TEMPERATURE VARIABILITY AND CHANGE AT VARIOUS ALTITUDES ACROSS LESOTHO AND ADJOINING AREAS: IMPLICATIONS FOR AGRICULTURE

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A research report submitted to the Faculty of Science, University of the Witwatersrand, in partial fulfillment of the requirements for the degree of Master of Science

Johannesburg, 2017

DECLARATION

I declare that this Research Report is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(**Signature of candidate**)

24 day of March 2017 in Pretoria

ABSTRACT

Lesotho, being a mountainous area and due to the level of poverty and the dependency of its economy largely on agriculture, is particularly vulnerable to the impacts of climate change. This study examined maximum, minimum and mean temperature trends at various altitudes in Lesotho so as to determine possible implications of recent (70 - 80 years) altitudinal climate trends on the agricultural sector. Using seven stations at various altitudes across Lesotho, trends in maximum, minimum and mean temperatures were analyzed at monthly, annual and seasonal scales. The significant warming of minimum temperatures (Mokhotlong ($p=0.000$), Oxbow ($p=0.013$) and Qachasnek ($p=0.002$)) and maximum temperatures (Mokhotlong ($p<0.0001$), Oxbow ($p=0.007$) and Qachasnek ($p=0.000$)), were observed at the highland stations, located on the eastern side of Lesotho, while at the lowland stations as well as in the foothills, located on the western side of Lesotho, significant increases were only observed with minimum temperatures (Maseru ($p<0.0001$) and Mejametalana ($p=0.000$), Butha Buthe ($p=0.017$), located on the western side of Lesotho. In Mohaleshoek, located in the Senqu river valley, no significant trends were observed. In addition, a significant decrease in the number of days with frost was observed in both the highlands and the lowlands. With significant increases in maximum and minimum temperatures, a decline in agricultural production can be expected in the lowlands while a potential increase in areas suitable for agricultural production can be expected in the highlands.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the following:

- The Department of Agriculture, Forestry and Fisheries for funding my studies
- The South African Weather Service for providing the data for the study
- The Lesotho Meteorological Service for granting approval to use their data for the study
- Prof S.W. Grab for support, guidance and encouragement
- My life partner, Mr KB Tshabalala, for support, patience and understanding
- My family and friends for support and encouragement

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CHAPTER 1: INTRODUCTION

1.1 Background

Climate change is known to have been occurring naturally since the existence of life on earth (Khan *et al.*, 2009). Recently, the rate at which climate is changing has increased due to human activities (e.g. industrialization, land use change, agriculture, burning of fossil fuel etc.) and associated increases in greenhouse gas in the atmosphere, which in turn causes warming of the earth's surface (Prasad *et al.*, 2006; Janjua *et al.*, 2010; Valizadeh *et al.*, 2013). Studies have shown that temperatures are increasing globally (Asseng *et al.*, 2011) and that a global increase of between 2 and 4.5 ^{0}C is possible by the end of the 21st century (Salinger *et al.,* 2005). According to the IPCC 2013 report, the minimum and maximum temperatures over land have increased globally since 1950. A global average increase of 0.1 °C per decade for both maximum and minimum temperatures since 1950 is recorded in the IPCC 2013 report. This warming is accompanied by an increase in frequency and intensity of extreme weather events, with consequent natural disasters (Alexandrov & Hoogenboom, 2000; Moriondo *et al.*, 2010). Different parts of the world, different sectors of the economy and different social groups will be variably affected by these changes (Khan *et al.*, 2009). Africa is the most vulnerable to the impacts of climate change due to its lack of capacity and resources to cope with changes, as well as the dependency of its economies on agriculture (Mendelson *et al.*, 2000; Salinger *et al.*, 2005, Challinor *et al.,* 2007). The agricultural sector is the most vulnerable sector to climate change due to the dependency of agricultural production on weather and climate conditions (Moriondo *et al.*, 2010).

High lying areas as well as mountain regions are sensitive to climatic changes and therefore vulnerable (Liu *et al.*, 2009). Warming associated with climate change may lead to significant environmental changes including glacier shrinkage, permafrost melting, decrease in snow-packs and early snow-melt, which will in turn lead to changes in vegetation and

hydrological systems; these in turn will lead to the disruption of socio-economic structures of people (Beniston & Diaz, 1997; Beniston *et al.,* 2003). Early snow-melt is expected to alter the phenology of species, by either leading to early reproduction, which in turn leads to failure of finding suitable mates, failure by pollinators in finding pollen and nectar, and failure of flowers to be pollinated, some of which may lead to extinction of some species or create an environment suitable for new plant populations and consequent in shifts in species distribution (Beniston*,* 2003; Innouye, 2008). For example, in Mediterranean mountains, increasing temperatures at high altitudes has resulted in better growth and high cone production of *Pinus sylvestris* and *Juniperus communis* where these species were previously limited by cold conditions (Matias & Jump, 2015). At higher altitudes, early snow-melt poses a threat of extended exposure to dry conditions due to increased evapotranspiration of plants which were used to prolonged periods of snow cover, (Beniston, 2003). Early snow-melt also results in early flowering in plants which makes plants vulnerable to spring frost, if it occurs (Innouye, 2008).

In Lesotho, agriculture accounts for about 10 % of the country's GDP. About 60 – 70 % of the people are employed in the agricultural sector and about 80 % of the population is dependent on agriculture for their livelihoods (Gwimbi *et al.*, 2012). Only about 15 % of the land in Lesotho is suitable for growing crops, and thus agricultural production is limited to the lowlands at elevations between 1500 m – 1700 m (Moeletsi, 2004; Malebajoa, 2010). This is due to increased frost risk and drought risk at higher elevations. With the increase in temperature due to global warming, the frost risk decreases, which may in turn increase the area suitable for growing crops (Moeletsi, 2004). Some crop models suggest that global warming is beneficial to crops (Mendelson *et al.*, 1994). Lesotho, being in the temperate zone, is one of the areas where agriculture is expected to benefit from the impacts of warming (Mendelson, 2000), but this has not been comprehensively tested before.

Temperature and rainfall are the main factors determining the production potential of an area, thus, the significant increase in temperature predicted by climate models in various climate change scenarios, have the potential to limit the land's production potential (Malebajoa, 2010). People who live in Lesotho, Basotho, are highly dependent on agriculture for their livelihood. This Masters study is intended to analyze multi-decadal temperature trends at different altitudes across Lesotho and consider their impacts on agriculture, thereby hopefully assisting to better understand implications for crop production and its expansion into higher altitudes.

1.2 Aim

The study aims to examine maximum, minimum and mean temperature changes at various altitudes in Lesotho and the adjoining regions from the 1920's to 2013 (i.e. 70-80 years). In so doing, the objective is to determine possible implications of recent altitudinal climate trends on the agricultural sector.

1.3 Research questions

- What are the recent (last 70-80 years) temperature trends for Lesotho across various spatial dynamics?
- Do recent (last 70-80 years) temperature trends at higher altitudes differ to those at lower altitudes in Lesotho? If so, to what extent, and what would the implications be to agriculture?

1.4 Study area

Lesotho is located in southern Africa between 28 ^{0} and 31 ^{0} S and 27 ^{0} and 30 ^{0} E. Its total area is 30 355 km^{2} and the altitude ranges from 1388 m to 3482 m above sea level. It is divided into four physiographic zones based

on altitude; the highlands (>2000 m), the foothills to the east ranging from 1800 m – 2000 m, the lowlands to the west and the Senqu River valley both ranging from 1382 m – 1800 m (Figure 1.1) (Saha, 2011; Letsie, 2015). About 70 % of the total area consists of mountains and the main agricultural activities are confined to the lowlands (Moeletsi, 2004). Lesotho's climate is mainly influenced by the country's location and is classified as continental and temperate (LMS, 2013). Winters are dry and cold with extreme minimum temperatures of -10 ºC and even lower in the highlands. Summers are hot and humid, with highest maximum temperature between 16.5 ºC (highlands) and 30 ºC (lowlands). The average annual rainfall ranges between 450 mm in the lowlands to 1300 mm in the highlands, most of which falls between October and April, see Table 1.1, (Sood, 2007; Malebajoa, 2010; LMS, 2013).

The climate of Lesotho is affected by the tropics to the north and the temperate latitudes to the south. During the southern hemisphere summer, the subtropical high pressure band weakens and moves southwards, resulting in a decrease in mean pressure in the southern African interior, with resultant advection of Indian Ocean maritime air over the eastern half of South Africa and northerly flow of moist tropical air over the western parts (Linde, 2011). The influx of moist air coupled with orographic lifting results in the frequent development of thunderstorms, which is the major source of rainfall in Lesotho in summer (Sene *et. al*., 1998; Nel & Summer, 2008). During the southern hemisphere winter, the subtropical high pressure band strengthens and moves northwards resulting in westerly waves bringing along trails of cold fronts across the southern part of South Africa, see Figure 1.2 (Malebajoa, 2010; Linde, 2011). The Drakensberg often experiences cold fronts during winter months, some of these cold fronts are associated with cut off lows and are responsible for 80 % of snowfalls over the Drakensberg (Mulder & Grab, 2009).

Table 1.1: Annual rainfall and temperatures for the different physiographic zones of Lesotho (Source: Sood, 2007, page 11)

	Lowland	**Senqu River Valley**	**Foothills**	**Highlands**
Annual Rainfall (mm)	600 – 900	450 – 600	900 – 1000	1000 – 1300
Temperature Range (°C)	-11 to 38	-5 to 36	-8 to 30	-8 to 30
Average Temperature (°C)	17	16	14	13

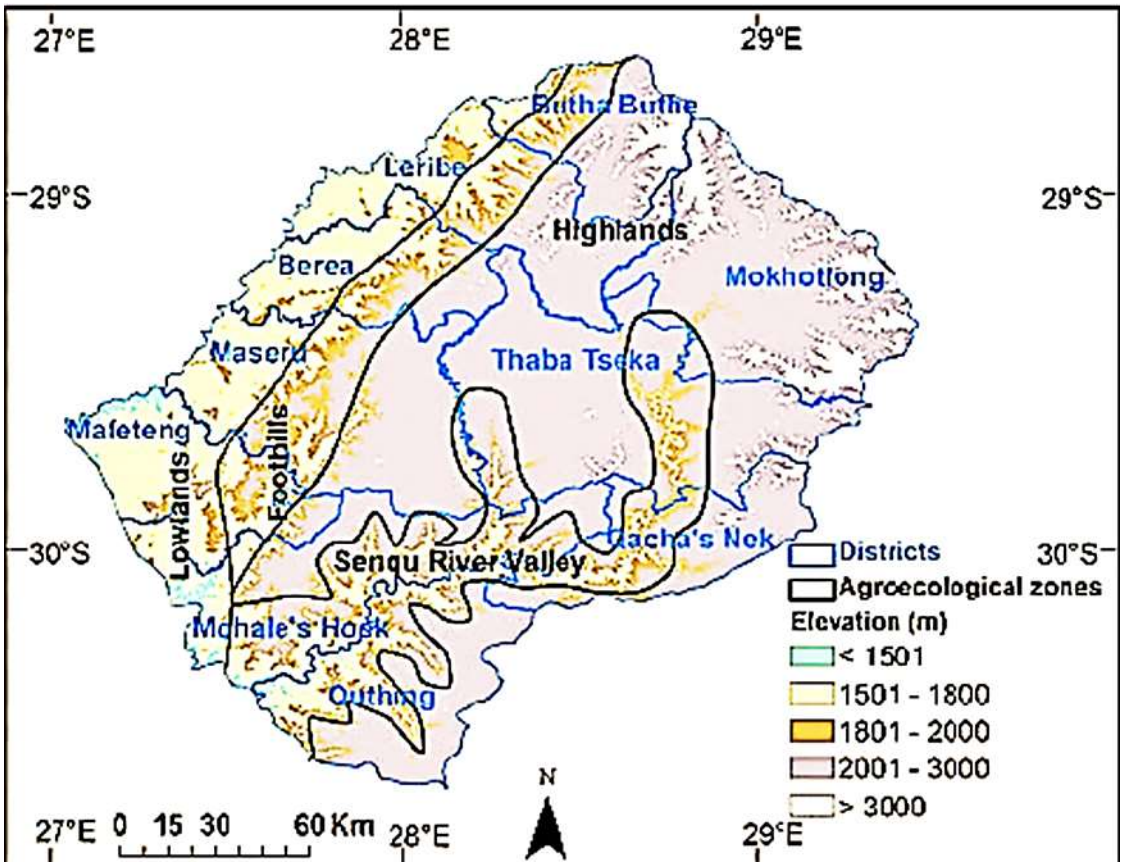


Figure 1.1: Physiographic zones of Lesotho and their height above sea level. (Source: Moeletsi & Walker, 2013, page 228)

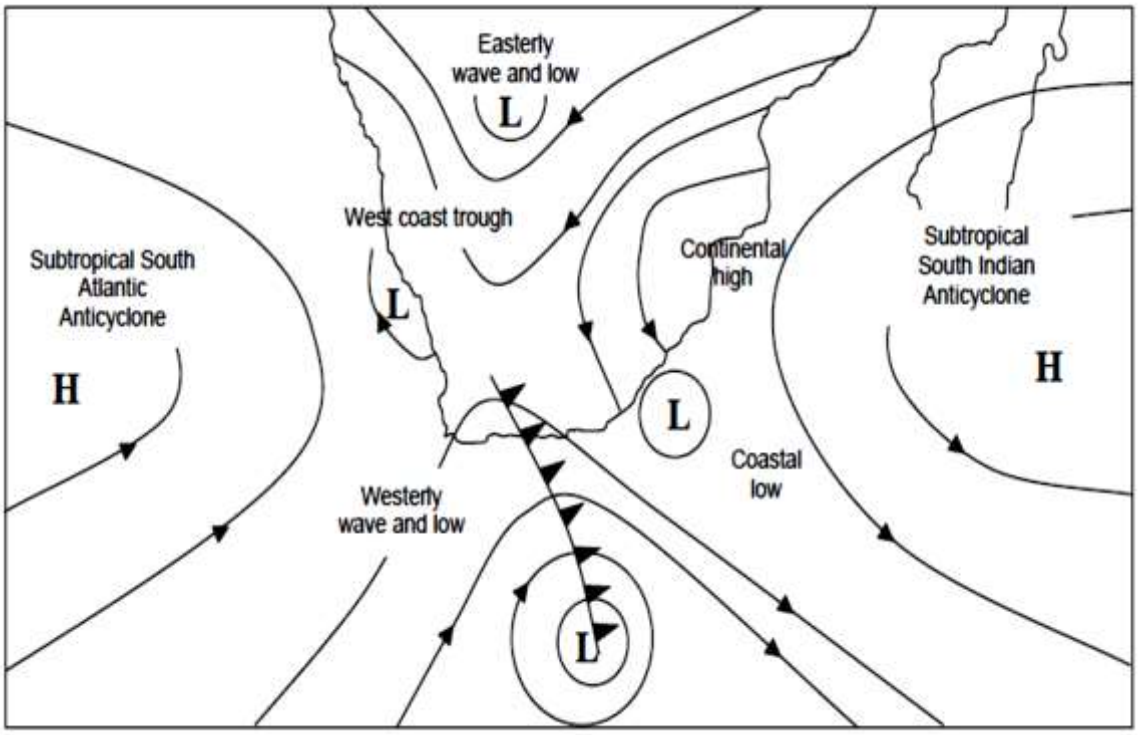


Figure 1.2: Winter circulation patterns in southern Africa. (Source: Linde, 2011, page 14).

Lesotho experiences its first seasonal frost from March in the highlands, while low lying areas usually experience their first frost between 1st and 15th May, with the last frost usually in September in the low lying areas and October in the high lying areas (Grab & Nash, 2010; Moeletsi & Walker, 2013). There are two types of frost; the advective frost which occurs as a result of the influx of cold air during the day or night, and radiation frost which is a result of radiative cooling in a clear and dry atmosphere which occurs at night (Jordan & Smith, 1995). On average, the numbers of frost days vary between 31 in the lowlands and 120 in the highlands (Grab & Nash, 2010). The river valleys experience the most severe frost and it occurs between May and September (Letsie, 2015).

Frost risk on agricultural production is dependent on the severity of the frost and the length of exposure of a crop to frost (Moeletsi, 2004).

Snowfall is another climate phenomenon which has an impact on agriculture and it occurs frequently in Lesotho, especially in high lying areas. Snowfalls peak in July and August, however, snowfalls also occur to a lesser extent in May/June and September/October (Grab & Nash, 2010; Grab & Linde, 2014). During the mid-season, snow cover lasting 1-5 days is widespread across all Lesotho mountain ranges, while snow cover lasting 6 – 10 days per annum is prevalent to a lesser extent, with the longest snow cover lasting 21 – 25 days only restricted to the southern Drakensberg (Grab & Linde, 2014). Snow poses a threat to agriculture because it damages crops and can lead to human and livestock deaths (Grab & Linde, 2014), but it also has positive impact on agriculture in that it increases soil moisture content during winter and insulates the underlying soil from freezing (Linde, 2011).

Lesotho is already under pressure to provide sustainable livelihoods for its growing population of 2.2 million people. There has been an increase in reliance on imports from South Africa to maintain food security (Grab & Linde, 2014), however, studies exploring the adaptability and distribution of crops to climate change are limited.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Various studies have shown that temperatures are increasing worldwide (IPCC, 2014). However, this warming is asymmetric; some areas are warming faster than others. Mountain areas are particularly of interest due to their unique climate and the ecosystem benefits derived from them (Beniston *et. al.*, 1997; Behnk*e, 20*11). Agricultural production depends on weather and climate (Wheeler *et al.,* 2000). Changes in weather patterns as well as in climate have an impact on growth and development of various crops. To optimize production, it is of importance to study impacts of climate change in specific areas so that appropriate mitigation interventions can be sort (Collier *et al.*, 2008). In this chapter results from various studies on climate change will be reviewed to see what changes have been observed and what impacts climate change has had on agriculture in various areas.

2.2 Temperature trends

Mountain regions are home to about 26% of the world's population and they play a major role of providing fresh surface water to adjoining lowland regions (Beniston *et. al.*, 1997; Behnk*e, 20*11). Warming in such mountain regions will result in altering the hydrological cycle by increasing evaporation which may in turn cause severe drying and associated increased risk of wild fires, drought and pests (Rangwala & Miller, 2012). Mountain environments are particularly vulnerable to the impacts of global warming because of the limited possibilities for species migration to more favorable locations (Liu *et al.,* 2009; Behnk*e, 2011*).

Some studies have shown that the rate of warming is higher in mountain regions and at high altitudes than at corresponding lower lying areas, yet others found no relationship between altitude and warming (Liu & Chen,

2000; You *et al.*, 2008; Liu *et al.*, 2009). For example, in a study conducted by Liu & Chen (2000), in which mean annual temperature trends for the Tibetan Plateau for 1961 – 2000 were analyzed. Their results indicate enhanced warming with an increase in altitude (Figure 2.1). Most of the stations in the Tibetan Plateau located at an altitude above 2000m showed significant warming with the most remarkable warming observed during winter (Liu & Chen, 2000). The findings are further supported by a more recent study which compared temperature trends for high elevation regions across the globe (Wang et al., 2014). In this study, high elevation stations were found to have enhanced rates of warming compared to their low lying counterparts (Table 2.1).

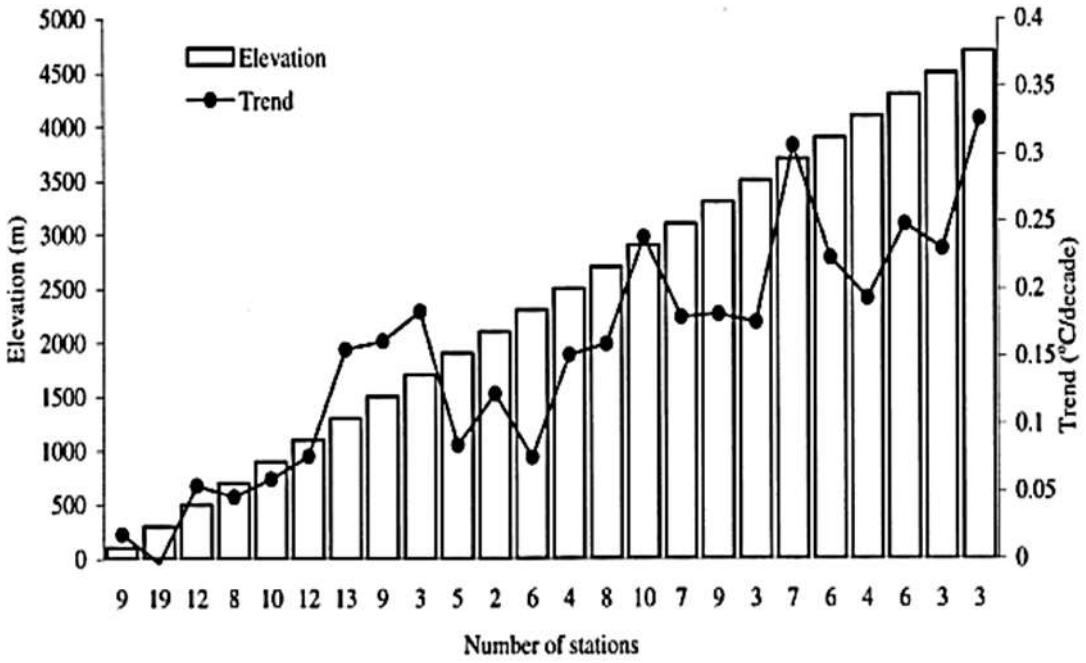


Figure 2.1: Annual mean temperature trends for 1961–1990 categorized according to the 24 elevation ranks of the 178 stations in the Tibetan Plateau and its surrounding areas. (Source: Liu & Chen, 2000, p1740).

Table 2.1: Trends for mean temperatures for high elevation regions across the globe. Bold values indicate significant trends at 95% confidence limit. (Source: Wang *et. al*., 2014, page 98).

No.	Paired Regions	Mann-Kendall trend test Z Total Warming Rate	Average Elevation (km)
1	North Tibetan Plateau	5.663(p<0.001) **2.095**	3.1365
	Loess Plateau	4.250 (p<0.001) **1.514**	1.0452
2	East Loess Plateau	4.215 (p<0.001) **1.495**	0.7992
	North China Plain	4.525 (p<0.001) **1.373**	0.0772
3	Southeast Rockies (USA)	3.474 (p<0.001) **1.415**	2.0733
	East lower region of SE Rockies	2.301 (p = 0.021) **0.930**	0.1772
4	Alps	4.465 (p<0.001) **1.639**	1.0501
	East lower region of Alps	3.362 (p<0.001) **1.471**	0.2045

However, the enhanced rate of warming was more pronounced for daily minimum (low temperatures) than for daily maximum (high temperatures) (Table 2.2). Furthermore, a study in the western United States (Colorado, Pacific Northwest and Sierra Nevada), found an increased rate of warming with height for minimum temperatures at all three stations, while the rate of warming with height for maximum temperature was only significant in Colorado, and was uniform at the other two stations (Figure 2.2) (Diaz & Eischeid, 2007).

Table 2.2: Temperature trends for mean temperatures across the globe for various seasons during 1961 - 2010. Bold values indicate significant trends at 95% confidence limit. (Source: Wang *et. al.,* 2014, page 98).

Region	Annual	Winter	Spring	Summer	Autumn
Mean temperature (°C)					
Tibetan Plateau	1.608	-9.051	2.212	2.001	11.271
Loess Plateau	9.074	-4.313	21.273	9.202	10.134
Northern Polar Area (North of 60°N)	-1.952	-16.026	11.186	-4.374	1.406
High Latitude Area (55–60°N)	3.212	-8.702	1.933	14.048	5.567
Trend (°C per 50 years)					
Tibetan Plateau	**1.867**	**3.020**	**1.396**	**1.356**	**1.898**
Loess Plateau	**1.595**	**2.827**	**1.768**	0.638	**1.146**
Northern Polar Area (North of 60°N)	**2.234**	**2.886**	**2.348**	**1.164**	**1.834**
High Latitude Area (55–60°N)	**1.638**	**2.336**	**1.861**	**1.143**	**1.240**

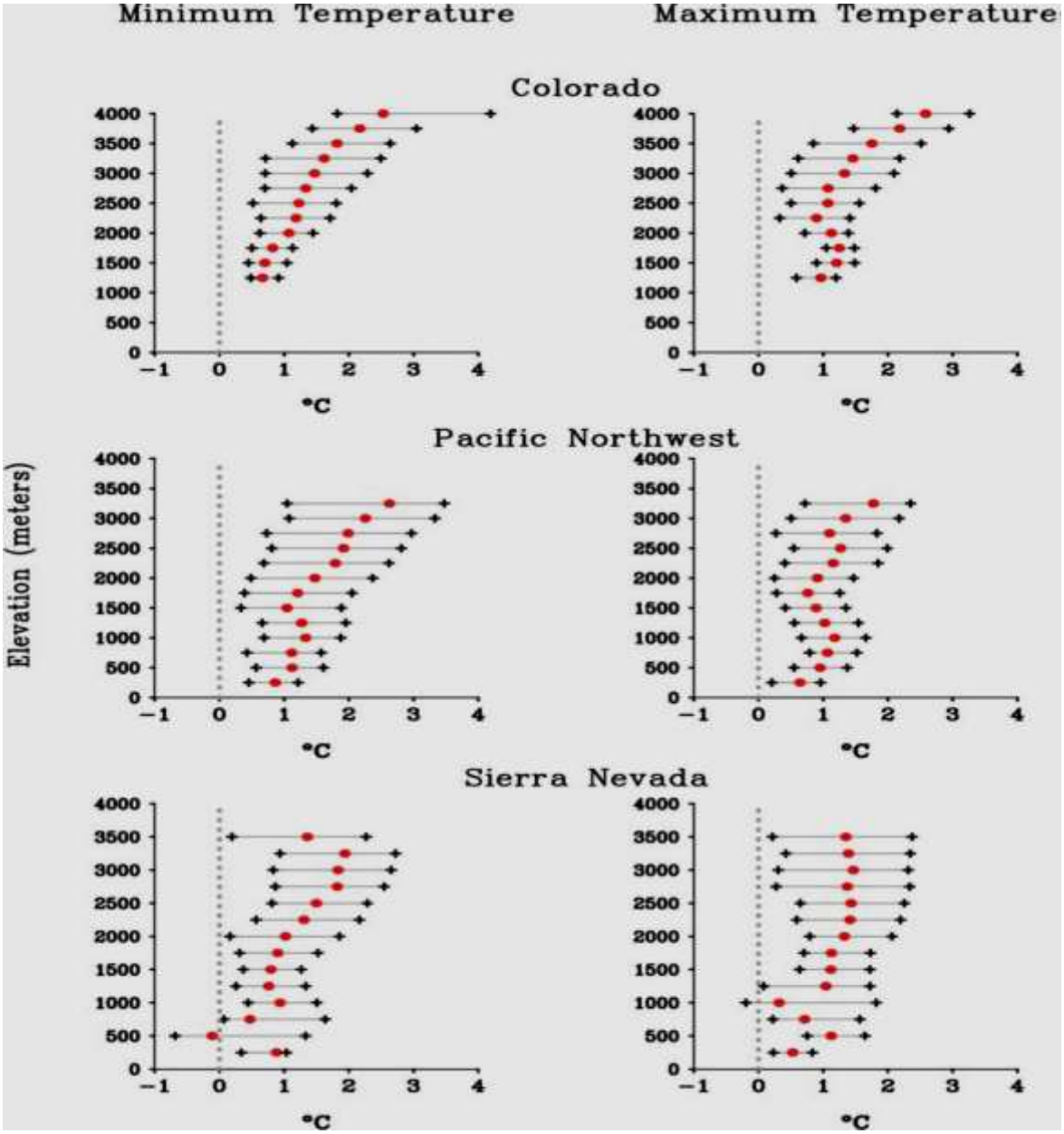


Figure 2.2: Annual mean maximum and minimum temperature trends (red dots) in a) Colorado Rockies, b) Pacific Nortwest and c) Sierra Nevada in the western United States for the period 1979-2006. The crosses are the approximate 5 and 95% cumulative distribution values. (Source: Diaz & Eisheid, 2007, page 4)

Contrary to the above findings, over the same area, an earlier study by Pepin and Losleben (2002) analyzed temperature trends over the Rocky Mountains of Colorado and found a decreasing rate of warming with height. This is supported by findings made by Vuille & Bradly (2000) in which they found decreased warming with height in the tropical Andes for the period 1939-1998 (Figure 2.3).

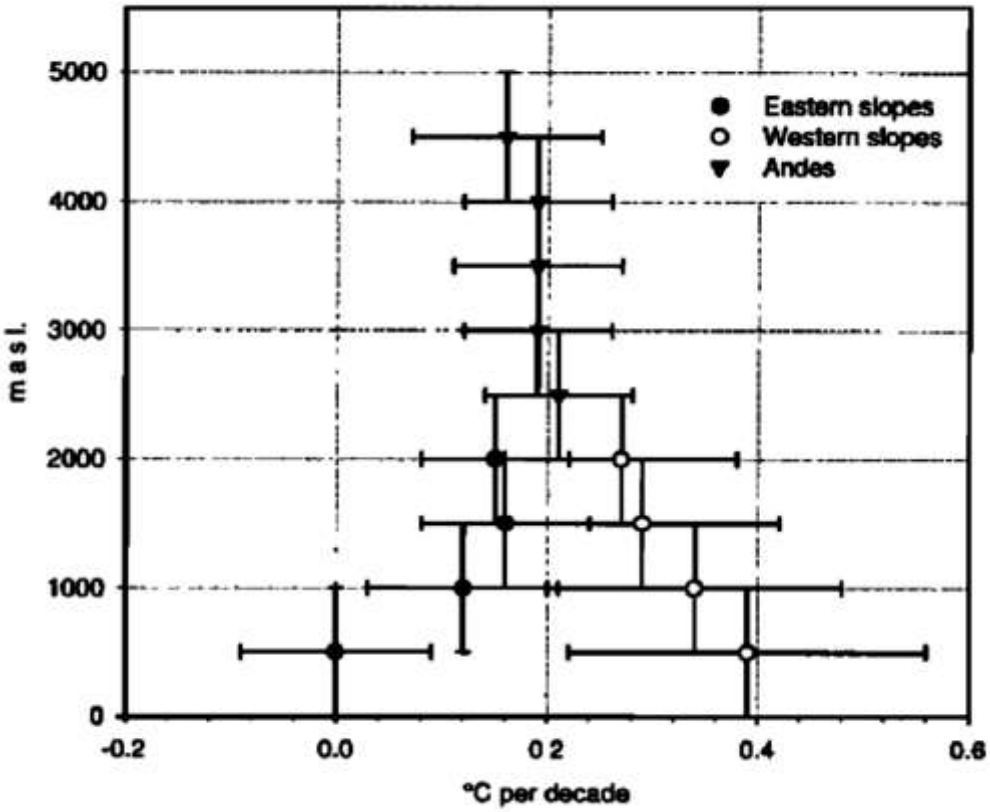


Figure 2.3: Rate of warming with height in the tropical Andes for the period 1939-1998. (Source: Vuille & Bradly, 2000, page 3887)

Some studies, however, found no relationship between rate of warming and altitude. For example, You *et. al*. (2008) in their study in the eastern and central Tibetan Plateau for 1961-2005, found no relationship between altitude and rate of warming. This, however, contradicts the finding by Liu & Chen (2000) who found enhanced warming with elevation in the Tibetan Plateau. In a study over the central Himalayas, Katell and Yao (2013)

observed a clear warming trend for maximum temperatures and a variable trend for minimum temperatures, and therefore came to the conclusion that there is no clear relationship between altitude and rate of warming (Figure 2.4).

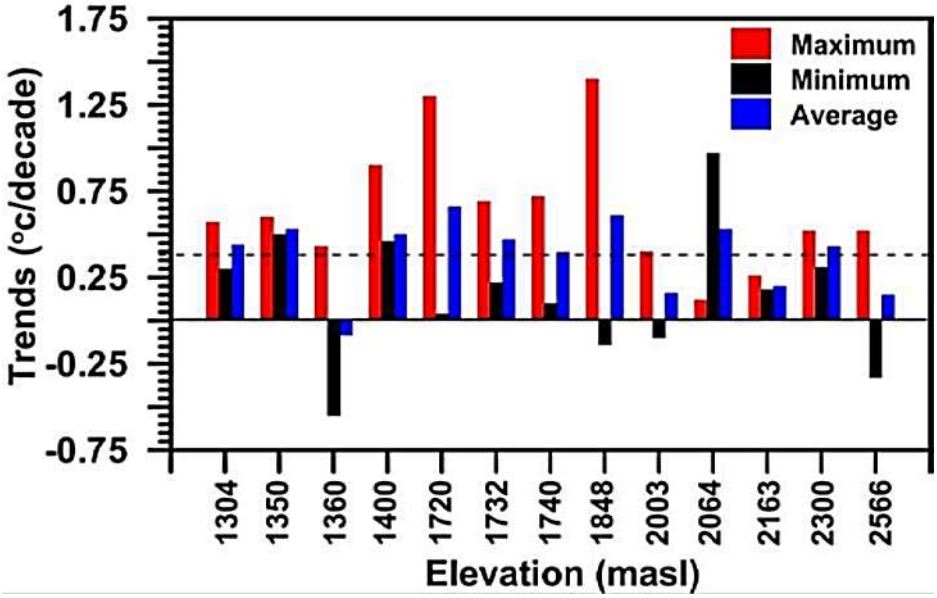


Figure 2.4: Maximum, minimum and average temperature trends per decade in the southern slope of Southern Himalayas from 1980 – 2009. (Source: Kattel & Yao, 2013, page 222)

There are thus conflicting reports on rates of climate warming with altitude. Some contradictions are found in different studies over the same area. The exact mechanism behind the contradictions could not be established, however, various factors such as the complexity of temperature change in response to climate change in highlands and mountains, or the use of different datasets by different researchers in terms of spatial and temporal coverage as well as different methodologies used by researchers to deal with questionable data, have been referred to by scientists as possibilities for the contrasting findings (Liu & Chen, 2000; You *et. al*., 2008; Liu *et al.*, 2009). The observed enhanced warming is believed by some researchers

to be due to an increase in snow melt, which decreases the rate at which the surface reflects solar radiation, resulting in more solar radiation being absorbed, which in turn increases warming. Apparently this effect is greatest closer to the 0^0C isotherm (Pepin & Lundquist, 2008). The warming, however, has been asymmetric, with minimum temperatures increasing at a much higher rate than maximum temperatures in winter at higher altitudes (Liu & Chen, 2000; Diaz & Eisched, 2007; Wang *et. al*., 2014).

2.3 Impact of warming on different types of crops

Temperature is one of the major role players on how climate affects crop production. Many rates of growth and development processes of crops depend on soil and air temperature (Wheeler *et al.,* 2000). The impact of extremely high temperatures, however, is dependent on the stage of development at which the crop is exposed to these temperature extremes as well as the duration of exposure (Porter & Semenov, 2005). Many crops, especially in Africa, are already grown close to their limit of thermal tolerance (Collier *et al.*, 2008). The ideal conditions for crops to develop optimally are crop specific, and since the existing crops are already close to their limit of tolerance, changing conditions in the absence of adaptation may cause reduced yield, but when adaptation is considered, may open many new opportunities (Collier *et al.*, 2008).

Mountain regions are characterized by low temperatures and prolonged snow cover. Snow provides protection against frost for plants during winter. Warming will thus result in increased snowmelt with consequent loss of cool climate zones (Beniston, 2003). Increase in temperature also results increase in evapotranspiration and thus exposing plants to summer desiccation (Beniston *et. al*., 2003). As a result mountain vegetation tends to shift upwards to areas where conditions are still favorable for their growth (Beniston, 2003; Matias & Jump, 2015).

Africa is regarded as the continent which is most vulnerable to climate change. This is mainly because of its climate is already warm, its economy depends highly on agriculture, the rates at which its population is growing is higher and the level of poverty is also high (Dube *et. al.,* 2016). However, the impacts will not be evenly shared among the various regions; it will depend on the region's ability to respond (Kotir, 2011). In some parts of Africa, the area suitable for agriculture is expected to decrease due to warming (Lane & Jarvis, 2007). Agricultural soils are also in danger of losing their productive capacity (Chipanshi *et al.*, 2003). Large regions of marginal agriculture will be forced out of production (Vogel, 2005) mainly due to drought especially in southern Africa where the climate is already hot and dry (Dube *et. al.,* 2016).

For example in some parts of South Africa, increase in temperature will have a negative impact on maize production with consequent threat to food security in the region as South Africa is a supplier for the staple crop to the region (Akpalu et. al., 2008). However, some parts are expected to gain new areas of cultivation, especially in mountain regions, due to such warming. The benefits are however crop specific, with sorghum showing more positive yields than maize in high lying areas (Zinyengere *et. al.,* 2014). Though there are gains, losses are however, more pronounced than gains (Kotir, 2011).

A decline of between 20-40% in production due to heat stress is expected in humid and west African countries, while production is expected to increase significantly (>50%) in southeastern Namibia and Lesotho (Ramirez-Villegas & Thorton, 2015). This increase in crop production may also bring along an increase in pests and diseases which might offset the benefits of warming (Moeletsi, 2004; IPCC, 2007; Rangwala & Miller, 2012). As climate change continues, these gains in production may decline and/or disappear completely. Maize in particular is showing a significant decline in suitable growing areas across the Sahel region, mainly due to warming (Ramirez-Villegas & Thorton, 2015).

Lesotho being a high altitude country in which production is limited by extended periods of cold conditions stands to benefit from favorable conditions associated with warming, as any potential loss in production due to high temperatures will be compensated by reduced cooling at high altitudes, which creates conditions favorable for crop growth (Zinyengere *et. al.*, 2014). Similarly, new opportunities for cassava are also expected to open up at high altitudes in East Africa. In addition, East Africa could see opportunities for bananas, groundnuts and millets as a consequence of climate warming. Some countries, however, may see most crops currently suitable climatologically no longer growing, thus forcing them to shift from crops to livestock or to more drought resistant crops (Ramirez-Villegas & Thorton, 2015).

In South Africa, areas in the west, which are cooler and wetter, stand to benefit from climate change while those in the east which are warmer and drier, will be negatively affected (Gbetibouo & Hassan, 2005). For example, KwaZulu Natal and Mpumalanga (Figure 2.5) in particular, may lose suitable areas for sugarcane due to heat, but a more heat tolerant crop such as sorghum may survive leading to farmers in these areas shifting from sugarcane to sorghum (Gbetibouo & Hassan, 2005). In addition, as winters become warmer, some summer crops such as maize may see a shift in planting period from summer season to winter season (Gbetibouo & Hassan, 2005).

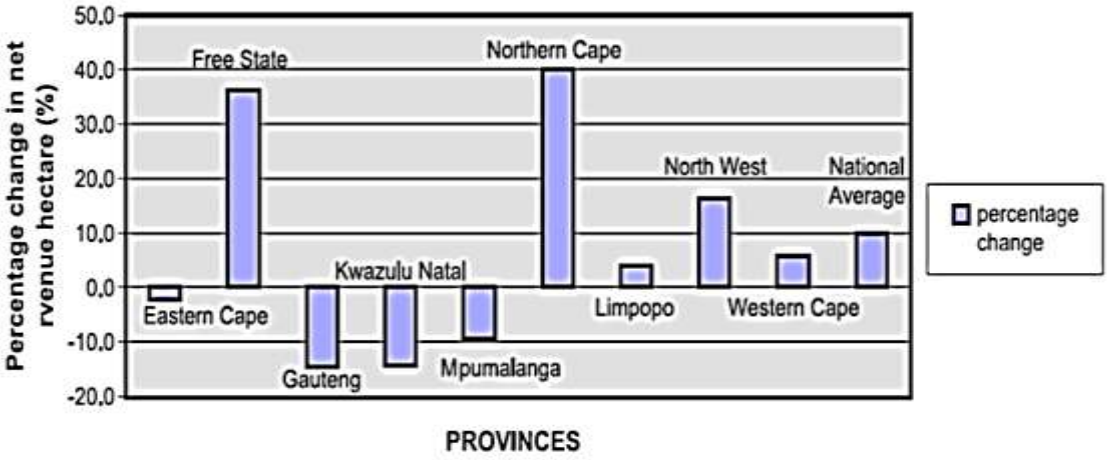


Figure 2.5: The effects of 2 °C increase in temperature on net revenue from various crops in South Africa (source: Gbetibouo & Hassan, 2005, page 149).

The main crops grown in Lesotho are maize, wheat, sorghum and to a lesser extent beans and peas (Mekbib *et al.*, 2012), with maize as the staple food for most of the country's population. Maize is a fast growing crop which is grown over a wide range of climate conditions, and it yields best under moderate to warm temperatures. Cool temperatures tend to slow the maturity process while high temperatures hasten the process. The optimum temperatures for maize germination and emergence, ranges between 20 to 22 ^{0}C, while optimum temperatures for the late vegetative stage ranges between 21 and 33 ^{0}C. Higher temperatures tend to hasten the germination process. The maize crop will experience heat stress when the mean daily temperature reaches ≥25 ^{0}C, and/or the daily maximum temperature is above 35 ^{0}C (Moeletsi, 2004).

Maize is a staple food for most people living in Lesotho (Basotho) (Moeletsi & Walker, 2012). Due to increasing temperatures, there is an expected potential loss of production area in the lowlands, with a resultant loss in yield of between 5 and 25% for maize. However, mountain areas

are found to be gaining new areas for production due to reduced frost, see figure 2.6 (Gwimbi et. al. 2013).

