates constituted the numerical day and the name of the month or, in later years, a completely numerical date. Brief notes on the city and citrus types also required translating. Therefore there was little margin for error, and where errors had occurred in translation these were easily detected as outliers (either during a manual review or once plotted) and retranslated.

There is a far greater margin for error and inconsistency in the conversion of dates from the Persian calendar to the Gregorian calendar. The modern Persian calendar, which forms the official calendar of Iran and Afghanistan, is a solar calendar adopted in 1925 (Dershowitz & Reingold, 2007). As in the Islamic calendar, years are counted since Mohammed's arrival in Medina, which in the Gregorian calendar is the year 622AD (Parise, 2002). However, as the Islamic calendar is a lunar calendar rather than the solar Persian calendar, the Gregorian calendar year 2011 AD, translates as the Persian calendar year 1390, but the Islamic calendar year 1432 (Parise, 2002; Dershowitz & Reingold, 2007). Each year begins on the spring equinox, a date which occurs on approximately 21 March on the Gregorian calendar (also known as the western or Christian calendar), calculated using astronomical rather than mathematical calculations (Dershowitz & Reingold, 2007). If the true astronomical spring equinox falls before noon Tehran time (GMT +3.5) on a particular day, that day becomes the first day of the year; if it falls after noon the following day becomes the first day of the year (Dershowitz & Reingold, 2007; Walker, 2009). By way of example, the year 1385 in the Persian calendar corresponds with the period from 21 March 2006 to 20 March 2007 in the Gregorian calendar (Ministry of Commerce, 2009). In leap years, the last month of the year has 30 instead of 29 days, where a leap year is defined as a year in which 366 days separate the two spring equinoxes (Dershowitz & Reingold, 2007). This can be approximated as grand cycle of 2 820 years, in which 2 137 years have 365 days, and 683 years are leap years with 366 days (Walker, 2009). This equates to approximately eight leap years in every 33 year period, rather than the eight leap years in a 32 year period in the Gregorian calendar (Walker, 2009).

The conversion from the solar calendar to the mathematically determined Gregorian calendar, with differences in the timing of the beginning of each year, inconsistencies in the occurrence of leap years, and differences in the numerical year itself, creates a considerable risk of error. The conversion of dates was undertaken at the University of Golestan, together with the translation. Consequently, there was consistency in the method of conversion, and any dates that were potentially erroneous could be re-checked. Some of the errors were easy to detect, such as dates of 31 November and consecutive years with 29 February, but there remains the potential for undetected errors. However, with consistency in conversion, the margin of error would only affect the absolute dates and their averages, and not the trends in changes over time. As these dates have been related to monthly, seasonal and annual averages of climate data, and indices such as thresholds, any conversion errors in dates will not affect the strength of the relationships with climate. The only relationship worthy of particular concern is that involving heat units, which are calculated up to the date of flowering. However, no years demonstrated any particularly unexpected results, or revealed patterns dissimilar to the remaining dataset.

6.4.3 Limitations of the data

Assuming that the errors and inconsistencies in data collection and translation are minimal, limitations exist which stem from the nature of the data itself. The climate datasets contained daily T_{max} and T_{min} values, together with three hourly wet and dry bulb temperatures. However, there were considerable gaps in these three hourly wet and dry bulb temperature records, with many months of data missing, particularly from the earlier years. In an attempt to use the most complete record, and to retain comparability with studies elsewhere in the world, only daily T_{max} and T_{min} values were used. However, the recording of T_{max} and T_{min} once every 24 hours obscures the temperature patterns within that period. The T_{max} record indicates the highest temperature experienced within a 24-hour period, but does not provide information regarding the duration for which that highest temperature occurred, or whether it was experienced more than once in that period (Coles, 2001). The predominant temperature experienced during the period is therefore unknown, and so limits calculations of the effects that temperatures may have on aspects of plant phenology and growth (Coles, 2001). This is particularly problematic when calculating thresholds, as a day with temperatures close to, but not exceeding, 35^{o}C for a large part of the day, may be far more detrimental to yields than a day during which the 35^{o}C threshold is exceeded for only a few minutes. Similarly, in this study the number of consecutive hours below 13^{o}C can at best be approximated by the number of consecutive days with minimum temperatures below 13^{o}C. Despite this forming the most continuous dataset available, and the measurement and use of daily T_{max} and T_{min} in climate change and phenology studies being commonplace globally (cf. Ghorbani & Soltani, 2003; Rigby & Porporato, 2008; Connellan et al., 2010; Gordo & Sanz, 2010; Grab & Craparo, 2011), little research has investigated sub-daily effects of particular temperatures and temperature thresholds on long term shifts in plant phenology, and certainly not for the flowering dates of citrus.

A further limitation exists due to the availability of only peak flowering dates. Whilst this phenological stage is one of the most climatically dependant, it does not convey any information about the onset or duration of flowering, nor does it indicate the absolute numbers of flowers on the trees or in the gardens (Beaubien & Freeland, 2000). Flowering has the potential to occur for a more prolonged or shortened period in response to climate variability and change, even if the peak date remains largely unchanged. For example, a very early first bloom can occur in late winter due to a sudden onset of rainfall and/ or unusually warm temperatures, whilst the majority of flowers bloom in season (Miller-Rushing et al., 2008a). The number of trees which experience peak flowering at the orchard or garden’s peak flowering time, and the number of flowers on the individual trees at that date, is also pertinent. A season in which low numbers of flowers are seen across an extended flowering period is phenologically and biologically different from one where peak flowering is captured during a narrow, but intense blooming period However, the use of data from only one phenological stage is not uncommon practise within the field, and is of concern for future research (Beaubien & Freeland, 2000).

6.4.4 Statistical limitations

6.4.4.1 Data Gaps

The primary limitation to the strength of statistical analyses, and their ability to accurately model and ascribe patterns to observed changes, arises from gaps in the data set. Missing data are inevitable in historical studies, particularly those which rely on manually collected data (Fitter et al., 1995; Ahas et al., 2002; Ledneva et al., 2004). Whether the missing data are interpolated through average values or modelled values, it is very unlikely that the interpolated value is identical to what the missing value would have been, and could consequently skew both the time trends and the relationships with climate variables (Ledneva et al., 2004; Nordli et al., 2008; Croitoru et al., 2012). For this reason the missing data summarized in *Table 6.6* were omitted from this study, rather than being replaced by interpolated values. This reduces the *n value* from the maximum 51 observations to only those complete observations for each variable (*Table 6.7*). The concern, both where interpolated values are included, but also where missing values are omitted, is that these missing values may have been distinct relative to the existing data. Had the missing value existed, a different trend or relationship might have resulted from the calculations.

Concerns regarding the possibility of missing values potentially changing the nature of identified trends are mitigated through the calculation of the statistical significance of each trend. The *p value* is calculated as a measure of statistical significance, determining the probability that the calculated trends and relationships would still hold in a greater dataset. The detrimental effect of a reduced *n value* resulting from the omission of missing data, which would not occur if interpolated values were included to maintain the total *n value*, ensures that the resultant lower level of statistical significance reported is a true probability that the results could not have been created by chance. However, even if the result is statistically significant, the limitations of a dataset with missing values, and their potential to dilute or strengthen correlations should still be considered.

Table 6.7: Gaps in the phenology and climate datasets for Gorgan, Kerman and Shiraz over the period 1960-2010.

Gaps in the Phenology and Climate Datasets	Number of gaps	% Gaps	Highest number of consecutive gaps	Date of most recent gap
GORGAN				
Orange Flowering	10	19.6	2	2002
Tangerine Flowering	8	15.7	3	1997
Sweet Lemon Flowering	10	19.6	3	1999
Sour Lemon Flowering	11	21.6	1	2004
Sour Orange Flowering	14	27.5	4	2004
Monthly T_{max}	0	0	0	-
Monthly T_{min}	0	0	0	-
Monthly Precipitation	0	0	0	-
Monthly Sunshine	246	38.2	191	Dec 2010
KERMAN				
Orange Flowering	8	15.7	2	2001
Tangerine Flowering	11	21.6	2	1992
Sweet Lemon Flowering	11	21.6	3	2002
Sour Lemon Flowering	11	21.6	3	1995
Sour Orange Flowering	9	17.7	3	2004
Monthly T_{max}	2	0.3	2	Feb 1968
Monthly T_{min}	2	0.3	2	Feb 1968
Monthly Precipitation	2	0.3	2	Feb 1968
Monthly Sunshine	107	17.5	60	Dec 2010
SHIRAZ				
Orange Flowering	7	13.7	3	1998
Tangerine Flowering	7	13.7	3	1988
Sweet Lemon Flowering	7	13.7	3	1988
Sour Lemon Flowering	12	23.5	3	2001
Sour Orange Flowering	9	17.7	3	1999
Monthly T_{max}	3	0.5	2	May 1985
Monthly T_{min}	2	0.3	1	May 1985
Monthly Precipitation	2	0.3	1	May 1985
Monthly Sunshine	65	10.6	49	Dec 2010

6.4.4.2 Collinearity

Multiple regression models were developed using both the *Enter* and *Backward* methods to ensure that only those significant contributing factors were included, and so that the detrimental effect of multicollinearity could be reduced. However, multicollinearity cannot be completely eliminated. Two explanatory factors which both demonstrate strong, individually significant, linear correlations with the dependant variable such that they are included in the multiple regression model, may have similar effects on the dependant variable. Absolute multicollinearity would occur, for example, if the same temperatures recorded first in degrees Celsius and then in degrees Fahrenheit were both included in the model. Whilst they have different absolute values, their trends over time and relationships with flowering dates would be identical. Less obvious cases exist where there is a strong relationship between two factors, such as sunshine hours and the percentage cloud cover on a particular day.

Where the addition of one of these collinear factors contributes significantly more predictive strength to the model, without dramatically increasing the standard error of the estimate, it should be included in the model despite the resultant multicollinearity. Any remaining effect of multicollinearity does not reduce the reliability or predictive strength of the models developed, as the regression model is sufficiently robust to provide equal weight to the influence of determining factors, regardless of whether they have very similar trends to one another, or are unique (Berry & Feldman, 1994). However, it does create difficulties in consistently attributing the relative effects of each of the determining factors in the completed model. With the overlap of causal effects of factors which are co-influenced, and hence act in conjunction with one another, the relative effects do not necessarily sum to 100% explanatory strength, nor can they be determined until the model is complete (Berry & Feldman, 1994; Underhill & Bradfield, 2009).

6.5 Additional Causal Factors for Shifts in Flowering Dates

Over 80% of the variability in the flowering dates of each of the five citrus types in each of the three cities can statistically be attributed to the studied climatic variables through multiple regression analysis. However, there remains a small percentage of the flowering date variability which is unaccounted for. Additional climatic and non-climatic causal factors which, for lack of available data, could not quantitatively be included in this study, would likely have contributed to the remaining inter-annual variability in flowering dates. The potential that these factors have to influence the timing of citrus flowering dates, particularly when acting in conjunction with the climatic variable studied, creates considerable incentive for the quantitative recording of such variables in future (Peñuelas et al., 2009; Keatley & Hudson, 2012). Whilst many of these factors have been highlighted previously in this chapter, they will be summarised as factors of future interest.

The first of these factors is soil moisture and temperature. These soil properties have a direct impact on the timing and extent of seasonal root flushes (Noling, 2011). The timing of root flushes has the potential to influence the timing of flowering, as the nutrient balance of the plant, to a large extent, prohibits concurrent root, vegetative and reproductive growth, with citrus root growth taking place during the dormant period of the phenological cycle (Fares & Alva, 2000; Noling, 2011). Soil moisture influences the plant's moisture intake, and hence an increase in soil moisture above a minimum threshold can potentially trigger floral induction in a water stressed region (Fares & Alva, 2000). For citrus, where the release from dormancy can occur as a result of either heat or water stress, a decrease in soil moisture could result in a more rapid completion of the dormancy requirements (Fares & Alva, 2000; Srivastava et al., 2000). More recent phenology studies are including soil moisture where the data are available, with water stress acting both to advance and delay flowering (Richardson et al., 2009; Hudson et al., 2010; Polgar & Primack, 2011). However, when compared with the direct effect of air temperature, Badeck et al. (2004) argue that soil properties such as moisture, nutrients and temperature have a negligible effect on plant phenology. Furthermore, as near surface soil moisture is largely determined by the amount and timing of precipitation rather than the groundwater level, and the near surface soil temperature is dependent on surface air temperatures, these factors are already partly accounted for indirectly in this study. Furthermore, as soil moisture and temperature are directly driven by atmospheric temperature and precipitation, the atmospheric and soil conditions would be likely to have effects on flowering dates which are largely collinear. Consequently, they would most likely be excluded from the final multiple regression models through the process of *Backward* regression anyway.

Closely associated with soil moisture, are changes in the quantity and timing of irrigation. As discussed in *section 1.3*, any changes in the amount and timing of irrigated water provided to the gardens in Kerman and Shiraz are likely to have a considerable impact on the timing of peak flowering, particularly as the flowering dates in these two cities are poorly associated with natural water availability through precipitation (Barnes & Bengtson, 1968; Atapour & Aftabi, 2002; Modarres & da Silva, 2007). Given changes in water availability in Iran, in addition to fluctuations in direct human freshwater consumption, there was probably considerable variability in the amount of irrigated water supplied over the 51-year study period (Rajendra et al., 2003; Faramazi, 2010). The quantity and timing of irrigation, and the total amount of water that the plants received each year, could potentially explain some of the change in flowering dates observed (Modarres & da Silva, 2007). However, these data are unavailable. As water stress increases in future decades, particularly in the arid regions of Iran, the potential to maintain sufficient irrigation will likely be compromised. It is therefore important to understand the degree to which the flowering time, and ultimately crop yields, of citrus are currently reliant on irrigation in each of these cities (Tubiello et al., 2007).

The timing, quantity, method and type of fertilization can similarly affect the timing of flowering. Fertilization provides essential nutrients which allow the plant to sustain vegetative and reproductive growth once dormancy has been broken. This can particularly affect the timing of peak flowering, as this phenological stage requires especially high plant concentrates of nitrates and phosphorous, both of which are provided predominantly through fertilization in cultivated soils (Barnes & Bengtson, 1968; Calvert, 1970). Delayed fertilization, or low concentrations of either phosphorous or nitrates in a particular fertilizer, may delay flowering, or result in reduced flower numbers (Barnes & Bengtson, 1968; Nerd et al., 1991). Similarly, changes in the method of fertilizer application and the type of fertilizer can influence the efficacy of the transfer of these nutrients to the plant and consequently result in shifts in peak flowering dates (Pasda et al., 2001; Miller et al., 2005). Whlist fertilization cannot mitigate climate induced changes in flowering dates indefinitely; information on the fertilization use would be of value to better understand the potential role of fertilization in driving shifts in flowering dates, and in preventing detrimental fertilization changes under conditions of climate variability and change (Tubiello et al., 2007).

Further agricultural management-related changes which are likely to have played some role in the observed shifts in flowering dates include the timing of fruit harvest and the frequency and manner in which pruning is undertaken (Srivastava et al., 2000; Stuckens et al., 2011). Both of these practices potentially have a significant impact on both the timing of onset of plant dormancy, as well as the seasonal nutrient balance as the removal of both reproductive and vegetative shoots increases the moisture and nutrient availability for the remainder of the plant (Krajewski & Rabe, 1995; Srivastava et al., 2000). The frequency and manner in which trees are pruned can further influence the amount of sunlight which reaches the lower branches, and hence the photosynthetic potential of the subsequent crop (Planchais and Sinoquet 1998; Pinkard, 2002). However, pruning during or directly after the dormant period necessarily results in a decrease in the number of buds, and hence in the quantity and possible timing of peak flowering (Guardiola, 1997). A further management related factor is changes in pest and disease control. Pests and disease can damage buds both during and after dormancy, and in so doing, delay the timing of flowering (Bellows & Morse, 1986; Rosenzweig et al., 1996; Tubiello et al., 2007). Agricultural management practices of interest to the timing of flowering include the growth and position of windbreaks and the replacement of damaged trees, both of which have an impact on the overall health of the orchard (Stuckens et al., 2011).

The impact of the increased development of the cities surrounding these orchards over the 51-year period is not without consequence. Continued population growth, rural-urban migration and the economic growth experienced following the end of the Islamic Revolution and Iran-Iraq war resulted in the considerable expansion of Iranian cities. This results not only in the urban heat island effect which should be detected in the temperature record, but also in changes in the wind strength and direction, evaporation, and potentially in cloud formation. These changes would likely contribute to the shifts in flowering dates over the study period, and would require both a more detailed climate dataset to include information on wind patterns and evaporation rates, and phenology data from individual gardens both within and outside the city boundaries, to be explained (Lu et al., 2006; Jochner et al., 2012).

Associated with an increase in city size, is the global issue of increased atmospheric CO_2 since the industrial revolution. Whilst CO_2 is taken up by plants and used in energy production through photosynthesis, the effects of continued increases in atmospheric CO_2 on both the plant health and productivity are uncertain (Tubiello et al., 2007). In studies where citrus trees are exposed to elevated CO_2 levels under differing heat increases in a humid subtropical environment, Allen and Vu (2009) report improvements in root growth, but little change in leaf growth and fine root biomass. In an earlier study of sour orange trees in the arid climate of Tucson, USA, which tested growth rates at ambient and heightened CO_2 levels, Idso and Kimball (1992) found an increase in tree growth of up to 3.8 times the normal rate. This study further found no differences in the photosynthetic success of those plants exposed to heightened CO_2, suggesting little change in the plant mechanisms for the intake and processing of atmospheric CO_2 (Idso & Kimball, 1992). Whilst these improvements in tree and root growth would be advantageous to citrus cultivation in Iran, as they would improve the trees' capacity to hold larger yields, and are consistent with findings of CO_2 'fertilization' improving crop yields, there remains the risk of a threshold existing beyond which atmospheric CO_2 concentrations are neutral or detrimental to the plant health and growth (Tubiello et al., 2007; Schlenker & Roberts, 2008). Furthermore, it is argued that plants may have improved water use efficiency under elevated atmospheric CO_2 concentrations, and consequently would be able to increase the rate of growth with less reliance on water, and hence offset some of the negative effects of the likely water stress (Beerling & Chaloner, 1992; Eamus, 2006).

As these increases in CO_2 are directly related to, and responsible for, global temperature increases, the secondary effects are of concern to the plant survival (Schneider, 2001; Tubiello et al., 2007; Allen and Vu, 2009). Finally, CO_2, largely produced through fossil fuels, is associated with a suite of other atmospheric pollutants which are of both direct concern to plants, and indirect concern through their contribution to acid rain and soil pollution (Turco, 2002; Tubiello et al., 2007). CO_2 loading cannot be included in multiple regression models, as at present, measures of atmospheric levels of CO_2 and changes in these concentrations are averaged across far greater time periods and over much larger geographic regions than the study period and site (Tubiello et al., 2007).

Chapter 7

CONCLUSIONS

[7]

7.1 Introduction

The study of the phenological responses of plant and animal species to long term fluctuations in temperature and precipitation is a rapidly advancing sub-discipline in climate change science (Schwartz, 1999; Sparks, 2005; Latifovic & Pouliot, 2007). Phenology has the potential to serve as an indicator of contemporary climate change impacts on the natural environment (Sparks and Carey, 1995; Badeck et al., 2004). This can inform strategies for both agricultural and ecosystem adaptation to climate change, through the identification of regions and species for which the phenological changes indicate particularly high or low stress in response to the changing climate (Hegland et al., 2009; Croitutu, 2012). In addition, phenological studies facilitate the projection of plant responses to future climate changes by extrapolating the current rates of phenological change resulting from climate warming and changes in precipitation (Morisette at al., 2009). The numerous phenological studies which have been conducted over the past four decades have highlighted the markedly species and location dependant nature of these plant and animal reactions to climate change which have taken place over the past century (Parmesan, 2007; Miller-Rushing & Primack, 2008b; Grab & Craparo, 2011).

Within this context, the primary aim of this study was to contribute to the discipline of phenology through the investigation of a species group and region for which phenological research to date is scarce. Through the analysis of the response of citrus flowering to climate variability and change in Iran, this study makes a contribution to improved global understanding of deciduous fruit tree phenology shifts in response to a changing climate. Furthermore, it provides information which can assist in maintaining profitable citrus yields in Iran through the identification of the rates of climate and phenological change, and the relative impacts of the various climatic factors in each of the three study cities.

This chapter synthesises the key findings of the study. It will first analyse the extent to which the aims and objectives have been achieved, and highlight the primary results produced. This is followed by a discussion of findings that were not initially anticipated, presenting results which are either inconsistent with the majority of phenology literature, or which demonstrate differences from the expected findings. A brief summary of the potential implications for agriculture in Iran follows. The chapter concludes with suggestions for future work on citrus phenology in Iran, the Middle East, and indeed the broader phenological discipline at a global scale.

7.2 Achievement of Study Aims

There were four primary research aims in this study which involved analysis of 51 years of meteorological and phenological data and the nature of relationships between them, whilst comparing the results from each of the study cities. The extent to which each of the specific study aims has been achieved and the resultant key findings will be discussed in the order in which the aims are presented in *section 1.5*.

1. To determine the flowering time of each of the five citrus types together with the climatic conditions in each of three cities.

This aim required an analysis of the climate and phenology conditions. Achieving this aim involved determining the average climatic conditions and peak (85%) flowering dates for each of the five citrus types over the period of 1960-2010, and the extent and nature of the variability in flowering and climatic conditions over this period. This was achieved through the calculation of the study period mean and variance, together with an analysis of the spread of the data through five-number summaries. The daily raw climate data spanned the 51-year study period, and with missing data for no more than three continuous months, closely resemble the true mean conditions. There were considerably more gaps in the phenological data, which necessarily decreases the confidence in calculations of average, variability and spread. However, as these gaps are distributed throughout the dataset, and do not extend beyond three continuous years, it is unlikely that they would have skewed these long-term calculations substantially.

Notable climatic differences between the three study cities were highlighted. Kerman, located in the landlocked Iranian Plateau has a typically arid climate, with the lowest precipitation of the three locations and the largest diurnal temperature range. By contrast Gorgan, which is situated in the Caspian Lowlands, has a humid climate with the highest precipitation of the three cities and the smallest annually averaged diurnal temperature range. The climate demonstrated through these findings is in agreement with the literature, and the climatic differences between the cities provide an interesting context for research on a common set of plant species or types.

The analysis of the phenology data for the period 1960-2010 highlights greater similarities between the peak flowering dates of the five citrus types within each of the cities, than for each of the citrus types across the three cities. Given the climatic differences between the three cities, this suggests that the climatic and environmental factors have stronger control on the peak flowering dates in citrus than the intrinsic qualities of each citrus type. Peak flowering occurred earliest in Kerman and latest in Gorgan, with flowering dates between cities ranging from late March to mid-May. For Shiraz, flowering occurred approximately two weeks later than Kerman. As Kerman and Shiraz have a more distinct seasonality than Gorgan, the difference in mean peak flowering date is arguably because winter conditions in Gorgan take longer to fulfil either the cold or drought requirements for the release from dormancy.

2. To determine the nature of any changes and trends in temperature and rainfall, and indices of these climate variables, over the period 1960–2010 for Gorgan, Kerman and Shiraz.

Linear correlation analysis of the climate variables was used in order to determine whether there had been any progressive change in the climatic conditions over the 51-year study period. The climate variables for which trends were analysed included both monthly and annual averages of T_{max}, T_{min}, precipitation and sunshine hours, in addition to the monthly and annual counts of days where temperatures exceeded previously defined thresholds suitable for citrus flowering (viz. T_{max} > 35°C, T_{min} < 13°C and T_{max} and T_{min} < 13°C). Similar to the mean climate calculated for the period 1960-2010, trends over this period varied between the three cities. Statistically significant increases in annual T_{max} and T_{min} are calculated for Kerman and Shiraz, with no statistically significant trends found for annual precipitation. By contrast, Gorgan has experienced a statistically significant decrease in precipitation over the study period, but displays no statistical trends in temperature. The strongest trends in annual threshold temperatures for the three cities are for the counts of days with T_{min} < 13°C, but similarly are significant only for Kerman and Shiraz. Trends in annual sunshine hours are strongest in Gorgan and weaker but statistically significant for Kerman. By contrast, annual sunshine trends are statistically insignificant for Shiraz. The difference in strength of trends between Kerman and Shiraz is interesting since these cities demonstrate similar trends for all other annual climate variables. This indicates greater complexity in the climatic differences between the three cities, and supports the individual analysis of the phenological responses of the five citrus types for each city.

Trends in the monthly averages of climate variables over the study period highlight further differences between the three study cities. Trends in T_{max} and T_{min} are generally statistically significant for the month of May for Gorgan, March through May for Kerman, and February through November for Shiraz. Therefore, the majority of months contribute to the statistically significant annual temperature trends calculated for Shiraz. By contrast, for Kerman and Gorgan monthly trends are significant only for a relatively narrow period which coincides with the mean timing of peak flowering in these cities. Trends in monthly precipitation are not statistically significant for any month in Shiraz, whereas in Gorgan and Kerman significant trends again coincide with peak flowering. Fewer months demonstrate significant trends in counts of days with T_{min} < 13°C, but they too include May for Gorgan, March-April for Kerman and April for Shiraz. Whilst Gorgan demonstrated the strongest trends in annual sunshine hours, very few months demonstrated significant time-trends. However, Kerman and Shiraz have significant trends for March and April. The coincidence of timing of peak flowering and these strong trends in climate variables suggest that some relationship between climate variability and shifts in the timing of phenological events are likely.

3. To determine the nature of any changes and trends in the peak flowering dates for each of the five citrus types in the cities of Shiraz, Kerman and Gorgan over the period 1960-2010.

As hypothesised, the identified trends in climate variables over the study period are simultaneous with shifts in the timing of peak flowering of all five citrus types in each of the three cities. The contrasts in climate trends and the mean flowering dates for Kerman and Shiraz, relative to Gorgan, are also evident in the phenological trends. Advances in flowering dates are observed for Kerman and Shiraz, but a delay in peak flowering is recorded for Gorgan. As with the mean flowering dates, the flowering date trends are consistent in direction, and similar in magnitude, across citrus types within each city, but vary considerably between cities. The largest and most consistent shift in flowering dates is observed for Shiraz, with an advance of 0.56-0.6d/yr. The slowest rate of change in flowering dates and the weakest trend is calculated for Gorgan, with a delay of only 0.05-0.1d/yr. No citrus type consistently demonstrated either the strongest or weakest trends across the three cities, and hence it can be further suggested that climatic and environmental factors play a more significant role in the shifts in peak flowering dates than the intrinsic biological controls. Whilst reports of advances in flowering dates in response to climate warming dominate in the literature, delayed flowering, as in Gorgan, is not unheard of, and the rates of change for all cities in this study are consistent with studies on deciduous fruit and citrus flowering elsewhere. The considerable differences in the trends in flowering dates across cities, and the more subtle differences between citrus types, support claims of high species and location specificity in phenological shifts.

4. To determine whether any significant relationships exist between changes in the timing of flowering with trends, variability and changes in climate factors for each of the five citrus types and three cities.

The inferred associations between the peak flowering dates and climate which were made on the basis of climatic and phenological distinctions between cities during the study period and the coincident timing of monthly climate trends and flowering, are confirmed here. Gorgan, which has the weakest time trends for both flowering dates and the majority of climate variables, demonstrates no statistically significant relationships between flowering and annual temperature, precipitation or temperature thresholds. Significant relationships with sunshine hours are found only for orange and tangerine. By contrast, Kerman and Shiraz, which both demonstrate statistically significant advances in flowering dates simultaneous with significant increases in temperature, demonstrate statistically significant relationships with T_{max}, T_{min} and days with $T_{min} < 13°C$ across all citrus types. It is notable that whilst Gorgan was the only city which had significant trends in annual precipitation, relationships between flowering dates and precipitation are significant only for Kerman. There are notable similarities in the phenological responses to the long-term climate variability and change in Kerman and Shiraz; however, the shifts in flowering dates in Shiraz are far more rapid than in Kerman. Furthermore, differences between cities in the climate variables which have statistically significant relationships with peak flowering, highlights a greater complexity in the primary climate drivers responsible for phenological change in each city and strengthens the argument for location specific studies.

The differences in those climatic factors which are statistically related to flowering in Kerman and Shiraz are heightened when examining the association between flowering dates and monthly climate variables. Similar to the climate trends, there are more months for which there are statistically significant relationships with flowering in Shiraz than in Kerman. Those months for Shiraz often overlap with those for Kerman, yet they are not always the months with the highest correlations. Furthermore, the relationships between flowering dates and monthly climate variables are in most cases significant in the months of peak flowering in each of the cities. This would indicate a direct influence of these climate variables in driving flowering time, whereas the significant relationships for months in the remaining seasons would suggest a more indirect influence on flowering through shifting related phenological events, such as leafing and root growth.

The dissimilarity in the climate drivers which are related to the shifts in flowering dates between citrus type and city becomes evident through multiple regression models developed using the *Backward* method. The elimination of variables which, whilst individually statistically related with flowering dates, do not contribute improved explanatory strength in the model, results in a set of distinct controlling climate variables for each citrus type in each city. Thus, whilst there is considerable similarity in the mean flowering dates and trends in flowering dates over the study period within each city, the combinations of climate factors which are most accurately associated with, and which are likely drivers of, these shifts, vary considerably. Whether they are in fact the absolute drivers of the changes in the timing of flowering of each of the citrus types in each city would require more empirical tests such as greenhouse experiments. Such investigation is important for future climate change adaptation in identifying the climate factors which are potentially more important for each of the citrus types in each city, and those cities and citrus types that will likely be most and least influenced by projected changes in those particular climate factors.

The limitations which arise from both the data and the statistical methods, all of which are discussed in *section 6.4*, have not compromised the achievement of the study aims. The distinct climate and phenological trends for each city facilitated comparisons between the three cities, and between the five citrus types. A relationship between the local climates in each city and the citrus flowering dates is observed. Increases in temperature and sunshine hours, together with decreases in precipitation and days with $T_{min} < 13°C$ and changes in the rate of accumulation of 200 HU over the period 1960-2010, are found to have been statistically strongly associated with the concurrent shifts in the timing of peak flowering.

7.3 Implications for Citrus Agriculture in Iran

The primary aim of this study to further contribute to the understanding of phenological responses to climate variability and change is largely academic in nature. However, the findings of this study have the potential to inform adaptation to continued climate change to facilitate continued successful citrus agriculture in Iran (Morisette et al., 2009; Blanc, 2012; Roshan & Grab, 2012). However, it must be noted that shifts in the timing of flowering of deciduous fruit trees are not directly associated with changes in the yield success. Rather, shifts in flowering dates have an indirect causal effect on crop success through changes in, *inter alia*, the plant nutrient balance, frost risk, and pollination potential (Cannell & Smith, 1986; Rigby & Porporato, 2008; Hegland et al., 2009). Critically climate-related shifts in flowering dates can serve as an indicator of the plant's overall vulnerability to climate variability and change (Beaubien & Freeland, 2000; Kafaki et al., 2009).

Using the rate of phenological shifts as an indicator of the extent to which a plant is affected by climate, both advances and delays in flowering dates are potentially of concern. With the results from this study, the rapid advance in flowering dates for Shiraz would serve as one such indicator of a plant experiencing, and hence responding to, climate stress. The slower shifts in flowering dates in Kerman and Gorgan would suggest a less severe climate stress, and consequently a greater likelihood of continued success of citrus agriculture in these two cities. However, whilst this particularly rapid advance in flowering dates in Shiraz can be explained with a high statistical confidence by climate factors, it does not unequivocally commit this city to experiencing losses in citrus yields under continued climate variability and change. Additional factors such as frost, the frequency and duration of temperatures exceeding thresholds suitable for citrus growth, the potential for pollination, and water availability, all serve as determinants of the future crop success in a specific region. Unfortunately, because these factors are seldom measured, they often cannot be included in models, as has been experienced in the present study.

Considering these additional factors, it is rather Kerman which is likely to experience the greatest loss in citrus agricultural production through continued climate variability and change in the 21st Century. As a city located in an already highly arid region, Kerman currently requires irrigation to supplement the low annual precipitation volumes. As precipitation has decreased over the 51-year study period, and potentially could continue to decrease in future decades, this reliance on irrigation is likely to increase. However, with a simultaneously growing population and increased evaporation rates, sustained, intensive irrigation may not be possible. The greatest risk for advanced flowering time is that of frost damage. Whilst Shiraz has experienced the most rapid flowering date advance, this has occurred concurrently with a relatively fast advance in last frost days, thereby preventing considerable risk. For Kerman, however, there has been a very slow shift in last frost dates, and hence a considerable frost risk to citrus before the end of the 21st century is tentatively predicted.

Of the three study cities, Gorgan is the most likely to continue fulfilling the requirements for citrus growth in future decades. Gorgan demonstrates the slowest rate of change in flowering dates, and the weakest correlation with climate variables. Whilst there have been statistically significant decreases in precipitation over the period 1960-2010, the Caspian Lowlands remain the only region in Iran which has sufficiently high rainfall to preclude irrigation. Should irrigation become necessary in future decades, projects for the desalination of water from the Caspian Sea, which began in 2012, would provide an adequate water supply (Mammadov, 2012). There is a delay in both flowering dates and last frost dates, but the slow rate of change in the timing of last frost events is such that citrus grown in Gorgan is not likely to face considerable frost risks in the near future. Furthermore, there are no statistically significant trends toward increased counts of threshold days with T_{max} > 35°C, or with T_{min} < 13°C. Consequently, likely losses in citrus production in Kerman could be compensated by continued productivity in Gorgan and the greater region of the Caspian Lowlands, provided that sufficient land is available and that resources and man-power are committed to such changes. It is thus likely that Iran will be able to maintain successful citrus yields, and continue to meet the predominantly local demand.

7.4 Future Work

The discipline of phenological responses to climate change is relatively new, and due to the considerable species and location specificity highlighted in the literature and confirmed in this study, it is one which requires continued research (Schwartz, 1999; Dal Monte, 2007). Of foremost importance is the need for the continued analysis of the phenological responses of as large a variety of species and locations as possible, with preference for those which have not yet received much attention (Ahas et al., 2002). This study fills only one of many such gaps. In particular, phenological studies remain sparse in much of the Middle East, in addition to central Asia, Africa and South America. Few phenological datasets exist for these regions, and consequently much effort needs to be directed towards both locating such data from unconventional sources such as records taken for agricultural planning, and tackling the unique data and analysis challenges that this presents, and towards developing phenological networks and monitoring programmes in these regions to enable future studies (van Vliet et al., 2003; Dal Monte, 2007).

In addition to these broad priorities for further research, this study highlights more specific research foci. The first opportunity for further research remains within Iran. As a region which already experiences considerable water stress and rapid population growth, the study of phenological responses to climate change is essential to improving adaptation capacity and ensuring sustained economic and food security (Rajendra et al., 2002; Faramazi, 2010). Thus, the collection of both phenological and climate data needs to be promoted. The differences between the advances in peak flowering dates for Kerman and Shiraz compared to the delayed flowering for Gorgan is a phenomenon which has received little attention to date. It would be of interest to determine the geographic and climatic boundaries between advanced and delayed citrus flowering in Iran, and the greater Middle Eastern region, particularly given the scarcity of reports of delayed flowering dates in the literature. It would also be beneficial to study a greater range of deciduous fruit trees in order to determine whether such regionally specific differences apply only to citrus. In addition to the study of flowering dates, phenological studies in Iran, the Middle East, and globally should endeavour to include a wider range of phenological events in their data recording and analysis; from leafing in early Spring, to harvest, leaf colouration and leaf fall in Autumn (Beaubien & Freeland, 2000; Kafaki et al., 2009). However, as phenological data in the region is scarce, this would most likely involve the inception of data collection, with subsequent analysis only possible some decades into the future. Alternately, such studies would rely on proxies for phenological data such as the timing of fertilizer application, pest control and yields. This study has highlighted the importance of various climatic factors in controlling flowering phenology, but was unable to include variables such as soil moisture and temperature, irrigation, and the impact of fertilization. Improved meteorological data collection to facilitate such studies would be beneficial (Beaubien & Freeland, 2005).

With very few former studies on the response of citrus phenology to climate change, a second clear research opportunity would involves the wider study of citrus phenology. This would facilitate more accurate inferences regarding the broader context of the role of location in the timing of citrus flowering (Gordo & Sanz, 2005). This is a particularly critical gap for the citrus group, which has the potential to be cultivated in both temperate and tropical environments under different dormancy regimes (Susanto et al., 1992; Rosenzweig et al., 1996; Sristava et al., 2000). It would thus be of interest to determine the similarities in climate drivers for flowering both within and across each of these climatic regions. Associated with this is the need for further experimental research to determine location-specific, and citrus type-specific, thresholds for temperature, precipitation and sunshine hours. Given the importance of citrus in global health and nutrition, and in agriculture-based economies, studies which facilitate the continued successful global production are of value (Economos & Clay, 199; Porter & Semenov, 2005).

The third area of future research highlighted from this study involves the more widespread use of multivariate approaches in using climate variability to explain phenological shifts. The majority of former studies focus primarily on the role of temperature, and analyse the effects of individual climate variables on phenological shifts (cf. Beaubien & Freeland, 2005; Gordo & Sanz, 2005; Miller-Rushing et al., 2007; Guédon & Legave, 2008; Grab & Craparo, 2011). The improved explanatory power which the simultaneous analysis of multiple climate variables provides, together with the more nuanced differences in climate drivers across city and citrus types, highlights this as a valuable method for inclusion in future studies. At the very least, multiple regression analysis should be examined as a tool on a larger selection of species to confirm its value (Keatley et al., 2002; Črepinšek & Kajfež-Bogataj, 2006).

Considering the considerable geographic and climatic differences between the cities of Gorgan, Kerman and Shiraz, and the changes in climate which have occurred in each of these cities over the period 1960-2010, it is remarkable that all three cities are able to produce citrus profitably. To facilitate continued success of these yields it is important that the agricultural managers of these gardens have a thorough understanding of the climatic factors which have had an impact on flowering dates of these citrus types, as well as of the continued change in climate and flowering date. The collection of phenological and climate data taking place in these gardens and cities is of critical importance to this, but equally necessary is the continued analysis of these data.

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Appendix

1 Time trend equations

1.1 Flowering Dates

GORGAN	KERMAN	SHIRAZ
Orange(d) = 0.097(yr) - 60.882	Orange(d) = -0.123(yr) + 331.74	Orange(d) = -0.626(yr) +1334.1
Tangerine(d) = 0.089(yr) - 44.621	Tangerine(d) = -0.145(yr) + 374.81	Tangerine(d) = -0.610(yr) +1303
Sweet lemon(d) = 0.072(yr) - 9.535	sweet lemon(d) = -0.168(yr) +422.30	Sweet lemon(d) = -0.645(yr) +1372.3
Sour lemon(d) = 0.068(yr) + 0.4907	Sour lemon(d) = -0.155(yr) + 397.56	Sour lemon(d) = -0.564(yr) +1211.9
Sour orange(d) = 0.053(yr) +30.470	Sour orange(d) = -0.171(yr) + 428.06	Sour orange(d) = -0.620(yr) +1324.8

1.2 Climate Variables

1.2.1 T_{max}

GORGAN	KERMAN	SHIRAZ
Jan(°C) = -0.011(yr) +34.869	Jan(°C) = 0.002(yr) +8.595	Jan(°C) = 0.008(yr) -2.704
Feb(°C) = 0.004(yr) +5.863	Feb(°C) = 0.028(yr) -39.659	Feb(°C) = 0.019(yr) -22.263
Mar(°C) = 0.039(yr) -62.002	Mar(°C) = 0.042(yr) -64.196	Mar(°C) = 0.029(yr) -38.630
Apr(°C) = 0.008(yr) +5.925	Apr(°C) = 0.066(yr) -106.44	Apr(°C) = 0.057(yr) -89.730
May(°C) = -0.013(yr) +53.038	May(°C) = 0.047(yr) -62.438	May(°C) = 0.041(yr) -49.586
Jun(°C) = 0.011(yr) +9.172	Jun(°C) = 0.013(yr) +9.564	Jun(°C) = 0.023(yr) -9.647
Jul(°C) = 0.008(yr) +16.352	Jul(°C) = 0.028(yr) -18.863	Jul(°C) = 0.031(yr) -24.056
Aug(°C) = 0.028(yr) -22.037	Aug(°C) = 0.026(yr) -17.926	Aug(°C) = 0.028(yr) -18.511
Sep(°C) = 0.025(yr) -19.2	Sep(°C) = 0.031(yr) -30.662	Sep(°C) = 0.020(yr) -6.445
Oct(°C) = 0.034(yr) -43.080	Oct(°C) = 0.041(yr) -55.826	Oct(°C) = 0.024(yr) -19.114
Nov(°C) = -0.010(yr) +38.354	Nov(°C) = 0.036(yr) -50.878	Nov(°C) = 0.012(yr) -2.638
Dec(°C) = -0.014(yr) + 41.488	Dec(°C) = 0.034(yr) -52.068	Dec(°C) = 0.021(yr) -27.671
Ann(°C) = 0.009(yr) +4.644	Ann(°C) = 0.033(yr) -41.258	Ann(°C) = 0.026(yr) -26.324

1.2.2 T_{min}

GORGAN	KERMAN	SHIRAZ
Jan(°C) = -0.022(yr) +47.424	Jan(°C) = 0.044(yr) -90.306	Jan(°C) = 0.031(yr) -60.864
Feb(°C) = -0.007(yr) + 16.792	Feb(°C) = 0.036(yr) -71.303	Feb(°C) = 0.045(yr) -86.524
Mar(°C) = 0.011(yr) -15.852	Mar(°C) = 0.019(yr) -33.936	Mar(°C) = 0.046(yr) -85.519
Apr(°C) = -0.005(yr) +20.228	Apr(°C) = 0.033(yr) -56.307	Apr(°C) = 0.078(yr) -144.64
May(°C) = -0.018(yr) +50.464	May(°C) = 0.039(yr) -65.153	May(°C) = 0.080(yr) -143.87
Jun(°C) = 0.010(yr) +1.210	Jun(°C) = 0.038(yr) -59.088	Jun(°C) = 0.073(yr) -127.14
Jul(°C) = 0.022(yr) -21.184	Jul(°C) = 0.046(yr) -73.242	Jul(°C) = 0.072(yr) -122.29
Aug(°C) = 0.024(yr) -25.501	Aug(°C) = 0.035(yr) -54.402	Aug(°C) = 0.076(yr) -131.60
Sep(°C) = 0.016(yr) -12.819	Sep(°C) = 0.045(yr) -79.886	Sep(°C) = 0.076(yr) -135.64
Oct(°C) = 0.011(yr) -7.901	Oct(°C) = 0.061(yr) -115.08	Oct(°C) = 0.085(yr) -158.63
Nov(°C) = -0.014(yr) +37.478	Nov(°C) = 0.072(yr) -143.21	Nov(°C) = 0.069(yr) -131.27
Dec(°C) = -0.024(yr) +52.108	Dec(°C) = 0.085(yr) -171.79	Dec(°C) = 0.057(yr) -112.21
Ann(°C) = 0.001(yr) +11.557	Ann(°C) = 0.046(yr) -84.099	Ann(°C) = 0.066(yr) -120.17

1.2.3 Precipitation

GORGAN	KERMAN	SHIRAZ
Jan(mm) = -0.825(yr) +1697.1	Jan(mm) = -0.202(yr) +427.55	Jan(mm) = 0.078(yr) -70.0
Feb(mm) = -0.089(yr) +232.37	Feb(mm) = -0.234(yr) +491.63	Feb(mm) = 0.143(yr) -233.32
Mar(mm) = -0.849(yr) +1759.9	Mar(mm) = -0.206(yr) +439.67	Mar(mm) = 0.136(yr) -219.08
Apr(mm) = -0.338(yr) +719.5	Apr(mm) = -0.318(yr) +648.91	Apr(mm) = -0.516(yr) +1052.3
May(mm) = -0.361(yr) +759.66	May(mm) = -0.160(yr) +326.73	May(mm) = -0.082(yr) +168.22
Jun(mm) = -0.331(yr) +685.37	Jun(mm) = 0.001(yr) -1.578	Jun(mm) = 0.003(yr) -6.563
Jul(mm) = -0.338(yr) +690.05	Jul(mm) = -0.047(yr) +94.649	Jul(mm) = -0.023(yr) +46.801
Aug(mm) = -0.287(yr) +595.28	Aug(mm) = -0.005(yr) +11.265	Aug(mm) = 0.048(yr) -93.653
Sep(mm) = 0.177(yr) -309.60	Sep(mm) = -0.002(yr) +3.345	Sep(mm) = 0.001(yr) -0.7753
Oct(mm) = -0.930(yr) +1907.0	Oct(mm) = 0.039(yr) -75.230	Oct(mm) = -0.001(yr) +6.629
Nov(mm) = -0.161(yr) +387.96	Nov(mm) = -0.005(yr) +13.948	Nov(mm) = 0.158(yr) -292.06
Dec(mm) = -0.354(yr) +761.56	Dec(mm) = 0.205(yr) -388.31	Dec(mm) = 0.704(yr) -1329.3
Ann(mm) = -4.687(yr) +9886.2	Ann(mm) = -0.857(yr) +1839.7	Ann(mm) = 0.682(yr) -1038.8

1.2.4 Sunshine hours

GORGAN	KERMAN	SHIRAZ
Jan(h) = -2279.0 + 1.213(yr)	Jan(h) = -758.94 + 0.480(yr)	Jan(h) = 306.89 - 0.047(yr)
Feb(h) = -2512.2 + 1.326(yr)	Feb(h) = -1206.2 + 0.708(yr)	Feb(h) = 202.78 + 0.008(yr)
Mar(h) = -3581.9 + 1.865(yr)	Mar(h) = -1369.6 + 0.801(yr)	Mar(h) = -228.02 + 0.237(yr)
Apr(h) = -1503.3 + 0.836(yr)	Apr(h) = -3271.6 + 1.766(yr)	Apr(h) = -1126.7 + 0.696(yr)
May(h) = -4779.8 + 2.501(yr)	May(h) = -1462.9 + 0.886(yr)	May(h) = -258.52 + 0.296(yr)
Jun(h) = -3776.4 + 2.005(yr)	Jun(h) = -471.28 + 0.400(yr)	Jun(h) = 528.98 - 0.087(yr)
Jul(h) = -4549.9 + 2.393(yr)	Jul(h) = -1041.0 + 0.694(yr)	Jul(h) = 659.22 - 0.160(yr)
Aug(h) = -7425.7 + 3.839(yr)	Aug(h) = -2055.6 + 1.205(yr)	Aug(h) = -84.233 + 0.211(yr)
Sep(h) = -2331.2 + 1.269(yr)	Sep(h) = -683.85 + 0.500(yr)	Sep(h) = 826.24 - 0.257(yr)
Oct(h) = -2809.9 + 1.508(yr)	Oct(h) = -1794.9 + 1.046(yr)	Oct(h) = 521.49 - 0.113(yr)
Nov(h) = -2043.9 + 1.102(yr)	Nov(h) = -147.57 + 0.195(yr)	Nov(h) = 430.78 - 0.097(yr)
Dec(h) = -1204.5 + 0.671(yr)	Dec(h) = -116.97 + 0.162(yr)	Dec(h) = 319.77 - 0.052(yr)
Ann(h) = - 35765 + 19.011(yr)	Ann(h) = - 10884 + 7.094(yr)	Ann(h) = 1743.0 + 0.812(yr)

1.2.5 Counts of days with T_{max} > 35°C

GORGAN	KERMAN	SHIRAZ
Jan(td) = 0(yr)	Jan(td) = 0(yr)	Jan(td) = 0(yr)
Feb(td) = 0(yr)	Feb(td) = 0(yr)	Feb(td) = 0(yr)
Mar(td) = 4.190-0.002(yr)	Mar(td) = 0(yr)	Mar(td) = 0(yr)
Apr(td) = 2.169 - 0.001(yr)	Apr(td) = -0.340 + 0.0002(yr)	Apr(td) = 0(yr)
May(td) = 63.577 - 0.031(yr)	May(td) = -133.71 + 0.069(yr)	May(td) = -95.781 + 0.050(yr)
Jun(td) = 76.862 – 0.036(yr)	Jun(td) = -50.031 + 0.034(yr)	Jun(td) = -95.44 + 0.060(yr)
Jul(td) = 87.401 – 0.040(yr)	Jul(td) = -92.678 + 0.058(yr)	Jul(td) = -9.377 + 0.020(yr)
Aug(td) = -66.242 + 0.038(yr)	Aug(td) = -110.74 + 0.063(yr)	Aug(td) = -138.81 + 0.084(yr)
Sep(td) = -14.954 + 0.009(yr)	Sep(td) = -22.290 + 0.013(yr)	Sep(td) = -30.999 + 0.021(yr)
Oct(td) = -31.224 + 0.016(yr)	Oct(td) = 0.918 – 0.001(yr)	Oct(td) = 0(yr)
Nov(td) = 1.836 – 0.0010(yr)	Nov(td) = 0(yr)	Nov(td) = 0(yr)
Dec(td) = 0(yr)	Dec(td) = 0(yr)	Dec(td) = 0(yr)
Ann(td) = 123.61 – 0.048(yr)	Ann(td) = -408.87 + 0.2369(yr)	Ann(td) = -370.46 + 0.235(yr)

1.2.6 Counts of days with T_{min} < 13°C

GORGAN	KERMAN	SHIRAZ
Jan(td) = 13.059 + 0.009(yr)	Jan(td) = 0(yr)	Jan(td) = 0(yr)
Feb(td) = 12.77 + 0.008(yr)	Feb(td) = 30.941 – 0.0019yr)	Feb(td) = 31.244 – 0.002(yr)
Mar(td) = 18.118 + 0.006(yr)	Mar(td) = 54.977 – 0.012(yr)	Mar(td) = 46.093 – 0.008(yr)
Apr(td) = -56.149 + 0.040(yr)	Apr(td) = 119.64 – 0.047(yr)	Apr(td) = 304.72 – 0.140(yr)
May(td) = -110.02 + 0.058(yr)	May(td) = 305.30 – 0.145(yr)	May(td) = 560.41 – 0.278(yr)
Jun(td) = -3.155 + 0.002(yr)	Jun(td) = 102.63 – 0.049(yr)	Jun(td) = 72.065 – 0.036(yr)
Jul(td) = 0(yr)	Jul(td) = 141.29 – 0.070(yr)	Jul(td) = -1.417 + 0.001(yr)
Aug(td) = 0(yr)	Aug(td) = 201.41 – 0.096(yr)	Aug(td) = 4.710 – 0.002(yr)
Sep(td) = -1.643 + 0.001(yr)	Sep(td) = 271.13 – 0.125(yr)	Sep(td) = 497.95 – 0.247(yr)
Oct(td) = -50.224 + 0.031(yr)	Oct(td) = 61.146 – 0.015(yr)	Oct(td) = 360.57 – 0.168(yr)
Nov(td) = 10.355 + 0.008(yr)	Nov(td) = 41.977 – 0.006(yr)	Nov(td) = 47.667 – 0.009(yr)
Dec(td) = 0.171 + 0.015(yr)	Dec(td) = 31.679 – 0.001(yr)	Dec(td) = 0(yr)
Ann(td) = -166.72 + 0.176(yr)	Ann(td) = 1211.0 – 0.477(yr)	Ann(td) = 1918.7 – 0.856(yr)