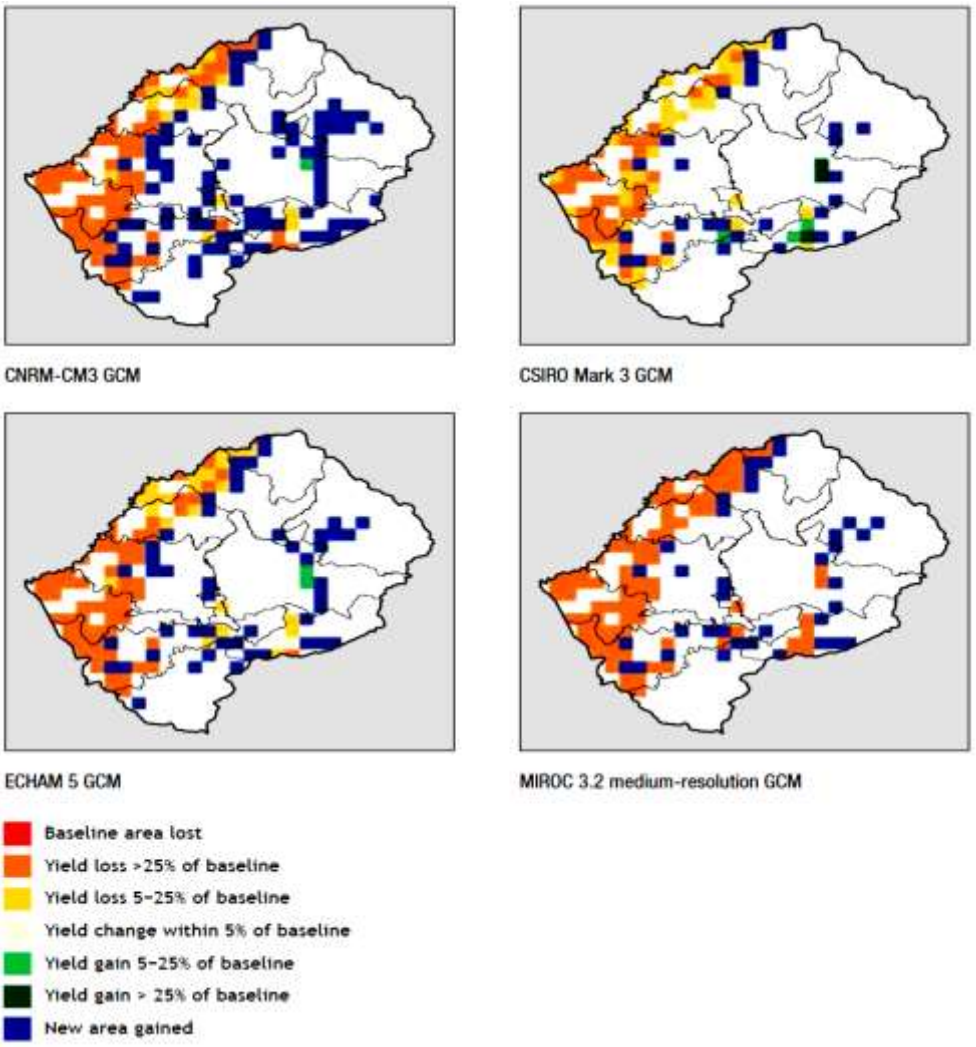


Figure 2.6: Projected changes in yield and new area gained with climate change in Lesotho (2000 – 2050) as predicted by four different models (CNRM-CM3, CSIRO Mark 3, ECHAM 5 and MIROC 3.2) for rain-fed maize. (Source: Gwimbi *et al.* 2013, page 94).

Wheat on the other hand, is a winter crop and therefore requires a long cold season (5 to 10 ^{0}C) to facilitate development before flowering can occur (Janjua *et al.*, 2010). Thus, higher temperatures tend to delay vernalization, and when experienced during grain filling, it has serious impacts due to its reduction in the leaf and ear area photosynthesis (Ortiz *et al.*, 2008). The optimum temperature for growing wheat is between 21

and 25 ^{0}C (van Gool, 2009).Temperatures higher than 25 ^{0}C tend to inhibit leaf appearance and stem elongation is slower at temperatures below 20 ^{0}C (Porter & Gawith, 1999).

For wheat, there is a potential loss of up to 25 % in yield in most areas, however the lowlands are expected gain up to 25 % in yield due to new areas gained due to temperature increases, see figure 2.7 (Gwimbi et. al. 2013).

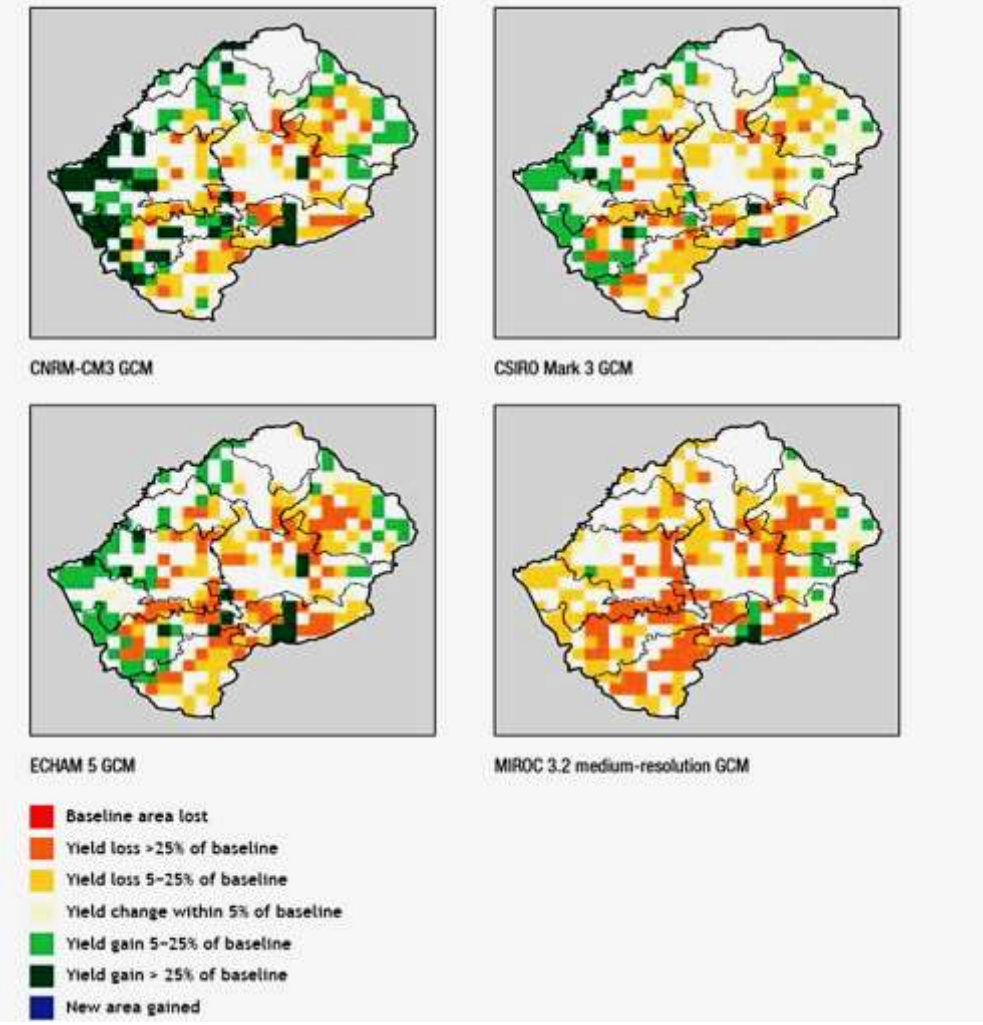


Figure 2.7: Changes in yield and new area gained with climate change in Lesotho (2000 – 2050) as predicted by four different models (CNRM-CM3, CSIRO Mark 3, ECHAM 5 and MIROC 3.2) for rain-fed wheat. (Source: Gwimbi et al. 2013, page 95).

Sorghum is a warm climate crop with an optimum mean temperature range of between 21 and 35 ^{0}C for seed germination, 26 to 34 ^{0}C for growth and development and 25 to 28 ^{0}C for reproductive growth (Prasad *et al.*, 2006). When temperatures are too high (above 40 ^{0}C), the vegetative stage of sorghum is shortened (Peacock, 1982; Dimes *et al.*, 2008), while low temperatures (below 10 ^{0}C) tend to limit production (Carter *et al.*, 1989). Sorghum yield losses are expected to be up to 25 % in the lowlands; however, new areas suitable for sorghum may gain up to 25 % in the foothills and Senqu river valley, with a potential corresponding 25 % increase in yields, see figure 2.8 (Gwimbi et. al. 2013).

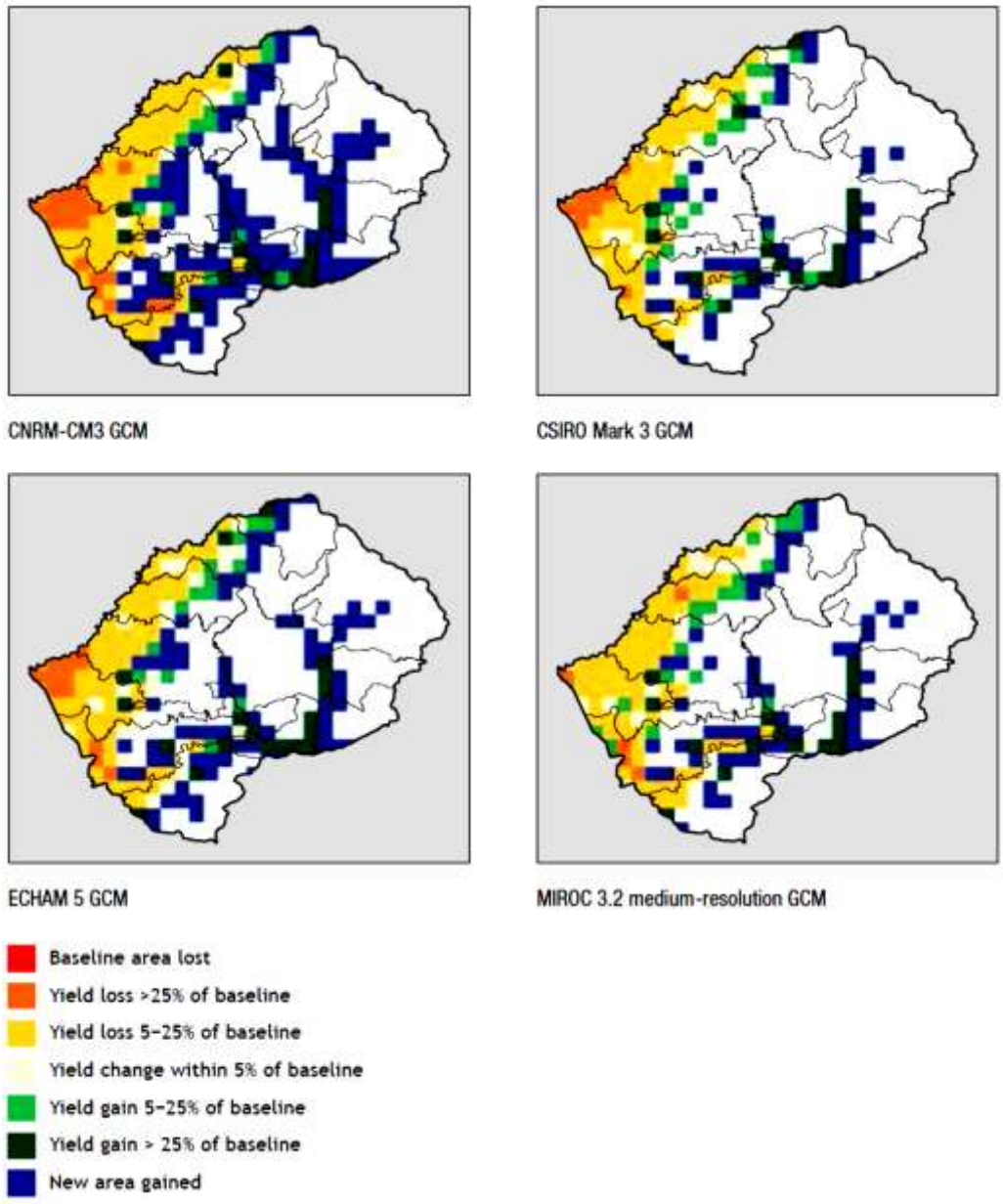


Figure 2.8: Projected changes in yield and new area gained with climate change in Lesotho (2000 – 2050) as predicted by four different models (CNRM-CM3, CSIRO Mark 3, ECHAM 5 and MIROC 3.2) for rain-fed sorghum. (Source: Gwimbi *et al.* 2013, page 96).

Various models indicate declining production, especially for maize and sorghum, mainly in the lowlands (western parts) where most agricultural production takes place in Lesotho. However, because of their coarse

resolution and inadequate treatment of land surface processes, especially in complex topographic areas, reliability of general circulation models' output is low on a regional scale (Liu & Chen, 2000; Pepin, 2000). This study therefore seeks to analyze temperature trends in high lying areas to establish whether the potential for agricultural production is increasing, as is predicted by models.

CHAPTER 3: DATA AND METHODOLOGY

3.1 Introduction

Data were obtained from two different sources. Firstly, monthly average maximum and minimum temperatures for an earlier period, from the 1920's to the 1950's (Table 3.1) for Maseru, Butha Buthe, Mohale's Hoek, Mokhotlong and Qacha's Nek were obtained from the NOAA central library website. Original daily temperatures for this earlier period seem no longer to exist, despite extensive searches and enquiries with both the Lesotho and South African Weather Services.

Secondly, daily maximum and minimum temperatures, for the later period of the study (1950's – 2013) were provided by the South African Weather Service (Table 3.1) with permission from the Lesotho Meteorological Services (who no longer have the records themselves). This data set comprises daily maximum and minimum temperatures from the 1950's onwards to the present day for Maseru, Butha Buthe, Mokhotlong, Qacha's Nek, Mohale's Hoek, and Oxbow.

Table 3.1: Station name, altitude and years of available data (Source: South African Weather Service and NOAA)

Station name	**Station number**	**Altitude (m)**	**Years included in study**
Maseru	1	1528	1926 – 2013
Mejametalana	2	1600	1968 - 2013
Mohale's Hoek	3	1530	1926 - 2013
Butha Buthe	4	1768	1926 - 2013
Qacha's nek	5	1972	1926 - 2013
Mokhotlong	6	2375	1931 - 2013
Oxbow	7	2591	1959 - 2013

Archived data are not free from errors such as missing data and suspicious readings, which arise for a variety of possible reasons not dealt with in this study. In this chapter, various methods used to ensure that data used are of suitable quality, as well as methods used to analyze such data, are described.

3.2 Filling in the missing data

The temperature values obtained from the NOAA library website were given in °F and were thus converted to °C using the formula:

$$T(°C) = (T(°F) – 32) \text{ X } 5/9$$

However, there were gaps in the data. The data for some years are entirely missing (Table 3.2) and such years were therefore excluded in this study. Butha Buthe being the worst with 40% of full year's data missing, followed by Qacha's Nek with 24% and Mokhotlong with 23%. The stations with the least full year's data missing are Maseru with only 3% and Mohaleshoek with 9% data missing. The percentage missing data for each station is for the period 1920's – 1950's is shown in Figure 3.2. Stations with percentage missing data greater than 30% for this particular period were excluded for this period for the study. Due to the high percentage of missing data in Butha Buthe for the period 1920's – 1950's, Butha Buthe was therefore excluded for this period in the study.

There were data gaps also identified in the daily maximum and minimum temperature data obtained from the SAWS for the period 1950's - 2013. The station with the highest percentage missing data is Mohaleshoek with 21%, followed by Maseru with 14%, then Qacha's Nek 13%, Butha Buthe 12%, Mokhotlong 8%, Oxbow 7% and Mejametalana 6% (Figure 3.2).

To fill in the missing data where a gap exists between two known values for monthly and daily temperatures, linear interpolation was used. In linear interpolation, the average using the value before and the value after the

missing data (gap) was calculated and the value obtained was used to fill in the gap (Shrestha *et. al.*, 1999; Henn *et. al*., 2015). Furthermore, where two or more consecutive days data are missing, the Fallback method as used by Dunis and Karalis (2003) and Moeletsi (2004) was used to fill data gaps but only where data are missing for 12 or less consecutive days. With the Fallback method, the missing data are estimated using the data from the nearest neighboring station. The average temperature for 15 days prior to the missing data and 15 days after the missing data were calculated for the station with missing data and the neighboring station respectively (Dunis & Karalis, 2003). The difference between the averages is then calculated and then added to the value at the neighboring station for the same day as the day with missing data. The result is then used to fill the value of the station with missing data. When gaps exist within the 15 days prior and/or after the missing data day, then the closest 15 day period with available data is used but not exceeding 25 days (Dunis & Karalis, 2003). Where data are missing for more than 12 consecutive days in a given month, such a month was regarded as a month without data. Monthly averages for the months with data were therefore calculated. Further gaps were identified from monthly averages and linear interpolation was furthermore applied to fill in the missing data where one gap existed between two known values. The remaining gaps were therefore left unfilled and such months were excluded from the study. For the purpose of the study, the neighboring station will be regarded as the closest of the stations used in the study to the station with missing data. In a few instances, several years of data were missing from a given station, and such years were thus excluded from the study.

Table 3.2: Percentage full year's missing data at five stations in Lesotho calculated from data obtained from NOAA central library for the period 1920's – 1950's. (Source: NOAA).

Station Name	Full years of available data	Full years of missing data	Percentage full year's missing data
Butha Buthe	1926-1943,1951,1959-1960	1944-1950, 1952-1958	40
Maseru	1926-1946,1948-1960	1947	3
Mohaleshoek	1926-1929, 1931-1946, 1948-1958, 1960	1930, 1947, 1959	9
Mokhotlong	1930-1939,1942, 1944-1945,1949-1957, 1959-1960	1940-1941, 1943, 1946-1948,1958	23
Qacha's Nek	1926-1941,1943-1945,1951, 1953-1957, 1959	1942,1946-1950,1952, 1958,	24

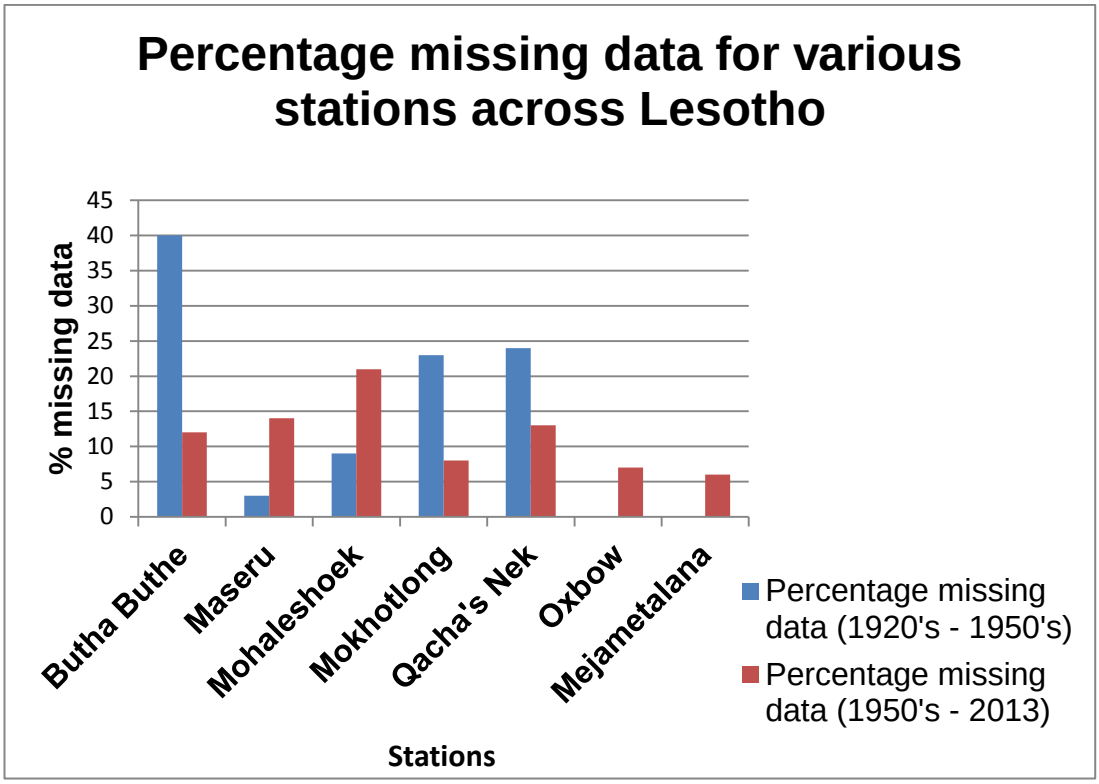


Figure 3.1: Percentage missing data at various stations in Lesotho for the period 1920's - 2013 (Source: NOAA & SAWS)

3.3 Quality control

Quality control on the data was performed by manually inspecting maximum and minimum temperatures and checking the data for any obvious errors such as minimum temperatures exceeding maximum temperatures in the data (Katell & Yao, 2013). Where such errors were detected, the values were corrected (e.g. swapped: maximum temperatures became minimum temperatures and visa versa). Typing errors as well as errors which were as a result of conversion from Fahrenheit to Celsius were also corrected. Furthermore, outliers were identified using the box plot for each month for each of the stations. With boxplot the interquartile range (difference between the first and the third quartile) is calculated and therefore used to create the upper and the lower fences by multiplying it with a constant value, which is 1.5 and used in

most studies (e.g. Eischeid et. al., 1995; Schwertman et. al., 2004 & Sun & Genton, 2011). All values that appeared above or below the fences were regarded as outliers. All outliers were removed and were thus treated as missing data, and the gaps filled using linear interpolation as described above.

3.4 Data analysis

From daily temperature data obtained from the SAWS for the period 1950's – 2013, monthly average maximum and minimum temperatures as well as mean (average between maximum and minimum temperatures) were calculated using the arithmetic mean method for the period 1968 to 2013. Four of the stations used in this study also have data for the earlier period, 1920's – 1950's, monthly averages for stations with data from the 1920's were combined to create a single record for that particular station which will run from the 1920's - 2013. Long-term temperature data are susceptible to changes that are due at times to relocation of sites, changes in instruments used, changes in observation practices or physical changes to area surrounding the recording station (Alexandersson & Moberg, 1997). To ensure that data are homogeneous throughout the study period, data were tested for homogeneity using the standard normal homogeneity test (SNHT) and Pettit's test as used in various temperature trend studies (Kattel *et. al*., 2012; Dogan *et. al*., 2014). The Kolmogorov-Smirnof test was used to test whether the data are normally distributed (Katell et. al., 2012). From the monthly average temperatures, mean annual and seasonal temperatures were also calculated using the arithmetic mean method (Katell et. al., 2012; Katell & Yao, 2013). The seasons were divided as follows:

Winter: June, July, August

Summer: December, January, February

Autumn: March, April, May

Spring: September, October, November

To determine temperature trends, stations were grouped into two groups based on the period of available data. The first group comprises stations for which data are available from 1968 to 2013, which includes Butha Buthe, Oxbow and Mejametalana, Mokhotlong, Maseru, Mohaleshoek and Qachasnek. The second group comprises stations for which data are available from 1931 – 2013, which includes Maseru, Mokhotlong, Mohaleshoek and Qachasnek. Linear regression was used to establish monthly maximum, minimum and mean temperature trends as well as annual and seasonal trends at each station for each of the study periods, 1931 – 2013 and 1968 – 2013 (Liu & Chen, 2000; Kothawale & Kumar, 2000; Katell *et. al*., 2012; Katell & Yao, 2013). Linear regression is described by Kattel & Yao (2013) as a group of techniques for fitting and studying the linear relationship between two variables, the equation of which is given by:

$$Y = tX + C + e$$

Where Y is the temperature in °C, X is time and 'C' is a constant and 'e' is the error of regression and the regression coefficient 't', is the trend. The statistical significance was tested using the Mann-Kendall test (Jain & Kumar, 2012). The Mann-Kendall test is used in various temperature trend analysis studies and is recommended by various authors as it is applicable with non-normal data set and is less sensitive to outliers (Abolverdi *et. al*., 2014; Buric *et. al*., 2014). The Kendall's tau, was used to measure the strength of a relationship between temperature trends and altitude. A positive relationship indicates that the rate of change increases with height while a negative relationship indicates that when rate of change increases the height decreases and vice versa (Karmeshu, 2012). The statistical significance was tested using the Mann-Kendall test (Jain & Kumar, 2012).

The trend in extreme temperatures was determined from daily minimum and maximum temperatures for the period 1968 – 2013, the period when daily maximum and minimum temperature data were available. The

average maximum temperature for Lesotho ranges from 16.5 °C in the highlands (>1900 m) and 29 °C in the lowlands (<1900 m) while the average minimum temperature ranges from -6.3 °C in the highlands and 4.3 °C in the lowlands (Moeletsi, 2004; Grab & Nash, 2010). Extreme maximum temperature is defined as temperature exceeding 90th percentile for all the stations (Beniston *et. al*., 2007). Extreme minimum temperature is defined as temperatures below the 10th percentile for all the stations (Vincent *et. al*., 2005). The number of days with temperature exceeding maximum temperature threshold and number of days with temperatures below the minimum temperature threshold for each month were determined for summer and winter respectively since the maximum and minimum temperature thresholds occur in summer and winter respectively. The trends were analyzed with linear regression and statistical significance test was done using Mann- Kendall test (Jain & Kumar, 2012)

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

For the purpose of comparison, stations were grouped according to equal length of the period of data availability, i.e. 1931 - 2013 and 1968 – 2013. Stations with data from 1931 include Maseru, Mokhotlong, Mohale's Hoek, Qachasnek and Butha Buthe, however, Butha Buthe was not included in the comparisons for the period 1931 – 2013 due to high percentage of missing data during that period. Stations with data from 1968 include, in addition to stations with data from 1931, Mejametalana and Oxbow. This chapter will show the temperature trends for all the stations for the two periods of study.

Before analysis, data were tested for homogeneity using the SNHT as well as the Pettit's test. The Pettit's test revealed non-homogeneity in the data for May – October, but data was homogeneous for the other months at all the stations while the SNHT on the other hand showed data were homogeneous for all the months. Data were also tested for normality using the Kolomogorov Smirnov statistical test at 95% confidence limit. The p-values for maximum, minimum and mean temperatures were higher than 0.05 for all the months. Data, therefore, follow a normal distribution at the 95% confidence limit (Tables 4.1 – 4.3).

Table 4.1: Kolmogorov-Smirnov test for normality of maximum temperatures at various stations in Lesotho for the period 1968 – 2013.

	Kolmogorov-Smirnov test for normality p-values at α = 0.05						
	Maseru	**Mejametalana**	**Mohaleshoek**	**Butha Buthe**	**Qacha**	**Mokhotlong**	**Oxbow**
Jan	0.734	0.881	0.856	0.938	0.768	0.539	0.894
Feb	0.778	0.546	0.518	0.554	0.885	0.988	0.812
Mar	0.325	0.926	0.728	0.268	0.953	0.901	0.470
Apr	0.940	0.588	0.918	0.977	0.953	0.617	0.771
May	0.866	0.985	0.664	0.997	0.284	0.910	0.793
June	0.506	0.823	0.903	0.924	0.885	0.662	0.949
July	0.983	0.802	0.720	0.107	0.711	0.998	0.429
Aug	0.318	0.564	0.702	0.956	0.805	0.515	0.997
Sep	0.999	0.992	0.992	0.991	0.479	0.943	0.355
Oct	0.400	0.691	0.611	0.945	0.278	0.639	0.980
Nov	0.653	0.696	0.519	0.828	0.945	0.702	0.964
Dec	0.987	0.955	0.978	0.720	0.953	0.994	0.956

Table 4.2: Kolmogorov-Smirnov test for normality of minimum temperatures at various stations in Lesotho for the period 1968 – 2013.

	Kolmogorov-Smirnov test for normality p-values at α = 0.05						
	Maseru	**Mejametalana**	**Mohaleshoek**	**Butha Buthe**	**Qacha**	**Mokhotlong**	**Oxbow**
Jan	0.714	0.769	0.989	0.310	0.896	0.711	0.419
Feb	0.917	0.943	0.831	0.559	0.404	0.475	0.921
Mar	0.342	0.986	0.965	0.540	0.875	0.874	0.956
Apr	0.972	0.859	0.494	0.727	0.976	0.822	1.000
May	0.945	0.999	0.971	0.701	0.960	0.593	0.292
June	0.493	0.465	0.802	0.942	0.530	0.359	0.974
July	0.759	0.775	0.993	0.980	0.993	0.702	0.771
Aug	0.759	0.678	0.967	0.973	0.650	0.949	0.139
Sep	0.858	0.998	0.879	0.742	0.693	0.999	0.485
Oct	0.999	0.393	0.539	0.959	0.670	0.618	0.930
Nov	0.410	0.740	0.853	0.567	0.550	0.703	0.730
Dec	0.891	0.938	0.983	0.735	0.409	0.848	0.669

Table 4.3: Kolmogorov-Smirnov test for normality of mean temperatures at various stations in Lesotho for the period 1968 – 2013.

	Kolmogorov-Smirnov test for normality p-values at α = 0.05						
	Maseru	**Mejametalana**	**Mohaleshoek**	**Butha Buthe**	**Qacha**	**Mokhotlong**	**Oxbow**
Jan	0.979	0.889	0.466	0.379	0.425	0.711	0.534
Feb	0.930	0.896	0.980	0.132	0.548	0.475	0.719
Mar	0.890	0.990	0.968	0.450	0.829	0.874	0.196
Apr	0.220	0.772	0.384	0.963	0.905	0.822	0.998
May	0.853	0.897	0.967	0.944	0.514	0.593	0.920
June	0.655	0.486	0.775	0.623	0.894	0.359	0.627
July	0.441	0.235	0.964	0.903	0.833	0.702	0.584
Aug	0.977	0.681	0.856	0.982	0.650	0.949	0.223
Sep	0.735	0.931	0.837	0.995	1.000	0.999	0.644
Oct	0.610	0.652	0.641	0.839	0.855	0.618	0.965
Nov	0.859	0.875	0.541	0.822	0.938	0.703	0.878
Dec	0.730	0.631	0.223	0.962	0.757	0.848	0.946

4.2 Temperature trends for the period 1968 – 2013

4.2.1 Trends for monthly and annual maximum, minimum and mean temperatures for the period 1968 – 2013.

For the period 1968 – 2013, there are stations where data are missing for the full year. These gaps could not be filled with the methods described in the data and methodology chapter for filling in the missing data, therefore such years are excluded in the analysis of the data. In addition to full years' missing data, some months also could not be filled and were therefore excluded in the study. Table 4.4 presents the years as well as the range of the number of months for which data were excluded in this study for each of the stations.

Table 4.4: Number of full year's missing data per station as well as missing months at various stations in Lesotho for the period 1968 - 2013

Station	Full years of missing data	Range of monthly missing data
Butha Buthe	3 years (1990-1992)	2 - 7
Maseru	6 years (1980-81, 1983-84, 2007-08)	1 - 5
Mejametalana	1 year (2007)	1 - 3
Mohaleshoek	2 years (1986, 2007)	6 - 11
Mokhotlong	0	1 - 6
Oxbow	0	1 - 6
Qachasnek	1 year (1976)	3 - 13

For Maseru, monthly and annual maximum, minimum and mean temperature trends for the period 1968 - 2013 are shown in Figure 4.1 (a-m). From the results it can be seen that there is a maximum temperature trend for most of the warm months (i.e. January (-0.50 °C/decade), February (-0.15 °C/decade), September (-0.02 °C/decade) and Dec (-0.26 °C/decade)) as well as July (-0.10 °C/decade) which is a cold month. The annual maximum temperature trend over Maseru is also negative (-0.13 °C/decade). However, there is a positive maximum temperature trend in Maseru for most of the cold months (i.e. March (0.02 °C/decade), April (0.06 °C/decade), May (0.13 °C/decade), June (0.09 °C/decade) and August (0.07 °C/decade) (Table 4.5). On the other hand, there is a positive minimum temperature trend for all months, as also annually (Table 4.6). The mean temperature trend is positive for all months except for the summer months of January (-0.20 °C/decade), February (-0.20 °C/decade) and December (-0.10 °C/decade) (Table 4.7).

Minimum temperatures are increasing at a faster rate than maximum temperatures for all the months and annually in Maseru (see Table 4.5 and 4.6).

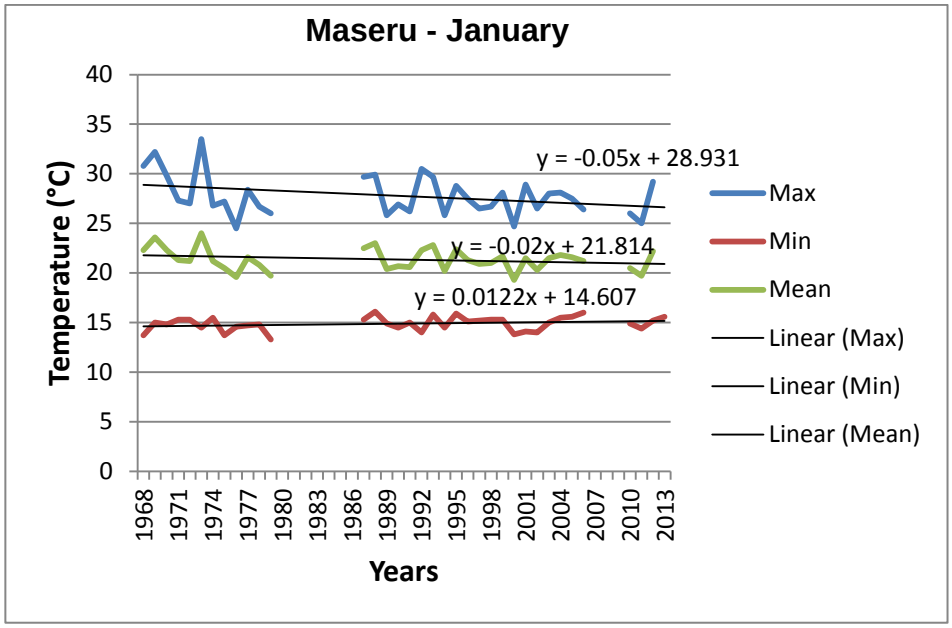
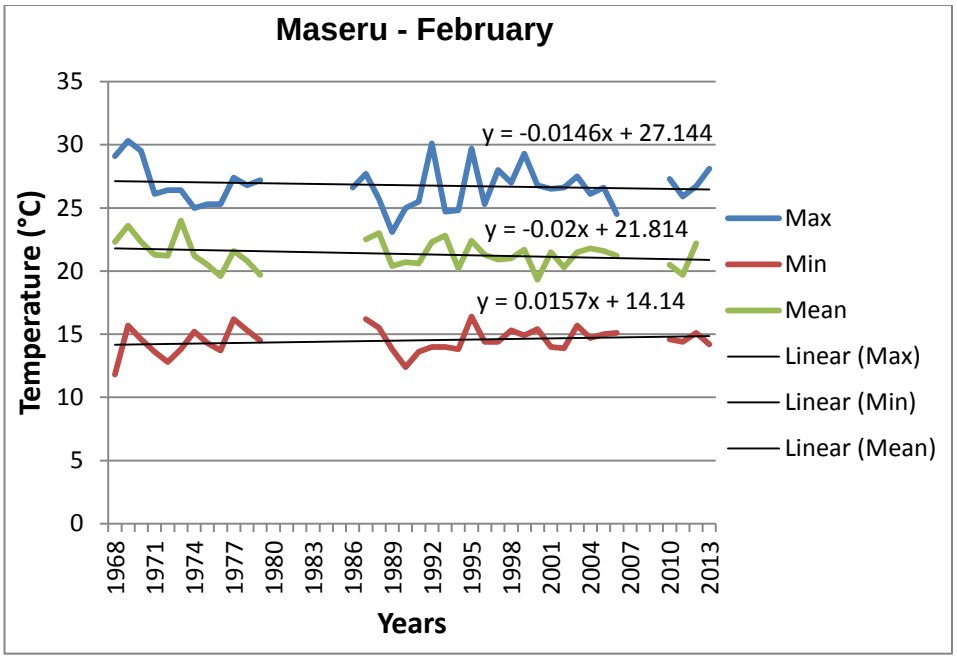


Figure 4.1(a)



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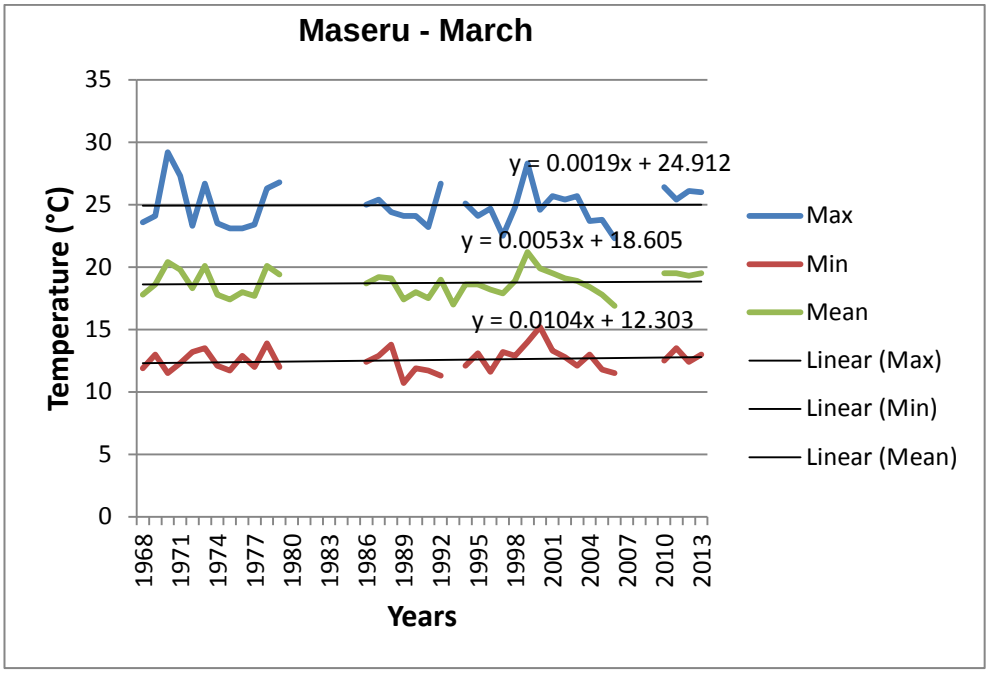

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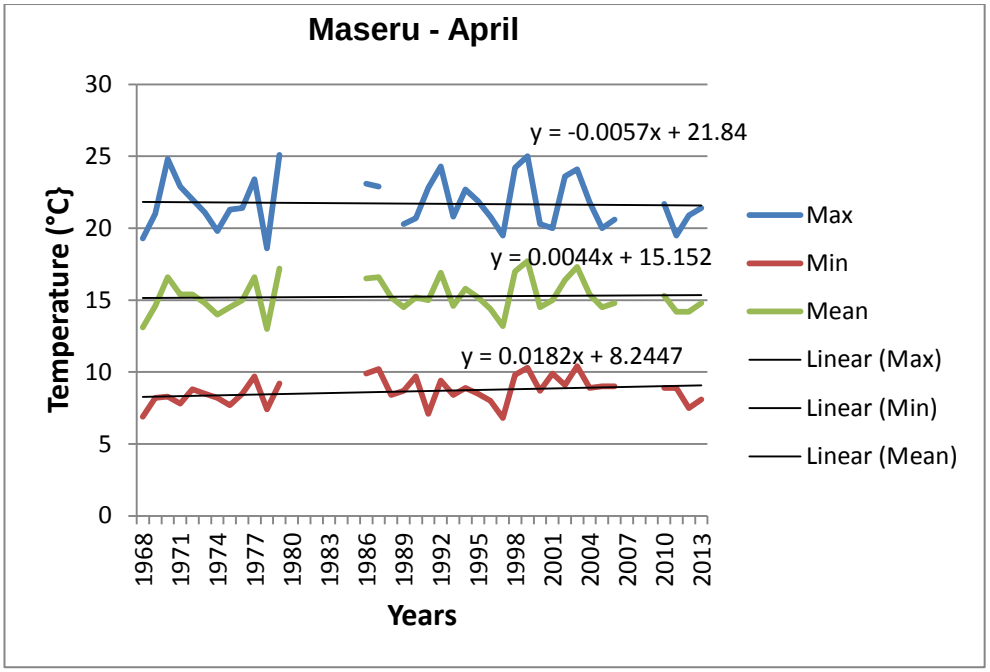