1.2.7 Counts of days with T_{max} & T_{min} < 13°C

GORGAN	KERMAN	SHIRAZ
Jan(td) = -39.546 + 0.029(yr)	Jan(td) = 91.505 – 0.038(yr)	Jan(td) = -83.087 + 0.051(yr)
Feb(td) = 16.731 – 0.001(yr)	Feb(td) = 113.35 – 0.053(yr)	Feb(td) = 116.83 – 0.055(yr)
Mar(td) = 192.29 – 0.091(yr)	Mar(td) = 107.97 – 0.053(yr)	Mar(td) = 6.366 – 0.003(yr)
Apr(td) = 85.911 – 0.042(yr)	Apr(td) = 23.827 – 0.012(yr)	Apr(td) = 7.424 – 0.004(yr)
May(td) = 1.695 – 0.0010(yr)	May(td) = 0(yr)	May(td) = 0(yr)
Jun(td) = 0(yr)	Jun(td) = 0(yr)	Jun(td) = 0(yr)
Jul(td) = 0(yr)	Jul(td) = 0(yr)	Jul(td) = 0(yr)
Aug(td) = 0(yr)	Aug(td) = 0(yr)	Aug(td) = 0(yr)
Sep(td) = 0(yr)	Sep(td) = 0(yr)	Sep(td) = 0(yr)
Oct(td) = 17.781 – 0.009(yr)	Oct(td) = 0(yr)	Oct(td) = 5.807 – 0.003(yr)
Nov(td) = -0.277 + 0.001(yr)	Nov(td) = 30.079 – 0.015(yr)	Nov(td) = 1.147 – 0.0003(yr)
Dec(td) = -107.56 + 0.060(yr)	Dec(td) = 81.051 – 0.036(yr)	Dec(td) = -8.790 + 0.009(yr)
Ann(td) = 167.03 – 0.054(yr)	Ann(td) = 373.23 – 0.170(yr)	Ann(td) = 25.983 + 0.005(yr)

2. Relationship between Flowering Dates and Climate Variables

2.1 T_{max}

GORGAN

Orange Flowering Dates (Y)

$Y = 129.73 + 0.165(T_{max}\ \text{Jan})$
$Y = 133.75 - 0.149(T_{max}\ \text{Feb})$
$Y = 134.34 - 0.163(T_{max}\ \text{Mar})$
$Y = 128.43 + 0.155(T_{max}\ \text{Apr})$
$Y = 172.51 - 1.511(T_{max}\ \text{May})$
$Y = 139.93 - 0.262(T_{max}\ \text{Jun})$
$Y = 125.46 + 0.193(T_{max}\ \text{Jul})$
$Y = 137.77 - 0.183(T_{max}\ \text{Aug})$
$Y = 114.81 + 0.566(T_{max}\ \text{Sep})$
$Y = 122.35 + 0.377(T_{max}\ \text{Oct})$
$Y = 134.82 - 0.159(T_{max}\ \text{Nov})$
$Y = 138.09 - 0.430(T_{max}\ \text{Dec})$
$Y = 142.99 - 0.488(T_{max}\ \text{Ann})$

Tangerine Flowering Dates (Y)

$Y = 128.39 + 0.347(T_{max}\ \text{Jan})$
$Y = 128.88 + 0.284(T_{max}\ \text{Feb})$
$Y = 130.56 + 0.130(T_{max}\ \text{Mar})$
$Y = 127.37 + 0.239(T_{max}\ \text{Apr})$
$Y = 167.74 - 1.309(T_{max}\ \text{May})$
$Y = 143.72 - 0.357(T_{max}\ \text{Jun})$
$Y = 122.47 + 0.308(T_{max}\ \text{Jul})$
$Y = 142.97 - 0.318(T_{max}\ \text{Aug})$
$Y = 112.18 + 0.682(T_{max}\ \text{Sep})$
$Y = 128.75 + 0.153(T_{max}\ \text{Oct})$
$Y = 136.67 - 0.211(T_{max}\ \text{Nov})$
$Y = 136.24 - 0.257(T_{max}\ \text{Dec})$
$Y = 125.35 + 0.315(T_{max}\ \text{Ann})$

Sweet Lemon Flowering Dates (Y)

$Y = 130.85 + 0.196(T_{max}\ \text{Jan})$
$Y = 136.85 - 0.270(T_{max}\ \text{Feb})$
$Y = 136.50 - 0.203(T_{max}\ \text{Mar})$
$Y = 131.95 + 0.063(T_{max}\ \text{Apr})$
$Y = 183.69 - 1.866(T_{max}\ \text{May})$
$Y = 149.59 - 0.520(T_{max}\ \text{Jun})$
$Y = 123.41 + 0.303(T_{max}\ \text{Jul})$
$Y = 154.14 - 0.638(T_{max}\ \text{Aug})$
$Y = 114.43 + 0.628(T_{max}\ \text{Sep})$
$Y = 119.24 + 0.565(T_{max}\ \text{Oct})$
$Y = 144.12 - 0.561(T_{max}\ \text{Nov})$
$Y = 141.86 - 0.5890(T_{max}\ \text{Dec})$
$Y = 155.73 - 0.977(T_{max}\ \text{Ann})$

KERMAN

Orange Flowering Dates (Y)

$Y = 89.611 - 0.243(T_{max}\ \text{Jan})$
$Y = 94.625 - 0.537(T_{max}\ \text{Feb})$
$Y = 105.96 - 1.028(T_{max}\ \text{Mar})$
$Y = 131.55 - 1.847(T_{max}\ \text{Apr})$
$Y = 131.64 - 1.496(T_{max}\ \text{May})$
$Y = 104.30 - 0.506(T_{max}\ \text{Jun})$
$Y = 113.03 - 0.737(T_{max}\ \text{Jul})$
$Y = 99.322 - 0.369(T_{max}\ \text{Aug})$
$Y = 104.55 - 0.574(T_{max}\ \text{Sep})$
$Y = 81.263 + 0.209(T_{max}\ \text{Oct})$
$Y = 88.981 - 0.123(T_{max}\ \text{Nov})$
$Y = 95.514 - 0.614(T_{max}\ \text{Dec})$
$Y = 155.36 - 2.776(T_{max}\ \text{Ann})$

Tangerine Flowering Dates (Y)

$Y = 85.293 + 0.150(T_{max}\ \text{Jan})$
$Y = 95.264 - 0.552(T_{max}\ \text{Feb})$
$Y = 112.95 - 1.359(T_{max}\ \text{Mar})$
$Y = 127.71 - 1.651(T_{max}\ \text{Apr})$
$Y = 128.43 - 1.367(T_{max}\ \text{May})$
$Y = 134.23 - 1.349(T_{max}\ \text{Jun})$
$Y = 118.94 - 0.886(T_{max}\ \text{Jul})$
$Y = 108.30 - 0.616(T_{max}\ \text{Aug})$
$Y = 92.626 - 0.174(T_{max}\ \text{Sep})$
$Y = 83.858 + 0.129(T_{max}\ \text{Oct})$
$Y = 91.719 - 0.234(T_{max}\ \text{Nov})$
$Y = 94.173 - 0.478(T_{max}\ \text{Dec})$
$Y = 148.58 - 2.478(T_{max}\ \text{Ann})$

Sweet Lemon Flowering Dates (Y)

$Y = 86.020 + 0.245(T_{max}\ \text{Jan})$
$Y = 100.99 - 0.805(T_{max}\ \text{Feb})$
$Y = 111.01 - 1.172(T_{max}\ \text{Mar})$
$Y = 130.76 - 1.718(T_{max}\ \text{Apr})$
$Y = 142.86 - 1.778(T_{max}\ \text{May})$
$Y = 124.23 - 1.007(T_{max}\ \text{Jun})$
$Y = 117.27 - 0.785(T_{max}\ \text{Jul})$
$Y = 110.26 - 0.619(T_{max}\ \text{Aug})$
$Y = 112.96 - 0.761(T_{max}\ \text{Sep})$
$Y = 83.300 + 0.222(T_{max}\ \text{Oct})$
$Y = 97.501 - 0.434(T_{max}\ \text{Nov})$
$Y = 100.43 - 0.784(T_{max}\ \text{Dec})$
$Y = 165.24 - 3.077(T_{max}\ \text{Ann})$

SHIRAZ

Orange Flowering Dates (Y)

$Y = 102.56 - 1.029(T_{max}\ \text{Jan})$
$Y = 116.31 - 1.780(T_{max}\ \text{Feb})$
$Y = 119.15 - 1.533(T_{max}\ \text{Mar})$
$Y = 156.16 - 2.736(T_{max}\ \text{Apr})$
$Y = 184.39 - 3.044(T_{max}\ \text{May})$
$Y = 249.95 - 4.412(T_{max}\ \text{Jun})$
$Y = 252.08 - 4.250(T_{max}\ \text{Jul})$
$Y = 242.58 - 4.105(T_{max}\ \text{Aug})$
$Y = 206.69 - 3.451(T_{max}\ \text{Sep})$
$Y = 184.89 - 3.390(T_{max}\ \text{Oct})$
$Y = 107.07 - 0.835(T_{max}\ \text{Nov})$
$Y = 92.223 - 0.151(T_{max}\ \text{Dec})$
$Y = 282.13 - 7.454(T_{max}\ \text{Ann})$

Tangerine Flowering Dates (Y)

$Y = 102.18 - 0.963(T_{max}\ \text{Jan})$
$Y = 116.42 - 1.751(T_{max}\ \text{Feb})$
$Y = 116.08 - 1.341(T_{max}\ \text{Mar})$
$Y = 151.93 - 2.524(T_{max}\ \text{Apr})$
$Y = 164.69 - 2.412(T_{max}\ \text{May})$
$Y = 192.51 - 2.810(T_{max}\ \text{Jun})$
$Y = 252.94 - 4.260(T_{max}\ \text{Jul})$
$Y = 178.69 - 2.358(T_{max}\ \text{Aug})$
$Y = 180.48 - 2.661(T_{max}\ \text{Sep})$
$Y = 188.96 - 3.525(T_{max}\ \text{Oct})$
$Y = 94.651 - 0.202(T_{max}\ \text{Nov})$
$Y = 95.934 - 0.373(T_{max}\ \text{Dec})$
$Y = 270.82 - 6.985(T_{max}\ \text{Ann})$

Sweet Lemon Flowering Dates (Y)

$Y = 102.82 - 0.948(T_{max}\ \text{Jan})$
$Y = 119.92 - 1.930(T_{max}\ \text{Feb})$
$Y = 125.58 - 1.796(T_{max}\ \text{Mar})$
$Y = 155.37 - 2.632(T_{max}\ \text{Apr})$
$Y = 170.29 - 2.569(T_{max}\ \text{May})$
$Y = 231.15 - 3.851(T_{max}\ \text{Jun})$
$Y = 266.05 - 4.583(T_{max}\ \text{Jul})$
$Y = 184.52 - 2.492(T_{max}\ \text{Aug})$
$Y = 205.50 - 3.376(T_{max}\ \text{Sep})$
$Y = 195.69 - 3.737(T_{max}\ \text{Oct})$
$Y = 96.213 - 0.238(T_{max}\ \text{Nov})$
$Y = 97.696 - 0.438(T_{max}\ \text{Dec})$
$Y = 294.25 - 7.861(T_{max}\ \text{Ann})$

Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)
Y = 132.65 + 0.190(T_{max} Jan)	Y = 93.388 - 0.302(T_{max} Jan)	Y = 96.435 - 0.304(T_{max} Jan)
Y = 133.00 + 0.1540(T_{max} Feb)	Y = 90.364 - 0.047(T_{max} Feb)	Y = 109.24 - 1.093(T_{max} Feb)
Y = 133.80 + 0.077(T_{max} Mar)	Y = 105.12 - 0.814(T_{max} Mar)	Y = 122.52 - 1.559(T_{max} Mar)
Y = 129.74 + 0.241(T_{max} Apr)	Y = 123.85 - 1.407(T_{max} Apr)	Y = 155.34 - 2.579(T_{max} Apr)
Y = 175.93 - 1.525(T_{max} May)	Y = 121.64 - 1.062(T_{max} May)	Y = 161.83 - 2.223(T_{max} May)
Y = 143.14 - 0.262(T_{max} Jun)	Y = 117.40 - 0.794(T_{max} Jun)	Y = 245.59 - 4.202(T_{max} Jun)
Y = 125.33 + 0.293(T_{max} Jul)	Y = 109.27 - 0.547(T_{max} Jul)	Y = 258.68 - 4.356(T_{max} Jul)
Y = 150.03 - 0.461(T_{max} Aug)	Y = 114.95 - 0.738(T_{max} Aug)	Y = 153.17 - 1.625(T_{max} Aug)
Y = 107.07 + 0.920(T_{max} Sep)	Y = 113.27 - 0.751(T_{max} Sep)	Y = 180.11 - 2.580(T_{max} Sep)
Y = 129.79 + 0.206(T_{max} Oct)	Y = 83.364 + 0.247(T_{max} Oct)	Y = 202.79 - 3.908(T_{max} Oct)
Y = 150.32 - 0.788(T_{max} Nov)	Y = 91.783 - 0.108(T_{max} Nov)	Y = 103.33 - 0.515(T_{max} Nov)
Y = 138.85 - 0.267(T_{max} Dec)	Y = 94.968 - 0.361(T_{max} Dec)	Y = 97.071 - 0.291(T_{max} Dec)
Y = 143.05 - 0.352(T_{max} Ann)	Y = 135.41 - 1.848(T_{max} Ann)	Y = 251.84 - 6.137(T_{max} Ann)
Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)
Y = 134.60 + 0.096(T_{max} Jan)	Y = 84.405 + 0.313(T_{max} Jan)	Y = 109.89 - 1.386(T_{max} Jan)
Y = 134.97 + 0.059(T_{max} Feb)	Y = 92.668 - 0.302(T_{max} Feb)	Y = 114.55 - 1.411(T_{max} Feb)
Y = 138.24 - 0.156(T_{max} Mar)	Y = 109.94 - 1.159(T_{max} Mar)	Y = 124.87 - 1.656(T_{max} Mar)
Y = 122.06 + 0.621(T_{max} Apr)	Y = 140.54 - 2.149(T_{max} Apr)	Y = 155.50 - 2.571(T_{max} Apr)
Y = 169.78 - 1.261(T_{max} May)	Y = 138.25 - 1.658(T_{max} May)	Y = 157.08 - 2.067(T_{max} May)
Y = 159.18 - 0.745(T_{max} Jun)	Y = 117.48 - 0.837(T_{max} Jun)	Y = 233.95 - 3.877(T_{max} Jun)
Y = 151.15 - 0.466(T_{max} Jul)	Y = 116.48 - 0.787(T_{max} Jul)	Y = 278.17 - 4.846(T_{max} Jul)
Y = 164.36 - 0.868(T_{max} Aug)	Y = 100.94 - 0.371(T_{max} Aug)	Y = 223.63 - 3.494(T_{max} Aug)
Y = 143.18 - 0.246(T_{max} Sep)	Y = 122.06 - 1.086(T_{max} Sep)	Y = 189.89 - 2.856(T_{max} Sep)
Y = 151.62 - 0.634(T_{max} Oct)	Y = 81.065 + 0.280(T_{max} Oct)	Y = 183.17 - 3.220(T_{max} Oct)
Y = 156.79 - 1.086(T_{max} Nov)	Y = 100.32 - 0.619(T_{max} Nov)	Y = 104.60 - 0.554(T_{max} Nov)
Y = 138.72 - 0.203(T_{max} Dec)	Y = 103.31 - 1.041(T_{max} Dec)	Y = 99.499 - 0.430(T_{max} Dec)
Y = 169.99 - 1.484(T_{max} Ann)	Y = 161.22 - 2.958(T_{max} Ann)	Y = 284.27 - 7.412(T_{max} Ann)
Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)
Y = 130.58 + 0.237(T_{max} Jan)	Y = 87.514 + 0.074(T_{max} Jan)	Y = 102.05 - 0.790(T_{max} Jan)
Y = 131.87 + 0.124(T_{max} Feb)	Y = 94.469 - 0.407(T_{max} Feb)	Y = 113.06 - 1.382(T_{max} Feb)
Y = 132.11 + 0.090(T_{max} Mar)	Y = 108.87 - 1.084(T_{max} Mar)	Y = 120.95 - 1.500(T_{max} Mar)
Y = 127.84 + 0.262(T_{max} Apr)	Y = 131.70 - 1.783(T_{max} Apr)	Y = 155.12 - 2.591(T_{max} Apr)
Y = 170.81 - 1.384(T_{max} May)	Y = 131.34 - 1.425(T_{max} May)	Y = 160.72 - 2.213(T_{max} May)
Y = 145.30 - 0.378(T_{max} Jun)	Y = 128.34 - 1.142(T_{max} Jun)	Y = 235.24 - 3.940(T_{max} Jun)
Y = 124.78 + 0.266(T_{max} Jul)	Y = 117.74 - 0.818(T_{max} Jul)	Y = 251.12 - 4.165(T_{max} Jul)
Y = 145.23 - 0.358(T_{max} Aug)	Y = 110.03 - 0.630(T_{max} Aug)	Y = 200.91 - 2.913(T_{max} Aug)
Y = 111.77 + 0.722(T_{max} Sep)	Y = 106.07 - 0.564(T_{max} Sep)	Y = 189.01 - 2.857(T_{max} Sep)
Y = 125.54 + 0.317(T_{max} Oct)	Y = 83.071 + 0.208(T_{max} Oct)	Y = 183.10 - 3.242(T_{max} Oct)
Y = 143.94 - 0.539(T_{max} Nov)	Y = 95.773 - 0.376(T_{max} Nov)	Y = 106.81 - 0.700(T_{max} Nov)
Y = 138.01 - 0.311(T_{max} Dec)	Y = 96.819 - 0.580(T_{max} Dec)	Y = 99.229 - 0.465(T_{max} Dec)
Y = 136.37 - 0.125(T_{max} Ann)	Y = 156.59 - 2.755(T_{max} Ann)	Y = 274.27 - 7.047(T_{max} Ann)

2.2 T_{min}

GORGAN	**KERMAN**	**SHIRAZ**
Orange Flowering Dates (Y)	Orange Flowering Dates (Y)	Orange Flowering Dates (Y)
$Y = 131.58 + 0.063(T_{min}\text{ Jan})$	$Y = 84.587 - 0.617(T_{min}\text{ Jan})$	$Y = 90.373 - 1.879(T_{min}\text{ Jan})$
$Y = 132.37 - 0.153(T_{min}\text{ Feb})$	$Y = 86.178 - 1.175(T_{min}\text{ Feb})$	$Y = 98.018 - 4.161(T_{min}\text{ Feb})$
$Y = 133.70 - 0.307(T_{min}\text{ Mar})$	$Y = 92.441 - 1.649(T_{min}\text{ Mar})$	$Y = 112.87 - 4.425(T_{min}\text{ Mar})$
$Y = 134.13 - 0.221(T_{min}\text{ Apr})$	$Y = 113.39 - 3.274(T_{min}\text{ Apr})$	$Y = 130.57 - 4.382(T_{min}\text{ Apr})$
$Y = 154.56 - 1.484(T_{min}\text{ May})$	$Y = 125.89 - 3.202(T_{min}\text{ May})$	$Y = 148.78 - 4.164(T_{min}\text{ May})$
$Y = 149.98 - 0.913(T_{min}\text{ Jun})$	$Y = 104.02 - 1.083(T_{min}\text{ Jun})$	$Y = 169.92 - 4.480(T_{min}\text{ Jun})$
$Y = 129.83 + 0.0850(T_{min}\text{ Jul})$	$Y = 103.43 - 0.956(T_{min}\text{ Jul})$	$Y = 161.71 - 3.455(T_{min}\text{ Jul})$
$Y = 140.64 - 0.385(T_{min}\text{ Aug})$	$Y = 100.49 - 0.949(T_{min}\text{ Aug})$	$Y = 161.90 - 3.665(T_{min}\text{ Aug})$
$Y = 130.01 + 0.091(T_{min}\text{ Sep})$	$Y = 97.889 - 1.110(T_{min}\text{ Sep})$	$Y = 137.95 - 3.179(T_{min}\text{ Sep})$
$Y = 131.91 - 0.009(T_{min}\text{ Oct})$	$Y = 89.737 - 0.563(T_{min}\text{ Oct})$	$Y = 122.19 - 3.217(T_{min}\text{ Oct})$
$Y = 134.47 - 0.307(T_{min}\text{ Nov})$	$Y = 86.563 + 0.105(T_{min}\text{ Nov})$	$Y = 99.745 - 2.092(T_{min}\text{ Nov})$
$Y = 135.29 - 0.671(T_{min}\text{ Dec})$	$Y = 85.999 - 0.201(T_{min}\text{ Dec})$	$Y = 92.096 - 1.611(T_{min}\text{ Dec})$
$Y = 145.22 - 1.056(T_{min}\text{ Ann})$	$Y = 111.62 - 3.662(T_{min}\text{ Ann})$	$Y = 142.50 - 5.268(T_{min}\text{ Ann})$
Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)
$Y = 131.02 + 0.563(T_{min}\text{ Jan})$	$Y = 85.293 - 0.565(T_{min}\text{ Jan})$	$Y = 90.782 - 1.974(T_{min}\text{ Jan})$
$Y = 130.76 + 0.512(T_{min}\text{ Feb})$	$Y = 86.869 - 0.867(T_{min}\text{ Feb})$	$Y = 97.832 - 3.856(T_{min}\text{ Feb})$
$Y = 131.98 + 0.093(T_{min}\text{ Mar})$	$Y = 93.923 - 1.770(T_{min}\text{ Mar})$	$Y = 113.82 - 4.525(T_{min}\text{ Mar})$
$Y = 127.48 + 0.481(T_{min}\text{ Apr})$	$Y = 116.25 - 3.502(T_{min}\text{ Apr})$	$Y = 133.24 - 4.591(T_{min}\text{ Apr})$
$Y = 137.63 - 0.332(T_{min}\text{ May})$	$Y = 126.91 - 3.219(T_{min}\text{ May})$	$Y = 145.84 - 3.964(T_{min}\text{ May})$
$Y = 142.26 - 0.485(T_{min}\text{ Jun})$	$Y = 108.99 - 1.358(T_{min}\text{ Jun})$	$Y = 170.33 - 4.453(T_{min}\text{ Jun})$
$Y = 112.37 + 0.879(T_{min}\text{ Jul})$	$Y = 101.06 - 0.790(T_{min}\text{ Jul})$	$Y = 163.27 - 3.512(T_{min}\text{ Jul})$
$Y = 122.80 + 0.425(T_{min}\text{ Aug})$	$Y = 105.85 - 1.287(T_{min}\text{ Aug})$	$Y = 158.47 - 3.441(T_{min}\text{ Aug})$
$Y = 121.65 + 0.558(T_{min}\text{ Sep})$	$Y = 97.477 - 1.002(T_{min}\text{ Sep})$	$Y = 138.17 - 3.178(T_{min}\text{ Sep})$
$Y = 134.40 - 0.134(T_{min}\text{ Oct})$	$Y = 91.223 - 0.711(T_{min}\text{ Oct})$	$Y = 121.98 - 3.221(T_{min}\text{ Oct})$
$Y = 133.55 - 0.111(T_{min}\text{ Nov})$	$Y = 87.247 - 0.240(T_{min}\text{ Nov})$	$Y = 102.13 - 2.549(T_{min}\text{ Nov})$
$Y = 134.91 - 0.485(T_{min}\text{ Dec})$	$Y = 85.352 - 0.659(T_{min}\text{ Dec})$	$Y = 92.581 - 1.743(T_{min}\text{ Dec})$
$Y = 125.18 + 0.586(T_{min}\text{ Ann})$	$Y = 114.32 - 3.929(T_{min}\text{ Ann})$	$Y = 143.19 - 5.319(T_{min}\text{ Ann})$
Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)
$Y = 132.06 + 0.398(T_{min}\text{ Jan})$	$Y = 88.788 - 0.065(T_{min}\text{ Jan})$	$Y = 91.532 - 1.531(T_{min}\text{ Jan})$
$Y = 133.76 - 0.120(T_{min}\text{ Feb})$	$Y = 88.378 - 1.276(T_{min}\text{ Feb})$	$Y = 97.570 - 3.292(T_{min}\text{ Feb})$
$Y = 134.87 - 0.253(T_{min}\text{ Mar})$	$Y = 95.030 - 1.723(T_{min}\text{ Mar})$	$Y = 113.79 - 4.360(T_{min}\text{ Mar})$
$Y = 132.36 + 0.091(T_{min}\text{ Apr})$	$Y = 116.29 - 3.361(T_{min}\text{ Apr})$	$Y = 132.56 - 4.430(T_{min}\text{ Apr})$
$Y = 156.43 - 1.511(T_{min}\text{ May})$	$Y = 130.25 - 3.336(T_{min}\text{ May})$	$Y = 147.43 - 4.022(T_{min}\text{ May})$
$Y = 163.60 - 1.520(T_{min}\text{ Jun})$	$Y = 108.87 - 1.243(T_{min}\text{ Jun})$	$Y = 169.12 - 4.341(T_{min}\text{ Jun})$
$Y = 121.93 + 0.496(T_{min}\text{ Jul})$	$Y = 106.34 - 0.982(T_{min}\text{ Jul})$	$Y = 162.59 - 3.440(T_{min}\text{ Jul})$
$Y = 137.05 - 0.163(T_{min}\text{ Aug})$	$Y = 108.04 - 1.319(T_{min}\text{ Aug})$	$Y = 158.28 - 3.390(T_{min}\text{ Aug})$
$Y = 122.55 + 0.550(T_{min}\text{ Sep})$	$Y = 105.11 - 1.532(T_{min}\text{ Sep})$	$Y = 140.43 - 3.274(T_{min}\text{ Sep})$
$Y = 128.18 + 0.375(T_{min}\text{ Oct})$	$Y = 93.090 - 0.707(T_{min}\text{ Oct})$	$Y = 121.51 - 3.090(T_{min}\text{ Oct})$
$Y = 136.30 - 0.343(T_{min}\text{ Nov})$	$Y = 88.981 + 0.120(T_{min}\text{ Nov})$	$Y = 102.83 - 2.524(T_{min}\text{ Nov})$
$Y = 135.94 - 0.5350(T_{min}\text{ Dec})$	$Y = 88.221 - 0.275(T_{min}\text{ Dec})$	$Y = 93.074 - 1.474(T_{min}\text{ Dec})$
$Y = 138.73 - 0.429(T_{min}\text{ Ann})$	$Y = 113.02 - 3.518(T_{min}\text{ Ann})$	$Y = 141.82 - 5.101(T_{min}\text{ Ann})$

Sour Lemon Flowering Dates (Y)

$Y = 133.51 + 0.478(T_{min} \text{ Jan})$
$Y = 133.60 + 0.383(T_{min} \text{ Feb})$
$Y = 133.42 + 0.254(T_{min} \text{ Mar})$
$Y = 133.09 + 0.175(T_{min} \text{ Apr})$
$Y = 149.68 - 0.957(T_{min} \text{ May})$
$Y = 148.92 - 0.699(T_{min} \text{ Jun})$
$Y = 135.03 - 0.002(T_{min} \text{ Jul})$
$Y = 139.50 - 0.199(T_{min} \text{ Aug})$
$Y = 126.64 + 0.422(T_{min} \text{ Sep})$
$Y = 133.74 + 0.087(T_{min} \text{ Oct})$
$Y = 137.82 - 0.315(T_{min} \text{ Nov})$
$Y = 136.35 - 0.271(T_{min} \text{ Dec})$
$Y = 133.47 + 0.118(T_{min} \text{ Ann})$

Sour Lemon Flowering Dates (Y)

$Y = 85.485 - 1.278(T_{min} \text{ Jan})$
$Y = 89.174 - 0.881(T_{min} \text{ Feb})$
$Y = 95.516 - 1.595(T_{min} \text{ Mar})$
$Y = 115.15 - 3.127(T_{min} \text{ Apr})$
$Y = 118.50 - 2.346(T_{min} \text{ May})$
$Y = 109.42 - 1.230(T_{min} \text{ Jun})$
$Y = 104.76 - 0.863(T_{min} \text{ Jul})$
$Y = 107.99 - 1.267(T_{min} \text{ Aug})$
$Y = 101.50 - 1.131(T_{min} \text{ Sep})$
$Y = 93.978 - 0.778(T_{min} \text{ Oct})$
$Y = 89.686 - 0.130(T_{min} \text{ Nov})$
$Y = 88.724 - 0.364(T_{min} \text{ Dec})$
$Y = 111.13 - 3.145(T_{min} \text{ Ann})$

Sour Lemon Flowering Dates (Y)

$Y = 92.808 - 1.259(T_{min} \text{ Jan})$
$Y = 99.000 - 3.293(T_{min} \text{ Feb})$
$Y = 111.76 - 3.788(T_{min} \text{ Mar})$
$Y = 133.04 - 4.380(T_{min} \text{ Apr})$
$Y = 137.73 - 3.212(T_{min} \text{ May})$
$Y = 161.12 - 3.837(T_{min} \text{ Jun})$
$Y = 157.17 - 3.122(T_{min} \text{ Jul})$
$Y = 147.04 - 2.781(T_{min} \text{ Aug})$
$Y = 131.87 - 2.614(T_{min} \text{ Sep})$
$Y = 118.62 - 2.648(T_{min} \text{ Oct})$
$Y = 99.422 - 1.510(T_{min} \text{ Nov})$
$Y = 93.112 - 0.364(T_{min} \text{ Dec})$
$Y = 135.46 - 4.344(T_{min} \text{ Ann})$

Sour Orange Flowering Dates (Y)

$Y = 134.79 + 0.353(T_{min} \text{ Jan})$
$Y = 134.96 + 0.216(T_{min} \text{ Feb})$
$Y = 132.80 + 0.485(T_{min} \text{ Mar})$
$Y = 136.05 - 0.027(T_{min} \text{ Apr})$
$Y = 155.93 - 1.303(T_{min} \text{ May})$
$Y = 164.45 - 1.424(T_{min} \text{ Jun})$
$Y = 166.58 - 1.336(T_{min} \text{ Jul})$
$Y = 147.57 - 0.515(T_{min} \text{ Aug})$
$Y = 153.24 - 0.889(T_{min} \text{ Sep})$
$Y = 142.98 - 0.523(T_{min} \text{ Oct})$
$Y = 141.79 - 0.700(T_{min} \text{ Nov})$
$Y = 137.08 - 0.266(T_{min} \text{ Dec})$
$Y = 146.64 - 0.859(T_{min} \text{ Ann})$

Sour Orange Flowering Dates (Y)

$Y = 88.669 + 0.137(T_{min} \text{ Jan})$
$Y = 87.754 - 0.967(T_{min} \text{ Feb})$
$Y = 96.195 - 2.339(T_{min} \text{ Mar})$
$Y = 121.11 - 4.030(T_{min} \text{ Apr})$
$Y = 132.61 - 3.609(T_{min} \text{ May})$
$Y = 113.03 - 1.556(T_{min} \text{ Jun})$
$Y = 111.45 - 1.324(T_{min} \text{ Jul})$
$Y = 102.22 - 0.970(T_{min} \text{ Aug})$
$Y = 104.38 - 1.596(T_{min} \text{ Sep})$
$Y = 91.208 - 0.531(T_{min} \text{ Oct})$
$Y = 88.204 + 0.163(T_{min} \text{ Nov})$
$Y = 87.428 - 0.266(T_{min} \text{ Dec})$
$Y = 112.84 - 3.654(T_{min} \text{ Ann})$

Sour Orange Flowering Dates (Y)

$Y = 93.213 - 1.633(T_{min} \text{ Jan})$
$Y = 100.36 - 3.781(T_{min} \text{ Feb})$
$Y = 115.81 - 4.412(T_{min} \text{ Mar})$
$Y = 136.00 - 4.626(T_{min} \text{ Apr})$
$Y = 145.58 - 3.729(T_{min} \text{ May})$
$Y = 185.28 - 5.148(T_{min} \text{ Jun})$
$Y = 179.90 - 4.182(T_{min} \text{ Jul})$
$Y = 167.86 - 3.806(T_{min} \text{ Aug})$
$Y = 144.29 - 3.397(T_{min} \text{ Sep})$
$Y = 123.18 - 3.069(T_{min} \text{ Oct})$
$Y = 103.90 - 2.380(T_{min} \text{ Nov})$
$Y = 94.715 - 1.219(T_{min} \text{ Dec})$
$Y = 147.35 - 5.474(T_{min} \text{ Ann})$

Pooled Flowering Dates (Y)

$Y = 132.32 + 0.390(T_{min} \text{ Jan})$
$Y = 132.54 + 0.259(T_{min} \text{ Feb})$
$Y = 132.90 + 0.097(T_{min} \text{ Mar})$
$Y = 131.09 + 0.225(T_{min} \text{ Apr})$
$Y = 148.42 - 0.970(T_{min} \text{ May})$
$Y = 150.16 - 0.835(T_{min} \text{ Jun})$
$Y = 126.71 + 0.296(T_{min} \text{ Jul})$
$Y = 132.60 + 0.039(T_{min} \text{ Aug})$
$Y = 123.35 + 0.517(T_{min} \text{ Sep})$
$Y = 131.37 + 0.152(T_{min} \text{ Oct})$
$Y = 136.36 - 0.322(T_{min} \text{ Nov})$
$Y = 135.68 - 0.432(T_{min} \text{ Dec})$
$Y = 133.03 + 0.037(T_{min} \text{ Ann})$

Pooled Flowering Dates (Y)

$Y = 87.580 - 0.239(T_{min} \text{ Jan})$
$Y = 87.957 - 0.965(T_{min} \text{ Feb})$
$Y = 94.633 - 1.736(T_{min} \text{ Mar})$
$Y = 116.03 - 3.399(T_{min} \text{ Apr})$
$Y = 124.48 - 2.949(T_{min} \text{ May})$
$Y = 109.32 - 1.310(T_{min} \text{ Jun})$
$Y = 106.09 - 1.007(T_{min} \text{ Jul})$
$Y = 105.14 - 1.152(T_{min} \text{ Aug})$
$Y = 99.619 - 1.088(T_{min} \text{ Sep})$
$Y = 91.502 - 0.566(T_{min} \text{ Oct})$
$Y = 88.398 + 0.067(T_{min} \text{ Nov})$
$Y = 87.651 - 0.254(T_{min} \text{ Dec})$
$Y = 109.93 - 3.185(T_{min} \text{ Ann})$

Pooled Flowering Dates (Y)

$Y = 92.482 - 1.887(T_{min} \text{ Jan})$
$Y = 99.242 - 3.596(T_{min} \text{ Feb})$
$Y = 114.13 - 4.265(T_{min} \text{ Mar})$
$Y = 132.51 - 4.366(T_{min} \text{ Apr})$
$Y = 143.85 - 3.690(T_{min} \text{ May})$
$Y = 169.65 - 4.341(T_{min} \text{ Jun})$
$Y = 165.49 - 3.533(T_{min} \text{ Jul})$
$Y = 161.63 - 3.532(T_{min} \text{ Aug})$
$Y = 139.66 - 3.152(T_{min} \text{ Sep})$
$Y = 121.85 - 3.020(T_{min} \text{ Oct})$
$Y = 102.61 - 2.273(T_{min} \text{ Nov})$
$Y = 94.297 - 1.674(T_{min} \text{ Dec})$
$Y = 142.10 - 5.042(T_{min} \text{ Ann})$

2.3 Precipitation

GORGAN

Orange Flowering Dates (Y)

Y = 132.69 - 0.015(Precip Jan)
Y = 129.46 + 0.044(Precip Feb)
Y = 134.06 - 0.031(Precip Mar)
Y = 132.36 - 0.013(Precip Apr)
Y = 129.34 + 0.059(Precip May)
Y = 132.42 - 0.021(Precip Jun)
Y = 132.13 - 0.020(Precip Jul)
Y = 131.41 + 0.014(Precip Aug)
Y = 133.13 - 0.031(Precip Sep)
Y = 133.51 - 0.029(Precip Oct)
Y = 132.44 - 0.010(Precip Nov)
Y = 131.91 - 0.002(Precip Dec)
Y = 136.33 - 0.008(Precip Ann)

Tangerine Flowering Dates (Y)

Y = 133.85 - 0.024(Precip Jan)
Y = 132.52 + 0.001(Precip Feb)
Y = 134.11 - 0.021(Precip Mar)
Y = 132.77 - 0.005(Precip Apr)
Y = 131.49 + 0.026(Precip May)
Y = 132.83 - 0.011(Precip Jun)
Y = 132.95 - 0.021(Precip Jul)
Y = 132.02 + 0.020(Precip Aug]
Y = 133.99 - 0.034(Precip Sep)
Y = 134.04 - 0.023(Precip Oct)
Y = 133.20 - 0.010(Precip Nov)
Y = 134.99 - 0.043(Precip Dec)
Y = 138.45 - 0.010(Precip Ann)

Sweet Lemon Flowering Dates (Y)

Y = 134.14 - 0.014(Precip Jan)
Y = 130.20 + 0.058(Precip Feb)
Y = 135.89 - 0.034(Precip Mar)
Y = 133.17 + 0.003(Precip Apr)
Y = 129.83 + 0.087(Precip May)
Y = 132.79 + 0.017(Precip Jun)
Y = 134.31 - 0.051(Precip Jul)
Y = 131.83 + 0.060(Precip Aug)
Y = 136.31 - 0.074(Precip Sep)
Y = 134.61 - 0.021(Precip Oct)
Y = 133.24 + 0.001(Precip Nov)
Y = 132.46 + 0.015(Precip Dec)
Y = 134.45 - 0.002(Precip Ann)

KERMAN

Orange Flowering Dates (Y)

Y = 86.050 + 0.020(Precip Jan)
Y = 86.740 - 0.005(Precip Feb)
Y = 83.777 + 0.087(Precip Mar)
Y = 84.374 + 0.139(Precip Apr)
Y = 85.710 + 0.089(Precip May)
Y = 86.380 + 0.328(Precip Jun)
Y = 86.324 + 0.276(Precip Jul)
Y = 86.182 + 0.692(Precip Aug)
Y = 86.791 - 0.810(Precip Sep)
Y = 86.286 + 0.165(Precip Oct)
Y = 86.362 + 0.043(Precip Nov)
Y = 85.452 + 0.064(Precip Dec)
Y = 79.786 + 0.049(Precip Ann)

Tangerine Flowering Dates (Y)

Y = 87.318 - 0.006(Precip Jan)
Y = 86.863 + 0.011(Precip Feb)
Y = 84.737 + 0.078(Precip Mar)
Y = 85.580 + 0.115(Precip Apr)
Y = 86.273 + 0.104(Precip May)
Y = 86.726 + 0.560(Precip Jun)
Y = 87.085 + 0.127(Precip Jul)
Y = 86.926 + 0.582(Precip Aug)
Y = 87.268 - 0.636(Precip Sep)
Y = 86.669 + 0.260(Precip Oct)
Y = 86.868 + 0.054(Precip Nov)
Y = 86.561 + 0.031(Precip Dec)
Y = 80.954 + 0.046(Precip Ann)

Sweet Lemon Flowering Dates (Y)

Y = 89.275 - 0.010(Precip Jan)
Y = 88.499 + 0.020(Precip Feb)
Y = 87.210 + 0.055(Precip Mar)
Y = 86.628 + 0.149(Precip Apr)
Y = 88.169 + 0.107(Precip May)
Y = 88.614 + 0.663(Precip Jun)
Y = 88.832 + 0.191(Precip Jul)
Y = 88.602 + 0.751(Precip Aug)
Y = 89.363 - 0.931(Precip Sep)
Y = 88.604 + 0.260(Precip Oct)
Y = 88.456 + 0.124(Precip Nov)
Y = 88.224 + 0.042(Precip Dec)
Y = 81.893 + 0.052(Precip Ann)

SHIRAZ

Orange Flowering Dates (Y)

Y = 89.681 + 0.004(Precip Jan)
Y = 89.720 + 0.003(Precip Feb)
Y = 88.835 + 0.023(Precip Mar)
Y = 86.562 + 0.132(Precip Apr)
Y = 88.635 + 0.322(Precip May)
Y = 90.110 - 0.318(Precip Jun)
Y = 89.744 + 0.342(Precip Jul)
Y = 90.505 - 0.488(Precip Aug)
Y = 90.444 - 59.736(Precip Sep)
Y = 89.449 + 0.105(Precip Oct)
Y = 90.295 - 0.011(Precip Nov)
Y = 90.976 - 0.013(Precip Dec)
Y = 87.995 + 0.006(Precip Ann)

Tangerine Flowering Dates (Y)

Y = 90.334 + 0.002(Precip Jan)
Y = 90.489 - 0.003(Precip Feb)
Y = 90.083 + 0.008(Precip Mar)
Y = 88.593 + 0.079(Precip Apr)
Y = 89.209 + 0.205(Precip May)
Y = 90.644 - 0.587(Precip Jun)
Y = 90.107 + 0.875(Precip Jul)
Y = 90.928 - 0.477(Precip Aug)
Y = 91.004 - 74.808(Precip Sep)
Y = 90.114 + 0.072(Precip Oct)
Y = 92.367 - 0.101(Precip Nov)
Y = 91.728 - 0.018(Precip Dec)
Y = 92.460 - 0.007(Precip Ann)

Sweet Lemon Flowering Dates (Y)

Y = 90.727 + 0.006(Precip Jan)
Y = 90.235 + 0.018(Precip Feb)
Y = 90.286 + 0.020(Precip Mar)
Y = 88.913 + 0.100(Precip Apr)
Y = 89.934 + 0.217(Precip May)
Y = 91.369 - 0.258(Precip Jun)
Y = 90.800 + 1.172(Precip Jul)
Y = 91.693 - 0.420(Precip Aug)
Y = 91.882 - 83.286(Precip Sep)
Y = 91.126 + 0.034(Precip Oct)
Y = 93.006 - 0.091(Precip Nov)
Y = 91.906 - 0.009(Precip Dec)
Y = 89.881 + 0.004(Precip Ann)

Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)
Y = 135.79 - 0.016(Precip Jan)	Y = 90.086 - 0.016(Precip Jan)	Y = 95.914 - 0.039(Precip Jan)
Y = 131.66 + 0.056(Precip Feb)	Y = 89.994 - 0.014(Precip Feb)	Y = 94.004 - 0.031(Precip Feb)
Y = 138.12 - 0.044(Precip Mar)	Y = 88.447 + 0.039(Precip Mar)	Y = 90.946 + 0.035(Precip Mar)
Y = 133.26 + 0.038(Precip Apr)	Y = 87.834 + 0.092(Precip Apr)	Y = 90.243 + 0.086(Precip Apr)
Y = 133.04 + 0.044(Precip May)	Y = 88.856 + 0.092(Precip May)	Y = 91.444 + 0.345(Precip May)
Y = 134.29 + 0.024(Precip Jun)	Y = 89.661 + 0.028(Precip Jun)	Y = 92.858 - 0.769(Precip Jun)
Y = 135.85 - 0.050(Precip Jul)	Y = 89.489 + 0.198(Precip Jul)	Y = 92.709 + 0.014(Precip Jul)
Y = 134.03 + 0.037(Precip Aug)	Y = 88.961 + 1.152(Precip Aug)	Y = 93.396 - 1.253(Precip Aug)
Y = 136.89 - 0.050(Precip Sep)	Y = 89.837 - 0.802(Precip Sep)	Y = 93.085 - 68.232(Precip Sep)
Y = 136.47 - 0.024(Precip Oct)	Y = 89.499 + 0.141(Precip Oct)	Y = 92.286 + 0.088(Precip Oct)
Y = 134.99 - 0.0002(Precip Nov)	Y = 89.959 - 0.075(Precip Nov)	Y = 93.317 - 0.030(Precip Nov)
Y = 134.28 + 0.012(Precip Dec)	Y = 88.902 + 0.037(Precip Dec)	Y = 92.820 - 0.002(Precip Dec)
Y = 135.51 - 0.001(Precip Ann)	Y = 85.001 + 0.034(Precip Ann)	Y = 92.889 - 0.001(Precip Ann)
Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)
Y = 136.13 - 0.007(Precip Jan)	Y = 87.766 + 0.016(Precip Jan)	Y = 92.854 + 0.006(Precip Jan)
Y = 133.26 + 0.046(Precip Feb)	Y = 88.059 + 0.006(Precip Feb)	Y = 92.711 + 0.011(Precip Feb)
Y = 138.41 - 0.035(Precip Mar)	Y = 86.721 + 0.047(Precip Mar)	Y = 92.205 + 0.022(Precip Mar)
Y = 137.62 - 0.040(Precip Apr)	Y = 85.677 + 0.150(Precip Apr)	Y = 90.576 + 0.095(Precip Apr)
Y = 133.79 + 0.045(Precip May)	Y = 87.412 + 0.085(Precip May)	Y = 92.321 + 0.179(Precip May)
Y = 134.24 + 0.054(Precip Jun)	Y = 88.264 - 0.089(Precip Jun)	Y = 93.412 - 0.272(Precip Jun)
Y = 135.66 + 0.006(Precip Jul)	Y = 87.839 + 0.419(Precip Jul)	Y = 92.881 + 0.516(Precip Jul)
Y = 134.24 + 0.058(Precip Aug)	Y = 87.619 + 1.097(Precip Aug)	Y = 93.835 - 0.483(Precip Aug)
Y = 136.17 - 0.010(Precip Sep)	Y = 88.667 - 1.211(Precip Sep)	Y = 93.980 - 87.661(Precip Sep)
Y = 134.51 + 0.022(Precip Oct)	Y = 87.941 + 0.160(Precip Oct)	Y = 93.096 + 0.042(Precip Oct)
Y = 135.95 - 0.003(Precip Nov)	Y = 87.617 + 0.127(Precip Nov)	Y = 94.481 - 0.051(Precip Nov)
Y = 137.39 - 0.030(Precip Dec)	Y = 86.821 + 0.075(Precip Dec)	Y = 94.026 - 0.010(Precip Dec)
Y = 132.49 + 0.006(Precip Ann)	Y = 79.276 + 0.063(Precip Ann)	Y = 90.911 + 0.007(Precip Ann)
Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)
Y = 134.37 - 0.015(Precip Jan)	Y = 88.819 - 0.015(Precip Jan)	Y = 92.926 - 0.006(Precip Jan)
Y = 131.43 + 0.037(Precip Feb)	Y = 88.340 + 0.003(Precip Feb)	Y = 92.222 + 0.002(Precip Feb)
Y = 136.17 - 0.036(Precip Mar)	Y = 86.767 + 0.052(Precip Mar)	Y = 92.132 + 0.006(Precip Mar)
Y = 133.76 - 0.006(Precip Apr)	Y = 86.362 + 0.111(Precip Apr)	Y = 89.866 + 0.092(Precip Apr)
Y = 131.84 + 0.039(Precip May)	Y = 87.471 + 0.104(Precip May)	Y = 91.540 + 0.167(Precip May)
Y = 133.10 + 0.014(Precip Jun)	Y = 88.242 + 0.266(Precip Jun)	Y = 92.606 - 0.762(Precip Jun)
Y = 134.03 - 0.029(Precip Jul)	Y = 88.193 + 0.259(Precip Jul)	Y = 92.173 + 0.341(Precip Jul)
Y = 132.77 + 0.028(Precip Aug)	Y = 87.987 + 0.852(Precip Aug)	Y = 92.862 - 0.518(Precip Aug)
Y = 134.97 - 0.036(Precip Sep)	Y = 88.761 - 1.098(Precip Sep)	Y = 92.925 - 83.234(Precip Sep)
Y = 134.70 - 0.020(Precip Oct)	Y = 88.191 + 0.139(Precip Oct)	Y = 92.226 + 0.041(Precip Oct)
Y = 134.00 - 0.008(Precip Nov)	Y = 88.121 + 0.063(Precip Nov)	Y = 92.824 - 0.019(Precip Nov)
Y = 134.50 - 0.017(Precip Dec)	Y = 87.493 + 0.052(Precip Dec)	Y = 93.172 - 0.011(Precip Dec)
Y = 136.86 - 0.006(Precip Ann	Y = 81.752 + 0.048(Precip Ann)	Y = 92.138 + 0.001(Precip Ann)

2.4 Sunshine Hours

GORGAN	**KERMAN**	**SHIRAZ**
Orange Flowering Dates (Y)	Orange Flowering Dates (Y)	Orange Flowering Dates (Y)
Y = 131.60 + 0.010(Sun Jan)	Y = 86.892 + 0.001(Sun Jan)	Y = 98.143 - 0.036(Sun Jan)
Y = 139.77 - 0.053(Sun Feb)	Y = 87.141 + 0.001(Sun Feb)	Y = 91.191 - 0.003(Sun Feb)
Y = 136.35 - 0.024(Sun Mar)	Y = 101.04 - 0.064(Sun Mar)	Y = 117.08 - 0.110(Sun Mar)
Y = 134.46 - 0.009(Sun Apr)	Y = 100.36 - 0.056(Sun Apr)	Y = 134.64 - 0.173(Sun Apr)
Y = 137.40 - 0.021(Sun May)	Y = 105.60 - 0.064(Sun May)	Y = 133.55 - 0.130(Sun May)
Y = 132.98 + 0.001(Sun Jun)	Y = 101.00 - 0.044(Sun Jun)	Y = 59.772 + 0.086(Sun Jun)
Y = 133.92 - 0.004(Sun Jul)	Y = 76.023 + 0.031(Sun Jul)	Y = 70.088 + 0.059(Sun Jul)
Y = 135.20 - 0.010(Sun Aug)	Y = 99.895 - 0.038(Sun Aug)	Y = 175.85 - 0.255(Sun Aug)
Y = 131.92 + 0.006(Sun Sep)	Y = 78.095 + 0.029(Sun Sep)	Y = 9.551 + 0.256(Sun Sep)
Y = 135.24 - 0.011(Sun Oct)	Y = 90.164 - 0.011(Sun Oct)	Y = 97.362 - 0.024(Sun Oct)
Y = 137.63 - 0.030(Sun Nov)	Y = 92.920 - 0.025(Sun Nov)	Y = 98.957 - 0.037(Sun Nov)
Y = 134.54 - 0.013(Sun Dec)	Y = 93.962 - 0.033(Sun Dec)	Y = 85.659 + 0.022(Sun Dec)
Y = 145.88 - 0.006(Sun Ann)	Y = 135.53 - 0.015(Sun Ann)	Y = 169.64 - 0.024(Sun Ann)
Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)
Y = 138.10 - 0.028(Sun Jan)	Y = 81.590 + 0.031(Sun Jan)	Y = 101.17 - 0.049(Sun Jan)
Y = 141.33 - 0.055(Sun Feb)	Y = 91.782 - 0.019(Sun Feb)	Y = 90.724 + 0.002(Sun Feb)
Y = 138.28 - 0.030(Sun Mar)	Y = 104.28 - 0.074(Sun Mar)	Y = 107.33 - 0.068(Sun Mar)
Y = 137.32 - 0.019(Sun Apr)	Y = 100.54 - 0.052(Sun Apr)	Y = 126.10 - 0.137(Sun Apr)
Y = 141.12 - 0.034(Sun May)	Y = 109.62 - 0.073(Sun May)	Y = 136.96 - 0.1401(Sun May)
Y = 137.04 - 0.014(Sun Jun)	Y = 90.122 - 0.008(Sun Jun)	Y = 87.401 + 0.010(Sun Jun)
Y = 134.88 - 0.003(Sun Jul)	Y = 83.713 + 0.011(Sun Jul)	Y = 64.843 + 0.076(Sun Jul)
Y = 140.48 - 0.028(Sun Aug)	Y = 87.730 - 0.0001(Sun Aug)	Y = 177.65 - 0.260(Sun Aug)
Y = 136.22 - 0.010(Sun Sep)	Y = 65.893 + 0.070(Sun Sep)	Y = 11.198 + 0.253(Sun Sep)
Y = 139.34 - 0.026(Sun Oct)	Y = 84.912 + 0.010(Sun Oct)	Y = 91.122 - 0.0004(Sun Oct)
Y = 138.20 - 0.027(Sun Nov)	Y = 87.263 + 0.002(Sun Nov)	Y = 89.764 + 0.005(Sun Nov)
Y = 133.77 + 0.0002(Sun Dec)	Y = 88.178 - 0.003(Sun Dec)	Y = 89.470 + 0.007(Sun Dec)
Y = 149.07 - 0.007(Sun Ann)	Y = 120.16 - 0.010(Sun Ann)	Y = 153.71 - 0.019(Sun Ann)
Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)
Y = 132.72 + 0.012(Sun Jan)	Y = 84.941 + 0.024(Sun Jan)	Y = 103.07 - 0.055(Sun Jan)
Y = 141.89 - 0.058(Sun Feb)	Y = 92.061 - 0.013(Sun Feb)	Y = 99.438 - 0.035(Sun Feb)
Y = 138.45 - 0.029(Sun Mar)	Y = 101.62 - 0.055(Sun Mar)	Y = 112.47 - 0.086(Sun Mar)
Y = 137.22 - 0.017(Sun Apr)	Y = 102.63 - 0.055(Sun Apr)	Y = 127.21 - 0.138(Sun Apr)
Y = 139.53 - 0.025(Sun May)	Y = 103.97 - 0.050(Sun May)	Y = 132.67 - 0.125(Sun May)
Y = 130.29 + 0.020(Sun Jun)	Y = 97.060 - 0.025(Sun Jun)	Y = 75.393 + 0.046(Sun Jun)
Y = 131.30 + 0.015(Sun Jul)	Y = 87.385 + 0.005(Sun Jul)	Y = 32.096 + 0.174(Sun Jul)
Y = 139.14 - 0.021(Sun Aug)	Y = 101.50 - 0.035(Sun Aug)	Y = 168.41 - 0.229(Sun Aug)
Y = 135.92 - 0.007(Sun Sep)	Y = 79.603 + 0.031(Sun Sep)	Y = -27.292 + 0.377(Sun Sep)
Y = 132.79 + 0.009(Sun Oct)	Y = 92.694 - 0.011(Sun Oct)	Y = 93.600 - 0.006(Sun Oct)
Y = 139.75 - 0.035(Sun Nov)	Y = 97.136 - 0.032(Sun Nov)	Y = 88.839 + 0.013(Sun Nov)
Y = 140.84 - 0.048(Sun Dec)	Y = 94.445 - 0.024(Sun Dec)	Y = 93.869 - 0.009(Sun Dec)
Y = 143.55 - 0.004(Sun Ann)	Y = 127.81 - 0.012(Sun Ann)	Y = 155.84 - 0.019(Sun Ann)