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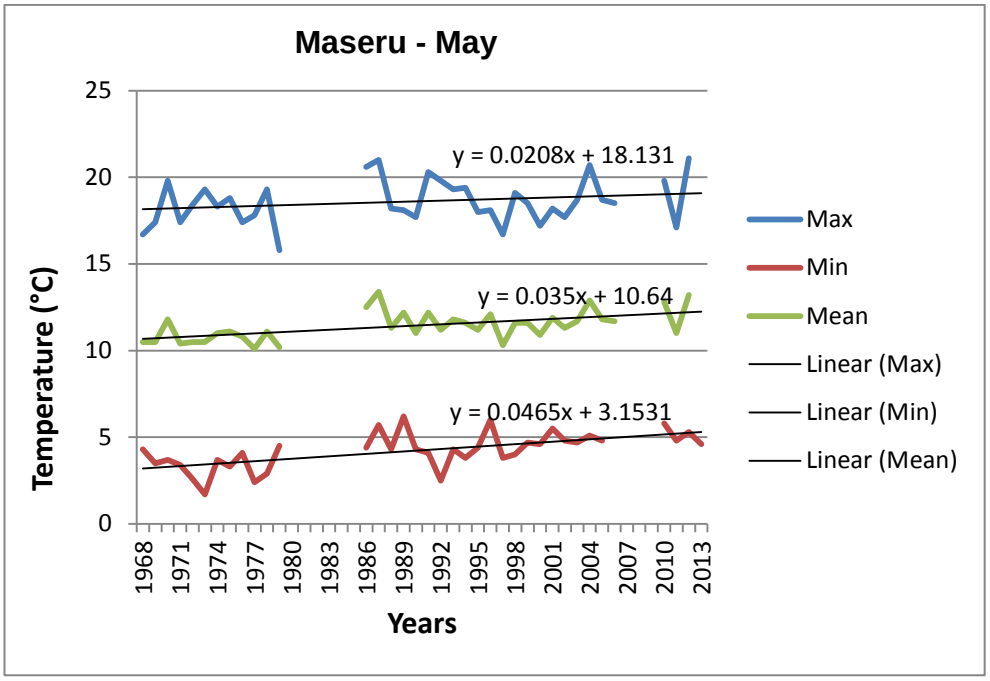

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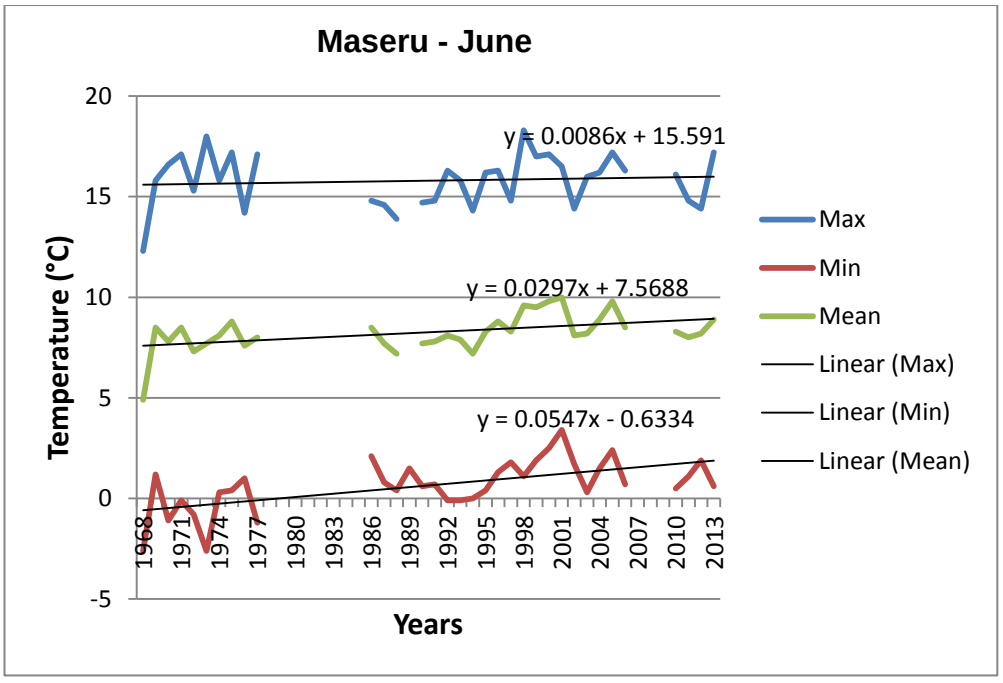

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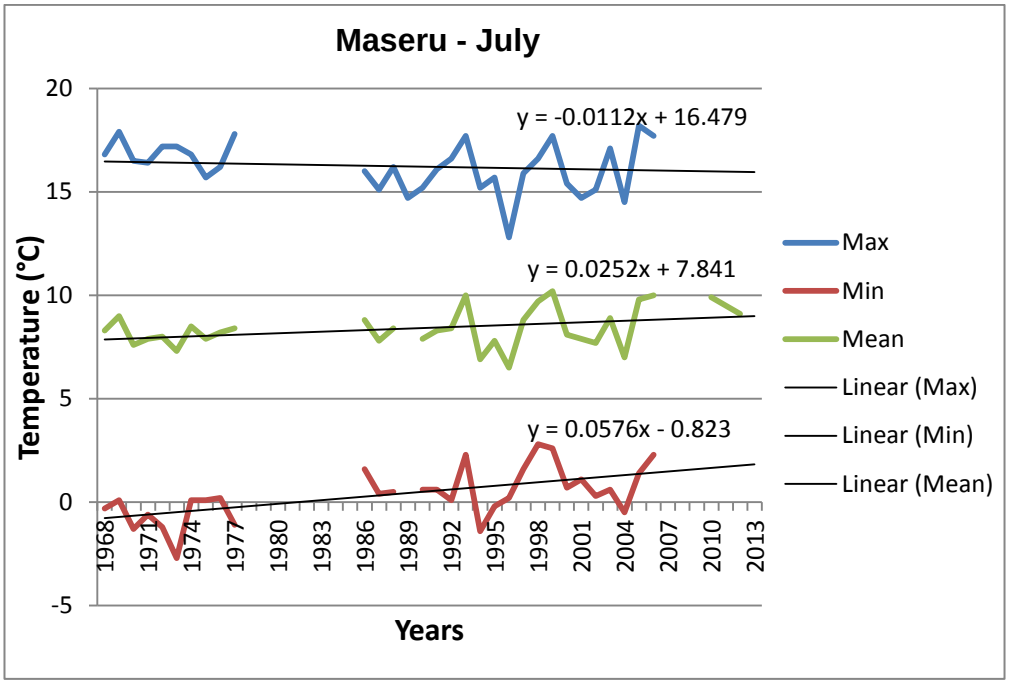

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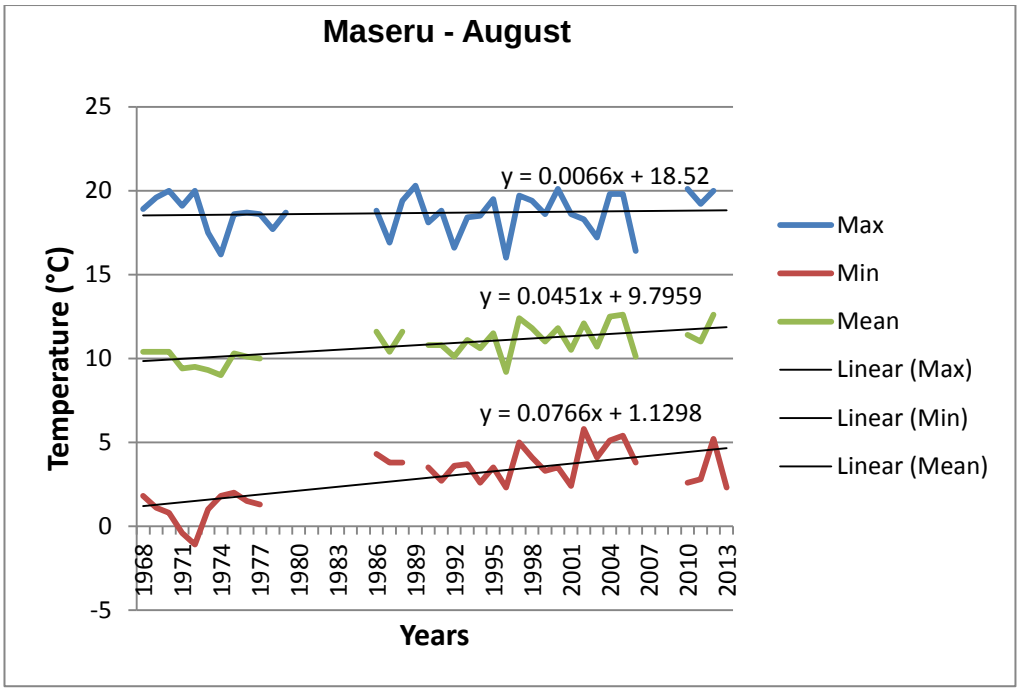


Figure 4.1(h)

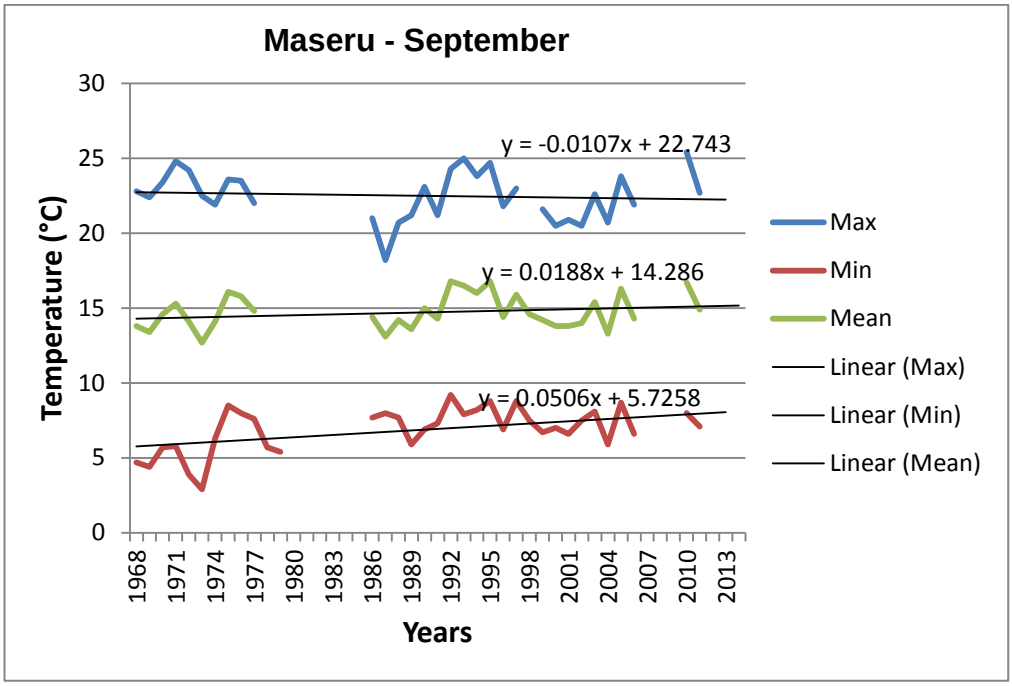
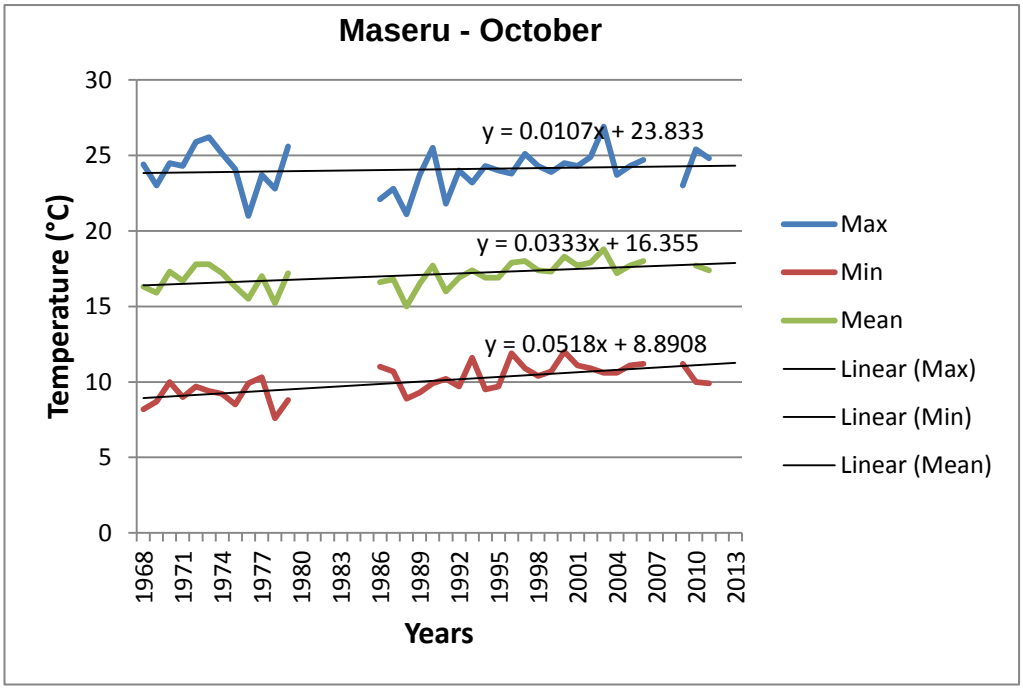


Figure 4.1(i)



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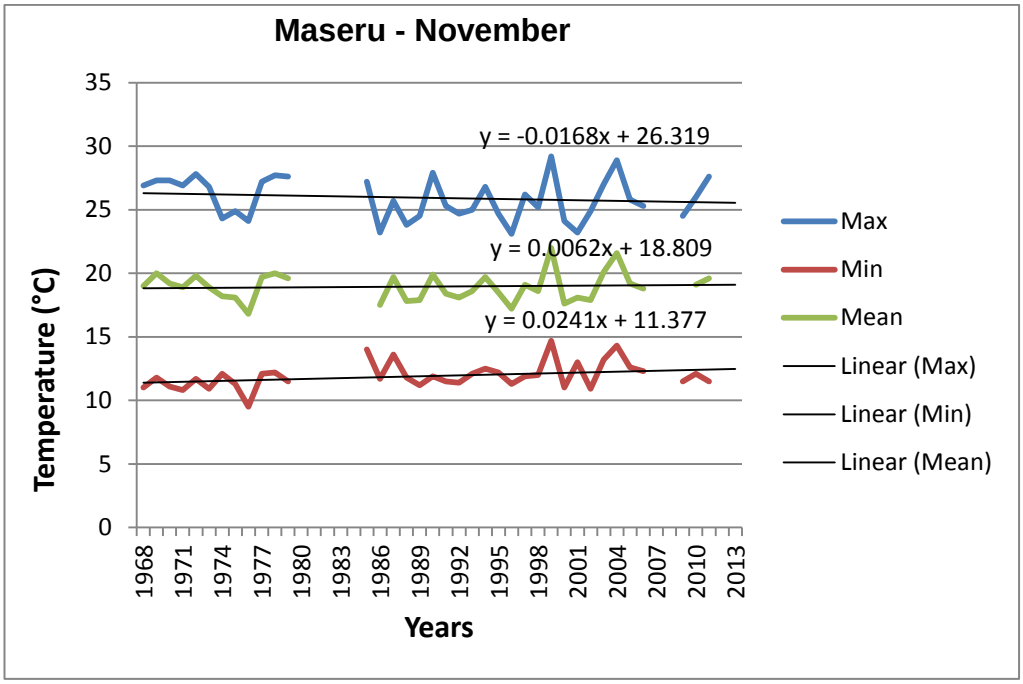

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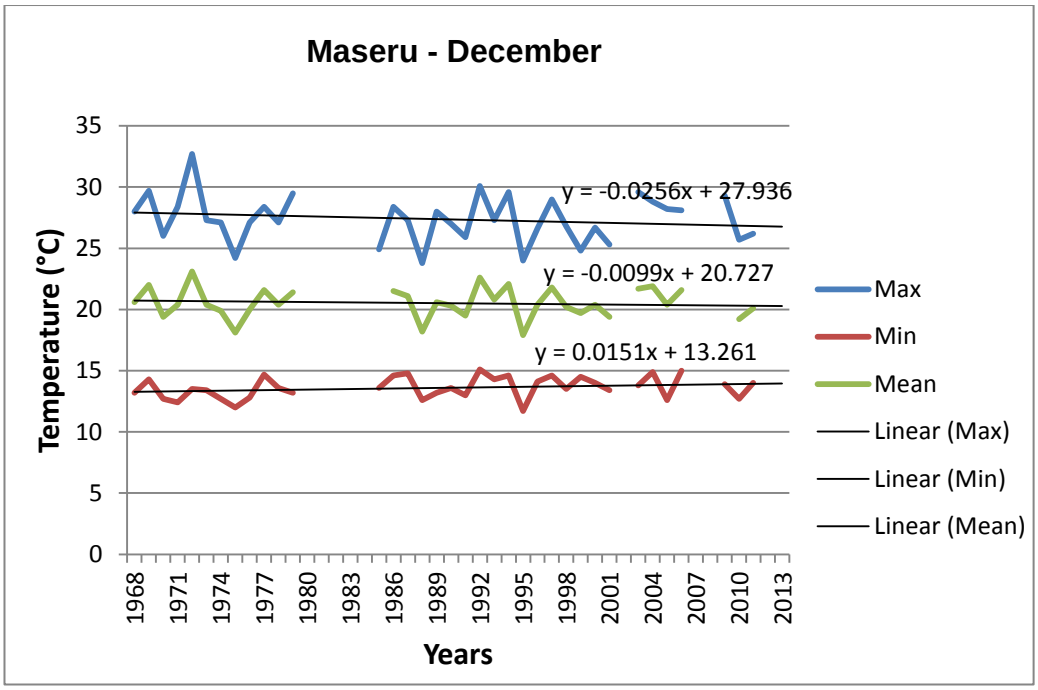


Figure 4.1(l)

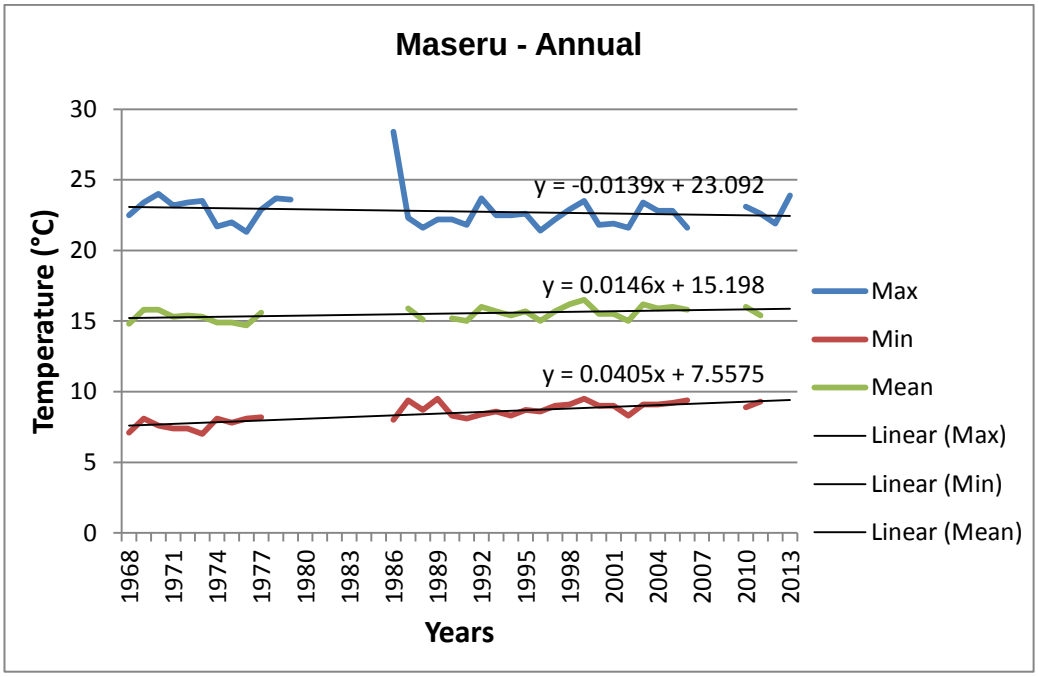


Figure 4.1(m)

Figure 4.1 (a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Maseru for the period 1968-2013.

For Mejametalana, monthly and annual maximum, minimum and mean temperature trends for the period 1968 - 2013 are shown in Figure 4.2 (a-m). The results show a negative maximum temperature trend in January (-0.28 °C/decade), February (-0.10 °C/decade) and December (-0.10 °C/decade), which are summer months. Positive maximum temperature trends can be seen in all the other months as well as annually (Table 4.5). Positive minimum temperature trends are recorded for all the months as well as annually over Mejametalana. With mean temperatures, the trends are positive for all the months except for January (-0.05 °C/decade), which is a summer month. Minimum temperature trends are higher than those for maximum temperatures in Mejametalana for all the months as well as annually, except for March where the maximum temperature trend is higher than that for minimum temperatures (0.16 °C/decade and 0.18 °C/decade for minimum and maximum temperature respectively).

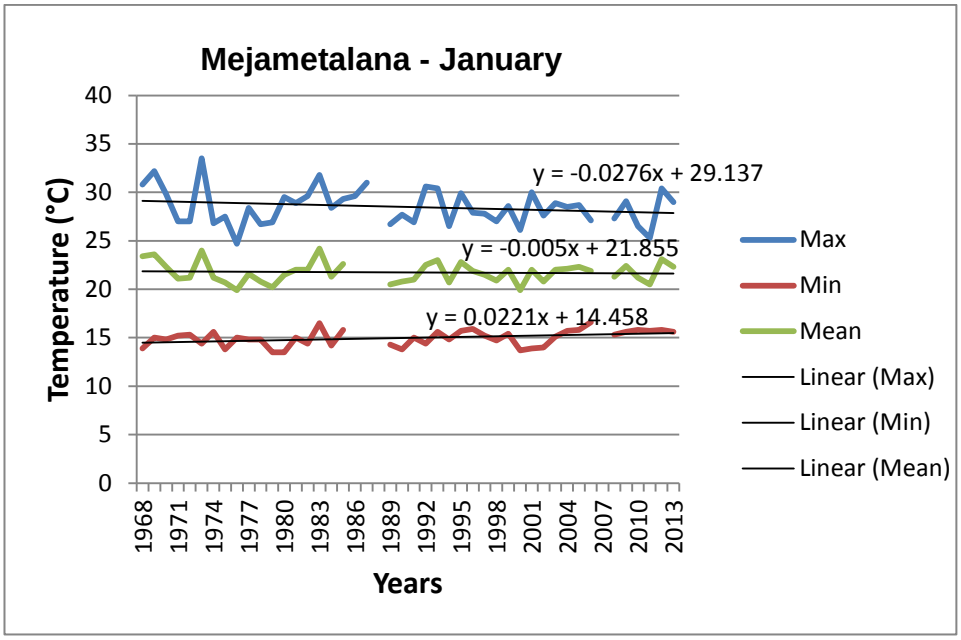
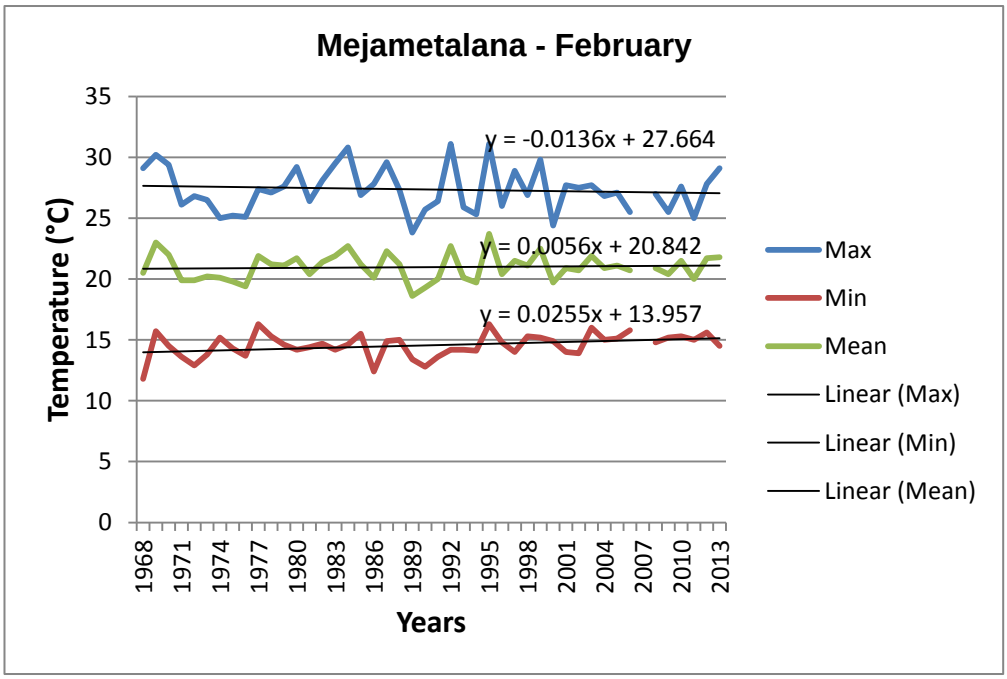


Figure 4.2(a)



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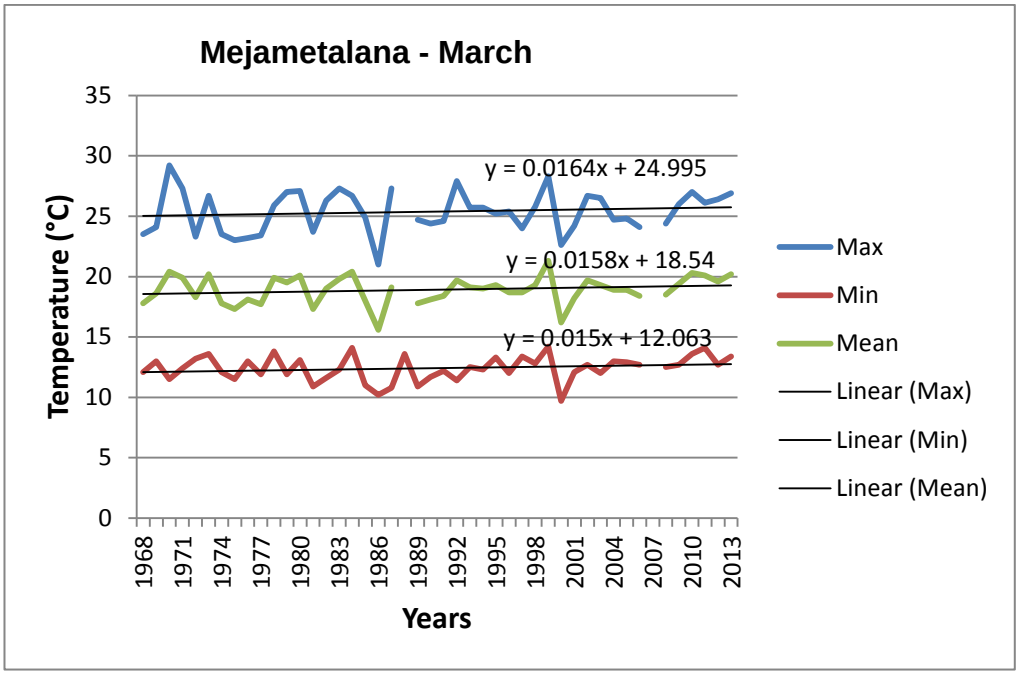

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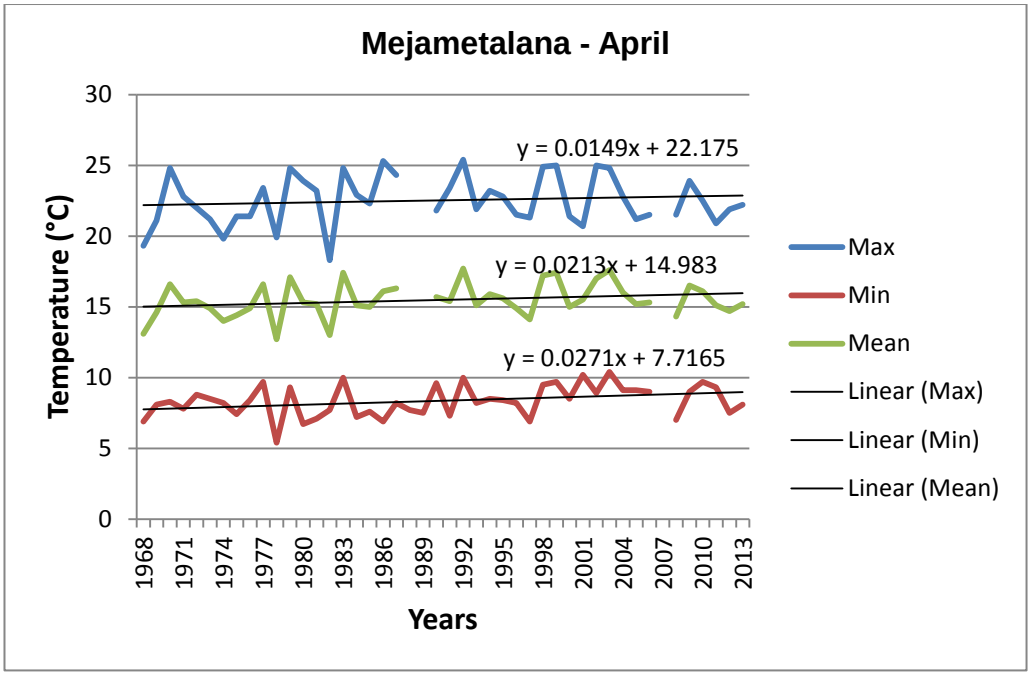
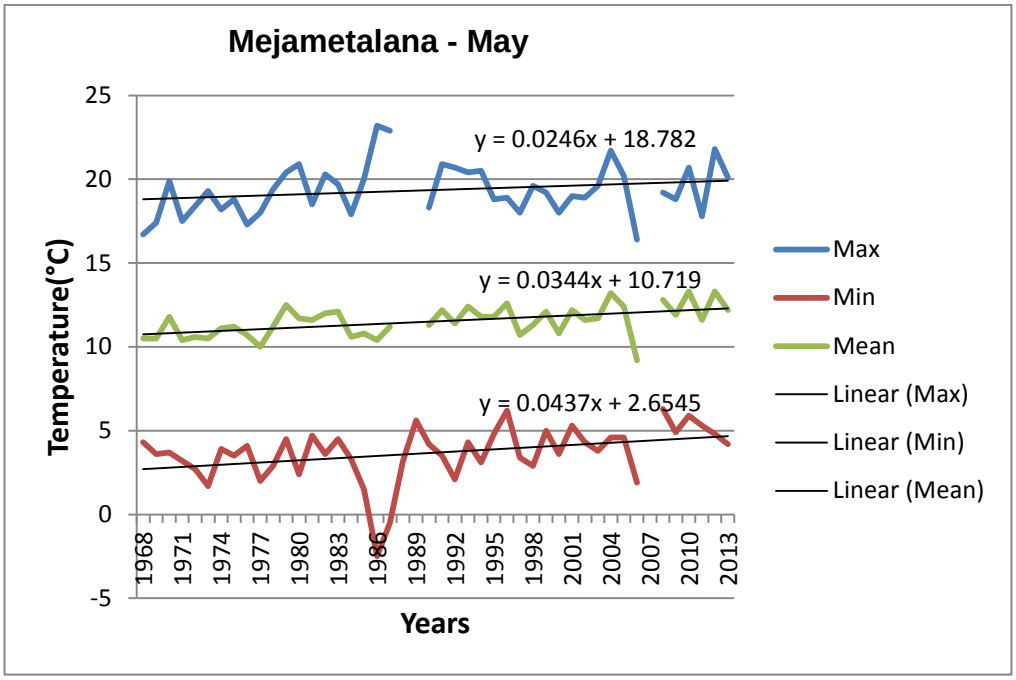


Figure 4.2(d)



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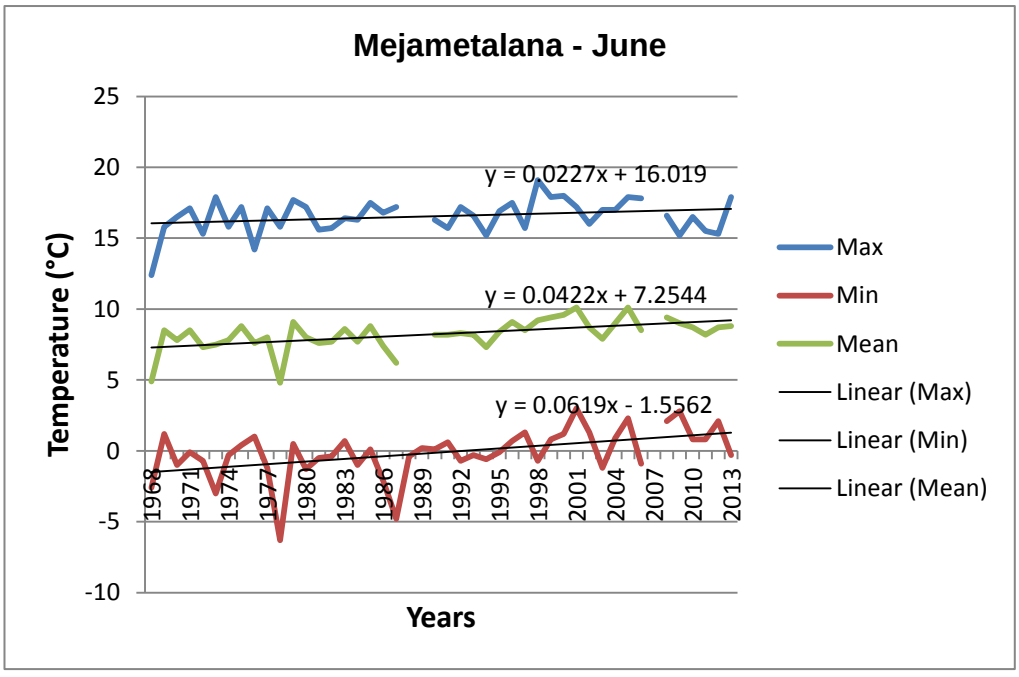

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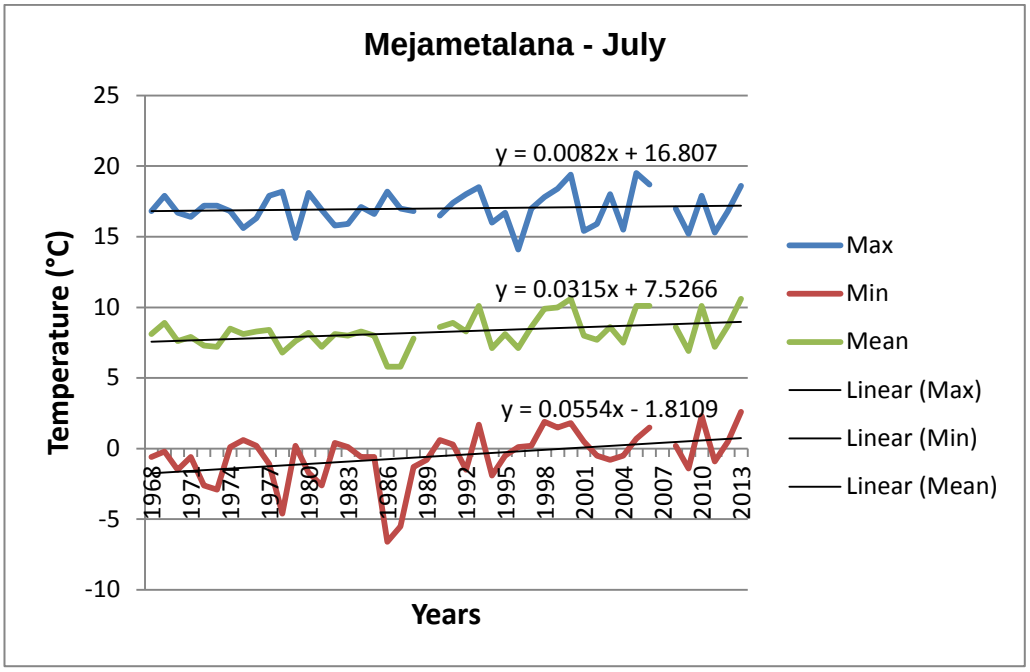

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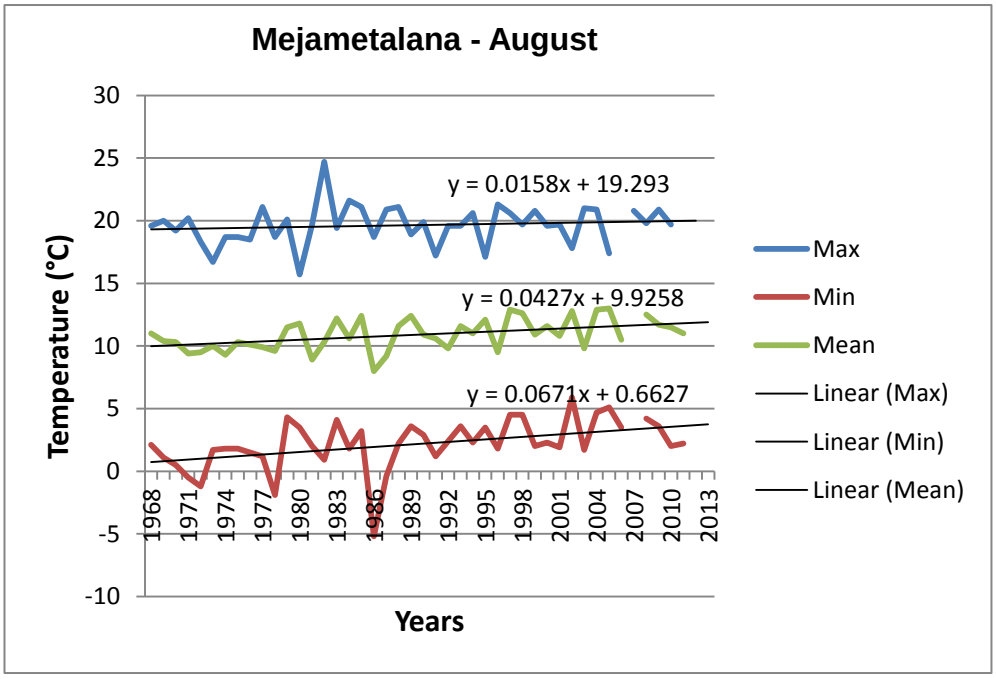


Figure 4.2(h)

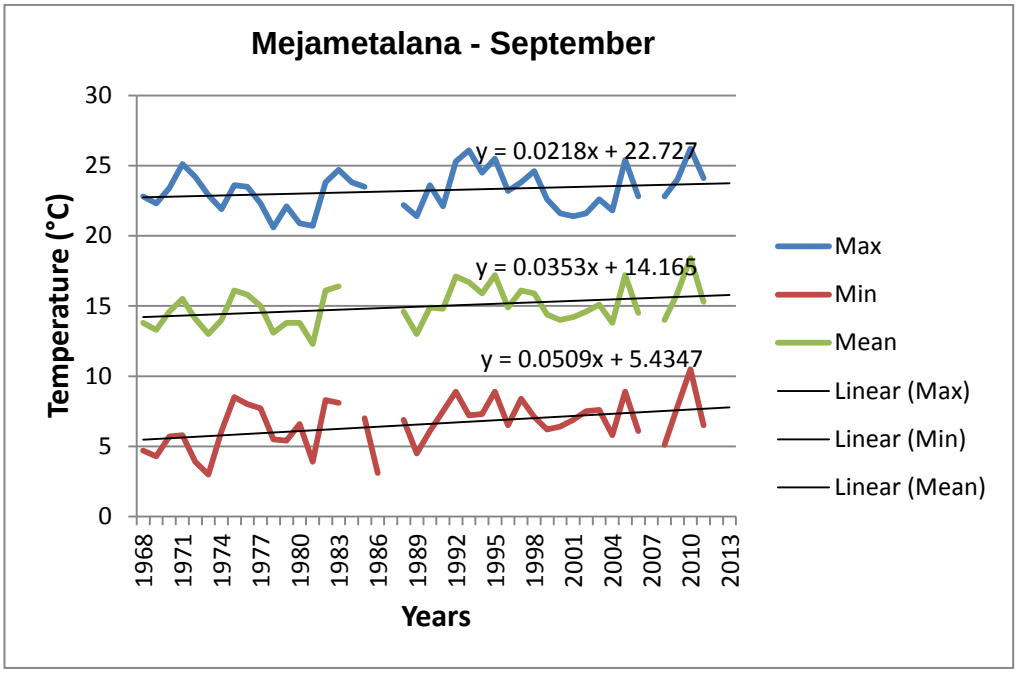
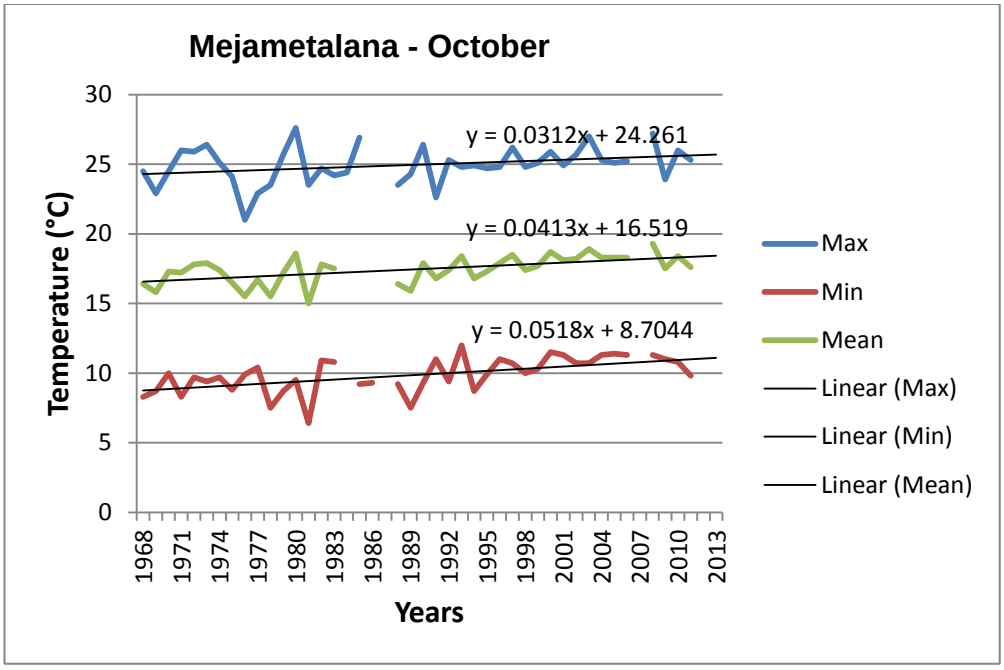