Sour Lemon Flowering Dates (Y)
Y = 138.76 - 0.018(Sun Jan)
Y = 139.85 - 0.028(Sun Feb)
Y = 139.47 - 0.022(Sun Mar)
Y = 137.61 - 0.008(Sun Apr)
Y = 138.54 - 0.011(Sun May)
Y = 129.23 + 0.031(Sun Jun)
Y = 131.05 + 0.023(Sun Jul)
Y = 139.20 - 0.013(Sun Aug)
Y = 133.46 + 0.014(Sun Sep)
Y = 133.94 + 0.012(Sun Oct)
Y = 140.94 - 0.032(Sun Nov)
Y = 134.54 + 0.011(Sun Dec)
Y = 135.06 + 0.001(Sun Ann)

Sour Orange Flowering Dates (Y)
Y = 142.53 - 0.039(Sun Jan)
Y = 146.22 - 0.068(Sun Feb)
Y = 144.71 - 0.051(Sun Mar)
Y = 137.38 - 0.003(Sun Apr)
Y = 137.64 - 0.005(Sun May)
Y = 128.67 + 0.037(Sun Jun)
Y = 126.46 + 0.046(Sun Jul)
Y = 136.13 + 0.003(Sun Aug)
y = 128.17 + 0.044(Sun Sep)
Y = 135.28 + 0.007(Sun Oct)
Y = 146.47 - 0.063(Sun Nov)
Y = 135.03 + 0.011(Sun Dec)
Y = 133.38 + 0.002(Sun Ann)

Pooled Flowering Dates (Y)
Y = 135.80 - 0.007(Sun Jan)
Y = 140.12 - 0.041(Sun Feb)
Y = 138.63 - 0.026(Sun Mar)
Y = 136.82 - 0.012(Sun Apr)
Y = 138.31 - 0.017(Sun May)
Y = 131.38 + 0.015(Sun Jun)
Y = 131.09 + 0.017(Sun Jul)
Y = 137.36 - 0.011(Sun Aug)
Y = 133.46 + 0.007(Sun Sep)
Y = 135.09 - 0.002(Sun Oct)
Y = 139.55 - 0.032(Sun Nov)
Y = 135.22 - 0.006(Sun Dec)
Y = 138.92 - 0.002(Sun Ann)

Sour Lemon Flowering Dates (Y)
Y = 89.125 + 0.005(Sun Jan)
Y = 87.702 + 0.012(Sun Feb)
Y = 102.24 - 0.056(Sun Mar)
Y = 100.18 - 0.042(Sun Apr)
Y = 107.72 - 0.060(Sun May)
Y = 100.48 - 0.033(Sun Jun)
Y = 88.752 + 0.004(Sun Jul)
Y = 105.03 - 0.045(Sun Aug)
Y = 82.665 + 0.023(Sun Sep)
Y = 90.116 - 0.0004(Sun Oct)
Y = 92.439 - 0.010(Sun Nov)
Y = 92.541 - 0.013(Sun Dec)
Y = 121.21 - 0.010(Sun Ann)

Sour Orange Flowering Dates (Y)
Y = 91.320 - 0.014(Sun Jan)
Y = 84.891 + 0.020(Sun Feb)
Y = 103.06 - 0.066(Sun Mar)
Y = 103.41 - 0.063(Sun Apr)
Y = 111.16 - 0.076(Sun May)
Y = 108.54 - 0.062(Sun Jun)
Y = 75.233 + 0.039(Sun Jul)
Y = 109.74 - 0.063(Sun Aug)
Y = 80.305 + 0.027(Sun Sep)
Y = 89.303 - 0.003(Sun Oct)
Y = 100.28 - 0.050(Sun Nov)
Y = 102.53 - 0.070(Sun Dec)
Y = 149.81 - 0.019(Sun Ann)

Pooled Flowering Dates (Y)
Y = 87.303 + 0.007(Sun Jan)
Y = 87.978 + 0.004(Sun Feb)
Y = 100.96 - 0.057(Sun Mar)
Y = 99.159 - 0.044(Sun Apr)
Y = 106.75 - 0.062(Sun May)
Y = 100.31 - 0.037(Sun Jun)
Y = 79.973 + 0.025(Sun Jul)
Y = 102.52 - 0.041(Sun Aug)
Y = 78.239 + 0.033(Sun Sep)
Y = 90.542 - 0.007(Sun Oct)
Y = 95.490 - 0.029(Sun Nov)
Y = 94.870 - 0.031(Sun Dec)
Y = 126.22 - 0.012(Sun Ann)

Sour Lemon Flowering Dates (Y)
Y = 96.112 - 0.015(Sun Jan)
Y = 90.654 + 0.011(Sun Feb)
Y = 113.72 - 0.085(Sun Mar)
Y = 126.18 - 0.132(Sun Apr)
Y = 120.21 - 0.083(Sun May)
Y = 46.071 + 0.131(Sun Jun)
Y = 27.860 + 0.191(Sun Jul)
Y = 204.99 - 0.337(Sun Aug)
Y = -28.702 + 0.384(Sun Sep)
Y = 87.575 + 0.018(Sun Oct)
Y = 92.155 + 0.003(Sun Nov)
Y = 108.92 - 0.073(Sun Dec)
Y = 148.00 - 0.017(Sun Ann)

Sour Orange Flowering Dates (Y)
Y = 104.51 - 0.050(Sun Jan)
Y = 103.84 - 0.044(Sun Feb)
Y = 115.80 - 0.090(Sun Mar)
Y = 126.09 - 0.126(Sun Apr)
Y = 114.31 - 0.062(Sun May)
Y = 35.065 + 0.165(Sun Jun)
Y = 42.441 + 0.151(Sun Jul)
Y = 157.20 - 0.189(Sun Aug)
Y = -2.823 + 0.307(Sun Sep)
Y = 75.568 + 0.062(Sun Oct)
Y = 87.886 + 0.025(Sun Nov)
Y = 92.962 + 0.005(Sun Dec)
Y = 137.76 - 0.013(Sun Ann)

Pooled Flowering Dates (Y)
Y = 98.729 - 0.027(Sun Jan)
Y = 97.543 - 0.021(Sun Feb)
Y = 109.18 - 0.067(Sun Mar)
Y = 127.37 - 0.136(Sun Apr)
Y = 121.39 - 0.086(Sun May)
Y = 56.218 + 0.102(Sun Jun)
Y = 51.063 + 0.122(Sun Jul)
Y = 160.69 - 0.203(Sun Aug)
Y = 3.302 + 0.283(Sun Sep)
Y = 88.187 + 0.016(Sun Oct)
Y = 95.615 - 0.012(Sun Nov)
Y = 91.009 + 0.009(Sun Dec)
Y = 143.70 - 0.015(Sun Ann)

2.5 $T_{max} > 35°C$

GORGAN

Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 131.71 + 0.975 (> 35°C Mar)
Y = 132.25 - 1.210(> 35°C Apr)
Y = 133.53 - 0.896 (> 35°C May)
Y = 132.44 - 0.119 (> 35°C Jun)
Y = 131.59 + 0.022 (> 35°C Jul)
Y = 131.84 - 0.008 (> 35°C Aug)
Y = 132.04 - 0.098 (> 35°C Sep)
Y = 131.56 + 0.688 (> 35°C Oct)
Y = 131.72 + 1.282 (> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 132.46 - 0.024 (> 35°C Ann)

Tangerine Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 132.48 + 1.762(> 35°C Mar)
Y = 132.98 - 1.203(> 35°C Apr)
Y = 134.45 - 0.993 (> 35°C May)
Y = 133.39 - 0.145 (> 35°C Jun)
Y = 132.03 + 0.060(> 35°C Jul)
Y = 132.83 - 0.032 (> 35°C Aug)
Y = 132.89 - 0.162 (> 35°C Sep)
Y = 132.55 + 0.031 (> 35°C Oct)
Y = 132.45 + 4.548(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 133.25 - 0.025 (> 35°C Ann)

Sweet Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 133.21 + 1.474(> 35°C Mar)
Y = 133.59 - 0.632(> 35°C Apr)
Y = 135.51 - 1.111(> 35°C May)
Y = 134.06 - 0.121(> 35°C Jun)
Y = 132.63 + 0.079(> 35°C Jul)
Y = 134.29 - 0.127(> 35°C Aug)
Y = 133.86 - 0.233(> 35°C Sep)
Y = 133.09 + 0.540(> 35°C Oct)
Y = 133.25 + 2.750(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 134.33 - 0.037(> 35°C Ann)

KERMAN

Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 86.524 + 2.476(> 35°C Apr)
Y = 88.579 - 0.810(> 35°C May)
Y = 88.352 - 0.102(> 35°C Jun)
Y = 89.836 - 0.151(> 35°C Jul)
Y = 86.583 – 0.0001(> 35°C Aug)
Y = 86.361 + 0.081(> 35°C Sep]
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 92.017 - 0.092(> 35°C Ann)

Tangerine Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 87.026 + 4.974(> 35°C Apr)
Y = 89.265 - 0.806(> 35°C May)
Y = 90.086 - 0.175(> 35°C Jun)
Y = 89.805 - 0.123(> 35°C Jul)
Y = 88.310 - 0.082(> 35°C Aug)
Y = 86.380 + 0.253(> 35°C Sep)
Y = 87.231 - 3.231(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 94.340 - 0.124(> 35°C Ann)

Sweet Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 90.920 - 0.784(> 35°C May)
Y = 92.149 - 0.178(> 35°C Jun)
Y = 90.910 - 0.087(> 35°C Jul)
Y = 89.535 - 0.038(> 35°C Aug)
Y = 88.659 + 0.115(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 96.019 - 0.118(> 35°C Ann)

SHIRAZ

Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 92.120 - 0.637(> 35°C May)
Y = 95.747 - 0.255(> 35°C Jun)
Y = 130.65 - 1.367(> 35°C Jul)
Y = 105.66 - 0.560(> 35°C Aug)
Y = 93.815 - 0.353(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 117.90 - 0.297(> 35°C Ann)

Tangerine Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 92.090 - 0.524(> 35°C May)
Y = 94.286 - 0.165(> 35°C Jun)
Y = 121.44 - 1.036(> 35°C Jul)
Y = 112.16 - 0.746(> 35°C Aug)
Y = 92.609 - 0.191(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 109.80 - 0.200(> 35°C Ann)

Sweet Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 93.320 - 0.658(> 35°C May)
Y = 98.792 - 0.324(> 35°C Jun)
Y = 115.81 - 0.820(> 35°C Jul)
Y = 115.21 - 0.823(> 35°C Aug)
Y = 93.356 - 0.185(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 115.47 - 0.251(> 35°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 134.74 + 3.157(> 35°C Mar)
Y = 135.33 - 0.957(> 35°C Apr)
Y = 137.05 - 1.001(> 35°C May)
Y = 135.36 - 0.066(> 35°C Jun)
Y = 134.34 + 0.066(> 35°C Jul)
Y = 135.67 - 0.086(> 35°C Aug)
Y = 135.00 - 0.009(> 35°C Sep)
Y = 134.80 + 0.407(> 35°C Oct)
Y = 134.79 + 3.711(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 135.68 - 0.024(> 35°C Ann)

Sour Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 135.34 + 5.199(> 35°C Mar)
Y = 136.30 - 1.340(> 35°C Apr)
Y = 136.46 - 0.349(> 35°C May)
Y = 136.55 - 0.126(> 35°C Jun)
Y = 137.15 - 0.139(> 35°C Jul)
Y = 137.68 - 0.196(> 35°C Aug)
Y = 136.83 - 0.393(> 35°C Sep)
Y = 136.55 - 2.094(> 35°C Oct)
Y = 135.86 - 3.861(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 138.59 - 0.089(> 35°C Ann)

Pooled Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 133.32 + 2.958(> 35°C Mar)
Y = 133.86 - 0.990(> 35°C Apr)
Y = 135.22 - 0.880(> 35°C May)
Y = 134.24 - 0.130(> 35°C Jun)
Y = 133.06 + 0.048(> 35°C Jul)
Y = 133.98 - 0.056(> 35°C Aug)
Y = 133.68 - 0.076(> 35°C Sep)
Y = 133.32 + 0.456(> 35°C Oct)
Y = 133.42 + 1.957(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 134.32 - 0.029(> 35°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 89.538 + 5.462(> 35°C Apr)
Y = 91.352 - 0.737(> 35°C May)
Y = 92.249 - 0.153(> 35°C Jun)
Y = 90.617 - 0.045(> 35°C Jul)
Y = 90.680 - 0.072(> 35°C Aug)
Y = 89.033 + 0.204(> 35°C Sep)
Y = 89.692 - 0.692(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 94.636 - 0.087(> 35°C Ann)

Sour Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 90.407 - 0.815(> 35°C May)
Y = 92.057 - 0.219(> 35°C Jun)
Y = 91.587 - 0.156(> 35°C Jul)
Y = 88.124 + 0.006(> 35°C Aug)
Y = 88.393 - 0.070(> 35°C Sep)
Y = 88.390 - 7.390(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 94.740 - 0.111(> 35°C Ann)

Pooled Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 88.329 + 3.671(> 35°C Apr)
Y = 90.281 - 0.767(> 35°C May)
Y = 91.666 - 0.188(> 35°C Jun)
Y = 90.995 - 0.121(> 35°C Jul)
Y = 89.216 - 0.056(> 35°C Aug)
Y = 88.102 + 0.098(> 35°C Sep)
Y = 88.454 - 2.704(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 94.845 - 0.110(> 35°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 93.566 - 0.236(> 35°C May)
Y = 99.944 - 0.313(> 35°C Jun)
Y = 112.38 - 0.663(> 35°C Jul)
Y = 106.82 - 0.510(> 35°C Aug)
Y = 95.047 - 0.213(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 113.60 - 0.220(> 35°C Ann)

Sour Orange Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 95.863 - 0.811(> 35°C May)
Y = 101.19 - 0.329(> 35°C Jun)
Y = 129.91 - 1.221(> 35°C Jul)
Y = 110.77 - 0.622(> 35°C Aug)
Y = 95.083 - 0.157(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 121.24 - 0.290(> 35°C Ann)

Pooled Flowering Dates (Y)
Y = 0(> 35°C Jan)
Y = 0(> 35°C Feb)
Y = 0(> 35°C Mar)
Y = 0(> 35°C Apr)
Y = 94.296 - 0.595(> 35°C May)
Y = 98.795 - 0.278(> 35°C Jun)
Y = 120.96 - 0.958(> 35°C Jul)
Y = 108.04 - 0.556(> 35°C Aug)
Y = 94.350 - 0.172(> 35°C Sep)
Y = 0(> 35°C Oct)
Y = 0(> 35°C Nov)
Y = 0(> 35°C Dec)
Y = 115.85 - 0.246(> 35°C Ann)

2.6 T_{min} < 13°C

GORGAN	KERMAN	SHIRAZ
Orange Flowering Dates (Y)	Orange Flowering Dates (Y)	Orange Flowering Dates (Y)
Y = 129.47 + 0.075(>13°C Jan)	Y = 0(>13°C Jan)	Y = 0(>13°C Jan)
Y = 110.00 + 0.778(>13°C Feb)	Y = 7.206 + 2.816(>13°C Feb)	Y = 39.809 + 1.768(>13°C Feb)
Y = 101.47 + 0.996(>13°C Mar)	Y = 27.111 + 1.936(>13°C Mar)	Y = -127.42 + 7.056(>13°C Mar)
Y = 130.09 + 0.075(>13°C Apr)]	Y = 45.623 + 1.538(>13°C Apr)	Y = 49.987 + 1.549(>13°C Apr)
Y = 129.60 + 0.471(>13°C May)	Y = 77.174 + 0.560(>13°C May)	Y = 81.292 + 0.991(>13°C May)
Y = 131.76 + 0.243(>13°C Jun)	Y = 85.699 + 0.204(>13°C Jun)	Y = 88.401 + 2.973(>13°C Jun)
Y = 0(>13°C Jul)	Y = 85.418 + 0.490(>13°C Jul)	Y = 89.977 + 2.023(>13°C Jul)
Y = 0(>13°C Aug)	Y = 84.792 + 0.177(>13°C Aug)	Y = 89.837 + 4.081(>13°C Aug)
Y = 131.80 - 0.035(>13°C Sep)	Y = 78.917 + 0.333(>13°C Sep)	Y = 84.578 + 0.868(>13°C Sep)
Y = 131.40 + 0.039(>13°C Oct)	Y = 35.586 + 1.670(>13°C Oct)	Y = 88.104 + 0.058(>13°C Oct)
Y = 127.78 + 0.153(>13°C Nov)	Y = -49.267 + 4.539(>13°C Nov)	Y = -245.03 + 11.219(>13°C Nov)
Y = 120.65 + 0.364(>13°C Dec)	Y = 124.90 - 1.238(>13°C Dec)	Y = 0(>13°C Dec)
Y = 119.50 + 0.067(>13°C Ann)	Y = 34.677 + 0.197(>13°C Ann)	Y = 70.454 + 0.087(>13°C Ann)
Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)	Tangerine Flowering Dates (Y)
Y = 144.33 - 0.381*(>13°C Jan)	Y = 0(>13°C Jan)	Jan = 0(>13°C Jan)
Y = 129.19 + 0.120(>13°C Feb)	Y = 116.97 - 1.058(>13°C Feb)	Y = -4.000 + 3.333(>13°C Feb)
Y = 123.32 + 0.305(>13°C Mar)	Y = 35.545 + 1.682(>13°C Mar)	Y = -144.08 + 7.611(>13°C Mar)
Y = 134.62 - 0.092(>13°C Apr)	Y = 47.727 + 1.495(>13°C Apr)	Y = 48.924 + 1.602(>13°C Apr)
Y = 132.00 + 0.115(>13°C May)	Y = 78.296 + 0.535(>13°C May)	Y = 81.526 + 0.923(>13°C May)
Y = 132.64 - 0.891(>13°C Jun)	Y = 85.596 + 0.349(>13°C Jun)	Y = 89.319 + 2.681(>13°C Jun)
Y = 0(>13°C Jul)	Y = 86.100 + 0.416(>13°C Jul)	Y = 90.488 - 0.488(>13°C Jul)
Y = 0(>13°C Aug)	Y = 83.976 + 0.300(>13°C Aug)	Y = 90.326 + 3.337(>13°C Aug)
Y = 132.64 - 0.220(>13°C Sep)	Y = 79.533 + 0.335(>13°C Sep)	Y = 84.536 + 0.895(>13°C Sep)
Y = 132.08 + 0.042(>13°C Oct)	Y = 31.003 + 1.839(>13°C Oct)	Y = 88.380 + 0.063(>13°C Oct)
Y = 128.21 + 0.169(>13°C Nov)	Y = -59.812 + 4.911(>13°C Nov)	Y = -196.89 + 9.623(>13°C Nov)
Y = 135.32 - 0.090(>13°C Dec)	Y = 164.13 - 2.487(>13°C Dec)	Y = 0(>13°C Dec)
Y = 130.05 + 0.014(>13°C Ann)	Y = 32.005 + 0.210(>13°C Ann)	Y = 69.800 + 0.092(>13°C Ann)
Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)	Sweet Lemon Flowering Dates (Y)
Y = 153.24 - 0.645(>13°C Jan)	Y = 0(>13°C Jan)	Y = 0(>13°C Jan)
Y = 134.31 - 0.035(>13°C Feb)	Y = 113.39 - 0.866(>13°C Feb)	Y = 51.967 + 1.383(>13°C Feb)
Y = 133.13 + 0.006(>13°C Mar)	Y = 12.220 + 2.503(>13°C Mar)	Y = -117.58 + 6.778(>13°C Mar)
Y = 132.60 + 0.032(>13°C Apr)	Y = 42.043 + 1.762(>13°C Apr)	Y = 51.648 + 1.529(>13°C Apr)
Y = 131.23 + 0.435(>13°C May)	Y = 79.448 + 0.590(>13°C May)	Y = 82.326 + 0.922(>13°C May)
Y = 133.46 - 1.459(>13°C Jun)	Y = 87.321 + 0.352(>13°C Jun)	Y = 90.260 + 2.398(>13°C Jun)
Y = 0(>13°C Jul)	Y = 87.336 + 0.724(>13°C Jul)	Y = 91.233 + 2.767(>13°C Jul)
Y = 0(>13°C Aug)	Y = 85.481 + 0.318(>13°C Aug)	Y = 91.116 + 3.942(>13°C Aug)
Y = 133.51 - 0.793(>13°C Sep)	Y = 79.694 + 0.417(>13°C Sep)	Y = 84.983 + 0.951(>13°C Sep)
Y = 133.85 - 0.047(>13°C Oct)	Y = 31.533 + 1.880(>13°C Oct)	Y = 89.069 + 0.067(>13°C Oct)
Y = 129.22 + 0.157(>13°C Nov)	Y = -80.209 + 5.654(>13°C Nov)	Y = -305.05 + 13.272(>13°C Nov)
Y = 133.30 + 0.001(>13°C Dec)	Y = 0(>13°C Dec)	Y = 0(>13°C Dec)
Y = 128.46 + 0.026(>13°C Ann)	Y = 25.325 + 0.241(>13°C Ann)	Y = 69.943 + 0.095(>13°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 152.86 - 0.581(>13°C Jan)
Y = 151.56 - 0.591(>13°C Feb)
Y = 142.12 - 0.236(>13°C Mar)
Y = 134.12 + 0.039(>13°C Apr)
Y = 133.79 + 0.2614*[L:May]
Y = 135.19 - 2.194(>13°C Jun)
Y = 0(>13°C Jul)
Y = 0(>13°C Aug)
Y = 134.88 + 0.500(>13°C Sep)
Y = 134.85 + 0.013(>13°C Oct)
Y = 128.41 + 0.257(>13°C Nov)
Y = 140.37 - 0.176(>13°C Dec)
Y = 129.15 + 0.032(>13°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 92.200 - 0.090(>13°C Feb)
Y = 29.328 + 1.966(>13°C Mar)
Y = 49.202 + 1.512(>13°C Apr)
Y = 82.625 + 0.420(>13°C May)
Y = 87.617 + 0.457(>13°C Jun)
Y = 88.108 + 0.575(>13°C Jul)
Y = 86.575 + 0.290(>13°C Aug)
Y = 83.545 + 0.278(>13°C Sep)
Y = 23.729 + 2.157(>13°C Oct)
Y = -35.822 + 4.194(>13°C Nov)
Y = 174.19 - 2.731(>13°C Dec)
Y = 41.903 + 0.181(>13°C Ann)

Sour Lemon Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 104.42 - 0.417(>13°C Feb)
Y = 6.790 + 2.790(>13°C Mar)
Y = 60.200 + 1.246(>13°C Apr)
Y = 86.163 + 0.700(>13°C May)
Y = 91.924 + 1.935(>13°C Jun)
Y = 92.816 - 3.816(>13°C Jul)
Y = 92.526 + 3.737(>13°C Aug)
Y = 87.862 + 0.686(>13°C Sep)
Y = 69.731 + 0.842(>13°C Oct)
Y = -226.55 + 10.697(>13°C Nov)
Y = 0(>13°C Dec)
Y = 36.006 + 0.258(>13°C Ann)