Figure 4.2(i)



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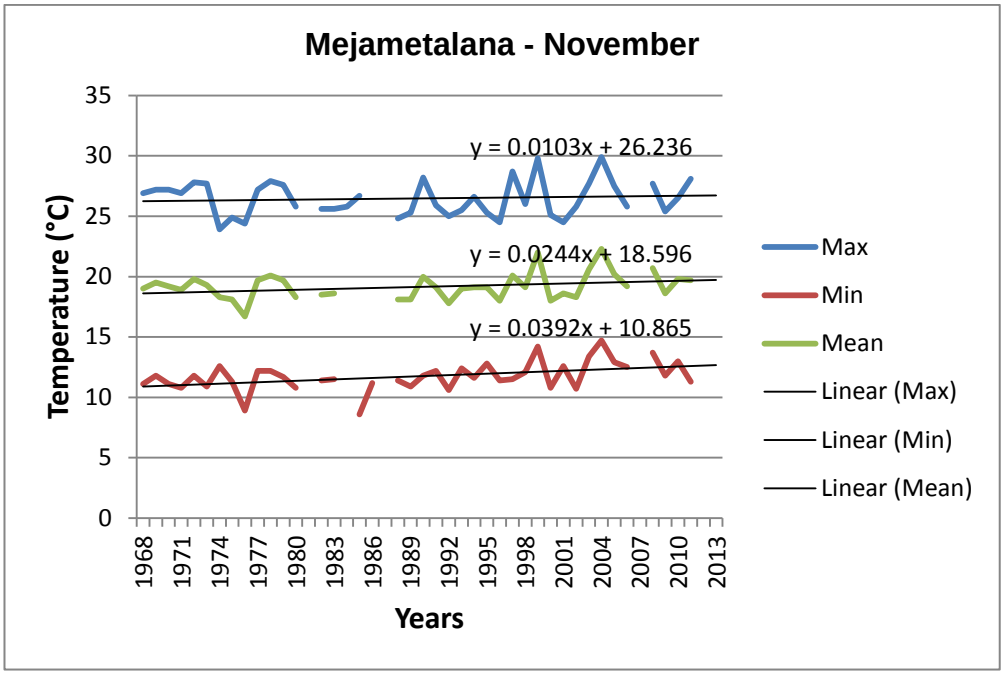

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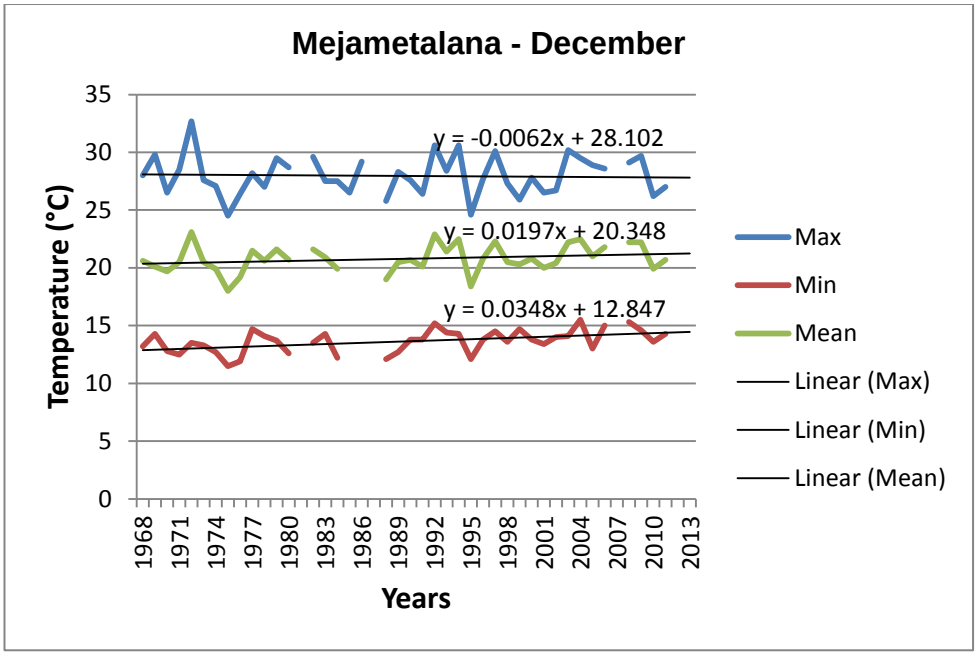


Figure 4.2(l)

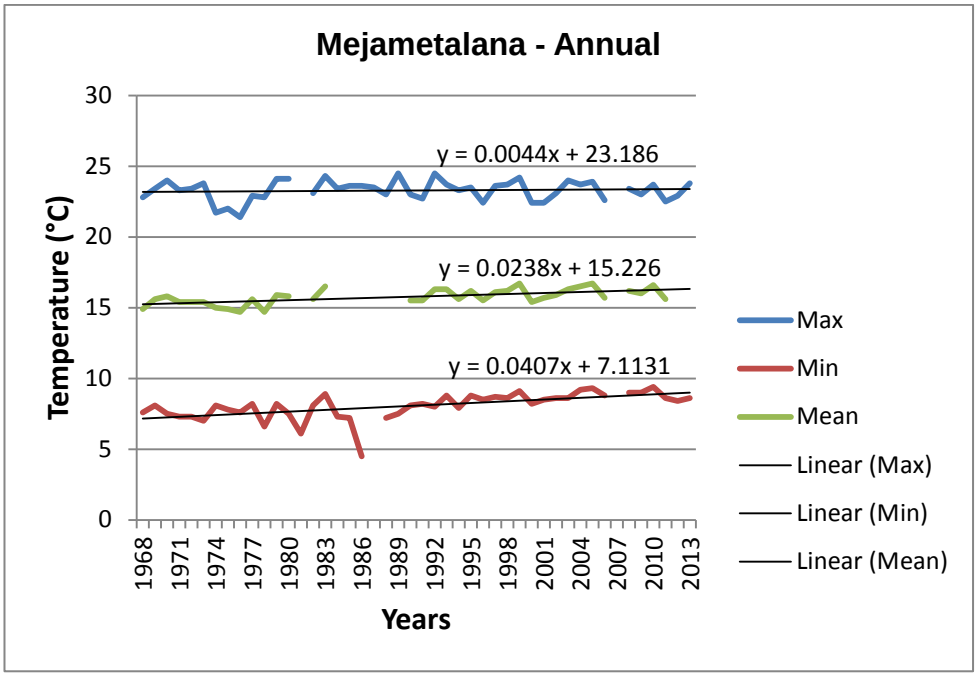


Figure 4.2(m)

Figure 4.2 (a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Mejametalana for the period 1968-2013.

For Butha Buthe, monthly and annual trends for maximum, minimum and mean temperatures for the period 1968 - 2013 are shown in Figures 4.3 (a-m). From the results, a dip in maximum, minimum and mean temperatures for January to April in 2003, can be seen, however the reason for the dip could not be established. A positive trend in maximum temperature was found annually and in all the months except January (-0.09 °C/decade) and February (-0.04 °C/decade), which are summer months. There is a positive trend in minimum as well as mean temperatures for all the months as well as annually at Butha Buthe. The trend in minimum temperature higher than the trend for maximum temperatures monthly, except for March and May where the trend for maximum temperature is higher than the trend for minimum temperature; (0.19 °C/decade; 0.15 °C/decade) and (0.27 °C/decade; 0.26 °C/decade) for March and May respectively.

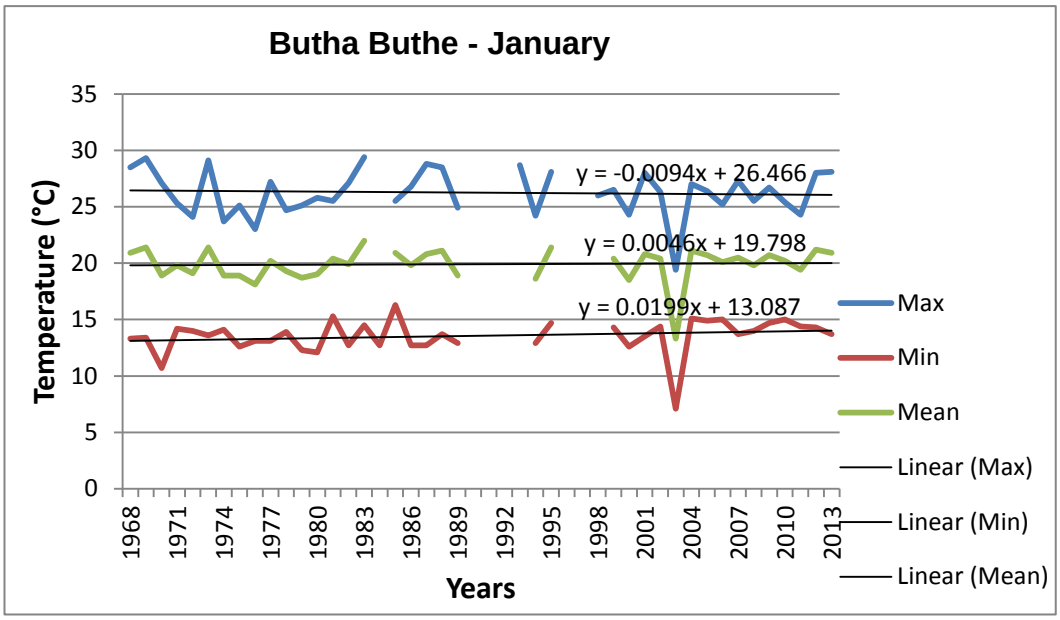


Figure 4.3(a)

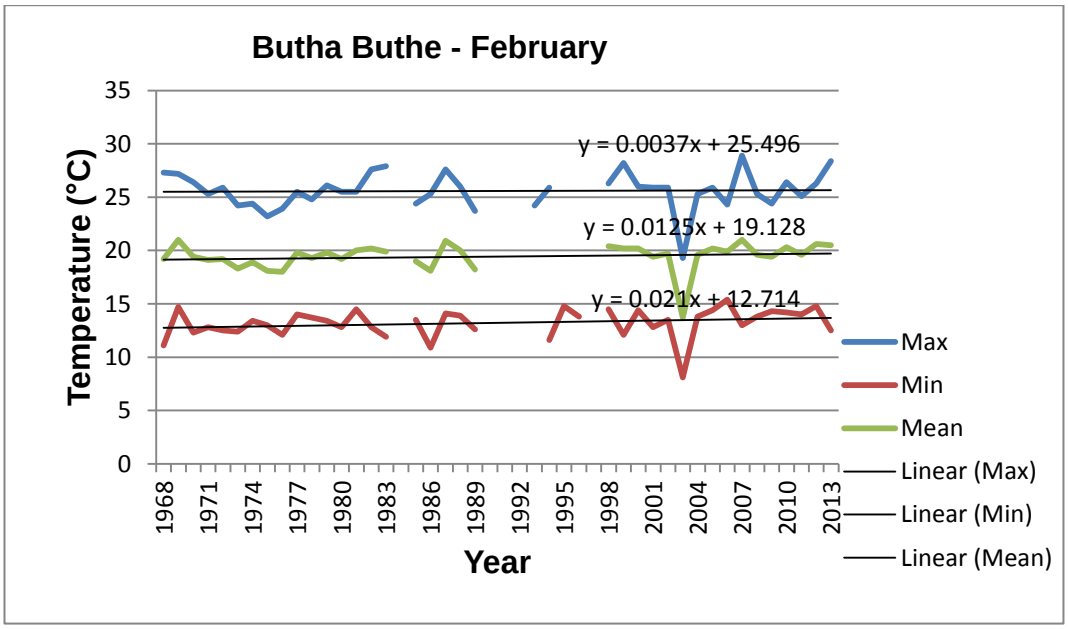
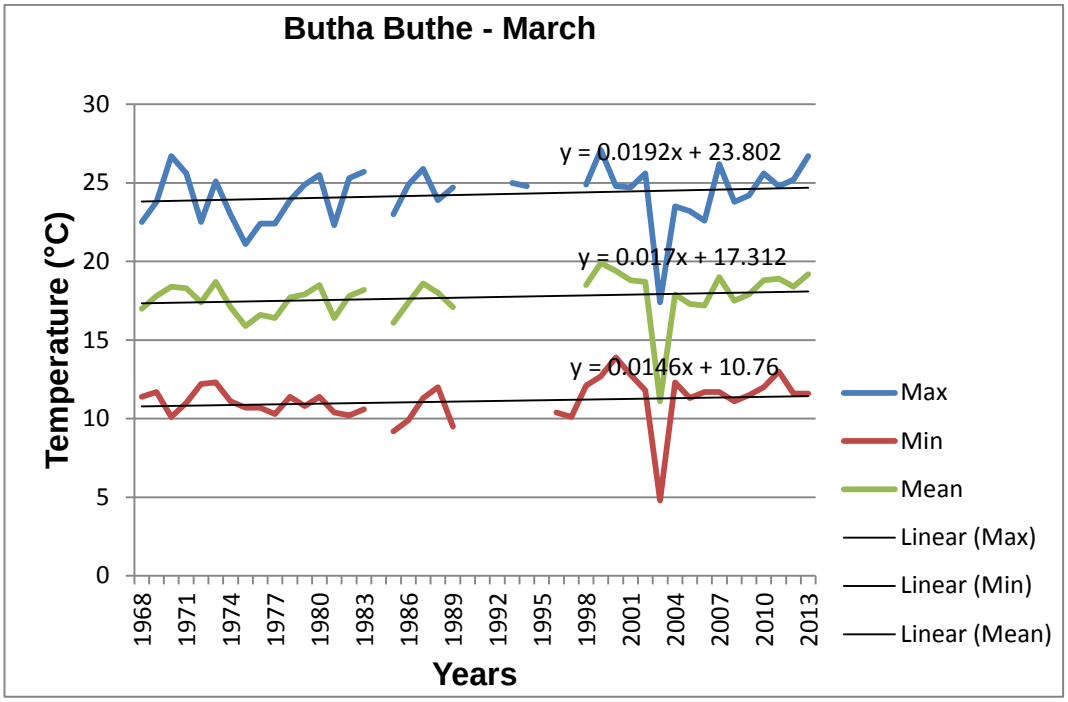


Figure 4.3(b)



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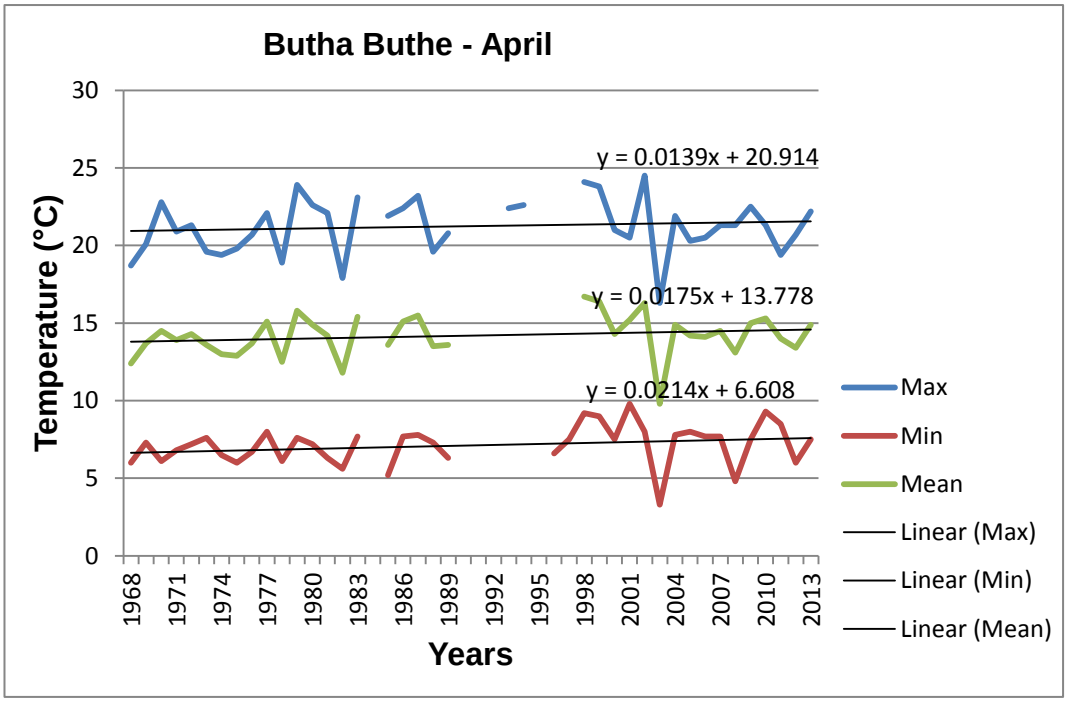

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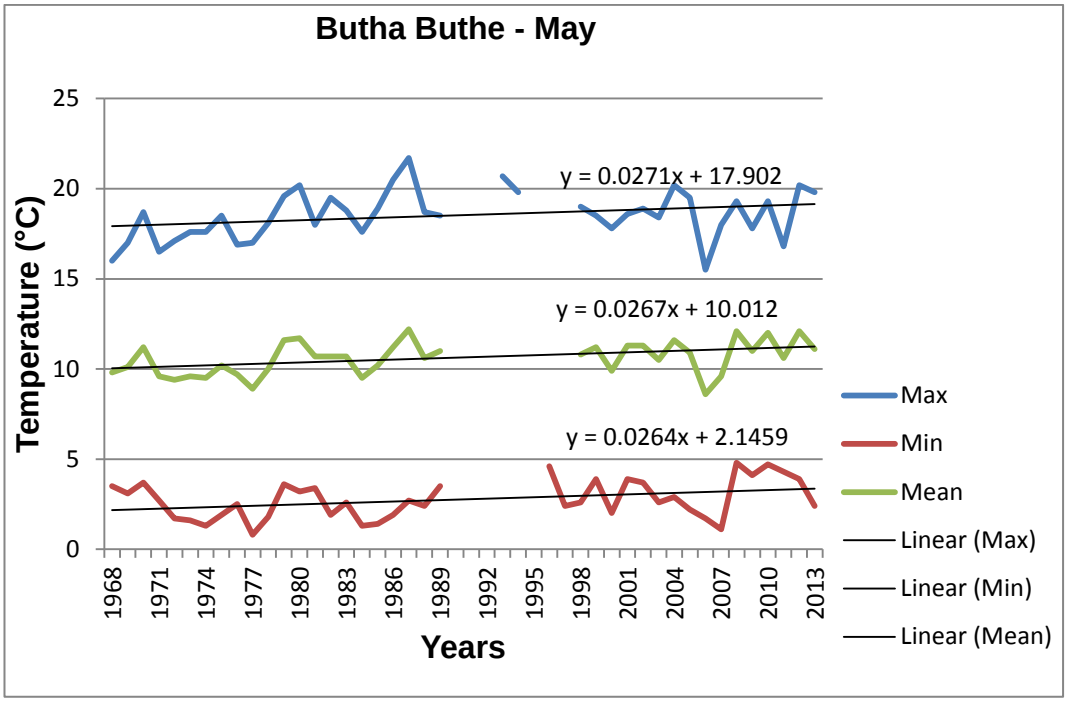

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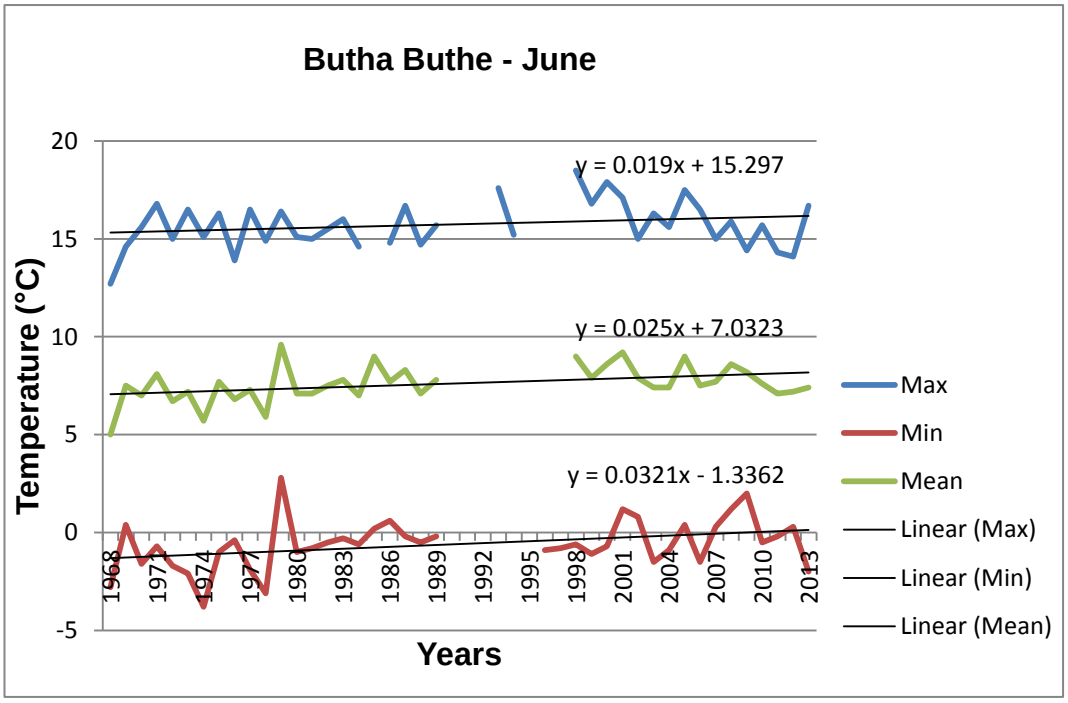

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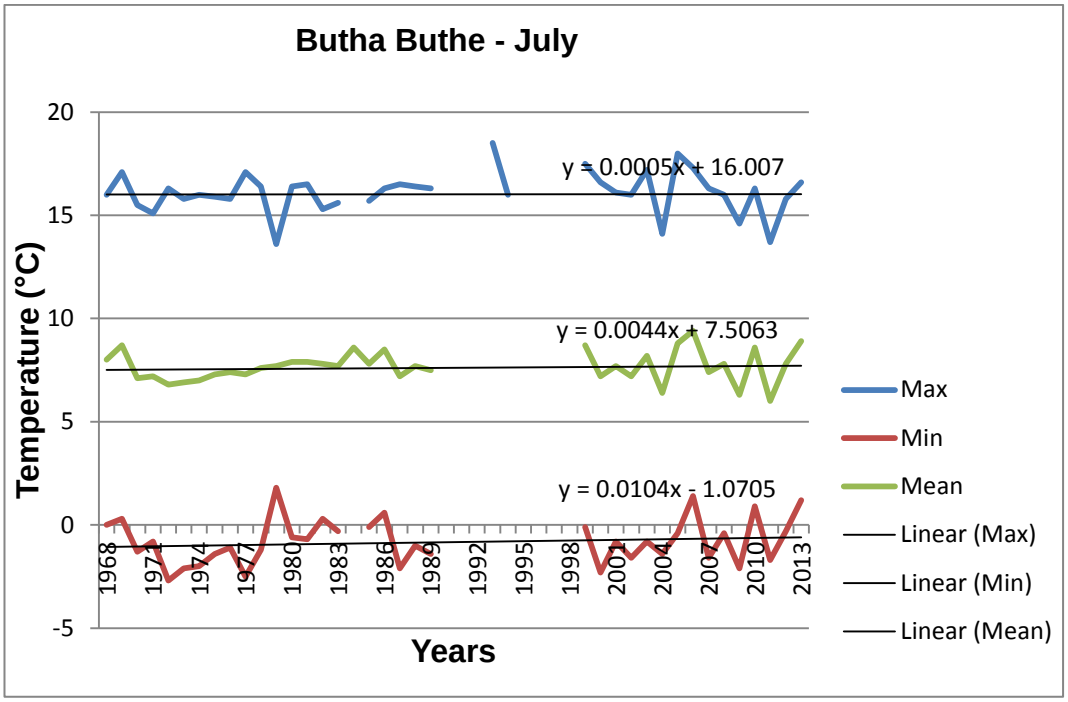


Figure 4.3(g)

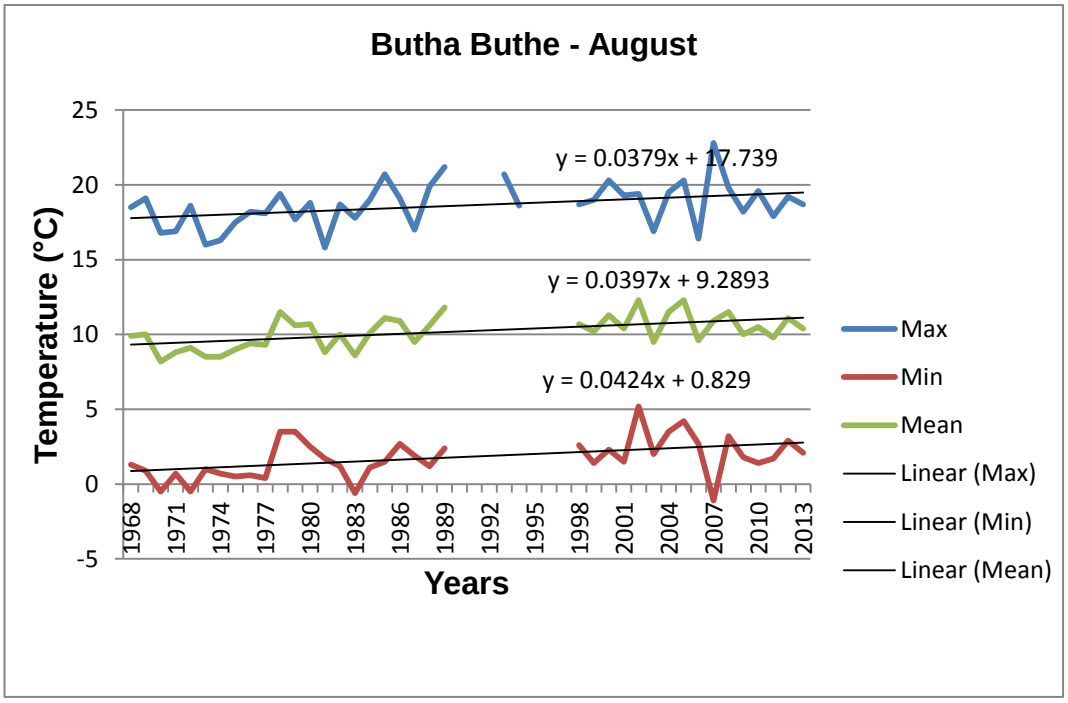


Figure 4.3(h)

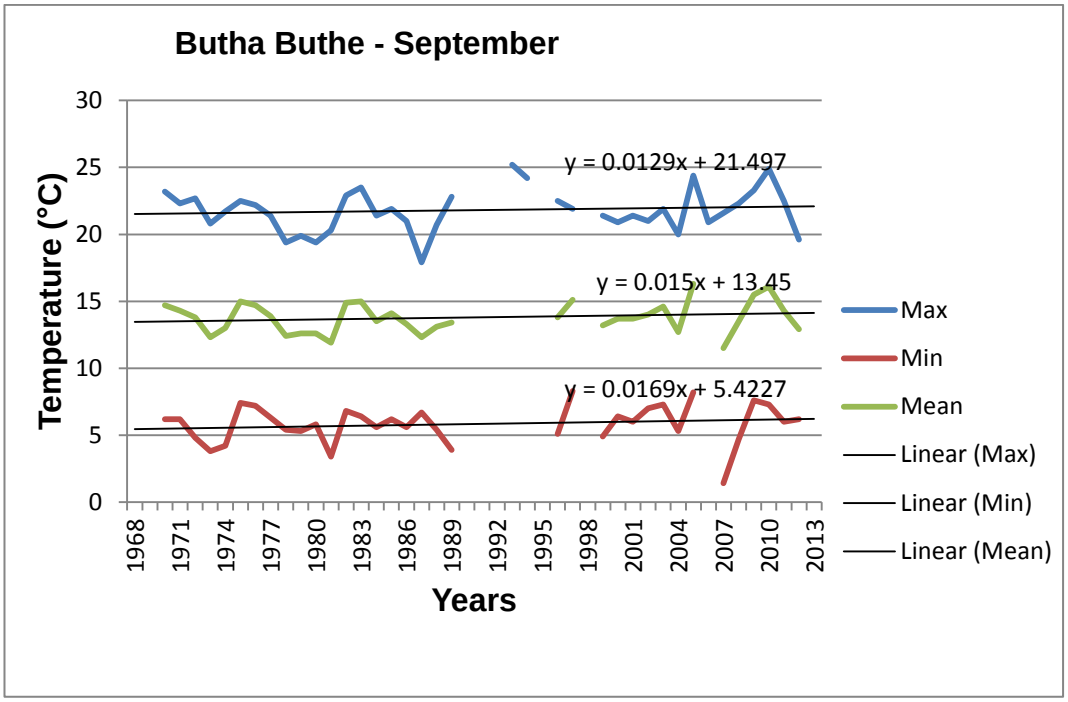
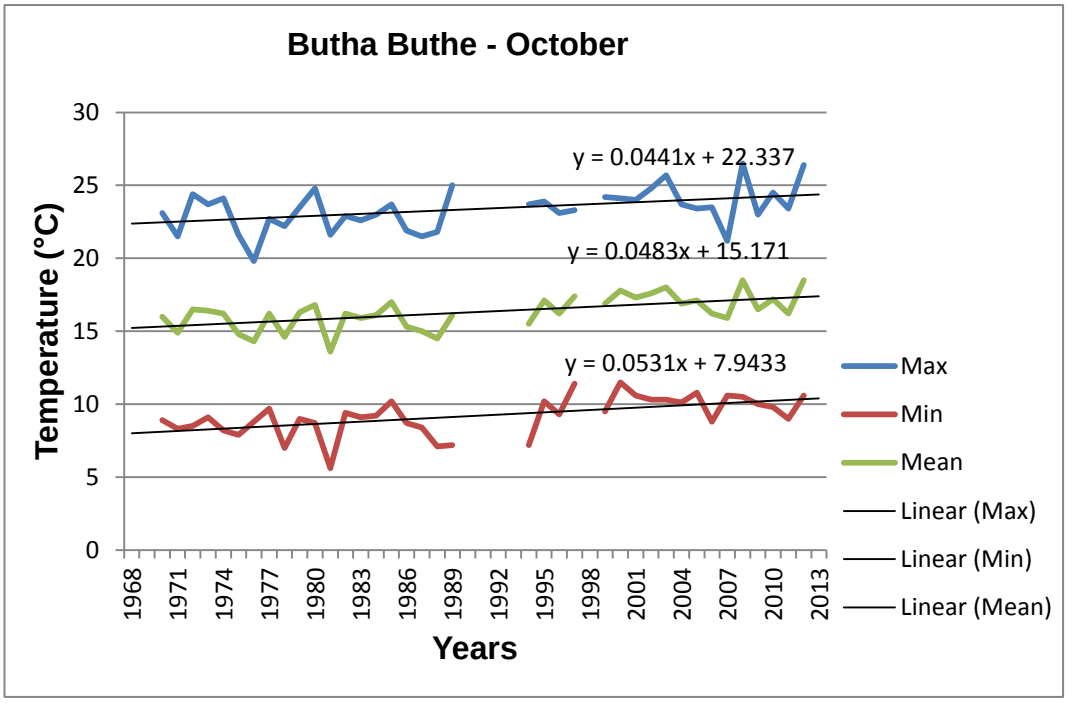


Figure 4.3(i)



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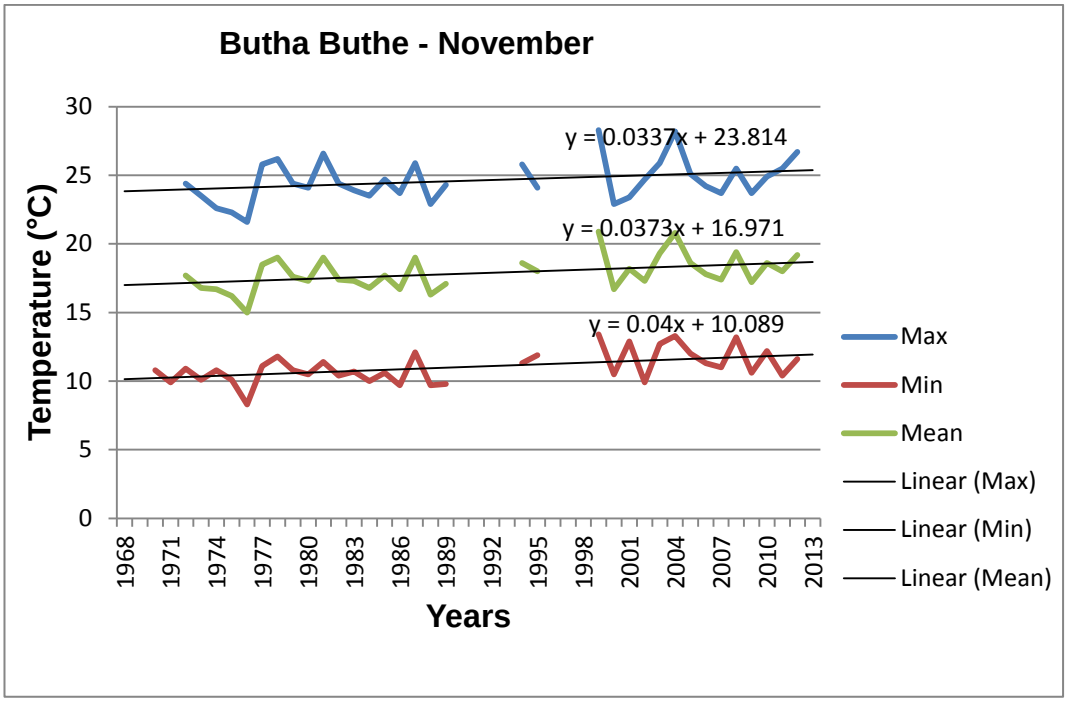

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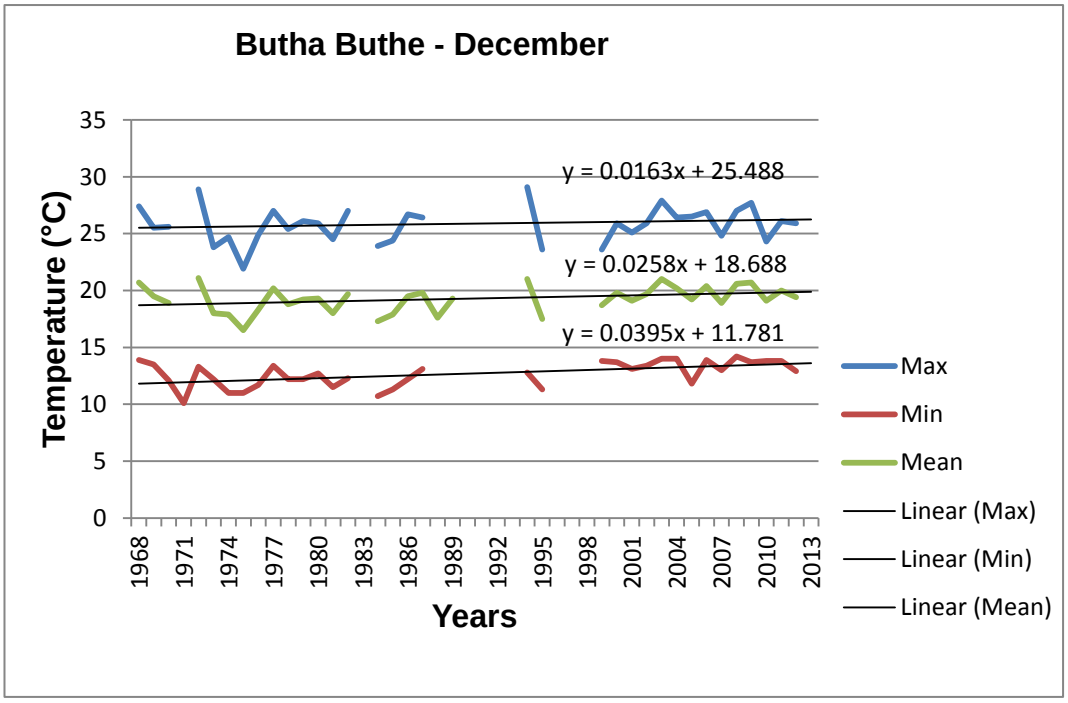


Figure 4.3(l)

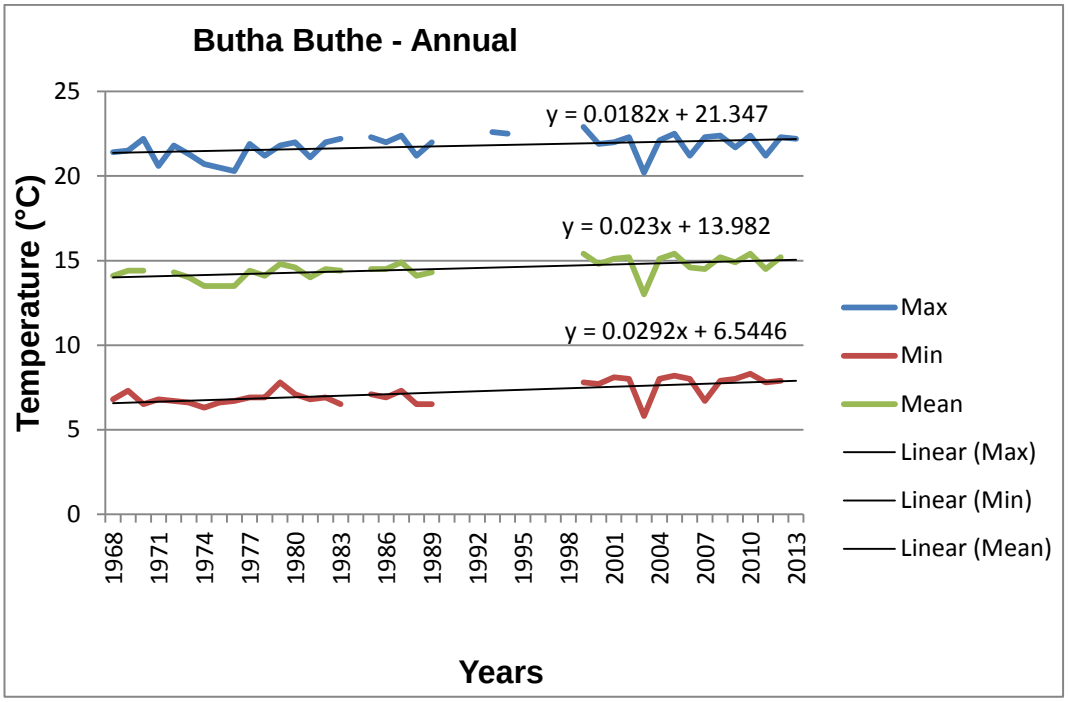


Figure 4.3(m)

Figure 4.3(a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Butha Buthe for the period 1968-2013.

For Mohaleshoek, monthly and annual trends for maximum, minimum and mean temperatures for the period 1968 - 2013 are shown in Figures 4.4 (a-m). From the results, a negative trend for maximum temperature can be seen with the summer months (i.e. January (-0.34 °C/decade), February (-0.34 °C/decade), December (-0.10 °C/decade)) as well as annually (-0.10 °C/decade), while the other months which are much cooler are showing a positive trend. The trends for minimum temperature over Mohaleshoek are negative for all the months with the exception of May (0.01 °C/decade), August (0.10 °C/decade), October (0.19 °C/decade) and November (0.02 °C/decade). The trend for minimum temperature is negative also at an annual scale over Mohaleshoek. The trends for mean temperatures are positive annually and for all the months except for January (-0.27 °C/decade) and February (-0.23 °C/decade) which are summer months.

The trends for maximum temperature are higher than the trends for minimum temperatures in May (0.31 °C/decade; 0.01 °C/decade), August (0.15 °C/decade; 0.10 °C/decade), October (0.53 °C/decade; 0.19 °C/decade) and November (0.10 °C/decade; 0.02 °C/decade) while the trends for minimum temperatures are higher than the trends for maximum temperatures for the remaining months as well as annually in Mohaleshoek.

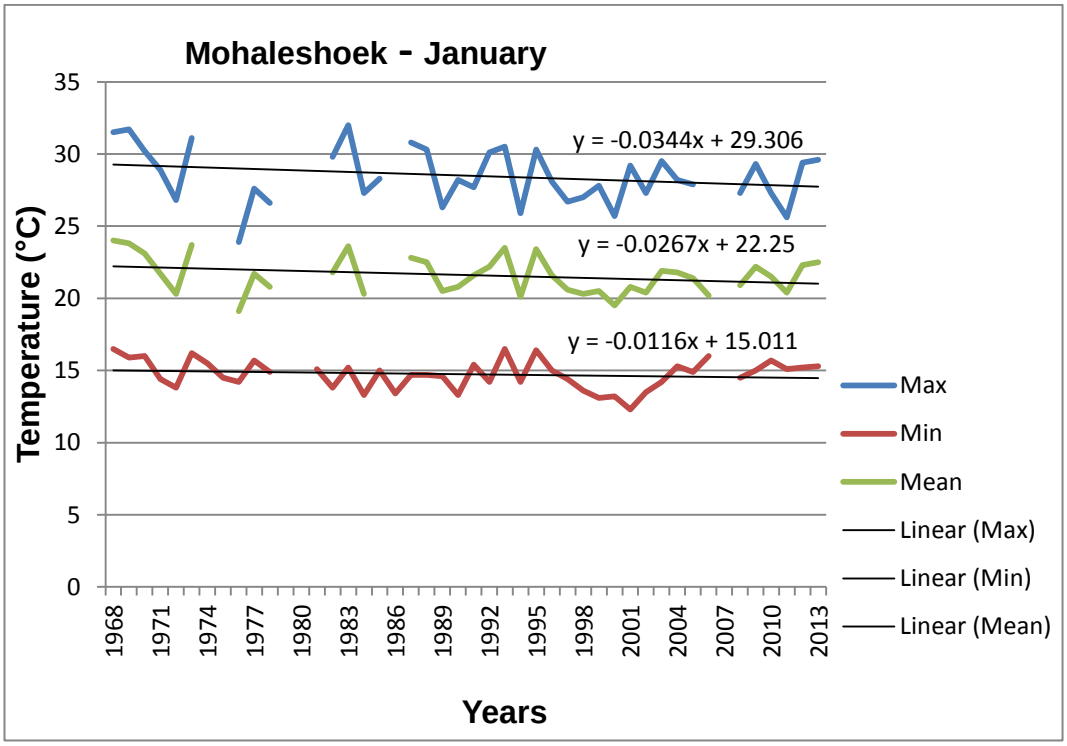
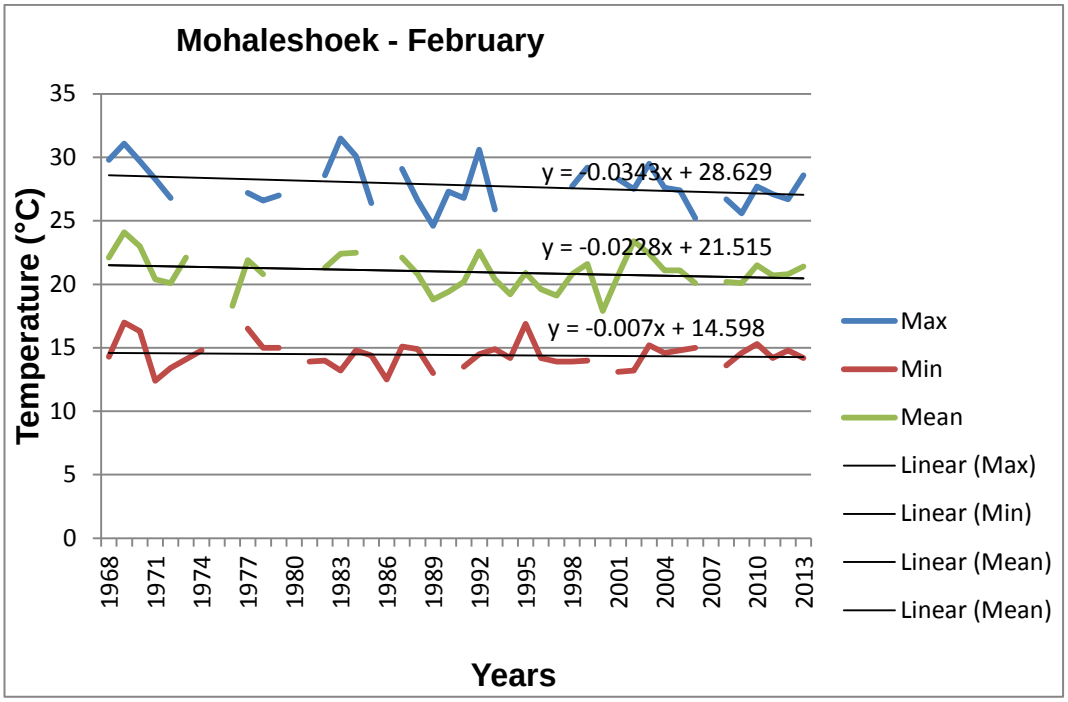


Figure 4.4(a)



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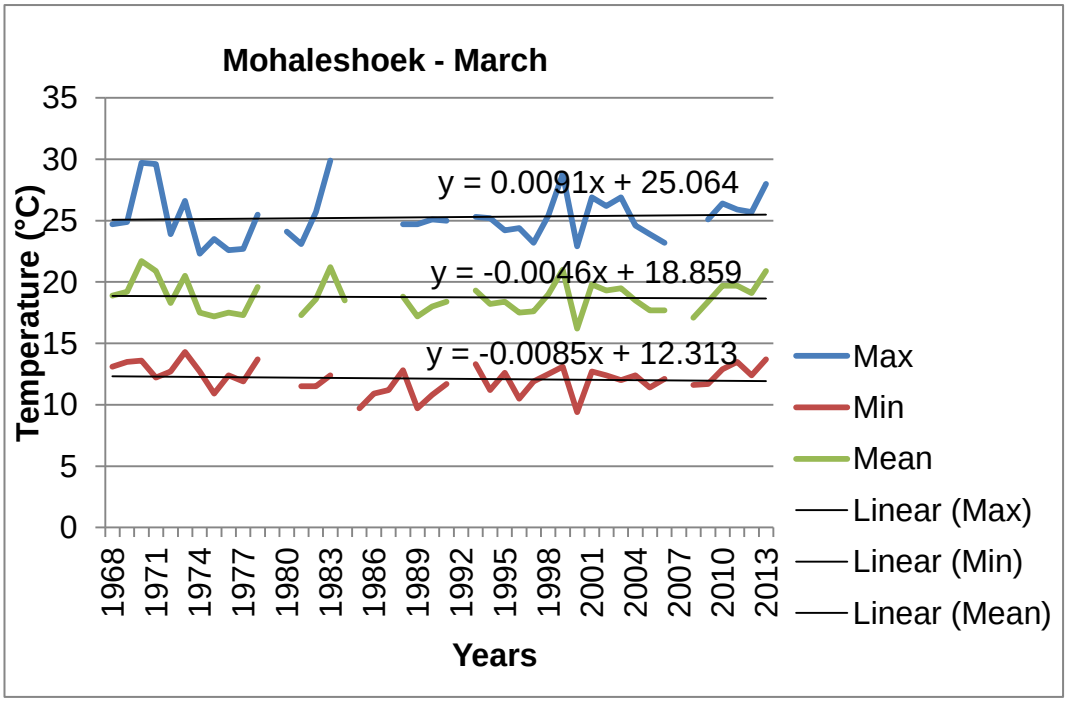

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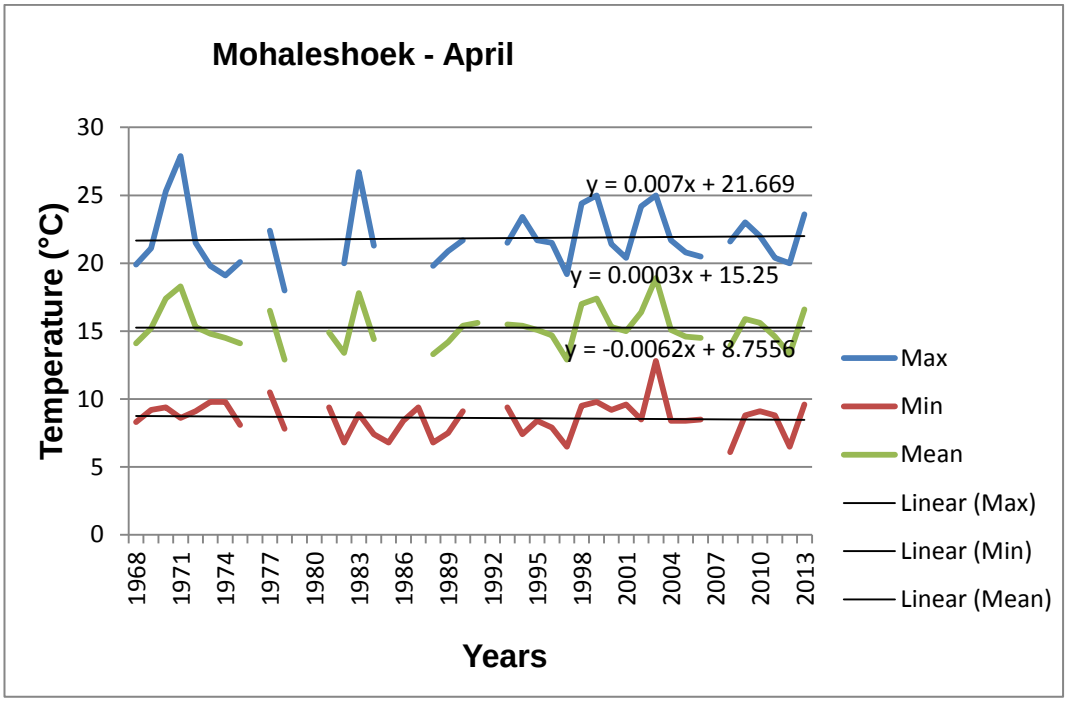
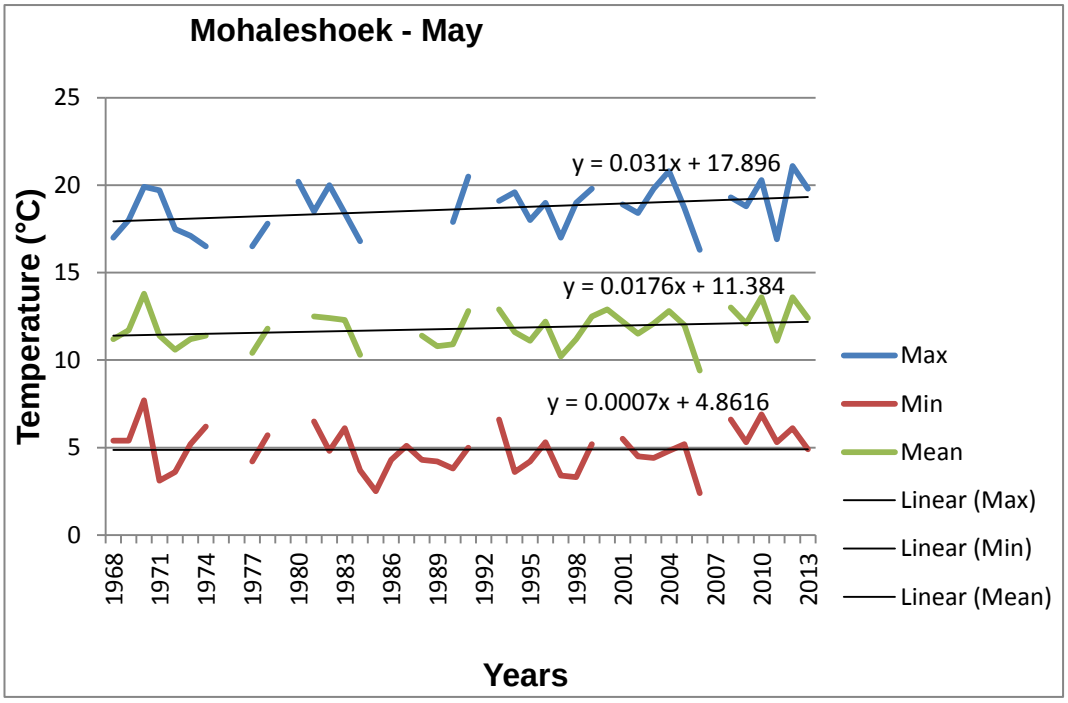


Figure 4.4(d)



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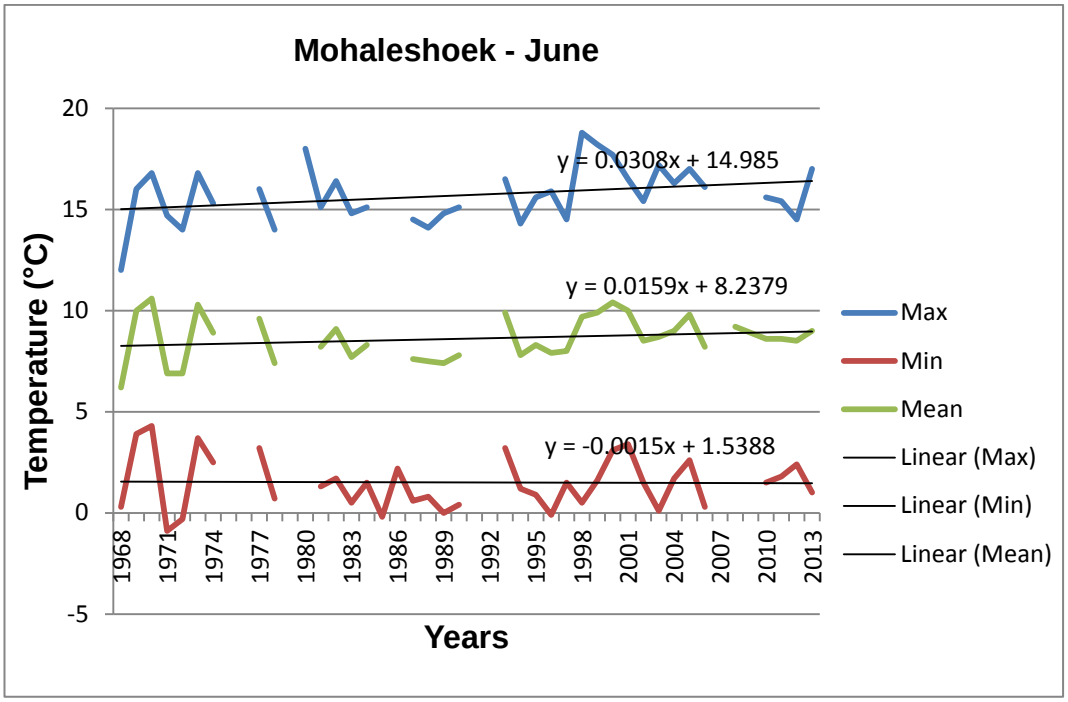

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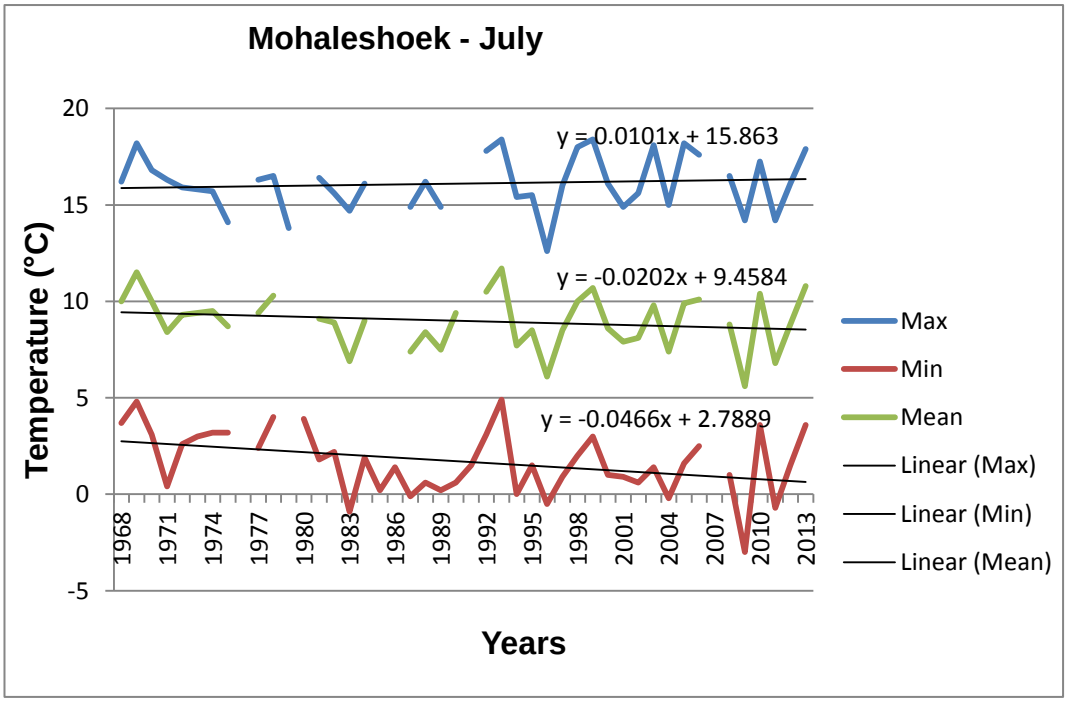

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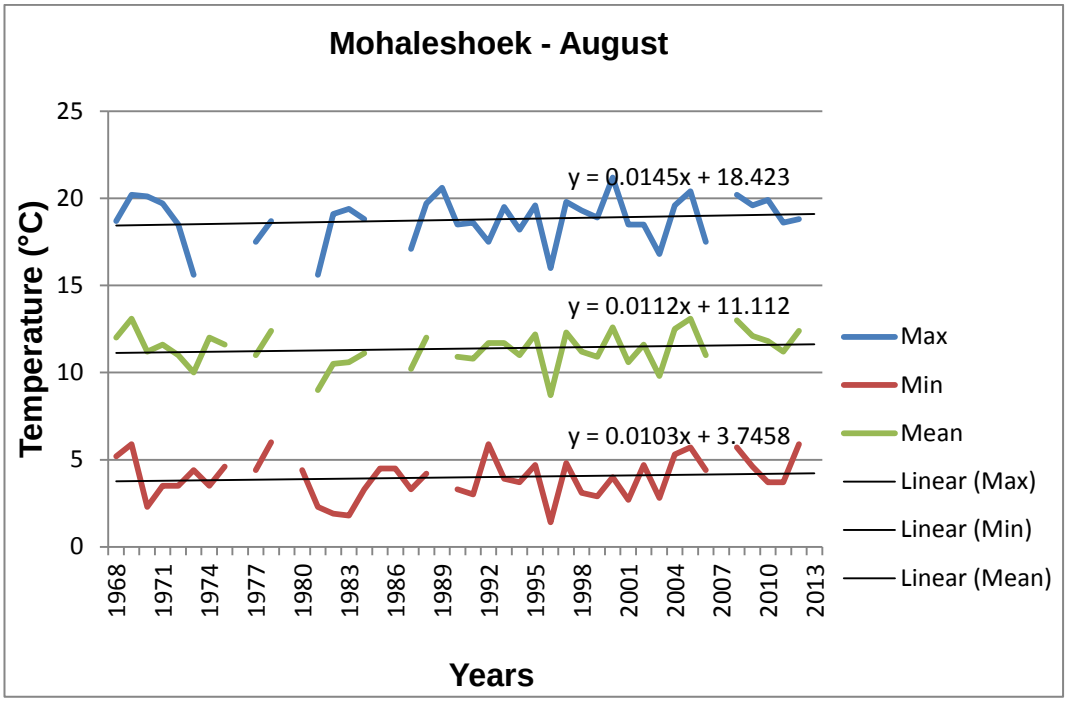


Figure 4.4(h)

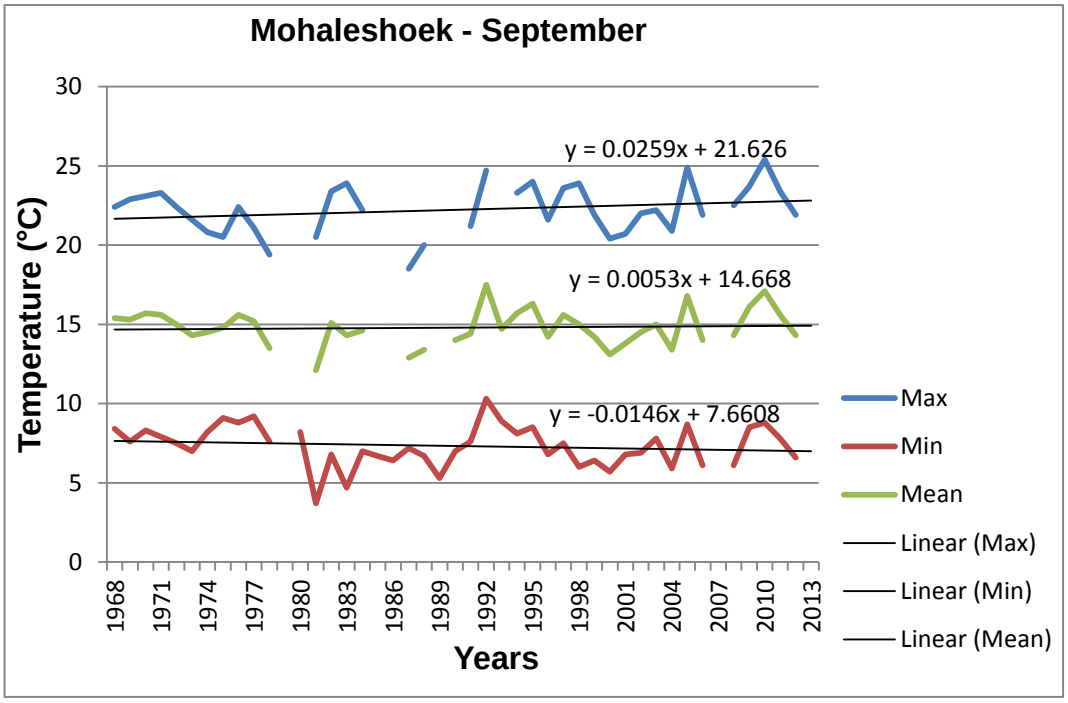


Figure 4.4(i)

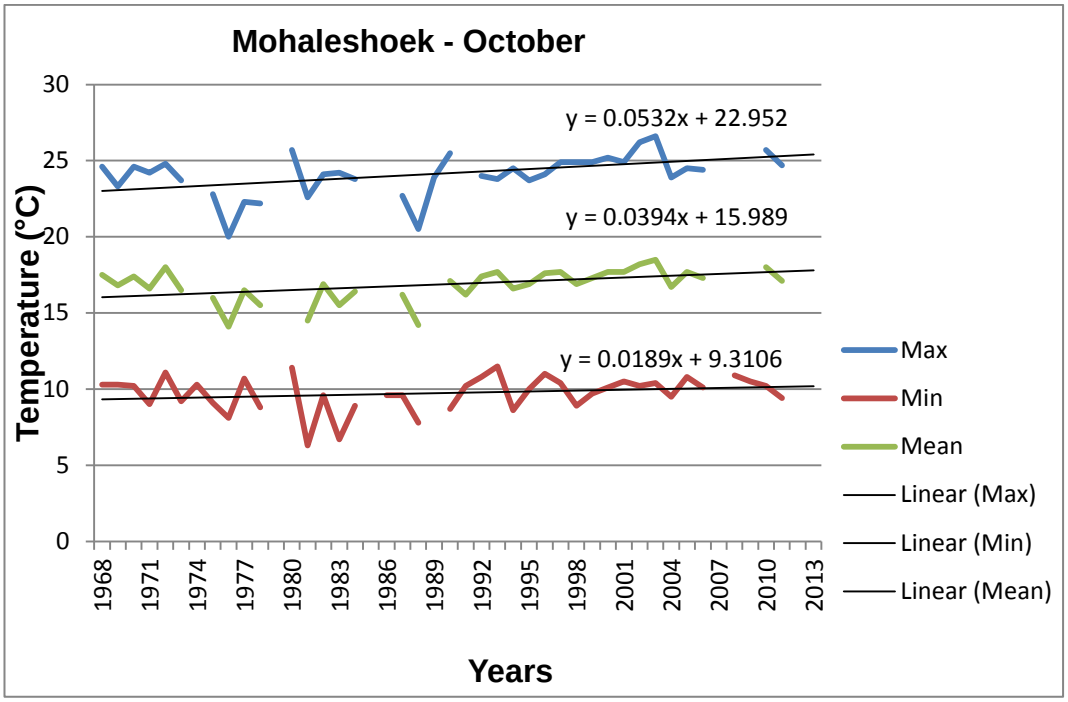
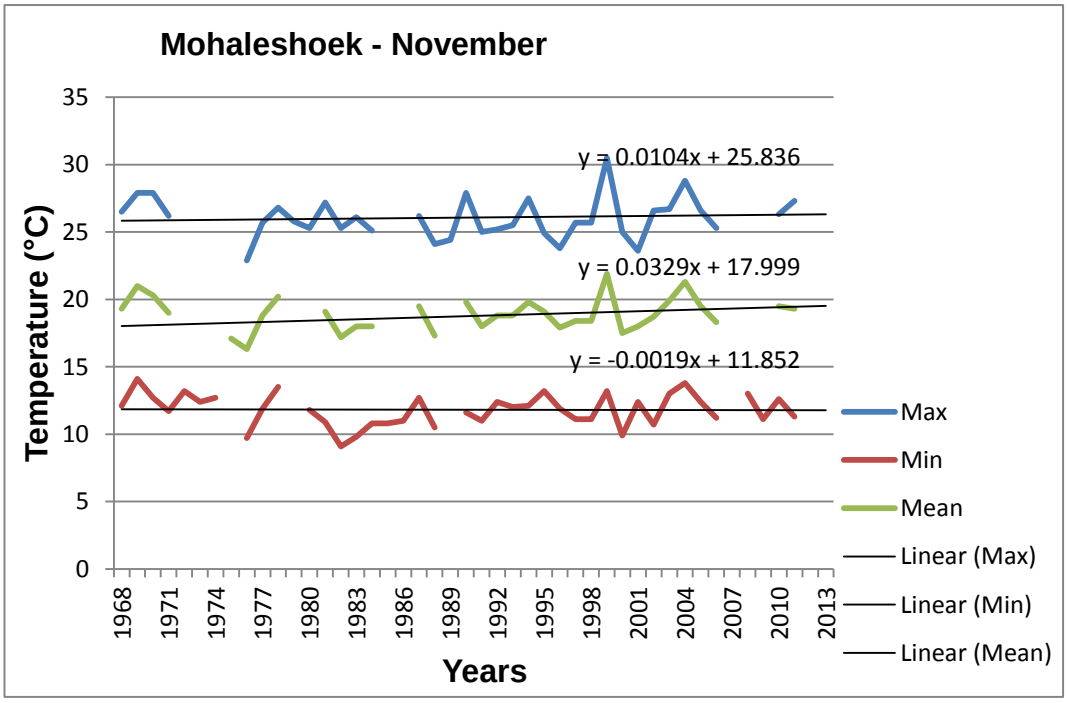


Figure 4.4(j)



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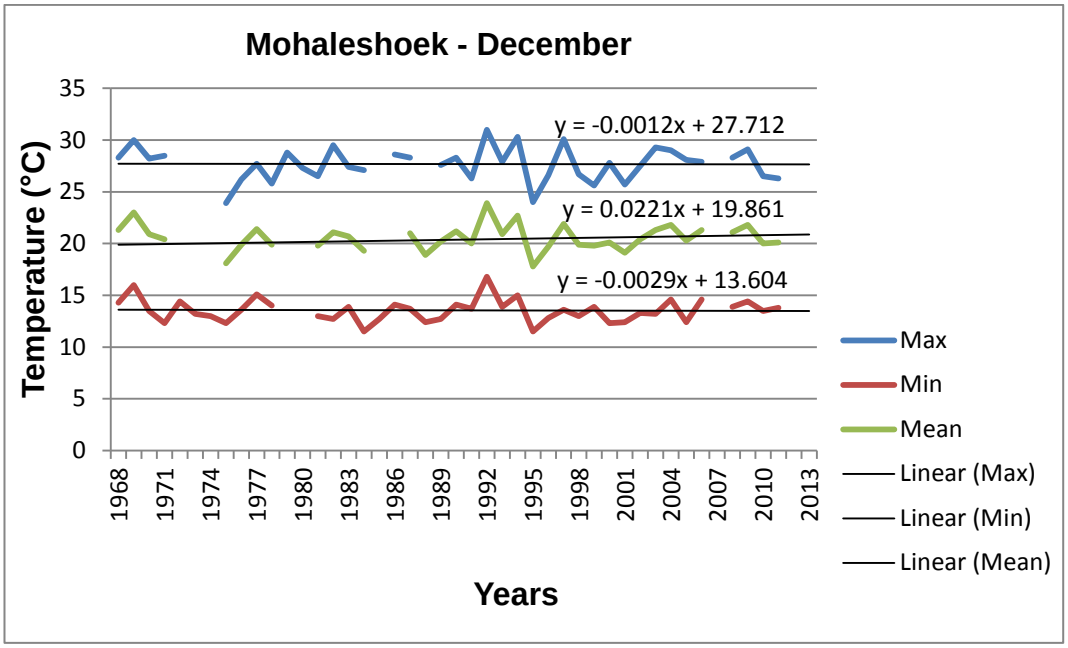

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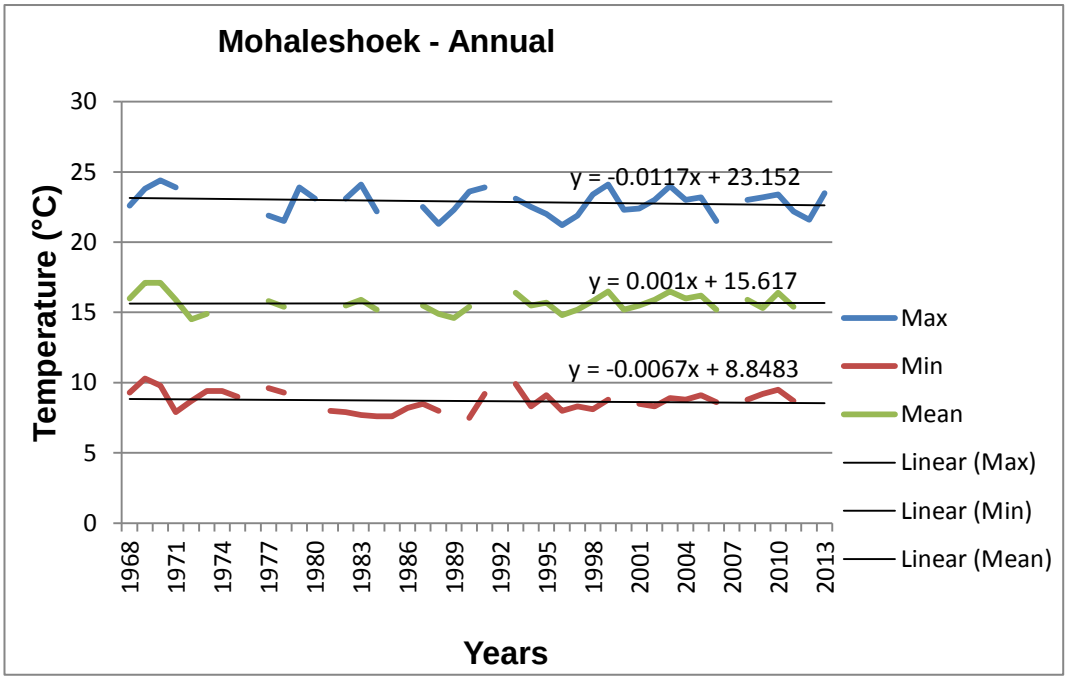


Figure 4.4(m)

Figure 4.4(a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Mohaleshoek for the period 1968-2013.

For Mokhotlong, monthly and annual trends for maximum, minimum and mean temperatures for the period 1968 - 2013 are shown in Figures 4.5 (a-m). From the results it can be seen that there is a positive trend for maximum temperature annually as well as for all the months except January (-0.14 °C/decade) which is a summer month. This positive trend can also be seen with minimum and mean temperatures. The trend for minimum temperatures is higher than the trend for maximum temperatures annually and monthly, except for November where the trends are 0.37 °C/decade and 0.38 °C/decade for minimum and maximum temperatures respectively.

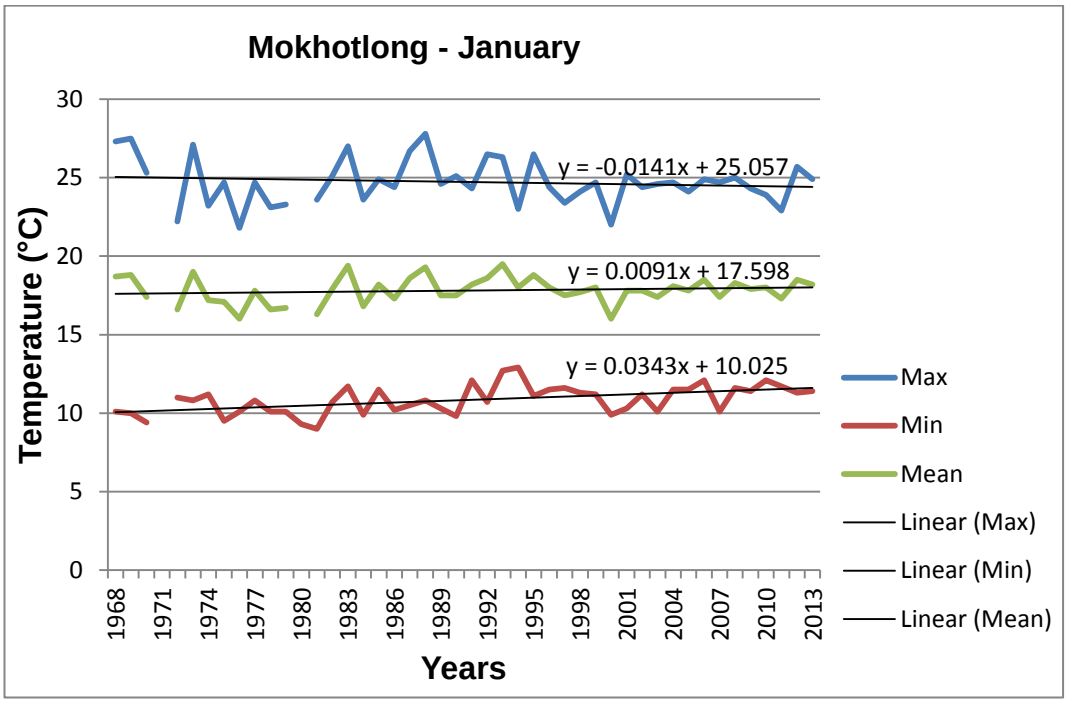
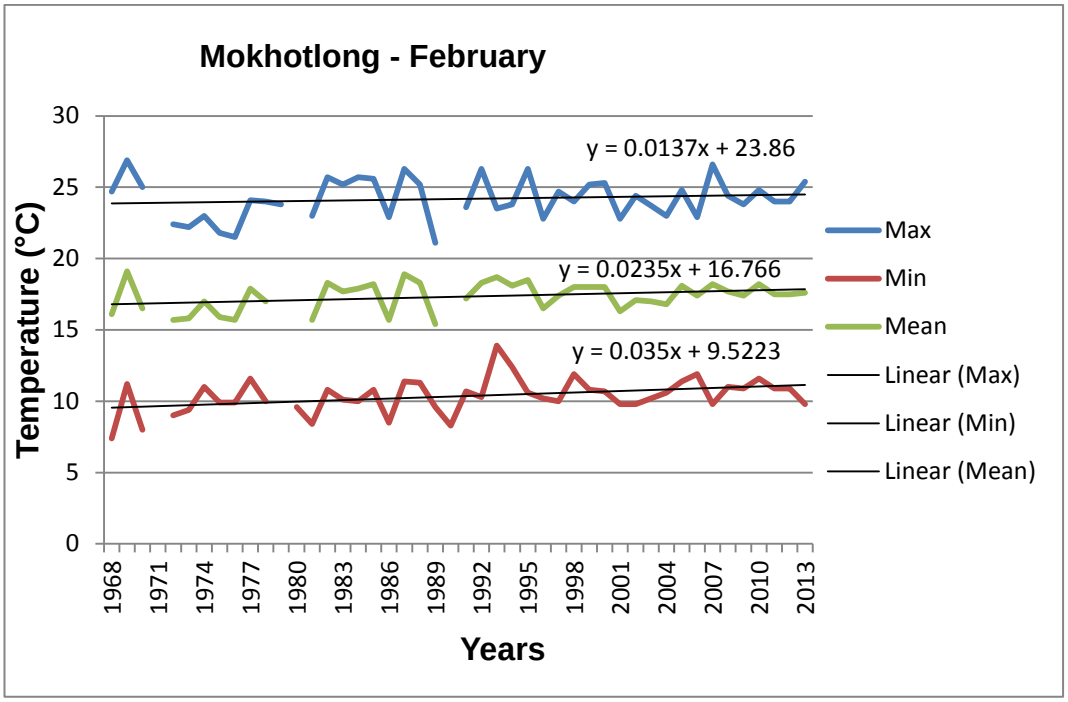


Figure 4.5(a)



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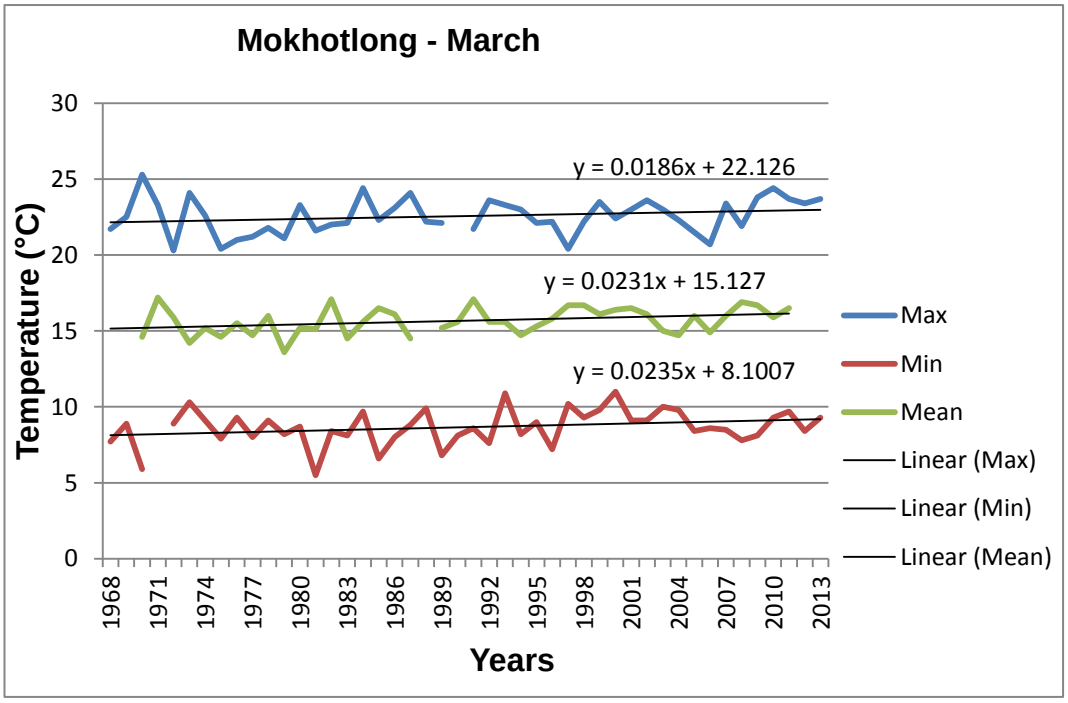

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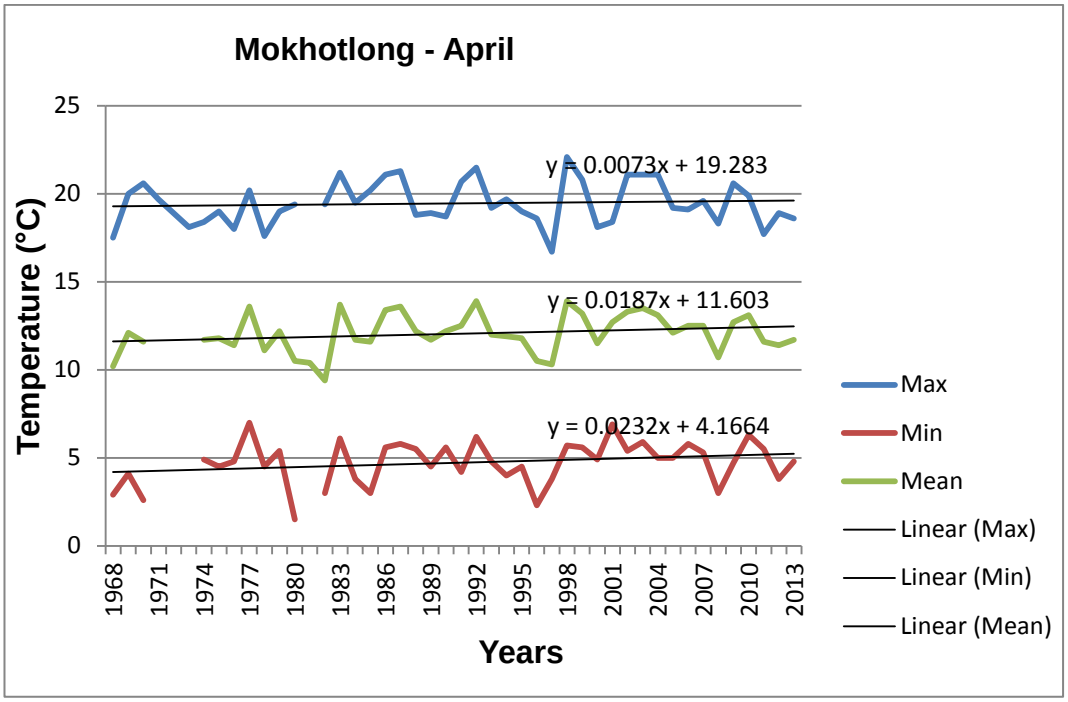