Sour Orange Flowering Dates (Y)
Y = 123.40 + 0.400(>13°C Jan)
Y = 144.26 - 0.303(>13°C Feb)
Y = 160.32 - 0.809(>13°C Mar)
Y = 135.31 + 0.020(>13°C Apr)
Y = 133.81 + 0.435(>13°C May)
Y = 135.69 + 2.306(>13°C Jun)
Y = 0(>13°C Jul)
Y = 0(>13°C Aug)
Y = 135.59 + 0.469(>13°C Sep)
Y = 134.85 + 0.085(>13°C Oct)
Y = 118.62 + 0.648(>13°C Nov)
Y = 146.15 - 0.338(>13°C Dec)
Y = 122.03 + 0.075(>13°C Ann)

Sour Orange Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 23.029 + 2.314(>13°C Feb)
Y = -63.873 + 4.936(>13°C Mar)
Y = 34.193 + 2.026(>13°C Apr)
Y = 76.627 + 0.691(>13°C May)
Y = 86.457 + 0.378(>13°C Jun)
Y = 86.200 + 0.791(>13°C Jul)
Y = 86.619 + 0.151(>13°C Aug)
Y = 77.774 + 0.452(>13°C Sep)
Y = 50.773 + 1.226(>13°C Oct)
Y = -68.488 + 5.232(>13°C Nov)
Y = 0(>13°C Dec)
Y = 21.664 + 0.250(>13°C Ann)

Sour Orange Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 96.867 - 0.133(>13°C Feb)
Y = -303.95 + 12.865(>13°C Mar)
Y = 55.750 + 1.443(>13°C Apr)
Y = 85.371 + 0.838(>13°C May)
Y = 91.918 + 3.497(>13°C Jun)
Y = 93.366 - 1.366(>13°C Jul)
Y = 93.122 + 4.439(>13°C Aug)
Y = 87.303 + 0.924(>13°C Sep)
Y = 91.260 + 0.061(>13°C Oct)
Y = -413.47 + 16.947(>13°C Nov)
Y = 0(>13°C Dec)
Y = 73.887 + 0.086(>13°C Ann)

Pooled Flowering Dates (Y)
Y = 146.31 - 0.415(>13°C Jan)
Y = 142.64 - 0.326(>13°C Feb)
Y = 137.47 - 0.131(>13°C Mar)
Y = 133.42 + 0.003(>13°C Apr)
Y = 132.11 + 0.301(>13°C May)
Y = 133.59 - 1.201(>13°C Jun)
Y = 0(>13°C Jul)
Y = 0(>13°C Aug)
Y = 133.51 - 0.035(>13°C Sep)
Y = 133.69 - 0.019(>13°C Oct)
Y = 127.21 + 0.243(>13°C Nov)
Y = 127.84 + 0.185(>13°C Dec)
Y = 128.76 + 0.026(>13°C Ann)

Pooled Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 68.603 + 0.702(>13°C Feb)
Y = 11.135 + 2.515(>13°C Mar)
Y = 45.402 + 1.607(>13°C Apr)
Y = 80.208 + 0.483(>13°C May)
Y = 86.673 + 0.380(>13°C Jun)
Y = 87.030 + 0.526(>13°C Jul)
Y = 85.785 + 0.250(>13°C Aug)
Y = 81.022 + 0.328(>13°C Sep)
Y = 36.361 + 1.700(>13°C Oct)
Y = -60.288 + 4.966(>13°C Nov)
Y = 145.22 - 1.835(>13°C Dec)
Y = 36.228 + 0.198(>13°C Ann)

Pooled Flowering Dates (Y)
Y = 0(>13°C Jan)
Y = 64.536 + 0.982(>13°C Feb)
Y = -119.01 + 6.859(>13°C Mar)
Y = 52.913 + 1.514(>13°C Apr)
Y = 84.163 + 0.854(>13°C May)
Y = 91.119 + 2.287(>13°C Jun)
Y = 92.440 - 1.040(>13°C Jul)
Y = 92.284 + 3.458(>13°C Aug)
Y = 86.477 + 0.871(>13°C Sep)
Y = 90.475 + 0.060(>13°C Oct)
Y = -277.10 + 12.366(>13°C Nov)
Y = 0(>13°C Dec)
Y = 71.575 + 0.093(>13°C Ann)

2.7 T_{max} and T_{min} < 13°C

GORGAN

Orange Flowering Dates (Y)

Y = 131.83 - 0.003(>>13°C Jan)
Y = 129.67 + 0.139(>>13°C Feb)
Y = 131.69 + 0.008(>>13°C Mar)
Y = 132.25 - 0.243(>>13°C Apr)
Y = 131.61 + 1.761(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 131.78 + 0.035(>>13°C Oct)
Y = 131.46 + 0.151(>>13°C Nov)
Y = 129.43 + 0.227(>>13°C Dec)
Y = 129.40 + 0.041(>>13°C Ann)

Tangerine Flowering Dates (Y)

Y = 133.55 - 0.052(>>13°C Jan)
Y = 133.05 - 0.032(>>13°C Feb)
Y = 133.19 - 0.057(>>13°C Mar)
Y = 133.44 - 0.435(>>13°C Apr)
Y = 132.52 + 0.485(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0 (>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 132.48 + 0.396(>>13°C Oct)
Y = 132.00 + 0.266(>>13°C Nov)
Y = 130.01 + 0.217(>>13°C Dec)
Y = 132.17 + 0.006(>>13°C Ann)

Sweet Lemon Flowering Dates (Y)

Y = 133.12 + 0.012(>>13°C Jan)
Y = 130.19 + 0.201(>>13°C Feb)
Y = 132.26 + 0.092(>>13°C Mar)
Y = 133.60 - 0.132(>>13°C Apr)
Y = 132.87 + 4.587(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 133.37 - 0.374(>>13°C Oct)
Y = 132.12 + 0.549(>>13°C Nov)
Y = 129.98 + 0.301(>>13°C Dec)
Y = 128.28 + 0.084(>>13°C Ann)

KERMAN

Orange Flowering Dates (Y)

Y = 84.385 + 0.144(>>13°C Jan)
Y = 83.784 + 0.369(>>13°C Feb)
Y = 84.888 + 0.592(>>13°C Mar)
Y = 86.237 + 1.479(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 0(>>13°C Oct)
Y = 85.922 + 0.461(>>13°C Nov)
Y = 84.484 + 0.222(>>13°C Dec)
Y = 80.056 + 0.180(>>13°C Ann)

Tangerine Flowering Dates (Y)

Y = 86.424 + 0.047(>>13°C Jan)
Y = 83.953 + 0.399(>>13°C Feb)
Y = 85.162 + 0.787(>>13°C Mar)
Y = 87.127 + 0.155(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 0(>>13°C Oct)
Y = 85.849 + 0.905(>>13°C Nov)
Y = 85.590 + 0.176(>>13°C Dec)
Y = 81.763 + 0.151(>>13°C Ann)

Sweet Lemon Flowering Dates (Y)

Y = 90.072 - 0.070(>>13°C Jan)
Y = 85.064 + 0.513(>>13°C Feb)
Y = 87.327 + 0.582(>>13°C Mar)
Y = 88.382 + 2.059(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 0(>>13°C Oct)
Y = 87.989 + 0.701(>>13°C Nov)
Y = 86.282 + 0.294(>>13°C Dec)
Y = 80.927 + 0.220(>>13°C Ann)

SHIRAZ

Orange Flowering Dates (Y)

Y = 88.471 + 0.088(>>13°C Jan)
Y = 84.327 + 0.693(>>13°C Feb)
Y = 87.766 + 1.742(>>13°C Mar)
Y = 89.767 + 11.233(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 89.611 + 6.033(>>13°C Oct)
Y = 90.303 - 0.441(>>13°C Nov)
Y = 90.819 - 0.084(>>13°C Dec)
Y = 85.267 + 0.130(>>13°C Ann)

Tangerine Flowering Dates (Y)

Y = 89.220 + 0.071(>>13°C Jan)
Y = 85.521 + 0.635(>>13°C Feb)
Y = 88.078 + 1.752(>>13°C Mar)
Y = 89.905 + 12.595(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 90.142 + 4.915(>>13°C Oct)
Y = 90.967 - 0.862(>>13°C Nov)
Y = 89.998 + 0.048(>>13°C Dec)
Y = 85.304 + 0.140(>>13°C Ann)

Sweet Lemon Flowering Dates (Y)

Y = 90.066 + 0.069(>>13°C Jan)
Y = 86.385 + 0.628(>>13°C Feb)
Y = 88.974 + 1.675(>>13°C Mar)
Y = 90.738 + 12.262(>>13°C Apr)
Y = 0(>>13°C May)
Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)
Y = 90.953 + 5.028(>>13°C Oct)
Y = 91.419 - 0.218(>>13°C Nov)
Y = 90.742 + 0.056(>>13°C Dec)
Y = 86.032 + 0.143(>>13°C Ann)

Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)	Sour Lemon Flowering Dates (Y)
Y = 135.24 - 0.015(>>13°C Jan)	Y = 87.499 + 0.144(>>13°C Jan)	Y = 94.455 - 0.098(>>13°C Jan)
Y = 134.78 + 0.012(>>13°C Feb)	Y = 89.051 + 0.082(>>13°C Feb)	Y = 89.688 + 0.406(>>13°C Feb)
Y = 134.72 + 0.022(>>13°C Mar)	Y = 88.376 + 0.481(>>13°C Mar)	Y = 90.430 + 1.758(>>13°C Mar)
Y = 135.48 - 0.258(>>13°C Apr)	Y = 88.730 + 2.520(>>13°C Apr)	Y = 91.972 + 9.694(>>13°C Apr)
Y = 134.55 + 5.670(>>13°C May)	Y = 0(>>13°C May)	Y = 0(>>13°C May)
Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)
Y = 135.25 - 1.224(>>13°C Oct)	Y = 0(>>13°C Oct)	Y = 92.237 + 6.258(>>13°C Oct)
Y = 133.95 + 0.449(>>13°C Nov)	Y = 88.757 + 0.577(>>13°C Nov)	Y = 93.198 - 0.891(>>13°C Nov)
Y = 133.14 + 0.166(>>13°C Dec)	Y = 88.693 + 0.111(>>13°C Dec)	Y = 94.253 - 0.185(>>13°C Dec)
Y = 132.48 + 0.040(>>13°C Ann)	Y = 85.183 + 0.127(>>13°C Ann)	Y = 91.875 + 0.024(>>13°C Ann)

Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)	Sour Orange Flowering Dates (Y)
Y = 136.69 - 0.050(>>13°C Jan)	Y = 89.035 - 0.054(>>13°C Jan)	Y = 89.787 + 0.196(>>13°C Jan)
Y = 135.21 + 0.037(>>13°C Feb)	Y = 86.189 + 0.259(>>13°C Feb)	Y = 89.576 + 0.491(>>13°C Feb)
Y = 134.83 + 0.089(>>13°C Mar)	Y = 86.287 + 0.680(>>13°C Mar)	Y = 90.972 + 1.791(>>13°C Mar)
Y = 136.03 - 0.163(>>13°C Apr)	Y = 87.408 + 2.823(>>13°C Apr)	Y = 92.487 + 11.846(>>13°C Apr)
Y = 135.30 + 5.619(>>13°C May)	Y = 0(>>13°C May)	Y = 0(>>13°C May)
Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)
Y = 135.81 - 0.249(>>13°C Oct)	Y = 0(>>13°C Oct)	Y = 92.915 + 5.851(>>13°C Oct)
Y = 134.95 + 0.403(>>13°C Nov)	Y = 87.145 + 0.779(>>13°C Nov)	Y = 93.128 + 0.308(>>13°C Nov)
Y = 134.63 + 0.104(>>13°C Dec)	Y = 84.723 + 0.380(>>13°C Dec)	Y = 93.512 - 0.018(>>13°C Dec)
Y = 134.27 + 0.025(>>13°C Ann)	Y = 81.204 + 0.192(>>13°C Ann)	Y = 88.145 + 0.140(>>13°C Ann)

Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)	Pooled Flowering Dates (Y)
Y = 136.69 - 0.050(>>13°C Jan)	Y = 87.923 + 0.032(>>13°C Jan)	Y = 91.864 + 0.032(>>13°C Jan)
Y = 135.21 + 0.037(>>13°C Feb)	Y = 86.111 + 0.299(>>13°C Feb)	Y = 88.425 + 0.527(>>13°C Feb)
Y = 134.83 + 0.089(>>13°C Mar)	Y = 86.818 + 0.585(>>13°C Mar)	Y = 90.685 + 1.386(>>13°C Mar)
Y = 136.03 - 0.163(>>13°C Apr)	Y = 87.647 + 2.565(>>13°C Apr)	Y = 91.778 + 10.906(>>13°C Apr)
Y = 135.30 + 5.619(>>13°C May)	Y = 0(>>13°C May)	Y = 0(>>13°C May)
Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)	Y = 0(>>13°C Jun)
Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)	Y = 0(>>13°C Jul)
Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)	Y = 0(>>13°C Aug)
Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)	Y = 0(>>13°C Sep)
Y = 135.81 - 0.249(>>13°C Oct)	Y = 0(>>13°C Oct)	Y = 92.122 + 5.047(>>13°C Oct)
Y = 134.95 + 0.403(>>13°C Nov)	Y = 87.420 + 0.685(>>13°C Nov)	Y = 92.416 + 0.005(>>13°C Nov)
Y = 134.63 + 0.104(>>13°C Dec)	Y = 86.471 + 0.210(>>13°C Dec)	Y = 92.751 - 0.035(>>13°C Dec)
Ann = 132.02 + 0.025(>>13°C Ann)	Y = 82.664 + 0.158(>>13°C Ann)	Y = 88.833 + 0.100(>>13°C Ann)

3. Growing Degree Days

3.1 Trends

GORGAN

Date of 200 HU accumulation

200 HU(d) = -188.77 + 0.161(yr)

HU accumulated by flowering

Orange = 1124.7 - 0.464(yr)

Tangerine = 677.43 - 0.235(yr)

Sweet Lemon = 1534.0 - 0.664(yr)

Sour Lemon = 1881.1 - 0.831(yr)

Sour Orange = 1210.2 - 0.487(yr)

Pooled = 987.75 - 0.387(yr)

KERMAN

Date of 200 HU accumulation (Y)

200 HU(d) = 787.67 - 0.331(yr)

HU accumulated by flowering (Y)

Orange = -176.40 + 0.098(yr)

Tangerine = -196.44 + 0.108(yr)

Sweet Lemon = -566.28 + 0.295(yr)

Sour Lemon = -502.40 + 0.264(yr)

Sour Orange = -146.97 + 0.083(yr)

Pooled = -170.47 + 0.096(yr)

SHIRAZ

Date of 200 HU accumulation (Y)

200(d) HU = 874.99 - 0.376(yr)

HU accumulated by flowering (Y)

Orange = 810.75 - 0.399(yr)

Tangerine = 1123.4 - 0.555(yr)

Sweet Lemon = 1211.5 - 0.598(yr)

Sour Lemon = 1097.5 - 0.540(yr)

Sour Orange = 1227.0 - 0.605(yr)

Pooled = 1133.9 - 0.559(yr)

3.2 Relationships with flowering dates

GORGAN

200 HU and flowering HU

Orange(HU) = 932.37 - 5.608(200HU)

Tangerine(HU) = 1130.4 - 7.039(200HU)

Sweet Lemon(HU) = 929.72 - 5.504(200HU)

Sour Lemon(HU) = 1013.5 - 6.030(200HU)

Sour Orange(HU) = 968.51 - 5.632(200HU)

Pooled(HU) = 1007.6 - 6.073(200HU)

200 HU and flowering date

Orange(d) = 110.06 + 0.167(200HU)

Tangerine(d) = 122.48 + 0.077(200HU)

Sweet Lemon(d) = 112.01 + 0.164(200HU)

Sour Lemon(d) = 121.37 + 0.105(200HU)

Sour Orange(d) = 121.27 + 0.112(200HU)

Pooled(d) = 120.01 + 0.104(200HU)

Flowering date and flowering HU

Orange(d) = 132.33 -0.003(HU)

Tangerine(d) = 128.57 + 0.020(HU)

Sweet Lemon(d) = 130.64 + 0.013(HU)

Sour Lemon(d) = 129.67 + 0.023(HU)

Sour Orange(d) = 127.13 + 0.035(HU)

Pooled(d) = 130.18 + 0.015(HU)

KERMAN

200 HU and flowering date

Orange(HU) = 122.99 - 0.805(200HU)

Tangerine(HU) = 100.00 - 0.621(200HU)

Sweet Lemon(HU) = 137.18 - 0.897(200HU)

Sour Lemon(HU) = 146.00 - 0.946(200HU)

Sour Orange(HU = 80.467 - 0.477(200HU)

Pooled(HU) = 107.64 - 0.671(200HU)

Orange(d) = 19.356 + 0.512(200HU)

Tangerine(d) = 23.349 + 0.489(200HU)

Sweet Lemon(d) = 18.823 + 0.535(200HU)

Sour Lemon(d) = 37.695 + 0.396(200HU)

Sour Orange(d) = 11.451 + 0.584(200HU)

Pooled(d) = 23.742 + 0.491(200HU)

Flowering date and flowering HU

Orange(d) = 88.059 -0.085(HU)

Tangerine(d) = 88.429 -0.067(HU)

Sweet Lemon(d) = 90.346 -0.069(HU)

Sour Lemon(d) = 91.04 -0.063(HU)

Sour Orange(d) = 87.261 + 0.054(HU)

Pooled(d) = 89.558 -0.060(HU)

SHIRAZ

200 HU and flowering date

Orange(HU) = 26.423 - 0.056(200HU)

Tangerine(HU) = 29.615 - 0.065(200HU)

Sweet Lemon(HU) = 35.856 - 0.093(200HU)

Sour Lemon(HU) = 53.554 - 0.211(200HU)

Sour Orange(HU) = 20.308 + 0.045(200HU)

Pooled(HU) = 30.354 - 0.047(200HU)

[Orange(d) = -18.204 + 0.838(200HU)

Tangerine(d) = -12.475 + 0.798(200HU)

Sweet Lemon(d) = -20.530 + 0.867(200HU)

Sour Lemon(d) = -9.267 + 0.791(200HU)

Sour Orange = -19.120 + 0.869(200HU)

Pooled(d) = -13.360 + 0.817(200HU)

Flowering date and flowering HU

Orange(d) = 86.245 + 0.197(HU)

Tangerine(d) = 86.041 + 0.209(HU)

Sweet Lemon(d) = 85.978 + 0.223(HU)

Sour Lemon(d) = 88.152 + 0.173(HU)

Sour Orange(d) = 87.508 + 0.223(HU)

Pooled(d) = 87.721 + 0.193(HU)

4. Multiple Regression Analysis

4.1 Multiple Regression Analysis using individually significant variables

GORGAN

Enter Regression Method

Orange Flowering Dates (Y) =
179.111 -1.165(T_{max} May) -0.288(T_{min} May) + 0.088(T_{min} Dec) + 0.030(Precip May) + 0.003(Precip Oct) -0.027(Sun Feb) -0.001(Sun Ann) + 0.496(T_{max}>35°C May) + 0.126(T_{min} < 13°C May) + 0.059(T_{max} & T_{min} < 13°C Dec) -0.081(200 HU)

Tangerine Flowering Dates (Y) =
209.315 -1.800(T_{max} May) + 0.461(T_{min} Jan) - 0.023(Precip Dec) + 0.418(T_{max}>35°C May) - 0.019(T_{max} & T_{min} < 13°C Dec) -0.001(Sun Ann) - 0.034(Sun Feb) -0.004(Sun Mar) + 0.012(Sun May) - 0.012(Sun Aug) -0.169(200 HU)

Sweet Lemon Flowering Dates (Y) =
122.299 -1.038(T_{max} May) -0.264(T_{min} May) + 0.473(T_{min} Jun) + 0.030(Precip Feb) + 0.041(Precip May) -0.023(Precip Sep) -0.333(T_{max}>35°C May) - 0.221(T_{min} < 13°C May) -1.644(T_{max} & T_{min} < 13°C May) + 0.176(T_{max} & T_{min} < 13°C Nov) + 0.171(T_{max} & T_{min} < 13°C Dec) + 0.032(T_{max} & T_{min} < 13°C Ann) + 0.036(Sun Feb) + 0.187(200 HU)

Sour Lemon Flowering Dates (Y) =
159.306 -1.114(T_{max} May) -0.221(T_{max}>35°C May) + 2.520(T_{max} & T_{min} < 13°C May) + 0.045(200 HU)

Sour Orange Flowering Dates (Y) =
127.751 -0.789(T_{max} May) + 4.302(T_{max}>35°C Mar) + 0.478(T_{min} < 13°C Nov) + 1.675(T_{max} & T_{min} < 13°C May) + 0.125(200 HU)

Pooled Flowering Dates (Y) =
151.197 -1.220(T_{max} May) + 0.323(T_{min} May) - 0.001(Precip May) -0.229(T_{max}>35°C May) + 0.073(T_{max} & T_{min} < 13°C Dec) + 0.076(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =
179.173 -1.245(T_{max} May) + 0.029(Precip May) - 0.030(Sun Feb) + 0.534(T_{max}>35°C May) + 0.193(T_{min} < 13°C May) + 0.036(T_{max} & T_{min} < 13°C Dec) -0.091(200 HU)

Tangerine Flowering Dates (Y) =
201.826 -1.698(T_{max} May) + 0.483(T_{min} Jan) - 0.019(Precip Dec) + 0.399(T_{max}>35°C May) - 0.034(Sun Feb) + 0.013(Sun May) -0.011(Sun Aug) - 0.145(200 HU)

Sweet Lemon Flowering Dates (Y) =
138.384 -1.071(T_{max} May) + 0.029(Precip Feb) + 0.033(Precip May) -0.030(Precip Sep) - 0.222(T_{max}>35°C May) -0.161(T_{min} < 13°C May) + 0.143(T_{max} & T_{min} < 13°C Nov) + 0.180(T_{max} & T_{min} < 13°C Dec) + 0.023(Sun Feb) + 0.141(200 HU)

Sour Lemon Flowering Dates (Y) =
159.306 -1.114(T_{max} May) -0.221(T_{max}>35°C May) + 2.520(T_{max} & T_{min} < 13°C May) + 0.045(200 HU)

Sour Orange Flowering Dates (Y) =
127.751 -0.789(T_{max} May) + 4.302(T_{max}>35°C Mar) + 0.478(T_{min} < 13°C Nov) + 1.675(T_{max} & T_{min} < 13°C May) + 0.125(200 HU)

Pooled Flowering Dates (Y) =
150.826 -1.209(T_{max} May) + 0.322(T_{min} May) - 0.231(T_{max}>35°C May) + 0.073(T_{max} & T_{min} < 13°C Dec) + 0.077(200 HU)

KERMAN

Enter Regression Method

Orange Flowering Dates (Y) =

49.018 -1.322(T_{max} Mar) + 01.032(T_{max} Apr) - 0.026(T_{max} May) + 4.673(T_{max} Ann)-1.828(T_{min} Feb) + 1.043(T_{min} Mar) -1.664(T_{min} Apr) -6.678(T_{min} May) - 2.038(T_{min} Jun) + 0.218(T_{min} Jul) -1.902(T_{min} Sep) + 5.284(T_{min} Ann) -0.065(Precip Mar) + 0.140(Precip Apr) + 0.058(Precip Ann)+ 1.294(T_{min} < 13°C Apr) - 0.545(T_{min} < 13°C May) + 0.702(T_{min} < 13°C Jul) + 0.215(T_{min} < 13°C Sep) -0.249(T_{min} < 13°C Ann)+ 0.031(T_{max} & T_{min} < 13°C Ann) -0.180(T_{max}>35°C May) + 0.078(Sun Mar) + 0.052(Sun Apr) + 0.028(Sun May) -0.008(Sun Ann)+ 0.298(200 HU)

Tangerine Flowering Dates (Y) =

55.304 + 1.343(T_{max} Mar) + 0.779(T_{max} Apr) + 1.092(T_{max} May) -0.276(T_{max} Ann)-1.304(T_{min} Mar) - 2.285(T_{min} Apr) + 0.122(T_{min} May) -0.548(T_{min} Jun) - 1.921(T_{min} Sep) + 3.158(T_{min} Ann)-0.003(Precip Ann) - 0.848-0.035(T_{max}>35°C Ann)+ 0.466(T_{min} < 13°C Apr) + 0.192(T_{min} < 13°C May) -0.525(T_{min} < 13°C Sep) - 0.641(T_{min} < 13°C Oct) -0.030(T_{min} < 13°C Ann) + 0.258(T_{max} & T_{min} < 13°C Feb) -0.012(T_{max} & T_{min} < 13°C Mar) -0.066(T_{max} & T_{min} < 13°C Ann) -0.117(Sun Mar) -0.017(Sun Apr) + 0.042(Sun May) + 0.279(200 HU)

Sweet Lemon Flowering Dates (Y) =

76.625 -0.775(T_{max} Mar) + 0.265(T_{max} Apr) -0.001(T_{max} May) + 3.684(T_{max} Ann)-1.862(T_{min} Feb) -0.654(T_{min} Mar) -2.273(T_{min} Apr) -2.825(T_{min} May) -1.198(T_{min} Jun) -0.223(T_{min} Aug) -1.702(T_{min} Sep) + 5.987(T_{min} Ann)+ 0.144(Precip Apr) + 0.012(Precip Ann) - 0.203(T_{max}>35°C May) -0.019(T_{min} < 13°C Apr) - 0.066(T_{min} < 13°C May) + 0.478(T_{min} < 13°C Jul) + 0.208(T_{min} < 13°C Sep) -0.930(T_{min} < 13°C Nov) + 0.001(T_{min} < 13°C Ann) -0.032(T_{max} & T_{min} < 13°C Feb) + 0.001(T_{max} & T_{min} < 13°C May) + 0.001(T_{max} & T_{min} < 13°C Ann)+ 0.019(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =