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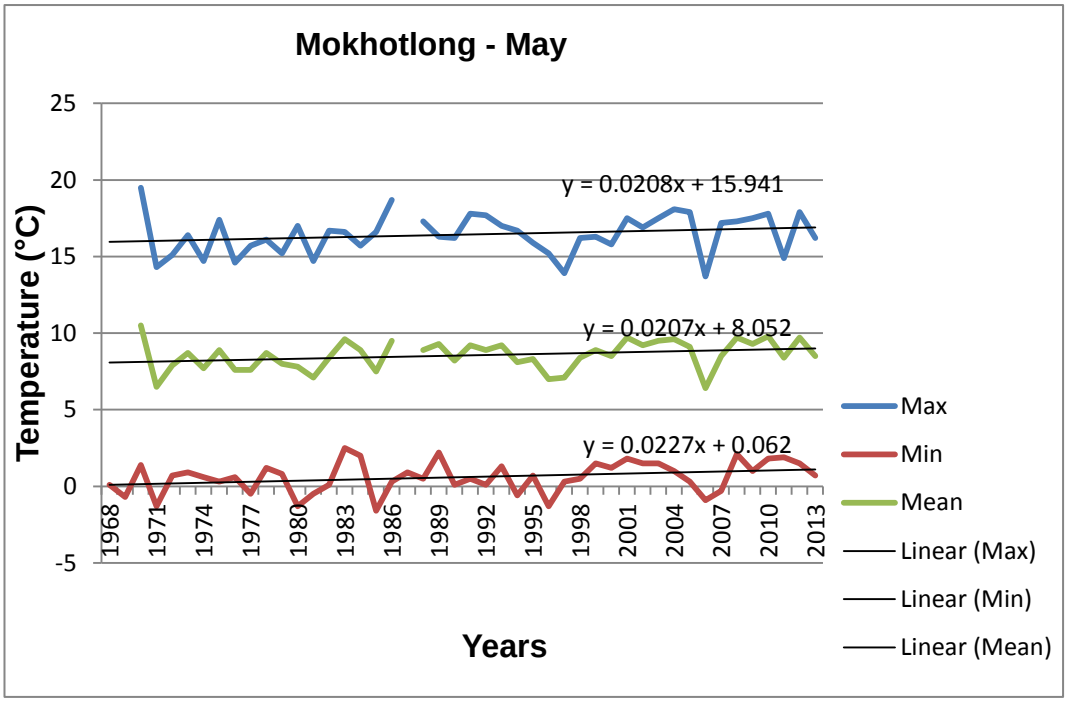

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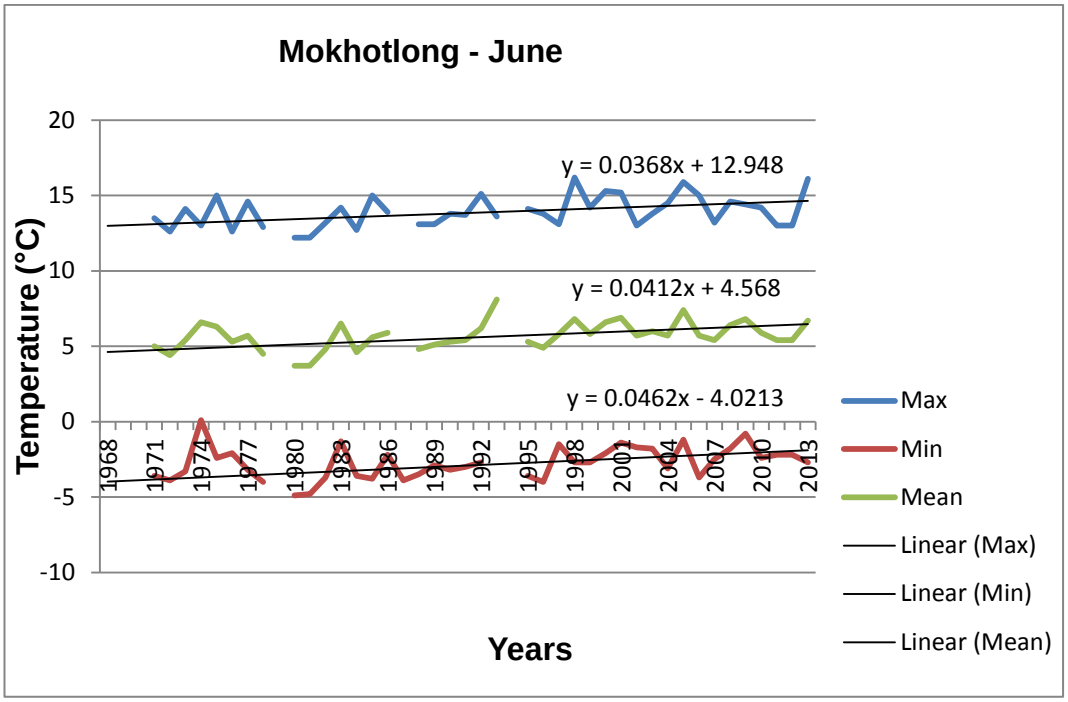

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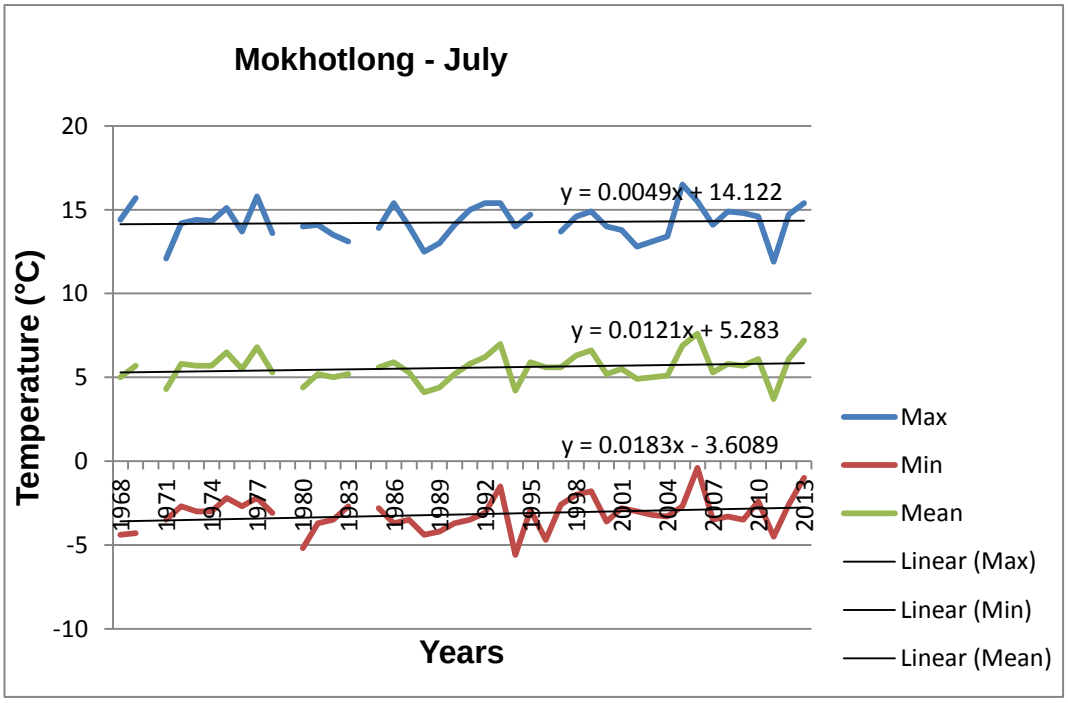

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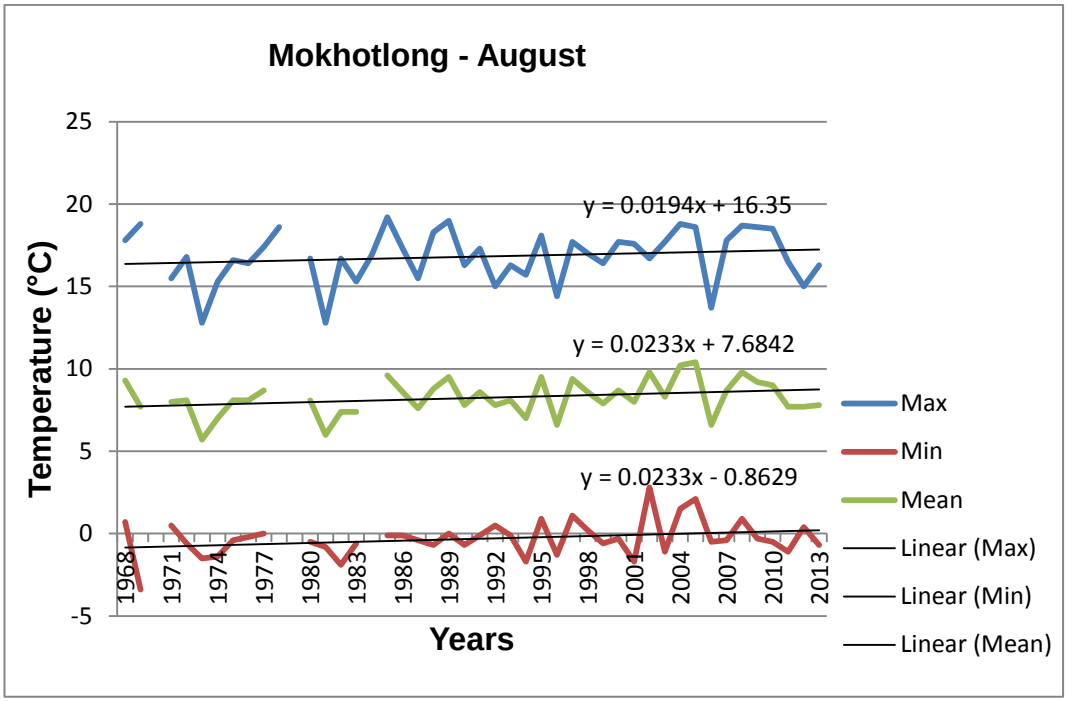

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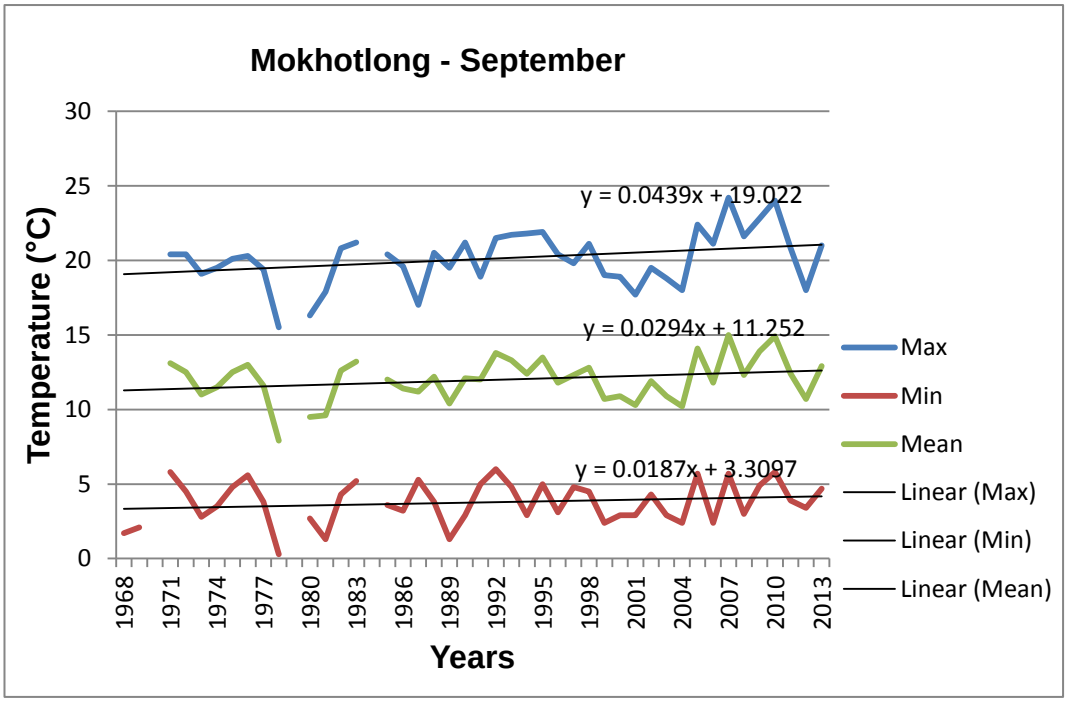
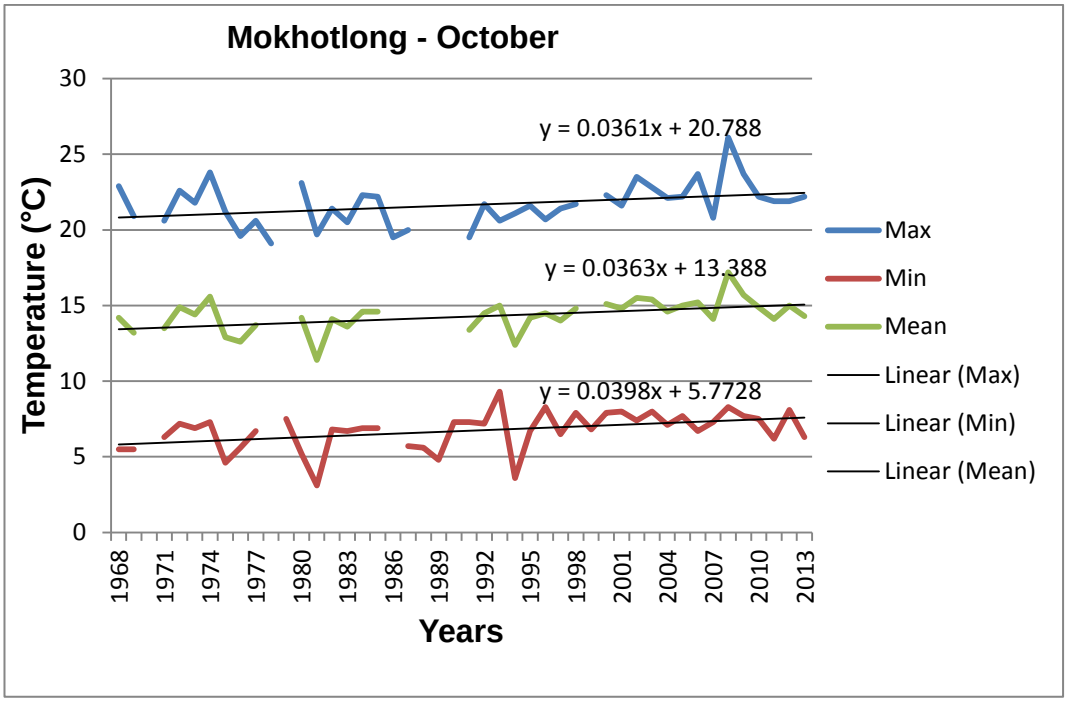


Figure 4.5(i)



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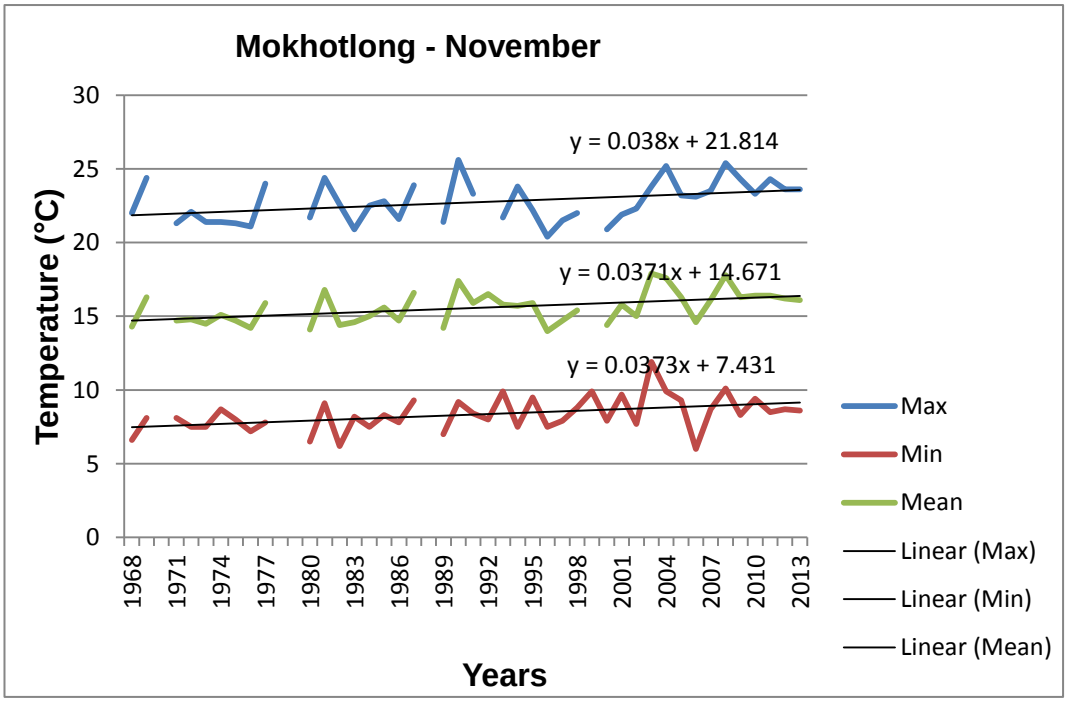

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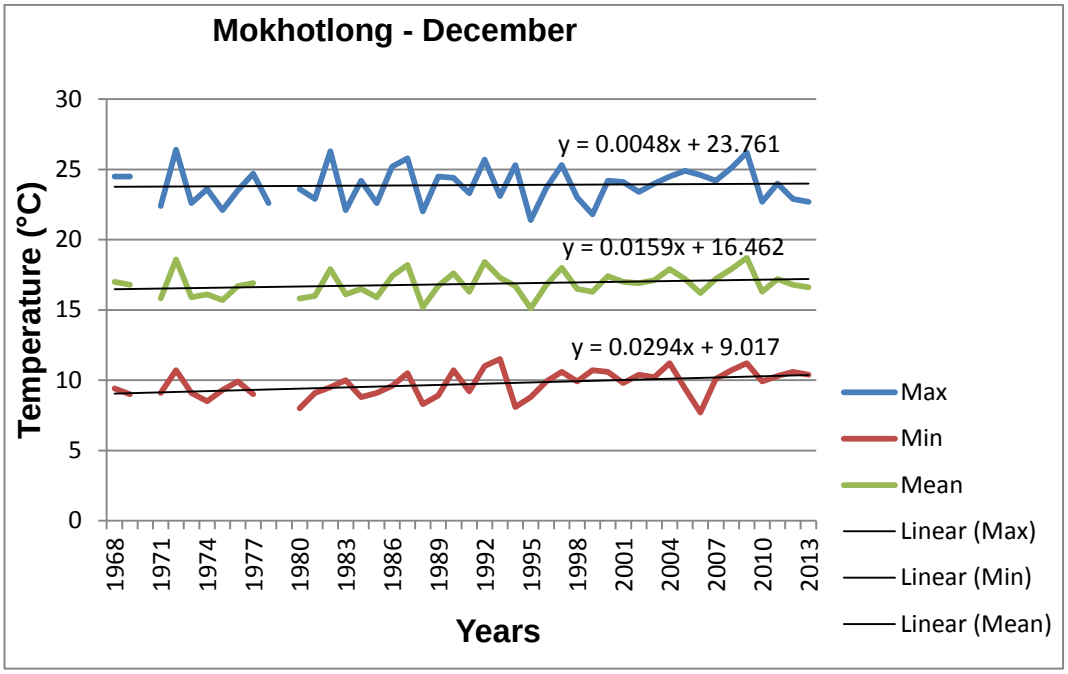


Figure 4.5(l)

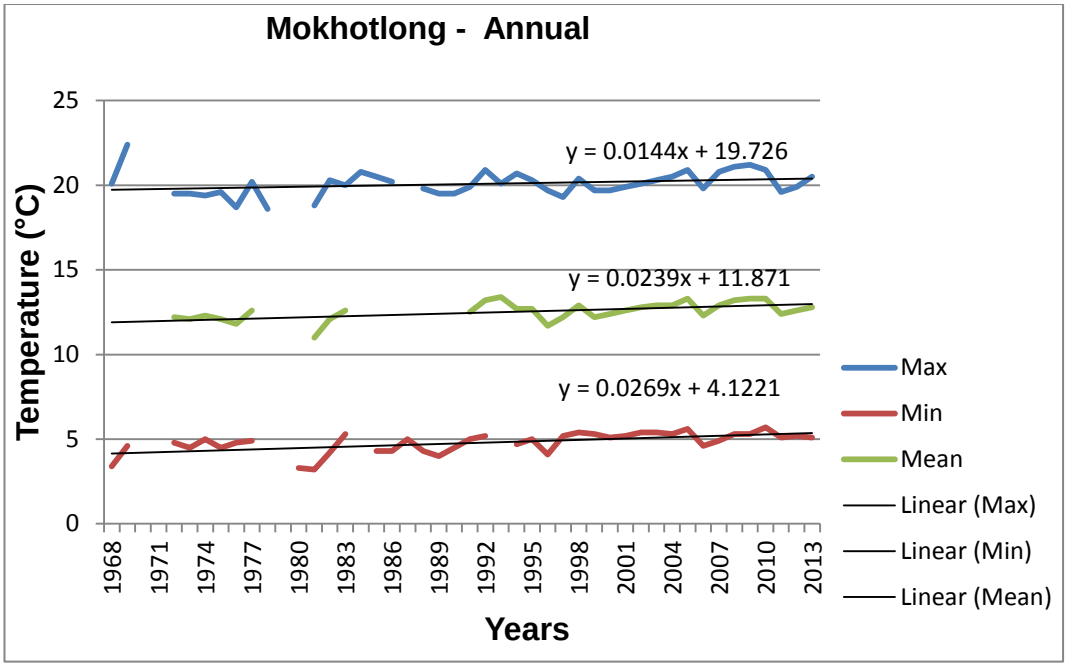


Figure 4.5(m)

Figure 4.5(a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Mokhotlong for the period 1968-2013.

For Oxbow, monthly and annual trends for maximum, minimum and mean temperatures for the period 1968 - 2013 are shown in Figures 4.6 (a-m). From the results it can be seen that the trends for maximum and mean temperatures are positive for all the months as well as annually. The trends for minimum temperatures are positive annually and monthly with the exception of July, which is winter month, where the trend for minimum temperature is negative (-0.06 °C/decade). The trends for maximum temperatures are higher than the trends for minimum temperatures annually as well as monthly with the exception of January, June, August and December ((0.17 °C/decade; 0.19 °C/decade), (0.49 °C/decade; 0.60 °C/decade), 0.22 °C/decade ; 0.31 °C/decade) and (0.02 °C/decade; 0.19 °C/decade) for January, June, August and December respectively), where the trends for maximum temperatures are lower than the trends for minimum temperatures.

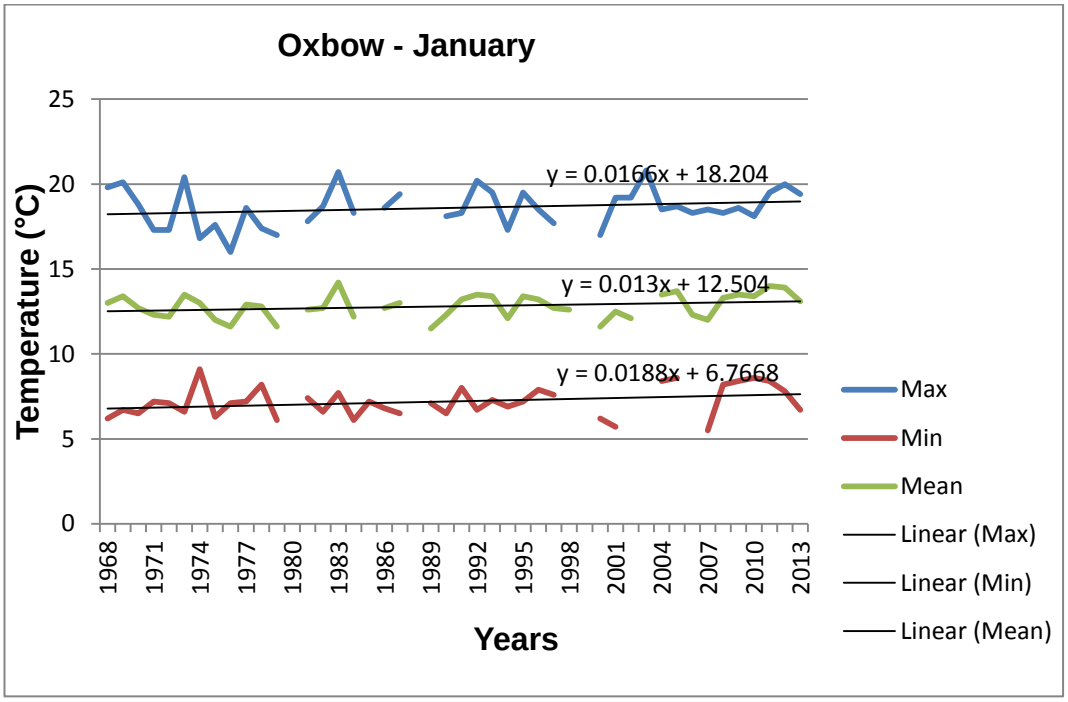
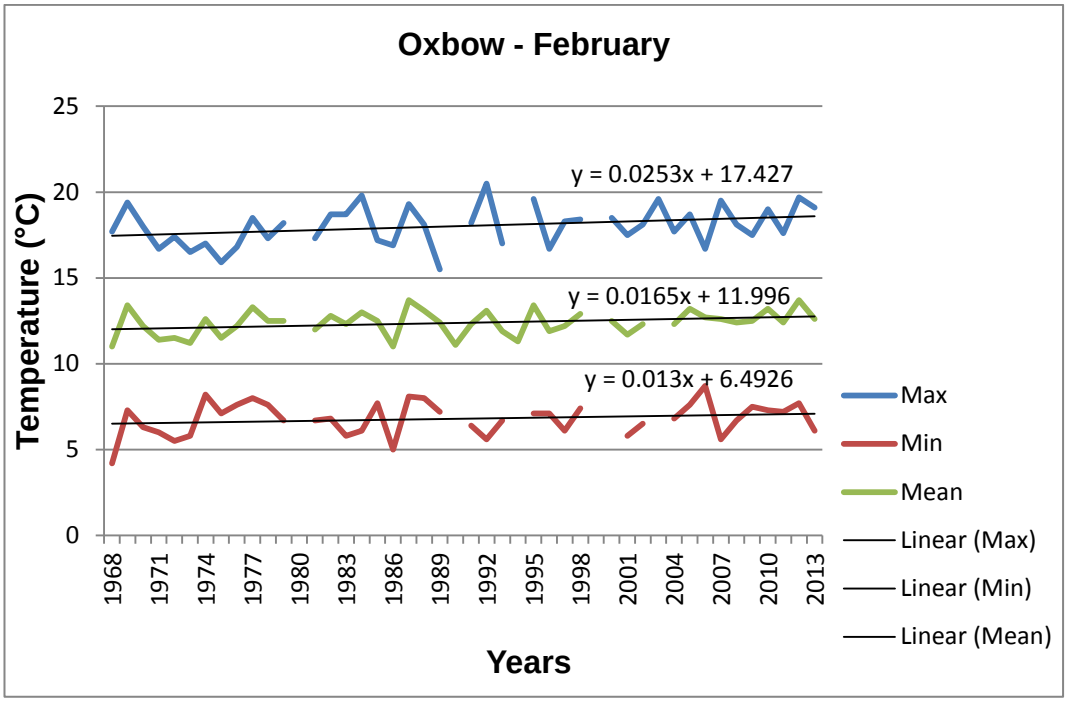


Figure 4.6(a)



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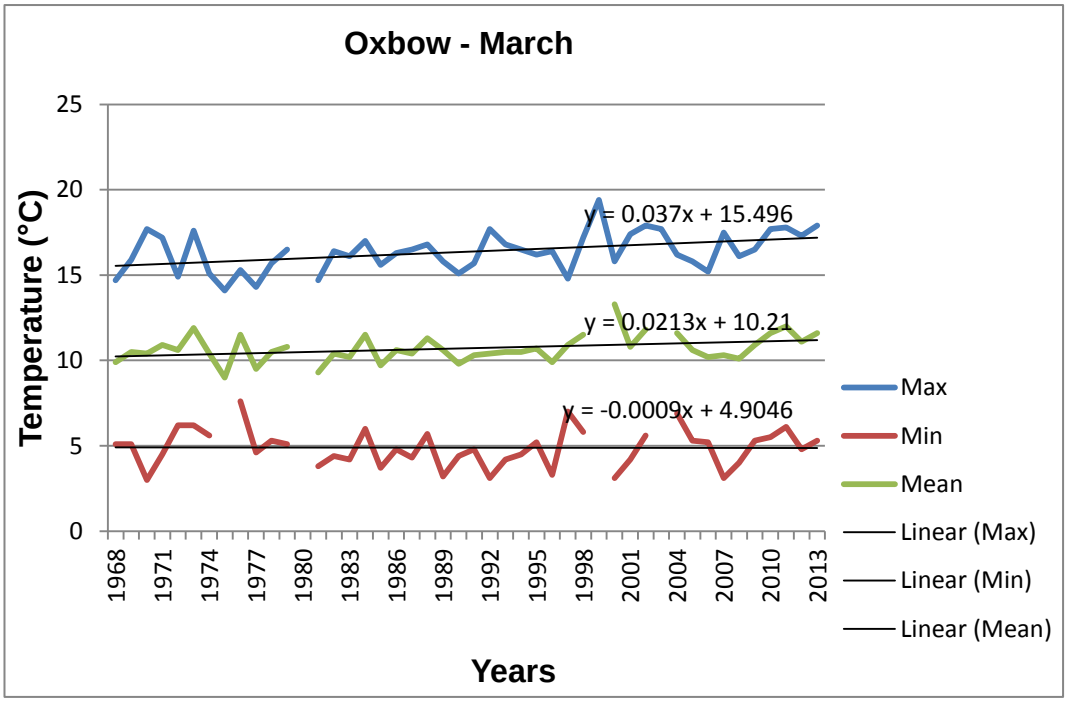

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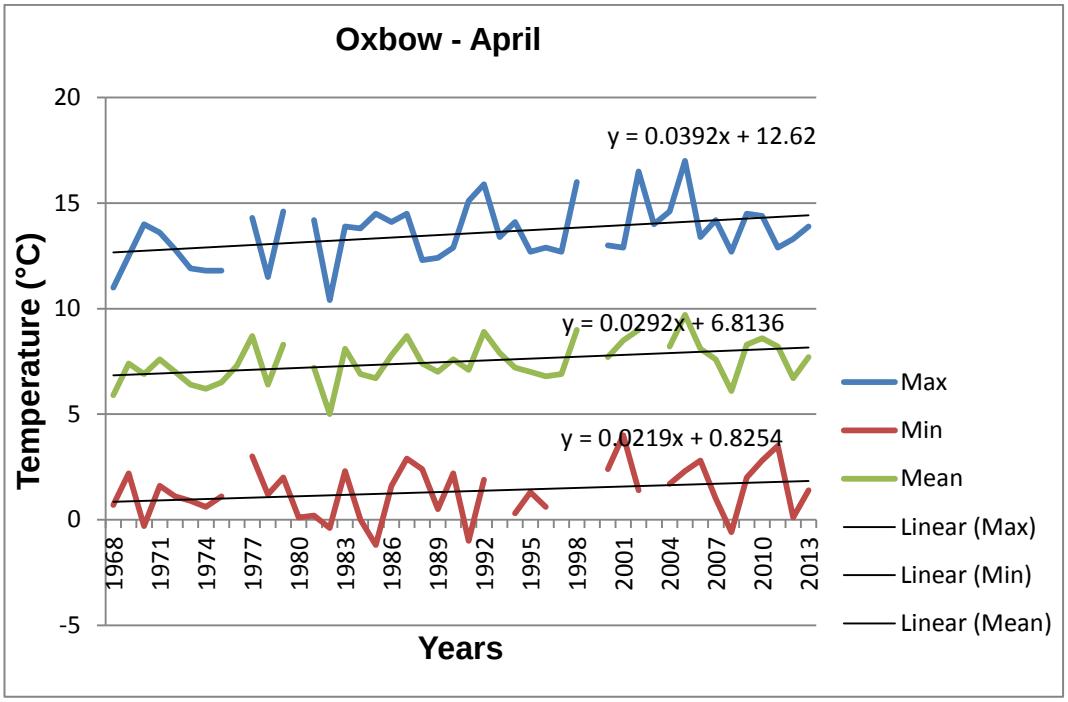

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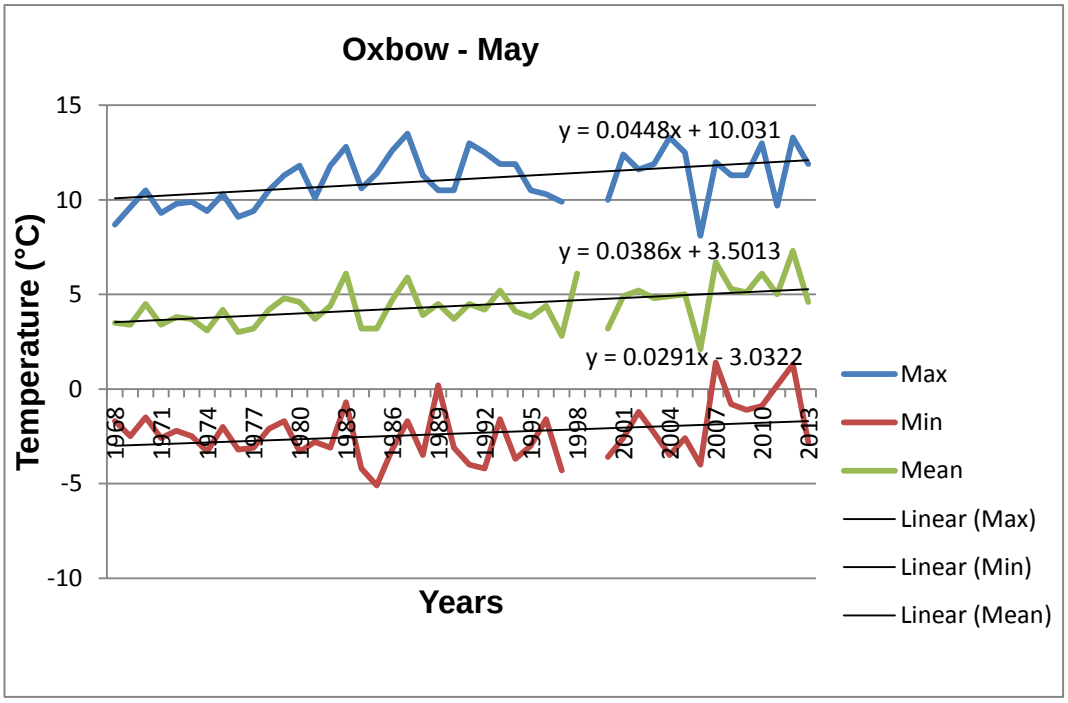

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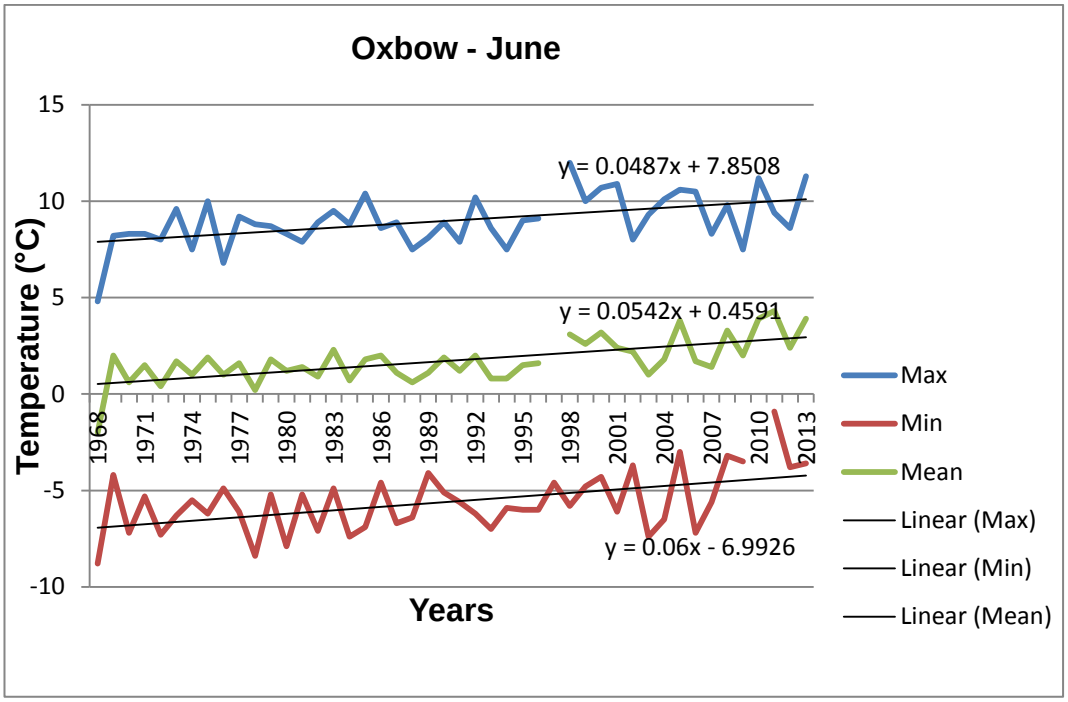

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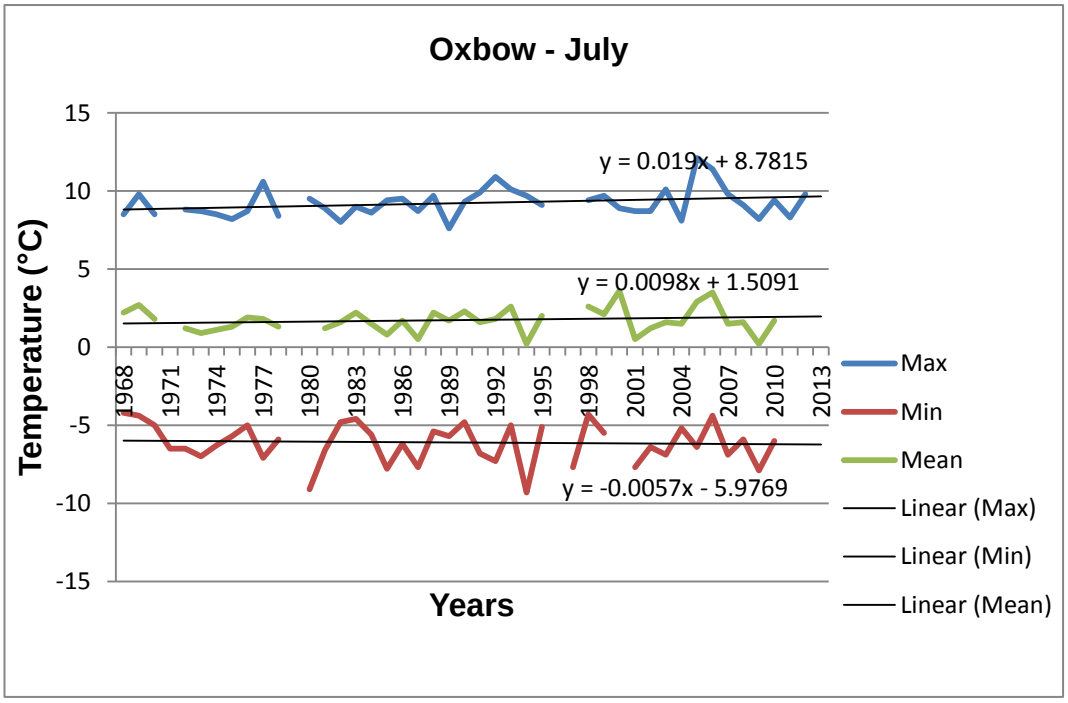

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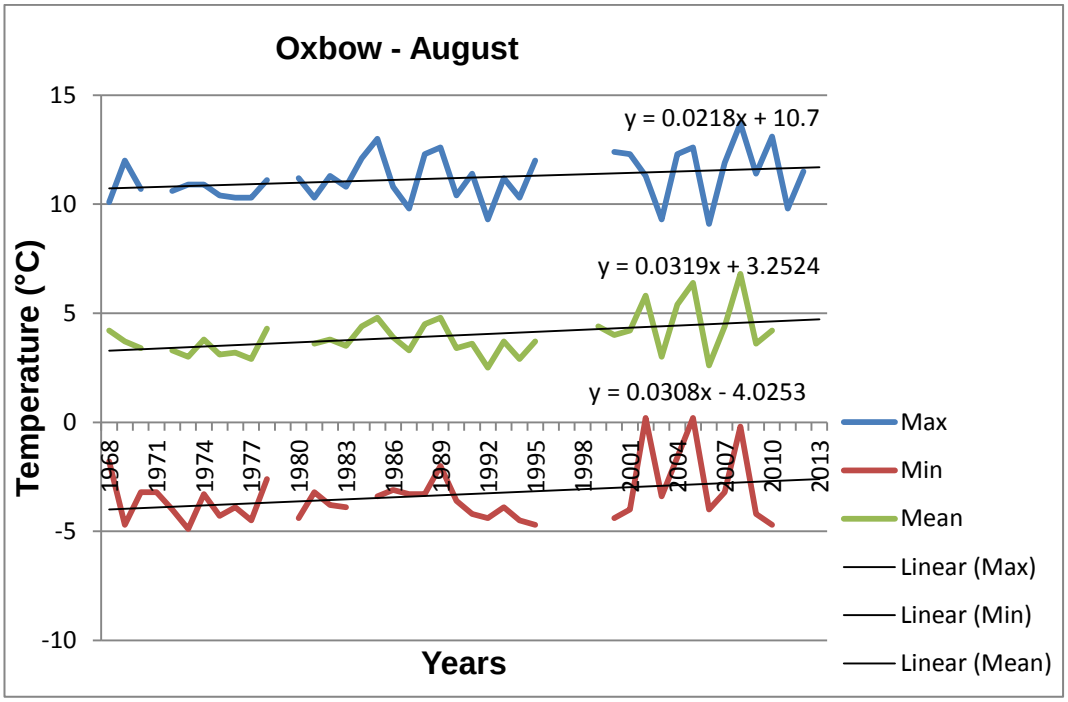


Figure 4.6(h)

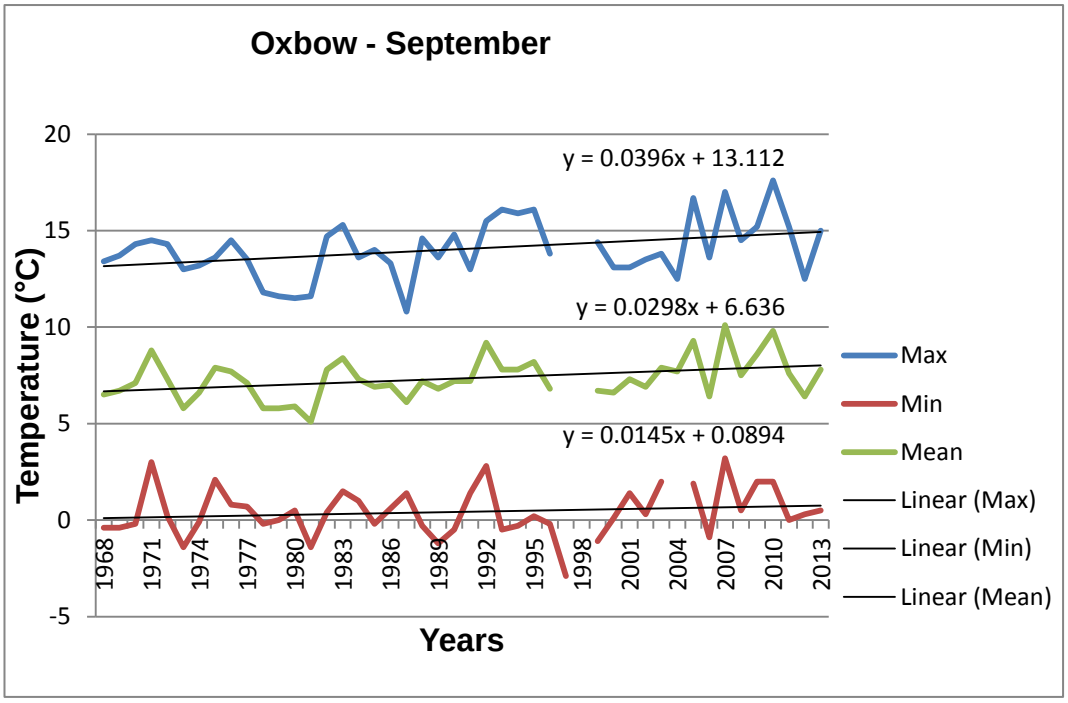
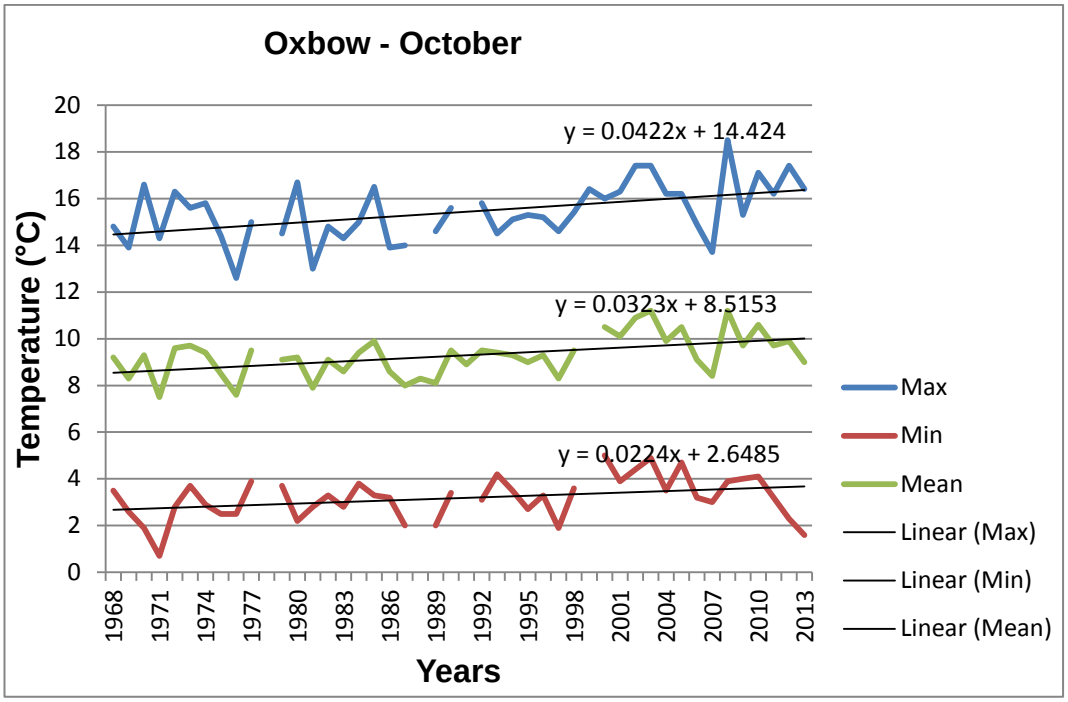


Figure 4.6(i)



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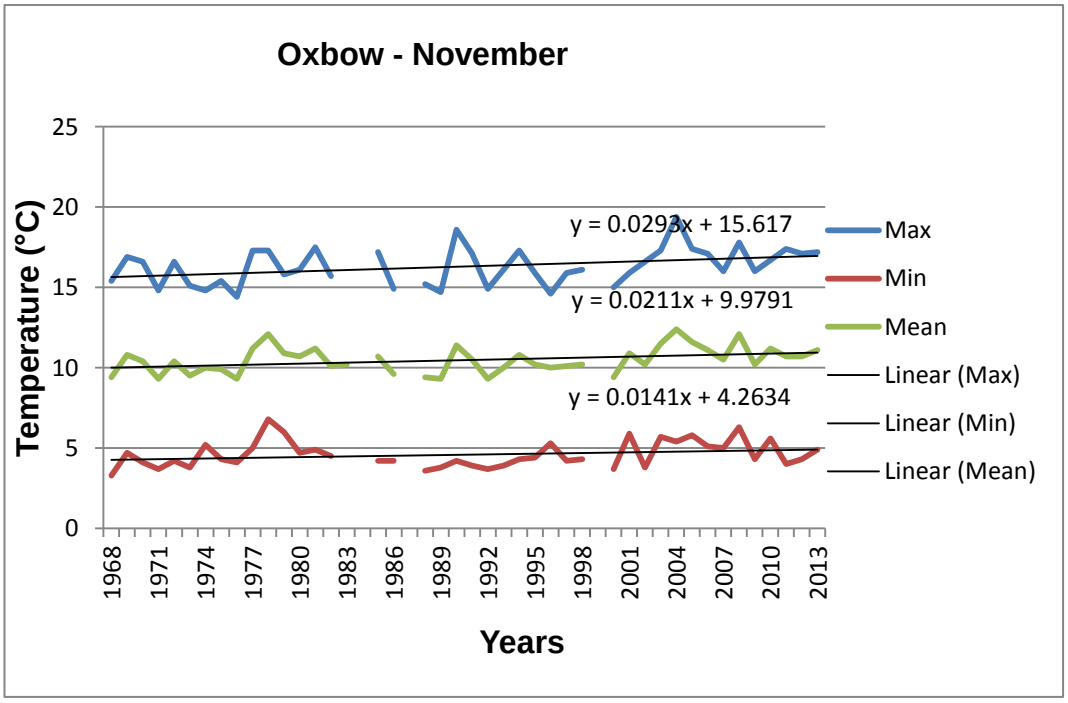

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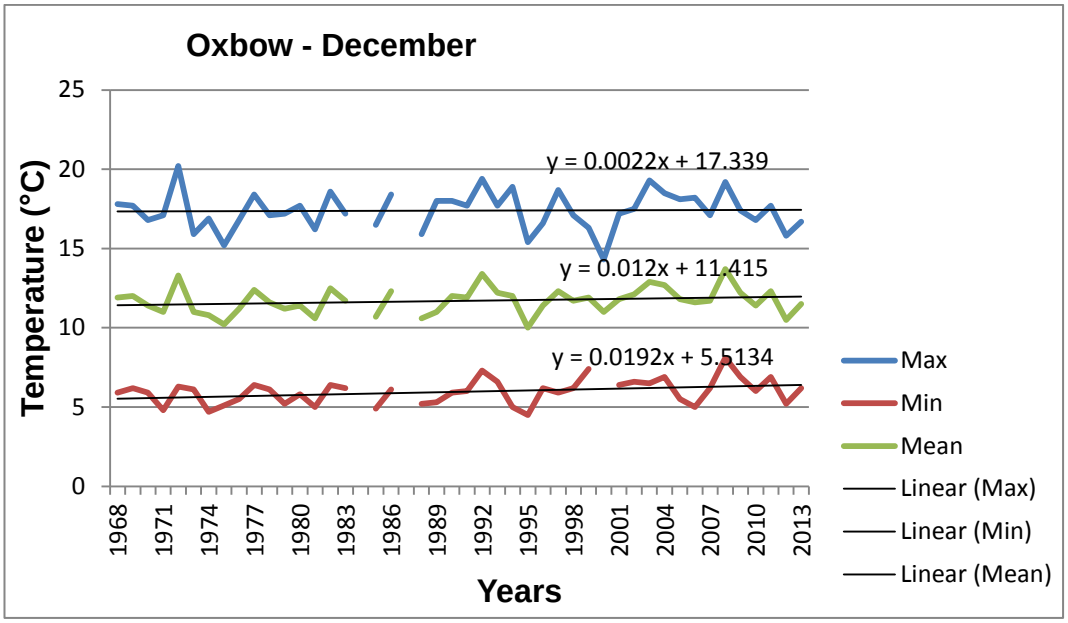


Figure 4.6(l)

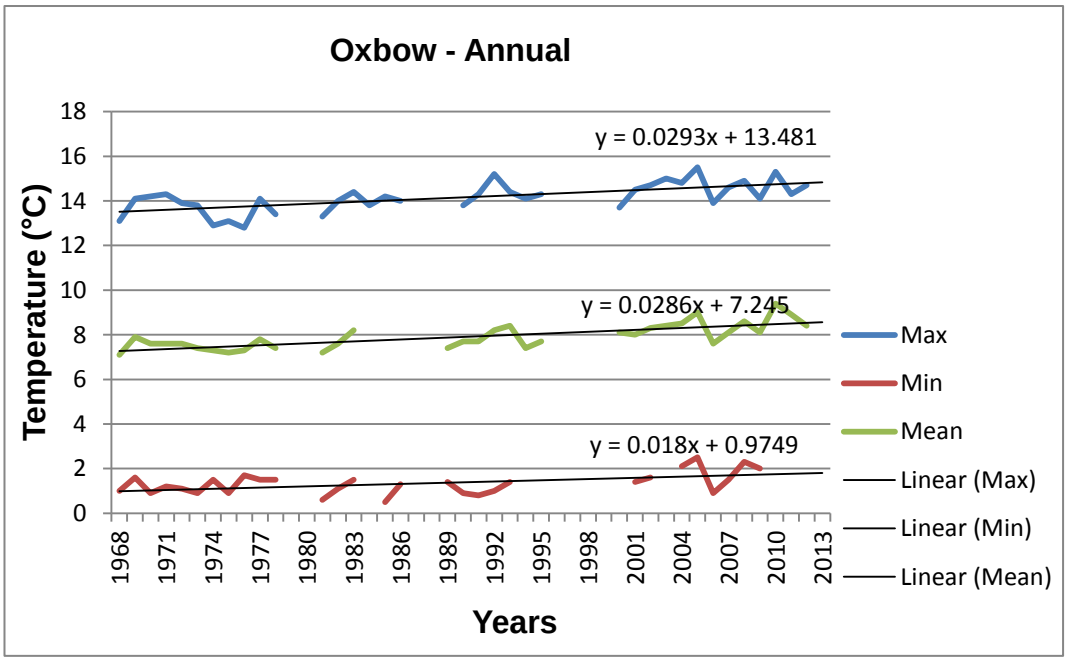


Figure 4.6(l)

Figure 4.6(a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Oxbow for the period 1968-2013.

For Qachasnek, monthly and annual trends for maximum, minimum and mean temperatures for the period 1968 - 2013 are shown in Figures 4.7 (a-m). From the results it is evident that there is a positive trend for maximum, minimum and mean temperatures annually and monthly. The trends for maximum temperatures are higher than the trends for minimum temperatures annually and monthly except for January, a summer month, and June, a winter month, where the trend for maximum temperature is lower than the trend for minimum temperature; (0.29 °C/decade; 0.36 °C/decade) and 0.35 °C/decade; 0.58 °C/decade) for January and June respectively.

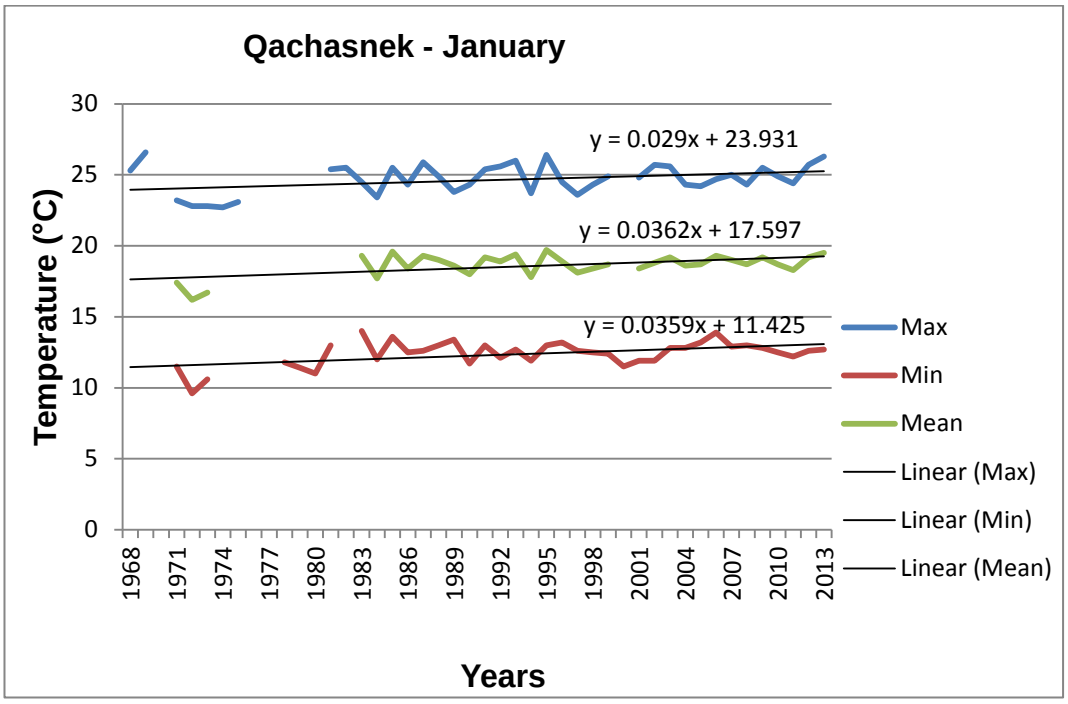


Figure 4.7(a)

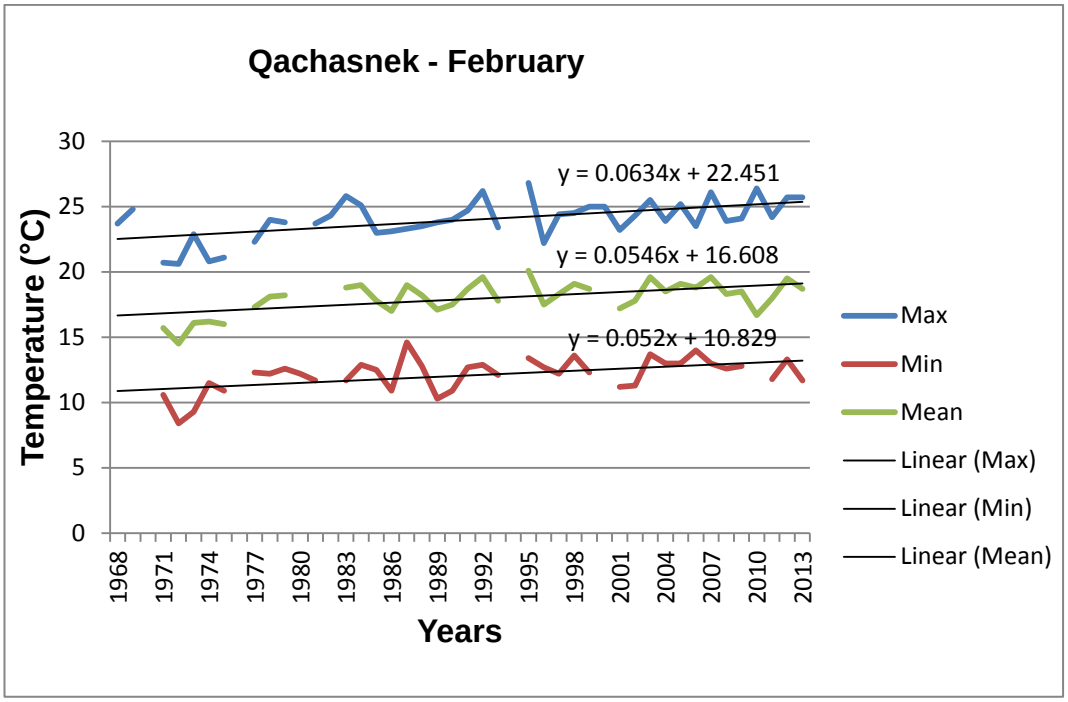
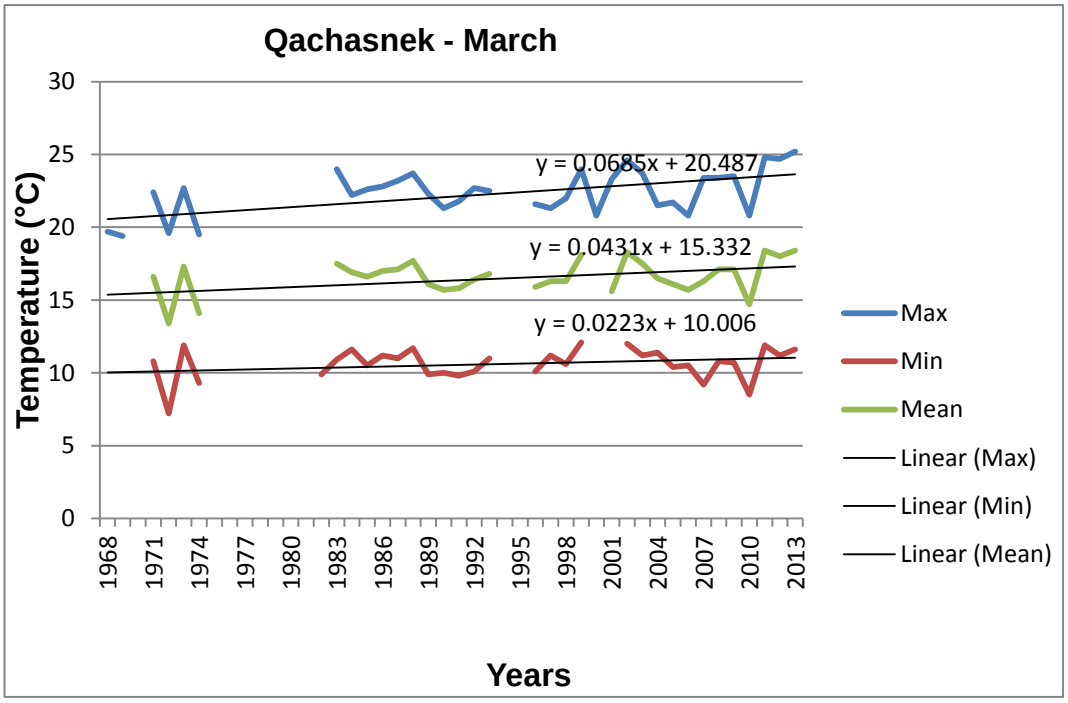


Figure 4.7(b)



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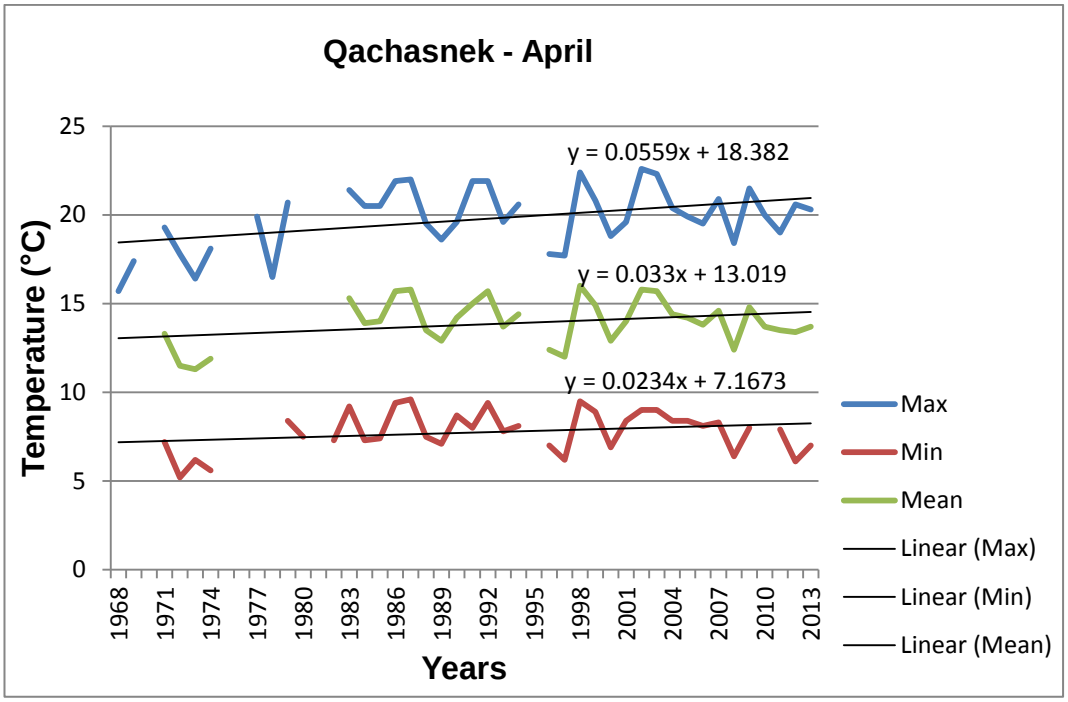

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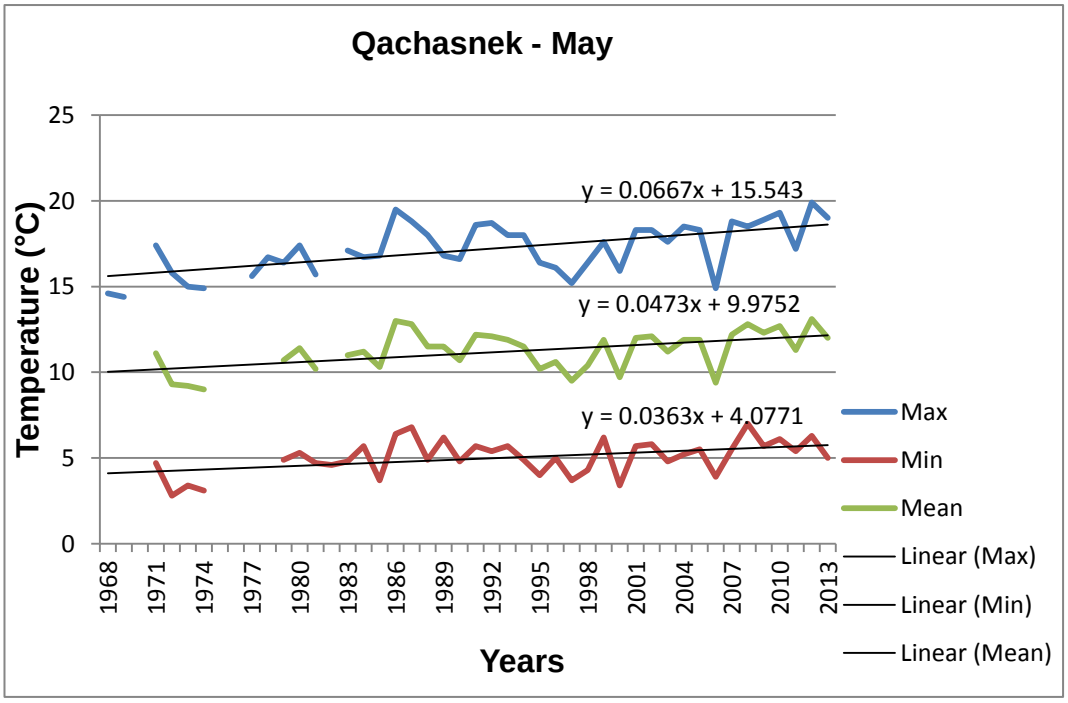

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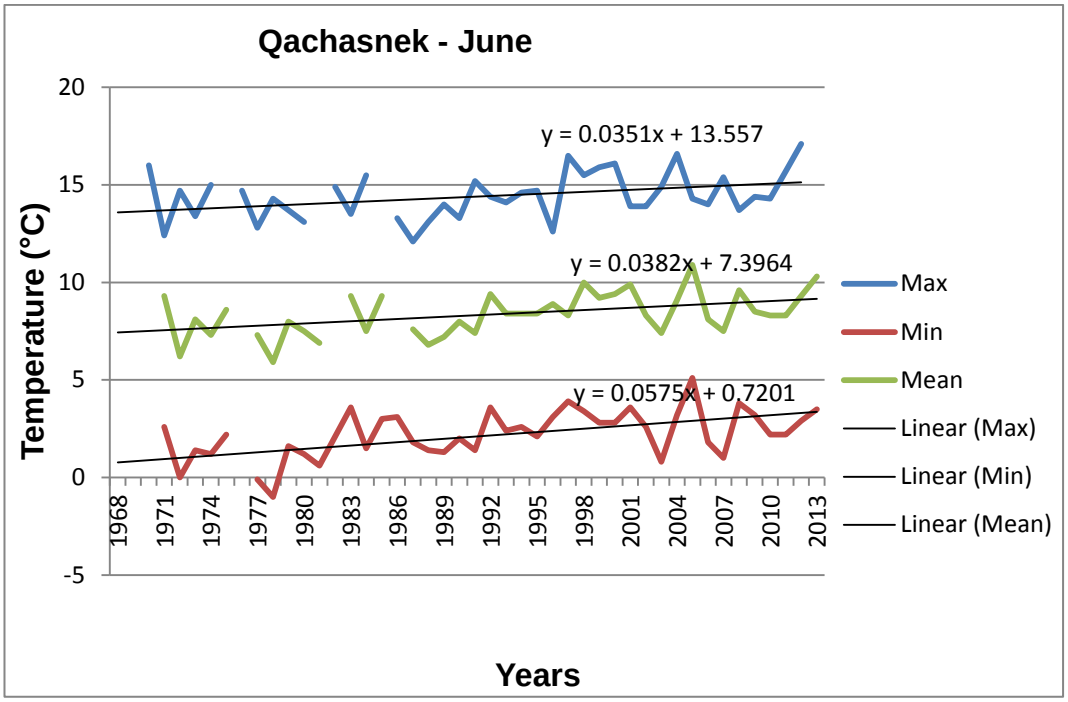

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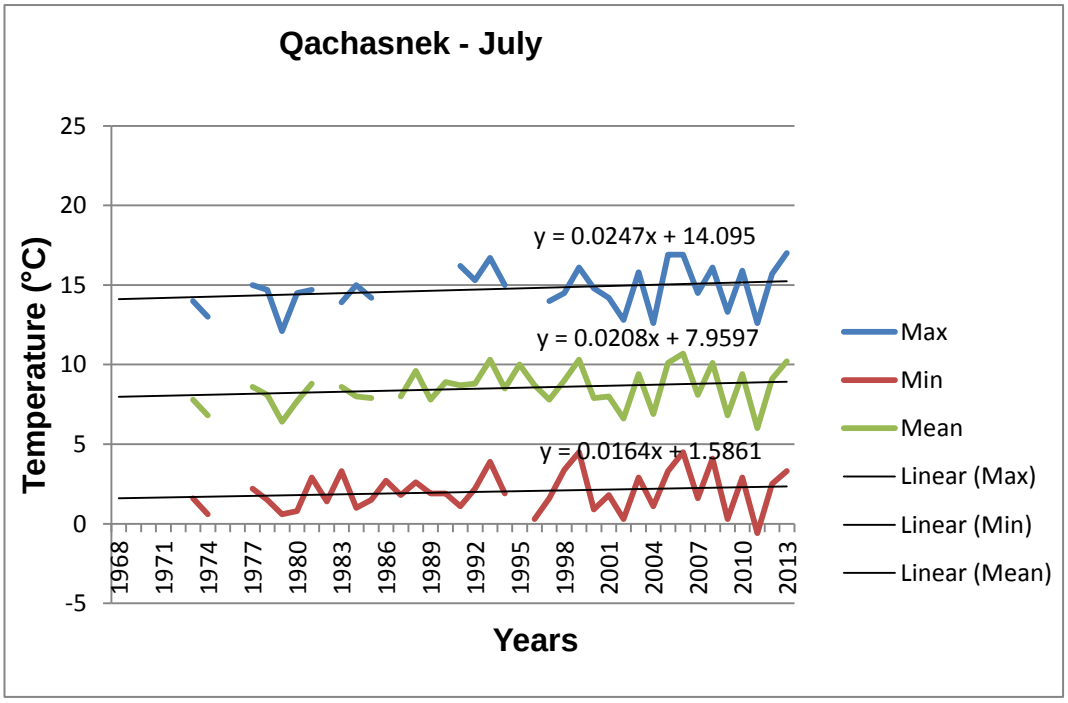

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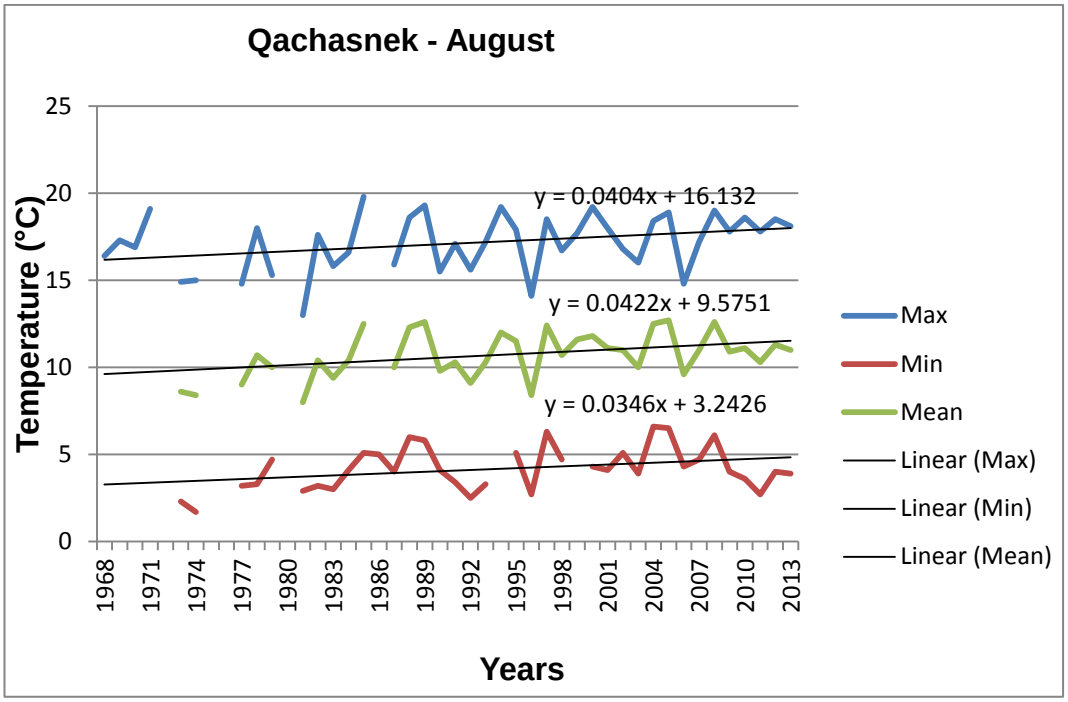


Figure 4.7(h)

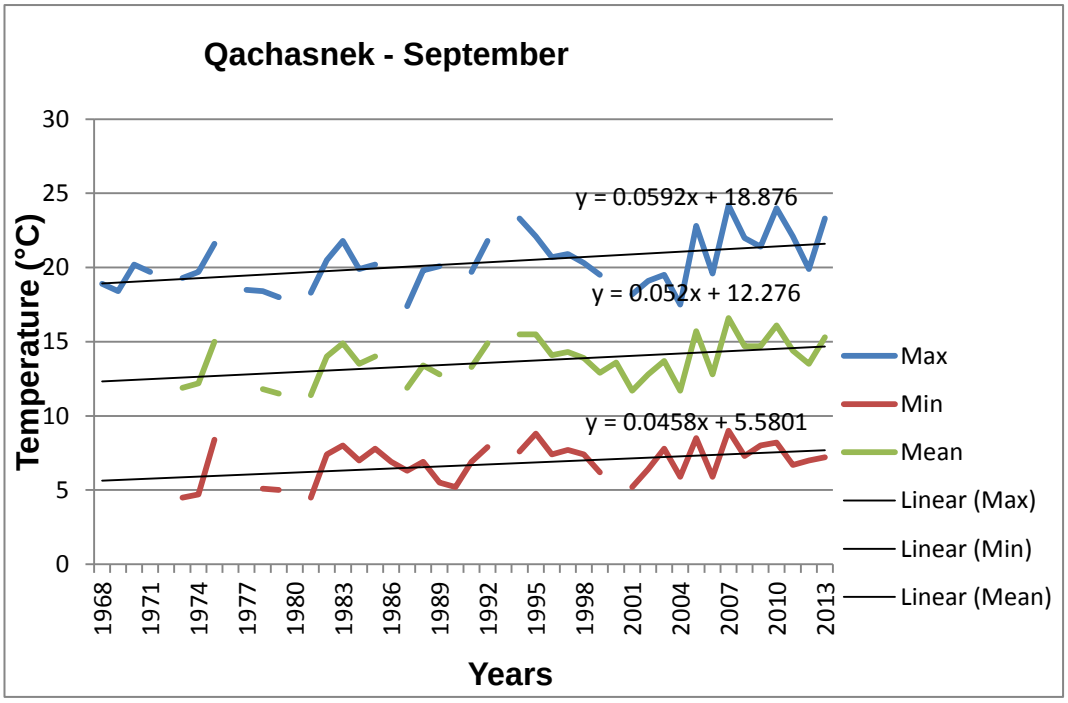
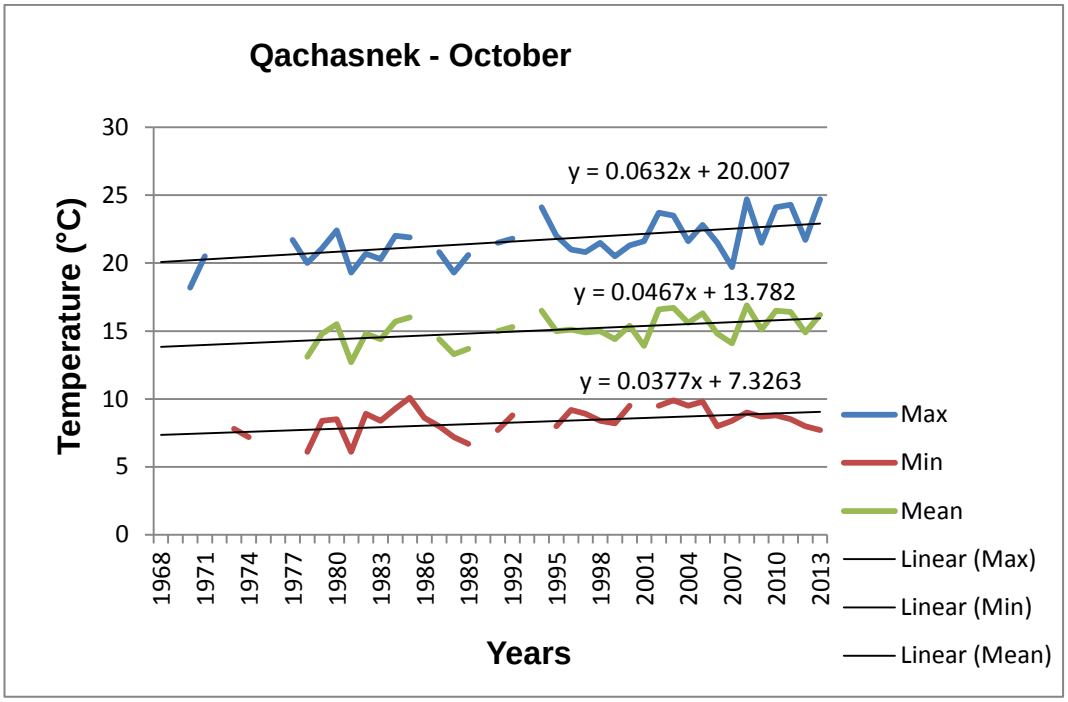


Figure 4.7(i)



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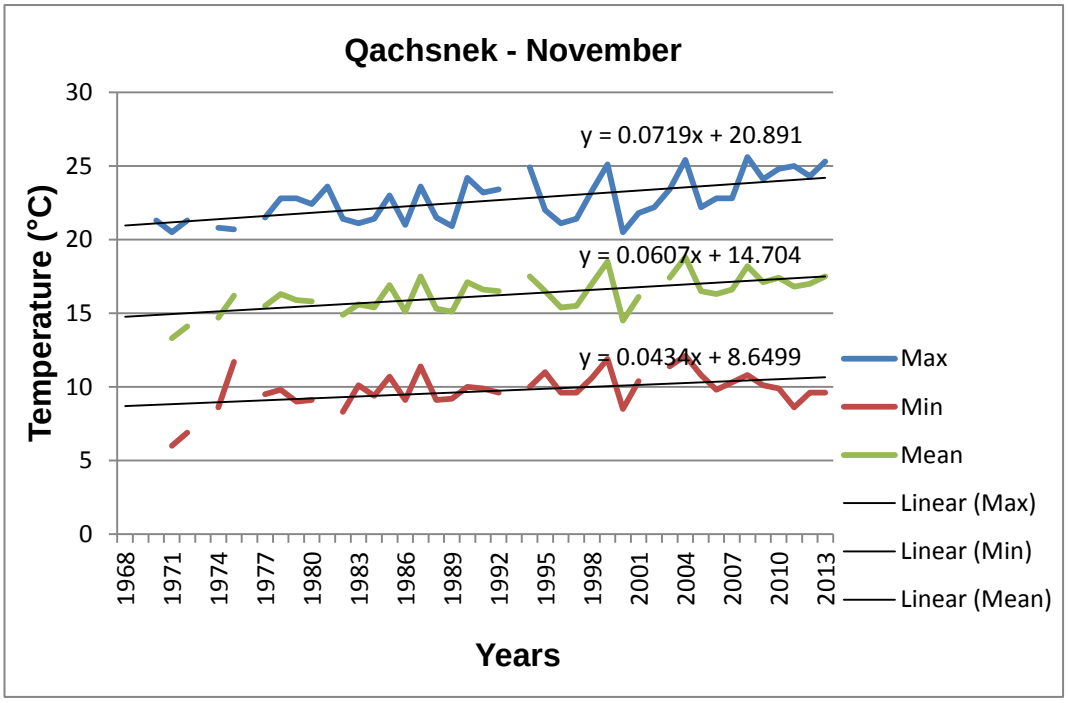

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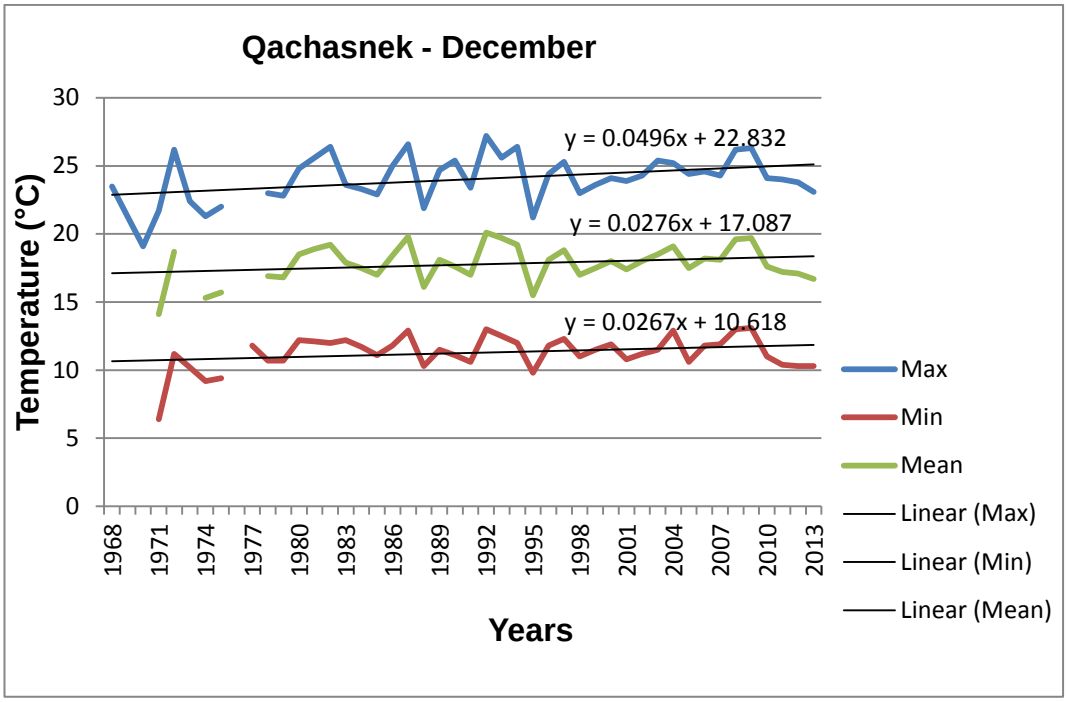


Figure 4.7(l)

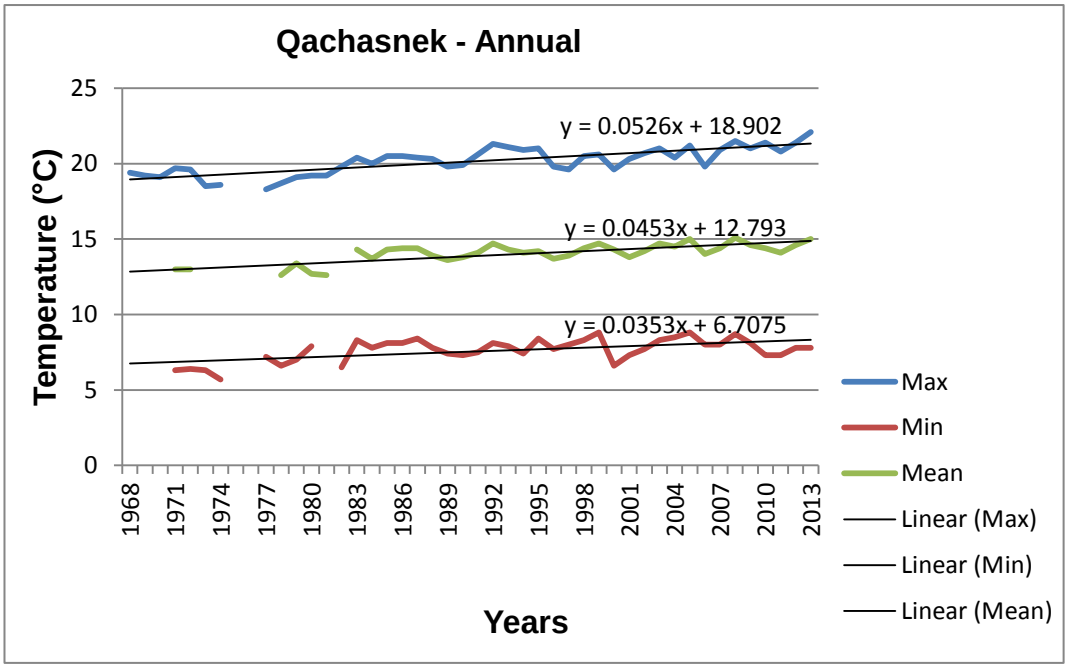


Figure 4.7(m)

Figure 4.7(a-m): Mean monthly and annual maximum, minimum and mean temperature trends for Qachasnek for the period 1968-2013.