44.831 -1.108(T_{max} Mar) + 1.032(T_{max} Apr) + 3.874(T_{max} Ann)-1.836(T_{min} Feb) + 0.887(T_{min} Mar) -1.797(T_{min} Apr) -5.564(T_{min} May) -1.818(T_{min} Jun) -2.049(T_{min} Sep) + 5.486(T_{min} Ann) -0.065(Precip Mar) + 0.136(Precip Apr) + 0.052(Precip Ann) + 1.261(T_{min} < 13°C Apr) - 0.478(T_{min} < 13°C May) + 0.525(T_{min} < 13°C Jul) - 0.182(T_{min} < 13°C Ann)-0.314(T_{max}>35°C May) + 0.058(Sun Mar) + 0.046(Sun Apr) + 0.041(Sun May) - 0.009(Sun Ann)+ 0.299(200 HU)

Tangerine Flowering Dates (Y) =

48.953 + 1.331(T_{max} Mar) + 0.706(T_{max} Apr) + 0.990(T_{max} May) -1.349(T_{min} Mar) -2.195(T_{min} Apr) - 0.525(T_{min} Jun) -1.870(T_{min} Sep) + 3.105(T_{min} Ann) - 0.813(T_{max}>35°C May) -0.025(T_{max}>35°C Ann)+ 0.433(T_{min} < 13°C Apr) + 0.147(T_{min} < 13°C May) - 0.531(T_{min} < 13°C Sep) -0.650(T_{min} < 13°C Oct) + 0.265(T_{max} & T_{min} < 13°C Mar) -0.072(T_{max} & T_{min} < 13°C Ann) -0.114(Sun Mar) -0.017(Sun Apr) + 0.039(Sun May) + 0.268(200 HU)

Sweet Lemon Flowering Dates (Y) =

80.939 -0.791(T_{max} Mar) -1.708(T_{min} Feb) -0.511(T_{min} Mar) -1.952(T_{min} Apr) -2.548(T_{min} May) -1.178(T_{min} Jun) -0.325(T_{min} Aug) -2.075(T_{min} Sep) + 0.132(Precip Apr) -0.232(T_{max}>35°C May) + 0.456(T_{min} < 13°C Jul) + 2.907(T_{max} Ann) + 6.063(T_{min} Ann)

Sour Lemon Flowering Dates (Y) =
109.492 -2.396(T_{max} Mar) + 0.148(T_{max} Apr) - 1.275(T_{max} May) + 7.720(T_{max} Ann) -0.220(T_{min} Jan) + 1.293(T_{min} Mar) -1.606(T_{min} Apr) -2.562(T_{min} May) - 2.754(T_{min} Jun) + 1.121(T_{min} Jul) + 0.365(T_{min} Aug) - 2.965(T_{min} Sep) -1.269(T_{min} Ann) + 0.104(Precip Apr) - 0.070(Precip May) + 0.090(Precip Ann) + 0.442(T_{max}>35°C May) + 0.402(T_{min} < 13°C Aug) - 0.177(T_{min} < 13°C Sep) -0.652(T_{min} < 13°C Oct) + 0.024(T_{min} < 13°C Ann) + 0.151(Sun Mar) -0.088(Sun May) -0.315(200 HU)

Sour Lemon Flowering Dates (Y) =
108.225 -2.055(T_{max} Mar) -1.038(T_{max} May) 7.262(T_{max} Ann)-0.349(T_{min} Jan) + 0.895(T_{min} Mar) -1.450(T_{min} Apr) -3.188(T_{min} May) -2.660(T_{min} Jun) + 0.978(T_{min} Jul) -3.003(T_{min} Sep) + 0.103(Precip Apr) -0.041(Precip May) + 0.079(Precip Ann)+ 0.477(T_{max}>35°C May) + 0.388(T_{min} < 13°C Aug) -0.201(T_{min} < 13°C Sep) + 0.125(Sun Mar) -0.087(Sun May) -0.299(200 HU)

Sour Orange Flowering Date (Y) =
138.148 -2.137(T_{max} Mar) + 1.335(T_{max} Apr) - 3.312(T_{max} May) -0.430(T_{max} Dec) + 10.761(T_{max} Ann)+ 0.318(T_{min} Mar) -3.291(T_{min} Apr) -4.563(T_{min} May) - 3.049(T_{min} Jun) + 0.652(T_{min} Jul) -1.970(T_{min} Sept) - 0.086(T_{min} Ann) + 0.068(Precip Apr) + 0.066(Precip Ann) -0.548(T_{max}>35°C May) + 6.997(T_{min} < 13°C Mar) + 1.382(T_{min} < 13°C Apr) -0.322(T_{min} < 13°C May) + 0.519(T_{min} < 13°C Jul) -5.787(T_{min} < 13°C Oct) -0.306(T_{min} < 13°C Ann)-0.344(T_{max} & T_{min} < 13°C Dec) + 0.299(T_{max} & T_{min} < 13°C Ann) + 0.084(Sun Mar) - 0.019(Sun Apr) + 0.032(Sun May) -0.012(Sun Dec) - 0.009(Sun Ann) -0.456(200 HU)

Sour Orange Flowering Date (Y) =
99.531 -1.911(T_{max} Mar) + 0.980(T_{max} Apr) -3.210(T_{max} May) -0.662(T_{max} Dec) + 12.097(T_{max} Ann)-2.484(T_{min} Apr) -4.005(T_{min} May) -2.873(T_{min} Jul) -1.986(T_{min} Sep) + 0.067(Precip Apr) + 0.066(Precip Ann) - 0.440(T_{max}>35°C May) + 6.719(T_{min} < 13°C Mar) + 1.326(T_{min} < 13°C Apr) -0.208(T_{min} < 13°C May) + 0.497(T_{min} < 13°C Jul) -5.480(T_{min} < 13°C Oct) - 0.269(T_{min} < 13°C Ann) -0.470(T_{max} & T_{min} < 13°C Dec) + 0.304(T_{max} & T_{min} < 13°C Ann)+ 0.081(Sun Mar) - 0.012(Sun Ann) -0.397(200 HU)

Pooled Flowering Date (Y) =
276.403 -2.090(T_{max} Mar) + 2.057(T_{max} Apr) + 0.464(T_{max} May) + 04.308(T_{max} Ann)-2.168(T_{min} Feb) + 0.506(T_{min} Mar) -4.721(T_{min} Apr) -3.263(T_{min} May) - 2.440(T_{min} Jun) + 0.571(T_{min} Jul) -0.807(T_{min} Aug) - 1.120(T_{min} Sep) + 05.015(T_{min} Ann)+ 0.268(Precip Apr) + 0.029(Precip Ann) -0.107(T_{max}>35°C May) - 0.013(T_{max}>35°C Ann) -0.716(T_{min} < 13°C Mar) + 0.521(T_{min} < 13°C Apr) + 0.092(T_{min} < 13°C May) + 0.561(T_{min} < 13°C Jul) + 0.818(T_{min} < 13°C Sep) - 5.581(T_{min} < 13°C Nov) -0.235(T_{min} < 13°C Ann) - 0.044(T_{max} & T_{min} < 13°C Ann)+ 0.052(Sun Mar) - 0.032(Sun May) -0.132(200 HU)

Pooled Flowering Date (Y) =
270.986-2.224(T_{max} Mar) + 2.107(T_{max} Apr) + 0.161(T_{max} May) + 5.477(T_{max} Ann)-2.083(T_{min} Feb) + 0.569(T_{min} Mar) -4.468(T_{min} Apr) -4.031(T_{min} May) - 2.582(T_{min} Jun) + 0.607(T_{min} Jul) -0.910(T_{min} Aug) - 1.099(T_{min} Sep) + 4.601(T_{min} Ann)+ 0.270(Precip Apr) + 0.034(Precip Ann)-0.589(T_{min} < 13°C Mar) + 0.549(T_{min} < 13°C Apr) + 0.601(T_{min} < 13°C Jul) + 0.881(T_{min} < 13°C Sep) -5.763(T_{min} < 13°C Nov) - 0.249(T_{min} < 13°C Ann) + 0.064(Sun Mar) -0.037(Sun May) -0.135(200 HU)

SHIRAZ

Enter Regression Method

Orange Flowering Dates (Y) =
-216.270 + 3.551(T_{max} Feb) -1.882(T_{max} Mar) + 5.761(T_{max} Apr) -0.007(T_{max} May) + 8.883(T_{max} Jun) + 3.883(T_{max} Jul) -11.755(T_{max} Aug) -5.039(T_{max} Oct) - 3.902(T_{max} Ann)-2.529(T_{min} Feb) + 14.708(T_{min} Mar) - 9.191(T_{min} Apr) + 10.307(T_{min} May) -12.529(T_{min} Jun) + 2.698(T_{min} Jul) + 10.865(T_{min} Aug) -1.378(T_{min} Sep) + 1.469(T_{min} Oct) + 0.280(T_{min} Nov) -15.166(T_{min} Ann)+ 0.707(T_{max}>35°C Aug) -2.780(T_{min} < 13°C Apr) + 0.399(T_{min} < 13°C May) -3.441(T_{min} < 13°C Jun) - 0.738(T_{min} < 13°C Sep) + 1.642(T_{min} < 13°C Nov) - 0.054(T_{min} < 13°C Ann) + 0.798(T_{max} & T_{min} < 13°C Feb) + 0.246(Sun Mar) -0.095(Sun Apr) -0.196(Sun Aug) + 2.935(200 HU)

Tangerine Flowering Dates (Y) =
-41.897 -0.014(T_{max} Feb) -0.035(T_{max} Mar) -2.388(T_{max} Jul) -1.793(T_{max} Oct) 7.402(T_{max} Ann)+ 2.559(T_{min} Feb) + 5.674(T_{min} Mar) + 1.166(T_{min} Apr) + 8.141(T_{min} Jun) + 7.132(T_{min} Jul) + 6.438(T_{min} Aug) + 3.419(T_{min} Sep) + 5.189(T_{min} Oct) + 5.683(T_{min} Nov) + 4.539(T_{min} Dec) 29.351(T_{min} Ann)-1.194(T_{min} < 13°C Apr) -1.043(T_{min} < 13°C May) -1.242(T_{min} < 13°C Sep) + 5.126(T_{min} < 13°C Nov) -7.580(T_{min} < 13°C Ann)+ 0.188(T_{max} & T_{min} < 13°C Feb) + 0.112(Sun Apr) -0.067(Sun May) - 0.172(Sun Aug) + 0.906(200 HU)

Sweet Lemon Flowering Dates (Y) =
-629.875 + 2.833(T_{max} Feb) -1.119(T_{max} Mar) + 10.112(T_{max} Apr) + 2.530(T_{max} May) -1.767(T_{max} Jun) - 1.327(T_{max} Jul) + 1.308(T_{max} Oct) -0.009(T_{max} Ann)+ 12.857(T_{min} Feb) + 17.593(T_{min} Mar) + 9.899(T_{min} May) + 10.939(T_{min} Jun) + 13.862(T_{min} Jul) + 13.823(T_{min} Aug) + 7.547(T_{min} Sep) + 11.765(T_{min} Oct) + 12.317(T_{min} Nov) + 4.655(T_{min} Ann) + 11.043(T_{max}>35°C Aug) -1.330(T_{min} < 13°C Apr) - 1.404(T_{min} < 13°C May) -0.827(T_{min} < 13°C Sep) + 12.551(T_{min} < 13°C Nov) -11.023(T_{min} < 13°C Ann) + 0.658(T_{max} & T_{min} < 13°C Feb) + 0.133(Sun Apr) - 0.465(Sun Aug) -0.294(Sun Sep) + 3.206(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =
-236.763 + 3.102(T_{max} Feb) -1.557(T_{max} Mar) + 7.326(T_{max} Apr) + 8.992(T_{max} Jun) + 4.709(T_{max} Jul) - 10.977(T_{max} Aug) -5.087(T_{max} Oct) -5.864(T_{max} Ann) - 2.796(T_{min} Feb) + 13.920(T_{min} Mar) -9.084(T_{min} Apr) + 8.910(T_{min} May) -12.279(T_{min} Jun) + 2.468(T_{min} Jul) + 9.034(T_{min} Aug) -9.968(T_{min} Ann) + 0.688(T_{max}>35°C Aug) -2.490(T_{min} < 13°C Apr) -2.994(T_{min} < 13°C Jun) - 0.576(T_{min} < 13°C Sep) -0.033(T_{min} < 13°C Ann)+ 0.521(T_{max} & T_{min} < 13°C Feb) + 0.253(Sun Mar) - 0.109(Sun Apr) -0.271(Sun Aug) + 3.262(200 HU)

Tangerine Flowering Dates (Y) =
-62.110 -3.185(T_{max} Jul) -1.353(T_{max} Oct) 7.235(T_{max} Ann)+ 3.536(T_{min} Mar) + 5.293(T_{min} Jun) + 4.898(T_{min} Jul) + 5.129(T_{min} Aug) + 2.887(T_{min} Oct) + 3.011(T_{min} Nov) + 1.965(T_{min} Dec) + 30.836(T_{min} Ann)-1.097(T_{min} < 13°C Apr) -0.615(T_{min} < 13°C May) -1.481(T_{min} < 13°C Sep) + 4.395(T_{min} < 13°C Nov) -5.609(T_{min} < 13°C Ann) + 0.258(T_{max} & T_{min} < 13°C Feb) + 0.089(Sun Apr) -0.061(Sun May) -0.132(Sun Aug) + 1.042(200 HU)

Sweet Lemon Flowering Dates (Y) =
-790.285 + 2.584(T_{max} Feb) + 9.887(T_{max} Apr) + 2.309(T_{max} May) -1.599(T_{max} Jun) + 0.665(T_{max} Oct) + 12.074(T_{min} Feb) + 15.864(T_{min} Mar) + 9.387(T_{min} May) + 10.060(T_{min} Jun) + 11.825(T_{min} Jul) + 12.393(T_{min} Aug) + 7.852(T_{min} Sep) + 10.114(T_{min} Oct) + 11.651(T_{min} Nov) + 9.513(T_{max}>35°C Aug) - 1.248(T_{min} < 13°C Apr) -1.292(T_{min} < 13°C May) - 0.661(T_{min} < 13°C Sep) + 14.451(T_{min} < 13°C Nov) - 9.567(T_{min} < 13°C Ann)+ 0.657(T_{max} & T_{min} < 13°C Feb) + 0.153(Sun Apr) -0.484(Sun Aug) -0.269(Sun Sep) + 3.427(200 HU)

Sour Lemon Flowering Dates (Y) =
473.007-3.052(T_{max} Mar) + 5.857(T_{max} Apr) + 6.235(T_{max} May) -9.722(T_{max} Jun) -1.423(T_{max} Jul) + 5.044(T_{max} Oct) -2.418(T_{max} Ann)-1.679(T_{min} Feb) + 1.469(T_{min} Mar) -0.991(T_{min} Apr) + 6.771(T_{min} May) + 2.011(T_{min} Jun) -0.798(T_{min} Jul) + 3.651(T_{min} Aug) + 3.886(T_{min} Sep) -1.756(T_{min} Oct) -1.653(T_{min} Nov) + 29.781(T_{min} Ann) + 1.056(T_{min} < 13°C Apr) + 1.634(T_{min} < 13°C May) -0.865(T_{min} < 13°C Sep) -10.399(T_{min} < 13°C Nov) -3.522(T_{min} < 13°C Ann) -0.247(Sun Apr) -0.153(Sun Aug) + 0.739(200 HU)

Sour Orange Flowering Dates (Y) =
-217.496 -1.168(T_{max} Mar) + 5.610(T_{max} Apr) + 5.086(T_{max} May) -4.693(T_{max} Jun) -1.740(T_{max} Jul) -0.308(T_{max} Aug) + 3.402(T_{max} Oct) -0.688(T_{max} Ann)+ 5.978(T_{min} Feb) + 7.943(T_{min} Mar) -0.931(T_{min} Apr) + 8.983(T_{min} May) + 8.177(T_{min} Jun) + 5.868(T_{min} Jul) + 5.955(T_{min} Aug) + 3.163(T_{min} Sep) + 6.383(T_{min} Oct) + 4.640(T_{min} Nov) + 8.791(T_{min} Ann)+ 3.555(T_{max}>35°C Aug) + 7.416(T_{min} < 13°C Mar) -1.428(T_{min} < 13°C Apr) + 1.161(T_{min} < 13°C May) -0.627(T_{min} < 13°C Sep) -1.016(T_{min} < 13°C Nov) -3.101(T_{min} < 13°C Ann) -0.230(Sun Aug) -0.339(Sun Sep) + 2.243(200 HU)

Pooled Flowering Dates (Y) =
6.013+ 1.068(T_{max} Feb) -0.961(T_{max} Mar) + 2.645(T_{max} Apr) + 2.313(T_{max} May) -2.097(T_{max} Jun) -2.531(T_{max} Jul) -3.970(T_{max} Aug) -0.626(T_{max} Oct) + 3.086(T_{max} Ann)+ 2.527(T_{min} Jan) -2.858(T_{min} Feb) + 2.604(T_{min} Mar) + 1.303(T_{min} Apr) -0.698(T_{min} Jun) + 1.803(T_{min} Jul) + 7.219(T_{min} Aug) -0.741(T_{min} Sep) -1.604(T_{min} Oct) -.521(T_{min} Nov) + 0.371(T_{min} Dec) + 0.505(T_{max}>35°C Aug) -0.054(T_{min} < 13°C Apr) -0.370(T_{min} < 13°C May) -0.334(T_{min} < 13°C Jun) -1.030(T_{min} < 13°C Sep) + 2.145(T_{min} < 13°C Nov) -0.600(T_{min} < 13°C Sep)+ 0.172(T_{max} & T_{min} < 13°C Feb) -0.097(Sun Apr) -0.052(Sun Aug) + 1.440(200 HU)

Sour Lemon Flowering Dates (Y) =
410.430 -3.154(T_{max} Mar) + 5.768(T_{max} Apr) + 5.379(T_{max} May) -9.925(T_{max} Jun) + 6.436(T_{max} Oct) + 2.122(T_{min} Mar) + 6.342(T_{min} May) + 3.183(T_{min} Jun) + 4.490(T_{min} Aug) + 5.055(T_{min} Sep) + 30.967(T_{min} Ann)+ 0.908(T_{min} < 13°C Apr) + 1.163(T_{min} < 13°C May) -0.792(T_{min} < 13°C Sep) -8.390(T_{min} < 13°C Nov) -4.784(T_{min} < 13°C Ann) -0.258(Sun Apr) -0.196(Sun Aug) + 0.654(200 HU)

Sour Orange Flowering Dates (Y) =
-439.551+ 4.188(T_{max} Apr) + 4.909(T_{max} May) -4.599(T_{max} Jun) + 1.398(T_{min} Mar) + 3.294(T_{min} May) + 3.170(T_{min} Jun) + 0.648(T_{min} Oct) + 1.269(T_{max}>35°C Aug) + 9.994(T_{min} < 13°C Mar) + 14.301(T_{min} Ann) -0.647(T_{min} < 13°C Apr) + 0.989(T_{min} < 13°C May) -0.767(T_{min} < 13°C Sep) -1.058(T_{min} < 13°C Ann) -0.181(Sun Aug) -0.172(Sun Sep) + 2.245(200 HU)

Pooled Flowering Dates (Y) =
57.137+ 0.826(T_{max} Feb) -1.086(T_{max} Mar) + 2.184(T_{max} Apr) + 2.670(T_{max} May) -1.885(T_{max} Jun) -2.298(T_{max} Jul) -4.199(T_{max} Aug) -1.169(T_{max} Oct) + 3.584(T_{max} Ann)+ 2.966(T_{min} Jan) -3.095(T_{min} Feb) + 3.017(T_{min} Mar) + 2.910(T_{min} Apr) + 1.794(T_{min} Jul) + 8.297(T_{min} Aug) -1.459(T_{min} Oct) + 1.165(T_{min} Dec) + 0.734(T_{max}>35°C Aug) -0.394(T_{min} < 13°C May) -1.032(T_{min} < 13°C Sep) -0.883(T_{min} < 13°C Ann) -0.113(Sun Apr) + 1.456(200 HU)

4.2 Multiple Regression Analysis using citrus-type generic variables

GORGAN

Orange Flowering Dates (Y) =
161.088 -0.833(T_{max} May) -0.655(T_{min} May) + 0.025(Precip May) + 0.132(T_{max}>35°C May) + 0.036(T_{min} < 13°C May) -0.675(T_{max} & T_{min} < 13°C May) + 0.089(T_{max} & T_{min} < 13°C Dec-0.007(Sun May) + 0.022(200 HU)

Tangerine Flowering Dates (Y) =
147.788 -0.949(T_{max} May) +0.328(T_{min} May) + 0.041(Precip May) - 0.283(T_{max}>35°C May) - 0.152(T_{min} < 13°C May) + 0.086(T_{max} & T_{min} < 13°C May) + 0.130(T_{max} & T_{min} < 13°C Dec)+ 0.005(Sun May) + 0.026(200 HU)

Sweet Lemon Flowering Dates (Y) =
137.207 -2.031(T_{max} May) +1.330(T_{min} May) + 0.030(Precip May) + 0.190(T_{max}>35°C May) - 0.125(T_{min} < 13°C May) + 1.278(T_{max} & T_{min} < 13°C May) + 0.250(T_{max} & T_{min} < 13°C Dec)+ 0.038(Sun May) + 0.149(200 HU)

Sour Lemon Flowering Dates (Y) =
82.048 -0.877(T_{max} May) +2.962(T_{min} May) + 0.057(Precip May) + 0.283(T_{max}>35°C May) + 0.203(T_{min} < 13°C May) + 2.316(T_{max} & T_{min} < 13°C May) + 0.290(T_{max} & T_{min} < 13°C Dec)+ 0.039(Sun May) + 0.129(200 HU)

Sour Orange Flowering Dates (Y) =
105.637 -0.535(T_{max} May) -0.163(T_{min} May) + 0.104(Precip May) + 0.272(T_{max}>35°C May) - 0.470(T_{min} < 13°C May) - 0.940(T_{max} & T_{min} < 13°C May) + 0.081(T_{max} & T_{min} < 13°C Dec)+ 0.041(Sun May) + 0.276(200 HU)

Pooled Flowering Dates (Y) =
135.127 -1.163(T_{max} May) +0.683(T_{min} May) + 0.045(Precip May) + 0.240(T_{max}>35°C May) - 0.051(T_{min} < 13°C May) + 0.606(T_{max} & T_{min} < 13°C May) + 0.152(T_{max} & T_{min} < 13°C Dec)+ 0.023(Sun May) + 0.089(200 HU)

KERMAN

Orange Flowering Dates (Y) =
-10.145 + 0.516(T_{max} Mar) + 0.568(T_{max} Mar) - 0.376(T_{max} Mar) - 0.325(T_{min} Mar) + 0.339(T_{min} Apr) + 0.859(T_{min} May) - 0.308(T_{min} Jun) - 0.717(T_{min} Sep) - 0.022(Precip Apr) - 0.480(T_{max}>35°C May) + 0.890(T_{min} < 13°C Apr) + 0.166(T_{min} < 13°C May) - 0.345(T_{min} < 13°C Sep) + 0.124(T_{max} & T_{min} < 13°CAnn) - 0.040(Sun Mar) - 0.010(Sun Apr) + 0.064(Sun May) + 0.420(200 HU)

Tangerine Flowering Dates (Y) =
40.366 + 0.886(T_{max} Mar) + 0.938(T_{max} Apr) + 0.429(T_{max} May) - 0.844(T_{min} Mar) - 2.074(T_{min} Apr) + 0.657(T_{min} May) - 0.396(T_{min} Jun) - 0.944(T_{min} Sep) + 0.001(Precip Apr) - 0.773(T_{max}>35°C May) + 0.584(T_{min} < 13°C Apr) + 0.100(T_{min} < 13°C May) – 0.384(T_{min} < 13°C Sep) - 0.006(T_{max} & T_{min} < 13°C Ann) - 0.097(Sun Mar) - 0.024(Sun Apr) + 0.073(Sun May) + 0.173(200 HU)

Sweet Lemon Flowering Dates (Y) =
142.346 - 0.924(T_{max} Mar) + 0.063(T_{max} Apr) -0.544(T_{max} May) + 0.328(T_{min} Mar) - 0.826(T_{min} Apr) -2.487(T_{min} May) - 0.766(T_{min} Jun) - 1.895(T_{min} Sep) + 0.080(Precip Apr) - 0.346(T_{max}>35°C May) + 0.313(T_{min} < 13°C Apr) - 0.256(T_{min} < 13°C May) -0.408(T_{min} < 13°C Sep) + 0.089(T_{max} & T_{min} < 13°C Ann) + 0.029(Sun Mar)+ 0.052(Sun Apr) + 0.078(Sun May) + 0.045(200 HU)

Sour Lemon Flowering Dates (Y) =
187.323 - 1.953(T_{max} Mar) + 0.407(T_{max} Apr) -0.087(T_{max} May) + 0.835(T_{min} Mar) - 2.929(T_{min} Apr) -1.342(T_{min} May) - 1.567(T_{min} Jun) - 2.024(T_{min} Sep) + 0.110(Precip Apr) - 0.407(T_{max}>35°C May) + 0.268(T_{min} < 13°C Apr) + 0.201(T_{min} < 13°C May) -0.264(T_{min} < 13°C Sep) - 0.044(T_{max} & T_{min} < 13°C Ann) + 0.058(Sun Mar)+ 0.029(Sun Apr) + 0.007(Sun May) -0.332(200 HU)

Sour Orange Flowering Dates (Y) =
98.337 - 3.227(T_{max} Mar) + 1.501(T_{max} Apr) + 0.763(T_{max} May) + 3.457(T_{min} Mar) - 5.016(T_{min} Apr)+ 1.683(T_{min} May) - 1.947(T_{min} Jun) - 0.996(T_{min} Sep) + 0.252(Precip Apr) + 0.200(T_{max}>35°C May) + 0.952(T_{min} < 13°C Apr) + 0.427(T_{min} < 13°C May) + 0.003(T_{min} < 13°C Sep) - 0.093(T_{max} & T_{min} < 13°C Ann) + 0.051(Sun Mar)+ 0.076(Sun Apr) -0.048(Sun May) -0.067(200 HU)

Pooled Flowering Dates (Y) =
136.688 - 1.184(T_{max} Mar) -0.110(T_{max} Apr) -0.399(T_{max} May) + 0.279(T_{min} Mar) - 1.878(T_{min} Apr)+ 0.312(T_{min} May) - 0.800(T_{min} Jun) - 1.004(T_{min} Sep) + 0.060(Precip Apr)-0.280(T_{max}>35°C May) + 0.635(T_{min} < 13°C Apr) - 0.001(T_{min} < 13°C May) -0.167(T_{min} < 13°C Sep) + 0.016(T_{max} & T_{min} < 13°C Ann) + 0.006(Sun Mar)+ 0.045(Sun Apr) + 0.036(Sun May) -0.115(200 HU)

SHIRAZ

Orange Flowering Dates (Y) =
529.241 -0.211(T_{max} Mar) -5.111(T_{max} Jul) -3.371(T_{max} Oct) -3.909(T_{min} Feb) + 0.301(T_{min} Mar) -0.681(T_{min} Apr) + 3.678(T_{min} May) -5.874(T_{min} Jun) + 4.764(T_{min} Jul) -0.845(T_{min} Aug) -0.305(T_{min} Sep) + 2.035(T_{min} Oct) -3.064(T_{min} Nov) -0.185(T_{max}>35°C Aug) -0.109(T_{min} < 13°C Apr) + 0.897(T_{min} < 13°C May) -1.426(T_{min} < 13°C Sep) -4.030(T_{min} < 13°C Nov) + 0.065(T_{max} & T_{min} < 13°C Feb) -0.057(Sun Apr) -0.176(Sun Aug) + 0.281(200 HU)

Tangerine Flowering Dates (Y) =
27.124 + 1.906(T_{max} Mar) -1.049(T_{max} Jul) -2.740(T_{max} Oct) -1.907(T_{min} Feb) -2.415(T_{min} Mar) -2.328(T_{min} Apr) - 2.715(T_{min} May) + 3.506(T_{min} Jun) -0.700(T_{min} Jul) + 0.350(T_{min} Aug) + 3.516(T_{min} Sep) -0.980(T_{min} Oct) -1.030(T_{min} Nov) + 0.119(T_{max}>35°C Aug) -0.380(T_{min} < 13°C Apr) -0.232(T_{min} < 13°C May) -0.141(T_{min} < 13°C Sep) + 1.871(T_{min} < 13°C Nov) + 0.076(T_{max} & T_{min} < 13°C Feb)+ 0.061(Sun Apr) -0.143(Sun Aug) + 0.849(200 HU)

Sweet Lemon Flowering Dates (Y) =
-306.818 + 1.168(T_{max} Mar) -0.455(T_{max} Jul) -0.821(T_{max} Oct) -0.852(T_{min} Feb) -0.430(T_{min} Mar) -1.486(T_{min} Apr) - 3.572(T_{min} May) + 1.561(T_{min} Jun) -0.401(T_{min} Jul) + 0.069(T_{min} Aug) + 0.900(T_{min} Sep) -0.848(T_{min} Oct) -0.079(T_{min} Nov) + 0.111(T_{max}>35°C Aug) -0.654(T_{min} < 13°C Apr) -0.793(T_{min} < 13°C May) -0.333(T_{min} < 13°C Sep) + 11.945(T_{min} < 13°C Nov) -0.121(T_{max} & T_{min} < 13°C Feb)+ 0.166(Sun Apr) -0.225(Sun Aug) + 1.217(200 HU)

Sour Lemon Flowering Dates (Y) =
-19.584 -0.637(T_{max} Mar) -1.077(T_{max} Jul) + 2.205(T_{max} Oct) -1.817(T_{min} Feb) -1.762(T_{min} Mar) -1.011(T_{min} Apr) - 1.177(T_{min} May) -3.373(T_{min} Jun) -3.373(T_{min} Jul) + 0.351(T_{min} Aug) + 1.992(T_{min} Sep) + 0.310(T_{min} Oct) -0.467(T_{min} Nov) -0.093(T_{max}>35°C Aug) -0.386(T_{min} < 13°C Apr) -0.651(T_{min} < 13°C May) -0.235(T_{min} < 13°C Sep) + 7.512(T_{min} < 13°C Nov) -0.434(T_{max} & T_{min} < 13°C Feb) -0.044(Sun Apr) -0.268(Sun Aug) + 0.418(200 HU)

Sour Orange Flowering Dates (Y) =
-208.752 + 0.418(T_{max} Mar) -1.545(T_{max} Jul) -0.035(T_{max} Oct) -3.051(T_{min} Feb) -0.329(T_{min} Mar) + 1.649(T_{min} Apr)+ 0.165(T_{min} May) -3.604(T_{min} Jun) -0.774(T_{min} Jul) -0.509(T_{min} Aug) + 1.083(T_{min} Sep) + 0.314(T_{min} Oct) -1.756(T_{min} Nov) + 0.153(T_{max}>35°C Aug) -0.542(T_{min} < 13°C Apr) -0.361(T_{min} < 13°C May) -0.632(T_{min} < 13°C Sep) + 10.562(T_{min} < 13°C Nov) -0.504(T_{max} & T_{min} < 13°C Feb) + 0.059(Sun Apr) -0.148(Sun Aug) + 1.255(200 HU)

Pooled Flowering Dates (Y) =
44.5669 + 0.052(T_{max} Mar) -2.582(T_{max} Jul) -0.243(T_{max} Oct) -2.121(T_{min} Feb) -0.376(T_{min} Mar) + 0.695(T_{min} Apr) -0.490(T_{min} May) -2.461(T_{min} Jun) + 0.841(T_{min} Jul) + 1.038(T_{min} Aug) + 0.536(T_{min} Sep) -0.493(T_{min} Oct) -2.180(T_{min} Nov) -0.199(T_{max}>35°C Aug) -0.146(T_{min} < 13°C Apr) -0.317(T_{min} < 13°C May) -0.701(T_{min} < 13°C Sep) + 4.323(T_{min} < 13°C Nov) -0.168(T_{max} & T_{min} < 13°C Feb) -0.020(Sun Apr) -0.103(Sun Aug) + 0.765(200 HU)

4.3 Multiple Regression Analysis using annually averaged variables

GORGAN

Enter Regression Method

Orange Flowering Dates (Y) =
143.227+ 0.931(T_{max} Ann) -3.151(T_{min} Ann) + 0.006(Precip Ann) + 0.001(Sun Ann) + 0.037(T_{max}>35°C Ann) -0.138(T_{min} < 13°C Ann) + 0.071(T_{max} & T_{min} < 13°C Ann) + 0.191(200 HU)

Tangerine Flowering Dates (Y) =
138.641-0.733(T_{max} Ann) + 0.344(T_{min} Ann) -0.002(Precip Ann) + 0.001(Sun Ann) -0.036(T_{max}>35°C Ann) -0.065(T_{min} < 13°C Ann) + 0.049(T_{max} & T_{min} < 13°C Ann) + 0.135(200 HU)

Sweet Lemon Flowering Dates (Y) =
73.767+ 1.832(T_{max} Ann) -0.859(T_{min} Ann) -0.001(Precip Ann) + 0.001(Sun Ann) -0.005(T_{max}>35°C Ann) -0.157(T_{min} < 13°C Ann) + 0.177(T_{max} & T_{min} < 13°C Ann) + 0.361(200 HU)

Sour Lemon Flowering Dates (Y) =
-16.869+ 4.143(T_{max} Ann) + 0.946(T_{min} Ann) + 0.006(Precip Ann) + 0.001(Sun Ann) -0.090(T_{max}>35°C Ann) + 0.050(T_{min} < 13°C Ann) + 0.176(T_{max} & T_{min} < 13°C Ann) + 0.184(200 HU)

Sour Orange Flowering Dates (Y) =
78.773+ 0.764(T_{max} Ann) -0.342(T_{min} Ann) + 0.021(Precip Ann) -0.001(Sun Ann) -0.014(T_{max}>35°C Ann) + 0.099(T_{min} < 13°C Ann) -0.003(T_{max} & T_{min} < 13°C Ann) + 0.120(200 HU)

Pooled Flowering Dates (Y) =
83.841+ 1.002(T_{max} Ann) -0.153(T_{min} Ann) + 0.003(Precip Ann) + 0.001(Sun Ann) + 0.001(T_{max}>35°C Ann) -0.031(T_{min} < 13°C Ann) + 0.083(T_{max} & T_{min} < 13°C Ann) + 0.213(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =
143.227+ 0.931(T_{max} Ann) -3.151(T_{min} Ann) + 0.006(Precip Ann) + 0.001(Sun Ann) + 0.037(T_{max}>35°C Ann) -0.138(T_{min} < 13°C Ann) + 0.071(T_{max} & T_{min} < 13°C Ann) + 0.191(200 HU)

Tangerine Flowering Dates (Y) =
125.290+ 0.001(Sun Ann) -0.049(T_{max}>35°C Ann) -0.074(T_{min} < 13°C Ann) + 0.066(T_{max} & T_{min} < 13°C Ann) + 0.141(200 HU)

Sweet Lemon Flowering Dates (Y) =
61.730+ 1.594(T_{max} Ann) + 0.001(Sun Ann) -0.114(T_{min} < 13°C Ann) + 0.180(T_{max} & T_{min} < 13°C Ann) + 0.346(200 HU)

Sour Lemon Flowering Dates (Y) =
-7.625+ 4.534(T_{max} Ann) + 0.006(Precip Ann) + 0.001(Sun Ann) -0.094(T_{max}>35°C Ann) + 0.180(T_{max} & T_{min} < 13°C Ann) + 0.205(200 HU)

Sour Orange Flowering Dates (Y) =
71.538+ 0.695(T_{max} Ann) + 0.021(Precip Ann) + 0.114(T_{min} < 13°C Ann) + 0.129(200 HU)

Pooled Flowering Dates (Y) =
93.479+ 0.595(T_{max} Ann) + 0.001(Sun Ann) -0.035(T_{min} < 13°C Ann) + 0.070(T_{max} & T_{min} < 13°C Ann) + 0.222(200 HU)

KERMAN

Enter Regression Method

Orange Flowering Dates (Y) =
-83.509+ 2.861(T_{max} Ann) + 0.311(T_{min} Ann) + 0.016(Precip Ann) + 0.001(Sun Ann) - 0.031(T_{max}>35°C Ann) +0.094(T_{min} < 13°C Ann) + 0.120(T_{max} & T_{min} < 13°C Ann) + 0.515(200 HU)

Tangerine Flowering Dates (Y) =
-79.422 + 2.852(T_{max} Ann) - 1.203(T_{min} Ann) + 0.017(Precip Ann) + 0.001(Sun Ann) + 0.044(T_{max}>35°C Ann) + 0.165(T_{min} < 13°C Ann) - 0.003(T_{max} & T_{min} < 13°C Ann) + 0.428(200 HU)

Sweet Lemon Flowering Dates (Y) =
-116.987+ 2.825(T_{max} Ann) + 1.831(T_{min} Ann) +0.005(Precip Ann) - 0.001(Sun Ann) - 0.010(T_{max}>35°C Ann) + 0.188(T_{min} < 13°C Ann) + 0.151(T_{max} & T_{min} < 13°C Ann) + 0.530(200 HU)

Sour Lemon Flowering Dates (Y) =
-72.846+2.723(T_{max} Ann) -0.610(T_{min} Ann) + 0.016(Precip Ann) + 0.001(Sun Ann) + 0.058(T_{max}>35°C Ann) + 0.209(T_{min} < 13°C Ann) - 0.001(T_{max} & T_{min} < 13°C Ann) + 0.289(200 HU)

Sour Orange Flowering Dates (Y) =
-117.119 + 2.943(T_{max} Ann)+ 1.200(T_{min} Ann) + 0.026(Precip Ann) -0.001(Sun Ann) + 0.001(T_{max}>35°C Ann) + 0.199(T_{min} < 13°C Ann) + 0.040(T_{max} & T_{min} < 13°C Ann) + 0.526(200 HU)

Pooled Flowering Dates (Y) =
-100.219 + 2.920(T_{max} Ann)+ 1.146(T_{min} Ann) + 0.016(Precip Ann) + 0.001(Sun Ann) - 0.023(T_{max}>35°C Ann) + 0.140(T_{min} < 13°C Ann) + 0.081(T_{max} & T_{min} < 13°C Ann) + 0.519(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =
-76.116+ 2.625(T_{max} Ann) + 0.015(Precip Ann) + 0.109(T_{min} < 13°C Ann) + 0.107(T_{max} & T_{min} < 13°C Ann) + 0.480(200 HU)

Tangerine Flowering Dates (Y) =
-81.261 + 3.195(T_{max} Ann) - 1.228(T_{min} Ann) + 0.019(Precip Ann) + 0.138(T_{min} < 13°C Ann + 0.450(200 HU)

Sweet Lemon Flowering Dates (Y) =
-116.432+ 2.682(T_{max} Ann) + 1.925(T_{min} Ann) - 0.001(Sun Ann) + 0.196(T_{min} < 13°C Ann) + 0.158(T_{max} & T_{min} < 13°C Ann) + 0.533(200 HU)

Sour Lemon Flowering Dates (Y) =
-81.783 +2.691(T_{max} Ann) + 0.016(Precip Ann) + 0.054(T_{max}>35°C Ann) + 0.217(T_{min} < 13°C Ann) + 0.323(200 HU)

Sour Orange Flowering Dates (Y) =
-107.680 + 2.653(T_{max} Ann)+ 1.162(T_{min} Ann) + 0.028(Precip Ann) + 0.192(T_{min} < 13°C Ann) + 0.514(200 HU)

Pooled Flowering Dates (Y) =
-93.720 + 2.592(T_{max} Ann)+ 1.071(T_{min} Ann) + 0.016(Precip Ann) + 0.154(T_{min} < 13°C Ann) + 0.066(T_{max} & T_{min} < 13°C Ann) + 0.497(200 HU)

SHIRAZ

Enter Regression Method

Orange Flowering Dates (Y) =
340.932 - 9.742(T_{max} Ann) - 1.888(T_{min} Ann) - 0.018(Precip Ann) - 0.008(Sun Ann) + 0.137(T_{max}>35°C Ann) +0.040(T_{min} < 13°C Ann) - 0.175(T_{max} & T_{min} < 13°C Ann) + 0.147(200 HU)

Backward regression Method

Orange Flowering Dates (Y) =
386.195 -10.717(T_{max} Ann) – 2.295(T_{min} Ann) - 0.023(Precip Ann) + 0.127(T_{max}>35°C Ann) +0.030(T_{min} < 13°C Ann) - 0.232(T_{max} & T_{min} < 13°C Ann)

Tangerine Flowering Dates (Y) =
335.845 - 10.723(T_{max} Ann) - 1.746(T_{min} Ann) - 0.061(Precip Ann) + 0.032(Sun Ann) + 0.340(T_{max}>35°C Ann) + 0.024(T_{min} < 13°C Ann) - 0.161(T_{max} & T_{min} < 13°C Ann) - 0.023(200 HU)

Tangerine Flowering Dates (Y) =
335.845 - 10.723(T_{max} Ann) - 1.746(T_{min} Ann) - 0.061(Precip Ann) + 0.032(Sun Ann) + 0.340(T_{max}>35°C Ann) + 0.024(T_{min} < 13°C Ann) - 0.161(T_{max} & T_{min} < 13°C Ann) - 0.023(200 HU)

Sweet Lemon Flowering Dates (Y) =
344.411 - 11.790(T_{max} Ann) - 1.289(T_{min} Ann) - 0.051(Precip Ann) + 0.034(Sun Ann) + 0.376(T_{max}>35°C Ann) + 0.024(T_{min} < 13°C Ann) - 0.234(T_{max} & T_{min} < 13°C Ann) + 0.038(200 HU)

Sweet Lemon Flowering Dates (Y) =
358.632 – 12.157(T_{max} Ann) - 1.362(T_{min} Ann) - 0.052(Precip Ann) + 0.035(Sun Ann) + 0.381(T_{max}>35°C Ann) + 0.023(T_{min} < 13°C Ann) - 0.243(T_{max} & T_{min} < 13°C Ann)

Sour Lemon Flowering Dates (Y) =
272.993 - 4.069(T_{max} Ann) - 7.742(T_{min} Ann) +0.009(Precip Ann) - 0.004(Sun Ann) + 0.189(T_{max}>35°C Ann) - 0.432(T_{min} < 13°C Ann) - 0.246(T_{max} & T_{min} < 13°C Ann) + 0.693(200 HU)

Sour Lemon Flowering Dates (Y) =
271.938 - 4.446(T_{max} Ann) – 6.971(T_{min} Ann) + 0.168(T_{max}>35°C Ann) - 0.395(T_{min} < 13°C Ann) - 0.247(T_{max} & T_{min} < 13°C Ann) + 0.653(200 HU)

Sour Orange Flowering Dates (Y) =
345.608 – 9.235(T_{max} Ann) – 2.856(T_{min} Ann) - 0.031(Precip Ann) + 0.014(Sun Ann) + 0.077(T_{max}>35°C Ann) + 0.011(T_{min} < 13°C Ann) - 0.238(T_{max} & T_{min} < 13°C Ann) + 0.048(200 HU)

Sour Orange Flowering Dates (Y) =
362.494 – 9.521(T_{max} Ann) – 3.139(T_{min} Ann) - 0.034(Precip Ann) + 0.018(Sun Ann) + 0.067(T_{max}>35°C Ann) -0.263(T_{max} & T_{min} < 13°C Ann)

Pooled Flowering Dates (Y) =
267.407 - 7.405(T_{max} Ann) - 1.916(T_{min} Ann) - 0.017(Precip Ann) - 0.003(Sun Ann) + 0.125(T_{max}>35°C Ann) + 0.031(T_{min} < 13°C Ann) - 0.141(T_{max} & T_{min} < 13°C Ann) + 0.228(200 HU)

Pooled Flowering Dates (Y) =
353.731 - 9.503(T_{max} Ann) - 2.435(T_{min} Ann) - 0.019(Precip Ann) + 0.146(T_{max}>35°C Ann) + 0.030(T_{min} < 13°C Ann) -0.197(T_{max} & T_{min} < 13°C Ann)

5. Multivariate Multiple Regression Analysis

5.1 Multivariate Multiple Regression Analysis with Generic Monthly Variables

GORGAN

$$y\begin{bmatrix} orange \\ tangerine \\ sweet\ lemon \\ sour\ lemon \\ sour\ orange \end{bmatrix} = \begin{bmatrix} -1.611 \\ -4.217 \\ -2.982 \\ -3.948 \\ -3.693 \end{bmatrix} T_{max}(May) + \begin{bmatrix} 2.563 \\ -1.668 \\ 0.078 \\ 5.930 \\ 18.212 \end{bmatrix} T_{min}(May) + \begin{bmatrix} 0.010 \\ -0.113 \\ 0.034 \\ -0.031 \\ 0.001 \end{bmatrix} Precip(May)$$

$$+ \begin{bmatrix} -0.019 \\ 0.025 \\ 0.026 \\ 0.003 \\ 0.043 \end{bmatrix} Sun(May) + \begin{bmatrix} 0.665 \\ 0.396 \\ 0.553 \\ 1.688 \\ 2.629 \end{bmatrix} T_{max} > 35°C(May) + \begin{bmatrix} 0.947 \\ -1.469 \\ 0.105 \\ 1.095 \\ 4.139 \end{bmatrix} T_{min} < 13°C(May)$$

$$+ \begin{bmatrix} 0.480 \\ -1.273 \\ -0.357 \\ 2.393 \\ 6.337 \end{bmatrix} T_{max}\&T_{min} < 13°C(May) + \begin{bmatrix} 0.080 \\ 0.276 \\ -0.151 \\ 0.062 \\ 0.357 \end{bmatrix} T_{max}\&T_{min} < 13°C(Dec) + \begin{bmatrix} -0.085 \\ 0.240 \\ 0.050 \\ 0.066 \\ 0.043 \end{bmatrix} 200HU$$

$$+ \begin{bmatrix} 144.845 \\ 242.863 \\ 199.301 \\ 132.379 \\ -57.474 \end{bmatrix}$$

5.2 Multivariate Multiple Regression Analysis with Annual Variables

GORGAN

$$y\begin{bmatrix} orange \\ tangerine \\ sweet\ lemon \\ sour\ lemon \\ sour\ orange \end{bmatrix} = \begin{bmatrix} -2.635 \\ -4.949 \\ 0.046 \\ -4.751 \\ -11.925 \end{bmatrix} T_{max}(Ann) + \begin{bmatrix} -4.137 \\ -2.634 \\ -5.068 \\ -2.679 \\ -1.280 \end{bmatrix} T_{min}(Ann) + \begin{bmatrix} 0.019 \\ 0.008 \\ 0.021 \\ 0.038 \\ 0.063 \end{bmatrix} Precip(Ann) +$$

$$\begin{bmatrix} -0.001 \\ -0.001 \\ -0.001 \\ -0.001 \\ -0.001 \end{bmatrix} Sun(Ann) + \begin{bmatrix} 0.054 \\ 0.077 \\ -0.004 \\ 0.127 \\ 0.301 \end{bmatrix} T_{max} > 35°C(Ann) + \begin{bmatrix} 0.044 \\ -0.078 \\ -0.244 \\ 0.205 \\ 0.677 \end{bmatrix} T_{min} < 13°C(Ann) +$$

$$\begin{bmatrix} 0.026 \\ 0.015 \\ 0.166 \\ 0.044 \\ -0.136 \end{bmatrix} T_{max}\&T_{min} < 13°C(Ann) + \begin{bmatrix} -0.223 \\ -0.063 \\ 0.183 \\ -0.333 \\ -0.927 \end{bmatrix} 200HU + \begin{bmatrix} 254.128 \\ 296.081 \\ 197.796 \\ 258.310 \\ 390.692 \end{bmatrix}$$

KERMAN

$$y\begin{bmatrix} orange \\ tangerine \\ sweet\ lemon \\ sour\ lemon \\ sour\ orange \end{bmatrix} = \begin{bmatrix} 3.085 \\ 3.301 \\ 3.462 \\ 3.678 \\ 2.701 \end{bmatrix} T_{max}(Ann) + \begin{bmatrix} 1.184 \\ -0.159 \\ -1.316 \\ 1.712 \\ -1.549 \end{bmatrix} T_{min}(Ann) + \begin{bmatrix} 0.018 \\ 0.028 \\ 0.008 \\ 0.017 \\ -0.002 \end{bmatrix} Precip(Ann) +$$

$$\begin{bmatrix} -0.001 \\ 0.001 \\ 0.001 \\ -0.001 \\ 0.001 \end{bmatrix} Sun(Ann) + \begin{bmatrix} -0.083 \\ -0.059 \\ -0.050 \\ -0.076 \\ 0.007 \end{bmatrix} T_{max} > 35°C(Ann) + \begin{bmatrix} 0.165 \\ 0.204 \\ 0.241 \\ 0.264 \\ 0.231 \end{bmatrix} T_{min} < 13°C(Ann) +$$

$$\begin{bmatrix} -0.067 \\ -0.103 \\ -0.096 \\ -0.122 \\ -0.049 \end{bmatrix} T_{max}\&T_{min} < 13°C(Ann) + \begin{bmatrix} 0.637 \\ 0.540 \\ 0.486 \\ 0.705 \\ 0.315 \end{bmatrix} 200HU + \begin{bmatrix} -120.520 \\ -115.166 \\ -111.877 \\ -170.394 \\ -70.553 \end{bmatrix}$$

SHIRAZ

$$y\begin{bmatrix} orange \\ tangerine \\ sweet\ lemon \\ sour\ lemon \\ sour\ orange \end{bmatrix} = \begin{bmatrix} -0.259 \\ -0.374 \\ -2.109 \\ 0.868 \\ 1.041 \end{bmatrix} T_{max}(Ann) + \begin{bmatrix} 2.069 \\ 0.417 \\ 2.021 \\ -2.402 \\ -2.938 \end{bmatrix} T_{min}(Ann) + \begin{bmatrix} -0.186 \\ -0.191 \\ -0.177 \\ -0.134 \\ -0.146 \end{bmatrix} Precip(Ann) +$$

$$\begin{bmatrix} 0.166 \\ 0.176 \\ 0.181 \\ 0.151 \\ 0.160 \end{bmatrix} Sun(Ann) + \begin{bmatrix} -0.234 \\ -0.177 \\ -0.165 \\ -0.112 \\ -0.147 \end{bmatrix} T_{max} > 35°C(Ann) + \begin{bmatrix} 0.027 \\ -0.111 \\ -0.093 \\ -0.354 \\ -0.303 \end{bmatrix} T_{min} < 13°C(Ann) +$$

$$\begin{bmatrix} -0.105 \\ -0.148 \\ -0.236 \\ -0.187 \\ -0.158 \end{bmatrix} T_{max}\&T_{min} < 13°C(Ann) + \begin{bmatrix} -0.163 \\ -0.154 \\ -0.021 \\ 0.268 \\ 0.070 \end{bmatrix} 200HU + \begin{bmatrix} -32.065 \\ 2.359 \\ 3.106 \\ 8.262 \\ 18.339 \end{bmatrix}$$