Table 4.5: Trends for monthly and annual maximum temperatures at various stations in Lesotho for the period 1968 – 2013. Red values indicate the rate at which maximum temperature is increasing is higher than for minimum temperature while bold values indicate equal rates for maximum and minimum temperatures for that particular month.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	-0.50	-0.28	-0.34	-0.09	0.29	-0.14	0.17
February	-0.15	-0.10	-0.34	-0.04	0.63	0.14	0.25
March	0.02	0.18	0.09	0.19	0.64	0.19	0.46
April	0.06	0.15	0.07	0.14	0.56	0.11	0.39
May	0.13	0.25	0.31	0.27	0.67	0.21	0.45
June	0.09	0.25	0.31	0.19	0.35	0.26	0.49
July	-0.10	0.05	0.10	0.01	0.25	0.05	0.19
August	0.07	0.21	0.15	0.38	0.40	0.19	0.22
September	-0.02	0.21	0.26	0.13	0.59	0.44	0.40
October	0.11	0.35	0.53	0.44	0.63	0.36	0.42
November	-0.17	0.11	0.10	0.34	0.72	0.38	0.29
December	-0.26	-0.10	-0.01	0.16	0.53	0.05	0.02
Annual	-0.13	0.06	-0.12	0.18	0.50	0.15	0.30

Table 4.6: Trends for monthly and annual minimum temperatures at various stations in Lesotho for the period 1968 – 2013. Red values indicate the rate at which maximum temperature is increasing is higher than for minimum temperature while bold values indicate equal rates for maximum and minimum temperatures for that particular month.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	0.12	0.27	-0.12	0.20	0.36	0.30	0.19
February	0.16	0.26	-0.07	0.21	0.52	0.35	0.13
March	0.10	0.16	-0.09	0.15	0.22	0.24	0.01
April	0.18	0.27	-0.06	0.21	0.23	0.23	0.22
May	0.47	0.44	0.01	0.26	0.36	0.23	0.29
June	0.55	0.62	-0.02	0.32	0.58	0.27	0.60
July	0.58	0.53	-0.47	0.10	0.16	0.18	-0.06
August	0.77	0.72	0.10	0.42	0.35	0.23	0.31
September	0.51	0.51	-0.15	0.17	0.46	0.19	0.15
October	0.52	0.50	0.19	0.53	0.38	0.40	0.22
November	0.24	0.39	0.02	0.40	0.43	0.37	0.14
December	0.15	0.32	-0.03	0.40	0.28	0.29	0.19
Annual	0.41	0.41	-0.07	0.29	0.37	0.27	0.18

Table 4.7: Trends for monthly and annual mean temperatures at various stations in Lesotho for the period 1968 – 2013.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	-0.20	-0.05	-0.27	0.05	0.36	0.09	0.13
February	-0.20	0.06	-0.23	0.13	0.55	0.24	0.17
March	0.05	0.16	0.05	0.17	0.43	0.23	0.21
April	0.04	0.21	0.003	0.18	0.33	0.19	0.29
May	0.35	0.34	0.18	0.27	0.47	0.21	0.39
June	0.30	0.42	0.16	0.25	0.38	0.41	0.54
July	0.25	0.32	-0.2	0.04	0.21	0.12	0.1
August	0.45	0.43	0.11	0.4	0.42	0.23	0.32
September	0.19	0.35	0.05	0.15	0.52	0.29	0.3
October	0.33	0.41	0.39	0.44	0.47	0.36	0.32
November	0.06	0.24	0.33	0.37	0.61	0.37	0.21
December	-0.10	0.20	0.22	0.26	0.28	0.16	0.12
Annual	0.15	0.24	0.01	0.23	0.45	0.24	0.29

For the period 1968 – 2013, there is a positive trend for maximum temperatures mainly during cooler months (March, April, May, June, August) while the trend for maximum temperature is negative during summer/warmer months (January, February, December) in Maseru, Mejametalana, Mohaleshoek and Butha Buthe. The positive trend for maximum temperatures extend to all the months in Qachasnek, Oxbow and Mokhotlong, the only exception being January in Mokhotlong where there is a negative trend for maximum temperature (-0.14 °C/decade).

There is a positive trend for minimum temperatures for all the stations annually and monthly with the exception of Oxbow in July (-0.06 °C/decade) and Mohaleshoek for January (-0.12 °C/decade), February (-0.07 °C/decade), March (-0.09 °C/decade), April (-0.06 °C/decade), June (-0.02 °C/decade), July (-0.47 °C/decade), September (-0.15 °C/decade), December (-0.03 °C/decade) and annually (-0.07 °C/decade). The trend

for minimum temperatures much higher than the trend for maximum temperatures except Oxbow in February (0.25 and 0.13 °C/decade), March (0.46 and 0.01 °C/decade), April (0.39 and 0.22 °C/decade), May (0.45 and 0.29 °C/decade), July (0.19 and -0.06 °C/decade) September (0.40 and 0.0.15 °C/decade), November (0.29 and 0.14 °C/decade) and Annually (0.30 and 0.18 °C/decade).

To test for the significance of the trends, the Mann-Kendall test statistics was used. The test results are presented in Table 4.8 – 4.10 below. The results from the Mann-Kendall test statistic show that the trends for maximum temperatures are only significant at 95% confidence limit at Mokhotlong in May ($p=0.33$) and June ($p=0.007$), Qachasnek in January ($p=0.04$), February ($p=0.000$), March ($p=0.009$), April ($p=0.041$), May ($p<0.0001$), June ($p=0.020$), August ($p=0.033$), September ($p=0.010$), October ($p=0.002$), November ($p<0.0001$), December ($p=0.036$) and Annually ($p<0.0001$) and Oxbow in February ($p=0.046$), March ($p=0.002$), April ($p=0.027$), May ($p=0.001$), June ($p=0.002$), September ($p=0.034$), October ($p=0.002$), November ($p=0.020$) and Annually ($p=0.000$) while there are no significant trends at all other stations at 95% confidence limit (Table 4.8).

The trends for minimum temperatures are significant at 95% confidence limit at Maseru for most of the cooler months (May ($p<0.000$), June (0.000), July (0.000), August (0.001) and October ($p<0.0001$)). At Mejametalana the trends are significant for all of the months except for March. At Butha Buthe and Qachasnek the trends for minimum temperatures are significant for most of the months with a few exceptions. In Mokhotlong, the trends for minimum temperatures are significant only during the cooler months; March ($p=0.017$), May ($p=0.013$), June ($p=0.002$), October ($p=0.002$), November ($p=0.005$) as well as annually ($p=0.000$). At Oxbow, the rates of change of minimum temperature are only significant in January ($p=0.043$), June ($p=0.002$), October ($p=0.040$), and December ($p=0.024$) as well as annually ($p=0.031$) (Table 4.9).

For the period 1968 – 2013, there is a significant increase in maximum temperatures at Mokhotlong, Oxbow and Qachasnek, all of which are located in the highlands. Significant increases in temperatures in the lowlands and the foothills which includes Maseru, Mejametalana and Butha Buthe are only observed with minimum temperatures. In contrast, there is no significant trend for both minimum and maximum temperatures for Mohaleshoek, which is situated in the Senqu river valley.

For mean temperatures, there are significant increases in the low lying areas, which include Maseru, Mejametalana and Butha Buthe mainly during the cooler months (i.e. March to October) while in high lying areas which include Qachasnek, Mokhotlong and Oxbow there is a significant rate of change of mean temperatures for some of the months (Table 4.10).

Table 4.8: Mann-Kendall test statistics for monthly and annual trends for maximum temperatures at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	0.059	0.379	0.131	0.963	**0.040**	0.550	0.225
February	0.725	0.739	0.192	0.691	**0.000**	0.438	**0.046**
March	0.628	0.307	0.218	0.199	**0.009**	0.045	**0.002**
April	0.685	0.593	0.333	0.435	**0.041**	0.747	**0.027**
May	0.339	0.098	0.056	0.023	**<0.0001**	**0.033**	**0.001**
June	0.494	0.232	0.119	0.388	**0.020**	**0.007**	**0.002**
July	0.485	0.504	0.856	0.520	0.176	0.753	0.087
August	0.614	0.341	0.481	0.013	**0.033**	0.306	0.060
September	0.514	0.250	0.266	0.818	**0.010**	0.087	**0.034**
October	0.375	0.016	0.002	0.020	**0.002**	**0.024**	**0.002**
November	0.458	0.686	0.817	0.139	**<0.0001**	**0.014**	**0.020**
December	0.307	0.888	0.950	0.413	**0.036**	0.723	0.761
Annual	0.402	0.708	0.512	**0.007**	**<0.0001**	**0.013**	**0.000**

Table 4.9: Mann-Kendall test statistics for monthly and annual trends for minimum temperatures at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	0.164	**0.009**	0.420	**0.036**	**0.021**	0.297	**0.043**
February	0.177	**0.026**	0.898	**0.033**	**0.001**	0.158	0.356
March	0.409	0.126	0.628	0.176	0.151	**0.017**	1.000
April	0.089	**0.028**	0.709	**0.043**	0.481	0.232	0.141
May	**<0.0001**	**0.004**	0.762	0.053	**0.008**	**0.013**	0.346
June	**0.000**	**0.001**	0.651	**0.017**	**0.000**	**0.002**	**0.002**
July	**0.000**	**0.004**	0.281	0.443	0.273	0.216	0.589
August	**0.001**	**0.001**	0.485	**0.003**	0.061	0.099	0.560
September	0.051	**0.026**	0.170	0.213	**0.019**	0.229	0.213
October	**<0.0001**	**0.000**	0.243	**0.000**	**0.033**	**0.002**	**0.040**
November	0.057	**0.005**	0.898	**0.023**	**0.008**	**0.005**	0.084
December	0.177	**0.003**	0.973	**0.003**	0.346	0.075	**0.024**
Annual	**<0.0001**	**<0.0001**	0.896	**0.000**	**0.002**	**0.000**	**0.031**

Table 4.10: Mann-Kendall test statistics for monthly and annual trends for mean temperatures at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
January	0.216	0.854	0.155	0.378	**0.022**	0.297	0.146
February	0.682	0.652	0.284	**0.026**	**0.000**	0.158	**0.044**
March	0.600	0.172	0.837	**0.021**	0.061	**0.017**	**0.019**
April	0.896	0.198	0.860	0.183	0.424	0.232	**0.010**
May	**0.002**	**<0.0001**	0.086	**0.004**	**0.001**	**0.013**	**0.000**
June	**0.007**	**0.000**	0.116	**0.024**	**0.006**	**0.002**	**<0.0001**
July	0.077	**0.038**	0.358	0.203	0.092	0.216	0.376
August	**0.000**	**0.003**	0.247	**0.001**	**0.016**	0.099	**0.025**
September	0.232	0.056	0.753	0.395	**0.013**	0.229	**0.023**
October	**0.001**	**<0.0001**	0.002	**0.001**	**0.004**	**0.002**	**0.003**
November	0.924	0.120	0.249	**0.028**	**<0.0001**	**0.005**	**0.020**
December	0.442	0.166	0.564	0.113	0.290	0.075	0.216
Annual	**0.021**	**0.000**	0.542	**0.000**	**<0.0001**	**0.000**	**<0.0001**

4.2.2 Trends for seasonal maximum, minimum and mean temperatures for the period 1968 – 2013.

Figures 4.8- 4.14 show seasonal temperature trends for the period 1968 - 2013.

For Butha Buthe, in the foothills, the results show a positive trend for maximum temperatures for winter (0.21 °C/decade), autumn (0.20 °C/decade) and spring (0.33 °C/decade) while the trend is negative for the summer season. The trend for minimum temperatures, however, is positive for all the seasons (Figure 4.8 a-b). The trends for minimum temperatures are higher than the trends for maximum temperatures for all

the seasons (winter (0.29, 0.21), summer (0.26, -0.19), autumn (0.21, 0.20) and spring (0.40, 0.33) for minimum and maximum temperature respectively). The trend for mean temperature is positive for all the seasons in Butha Buthe.

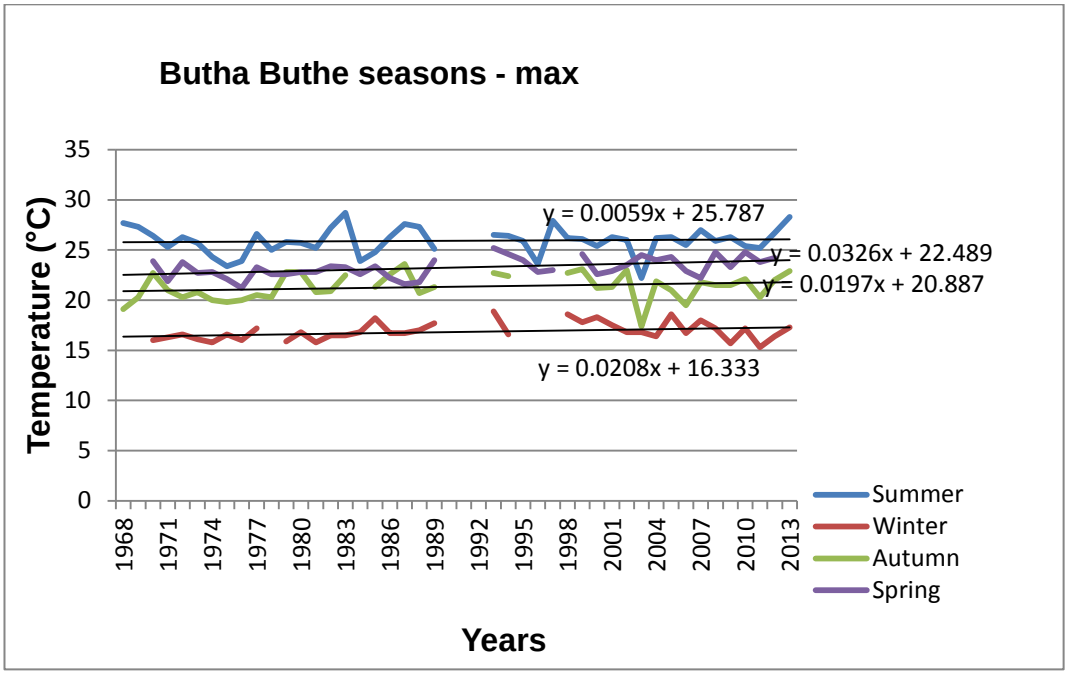


Figure 4.8(a)

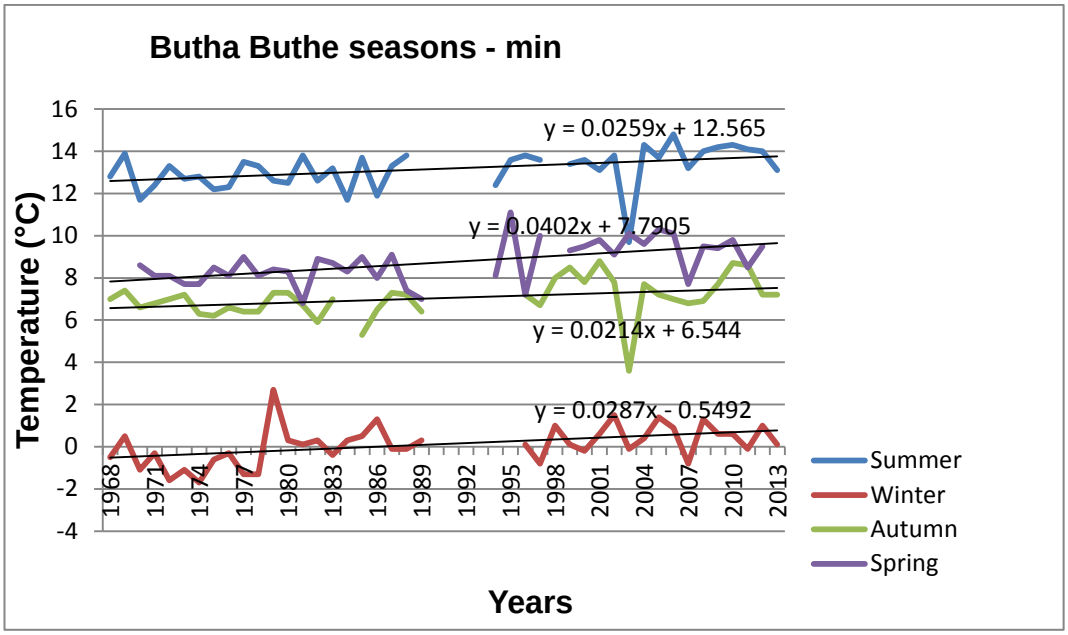


Figure 4.8(b)

Figure 4.8(a-b): Trends for seasonal maximum and minimum temperatures for Butha Buthe for the period 1968 – 2013.

For Maseru, situated in the lowlands, the results show a positive trend for both maximum and minimum temperatures (Figure 4.9 a-b). The trend for minimum temperatures is higher than the trend for maximum temperatures for all the seasons (i.e. winter (0.64 and 0.01 °C/decade), summer (0.40 and 0.24 °C/decade), autumn (0.26 and 0.08 °C/decade) and spring (0.44 and 0.07 °C/decade) for minimum and maximum temperature respectively). The trend for mean temperatures was found to be positive for all the seasons except for the summer season where the rate is negative (-0.12 °C/decade).

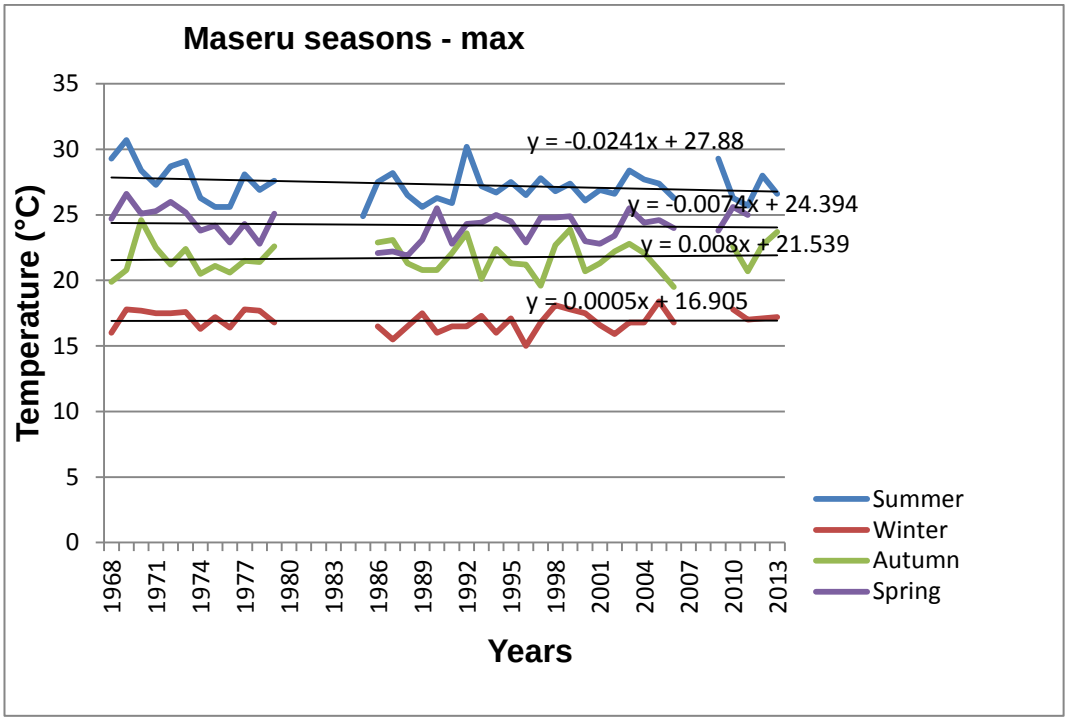


Figure 4.9(a)

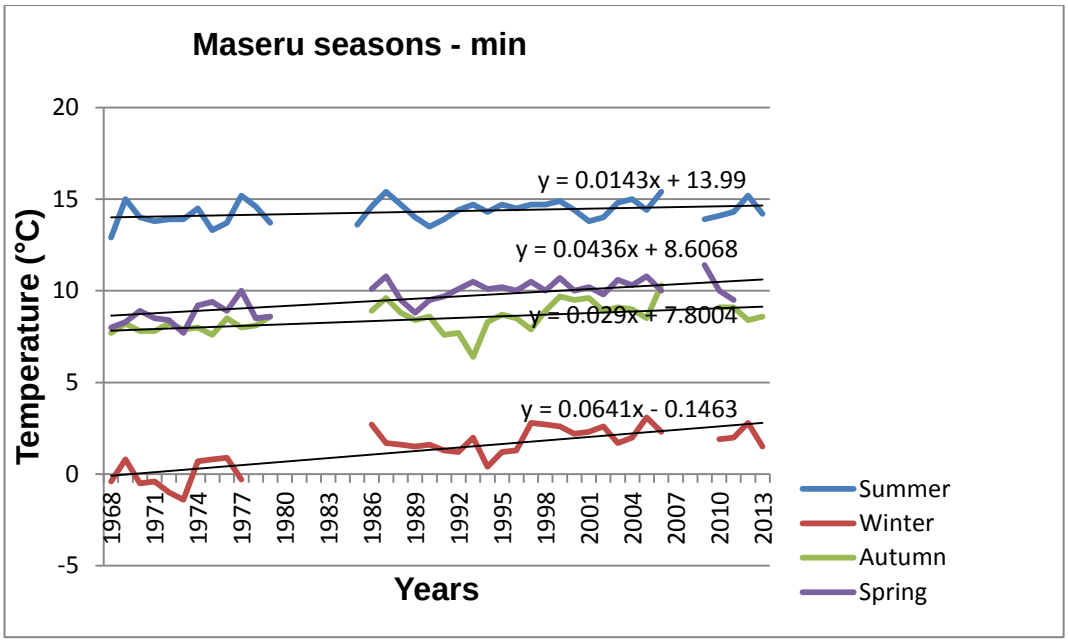


Figure 4.9(b)

Figure 4.9(a-b): Trends for seasonal maximum and minimum temperatures for Maseru for the period 1968 – 2013.

For Mejametalana, the results show a positive trend for maximum temperatures during winter (0.18 °C/decade), autumn (0.17 °C/decade) and spring (0.25 °C/decade) while the summer season has a negative (-0.12 °C/decade) trend for maximum temperatures (figure 4.10 a-b). The trend for minimum temperatures is positive for all the seasons (i.e. winter (0.65 °C/decade), summer (0.28 °C/decade), autumn (0.26 °C/decade) and spring (0.50 °C/decade). The trends for minimum temperatures are higher than the trends for maximum temperatures in Mejametalana for all the seasons (Table 4.11- 4.12).The trends for mean temperatures are positive in Mejametalana for all the seasons.

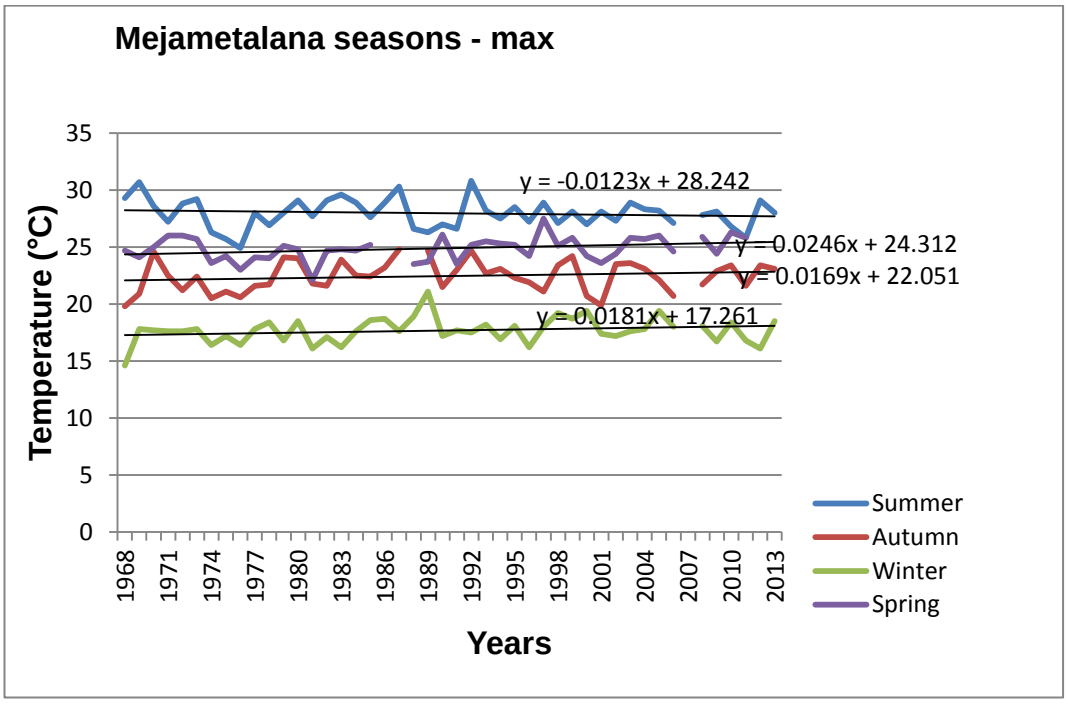


Figure 4.10(a)

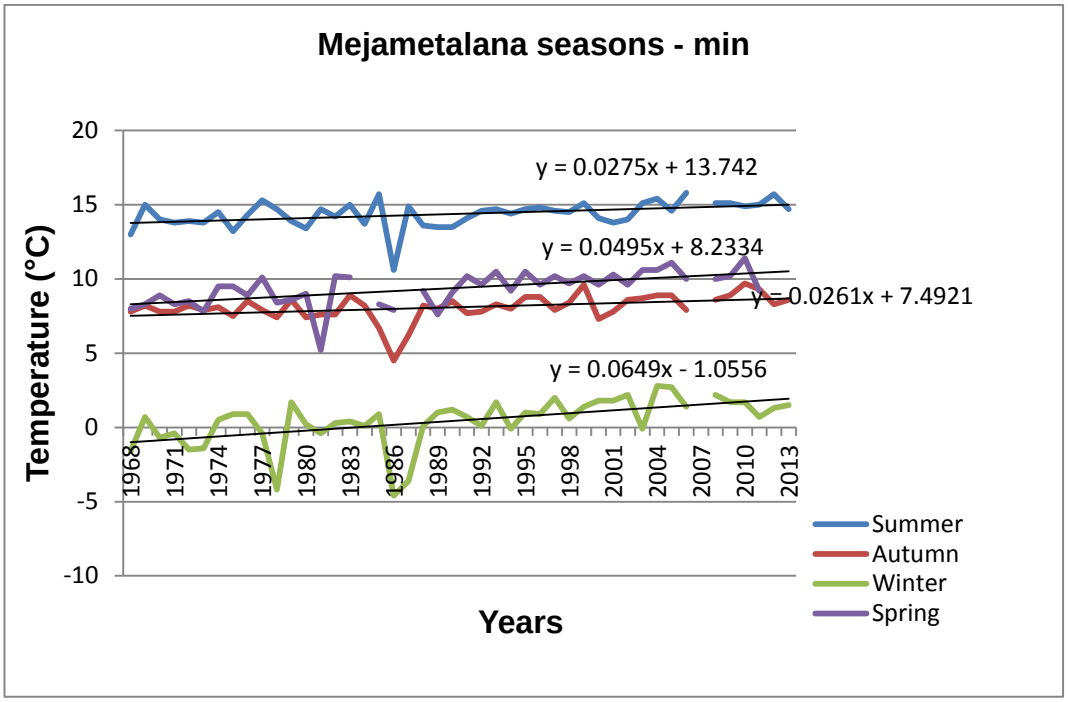


Figure 4.10(b)

Figure 4.10(a-b): Trends for seasonal maximum and minimum temperatures for Mejametalana for the period 1968 – 2013.

For Mohaleshoek, situated in the Senqu river valley, the results show a positive trend for maximum in winter (0.26 °C/decade), autumn (0.08 °C/decade) and in spring (0.26 °C/decade) while there is a negative trend for maximum temperature in summer (-0.19 °C/decade). On the contrary there is negative trend for minimum temperature for all the seasons (Figure 4.11 a-b). The trend for maximum temperature is higher than the trend for minimum temperature for winter (0.26 and -0.18 °C/decade), autumn (0.08 and -0.04 °C/decade) and spring (0.26 and -0.07 °C/decade) for maximum and minimum temperature respectively, while the trend for minimum temperature is higher than the trend for maximum temperature in summer (-0.05 and -0.19 °C/decade for minimum and maximum temperature respectively. The trend for mean temperature in Mohaleshoek

is positive for autumn (0.01 °C/decade) and spring (0.27 °C/decade) while negative for summer (-0.01 °C/decade) and winter (-0.09 °C/decade.

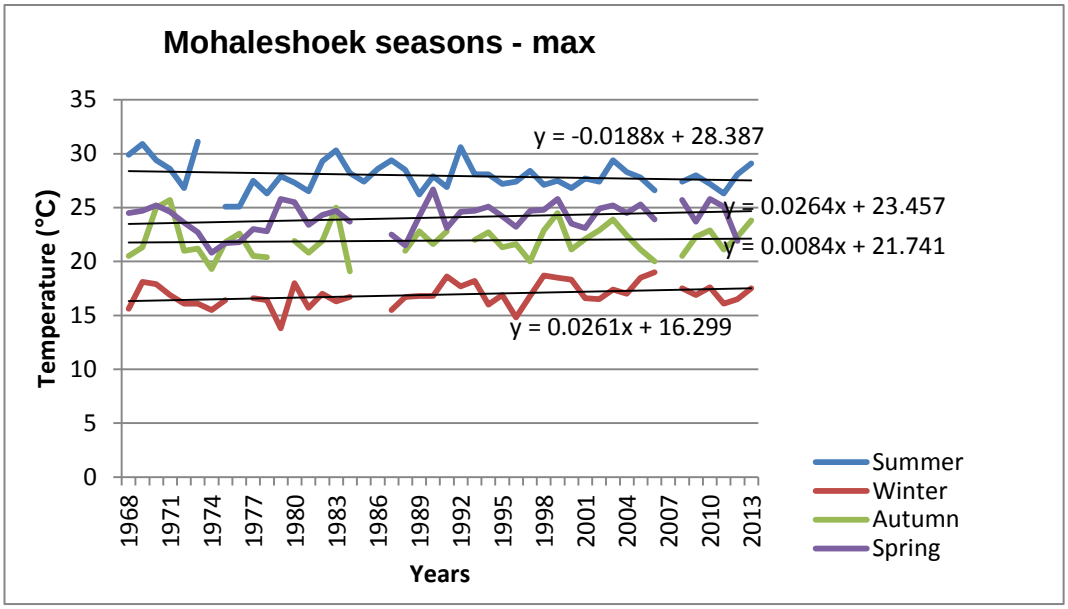


Figure 4.11(a)

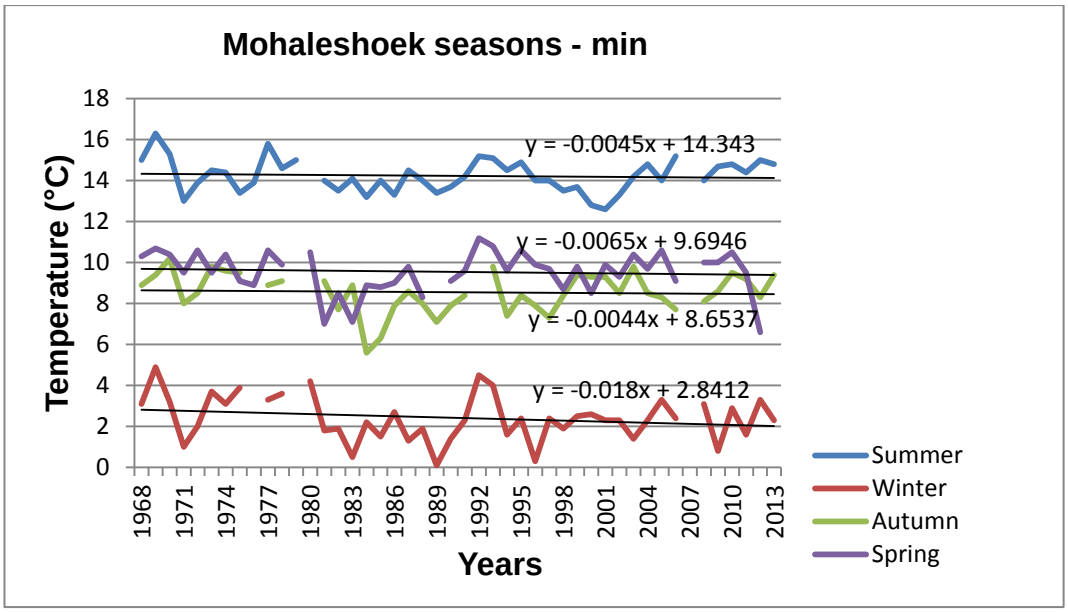


Figure 4.11(b)

Figure 4.11(a-b): Trends for seasonal maximum and minimum temperatures for Mohaleshoek for the period 1968 – 2013.

For Mokhotlong, situated in the highlands, the results show a positive trend for both maximum and minimum for all the seasons (Figure 4.12 a-b) with the trend for minimum temperature being higher than the trend for maximum temperature for all the seasons with the exception of winter where the trends are equal (0.27 °C/decade). The trend for the mean temperature is positive for all the seasons.

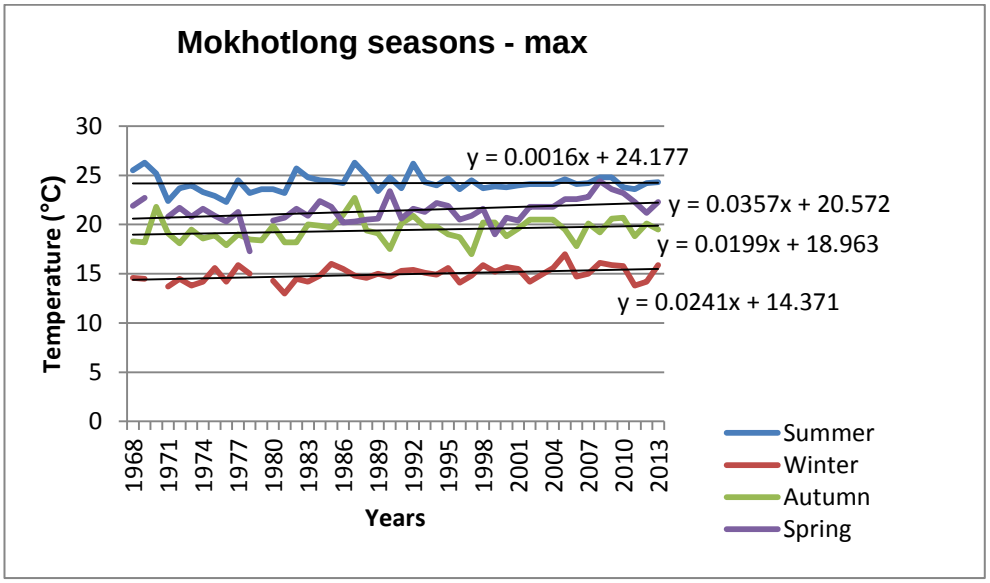


Figure 4.12(a)

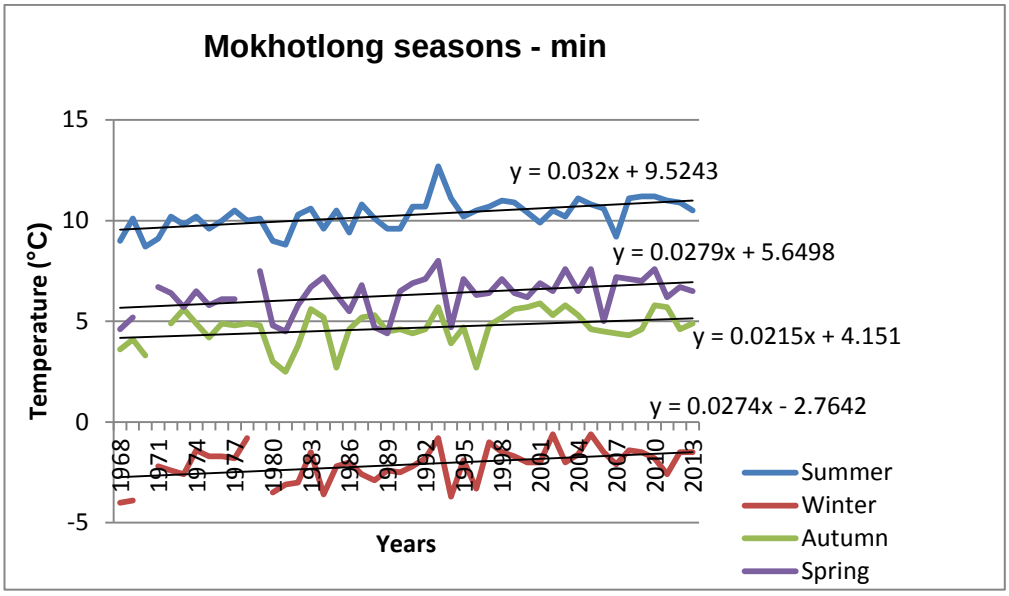


Figure 4.12(b)

Figure 4.12(a-b): Trends for seasonal maximum and minimum temperatures for Mokhotlong for the period 1968 – 2013.

For Oxbow, also situated in the highlands, the results show a positive trend for both maximum and minimum temperatures for all the seasons (Figure 4.13 a-b). The trend for maximum temperature is higher than the trend for minimum temperature in winter (0.30 and 0.16 °C/decade) in autumn (0.40 and 0.22 °C/decade) and in spring (0.26 and 0.10 °C/decade) for maximum and minimum temperature respectively. The trends for both maximum and minimum temperatures are the same in summer (0.16 °C/decade). The trend for mean temperature is positive for all the seasons.

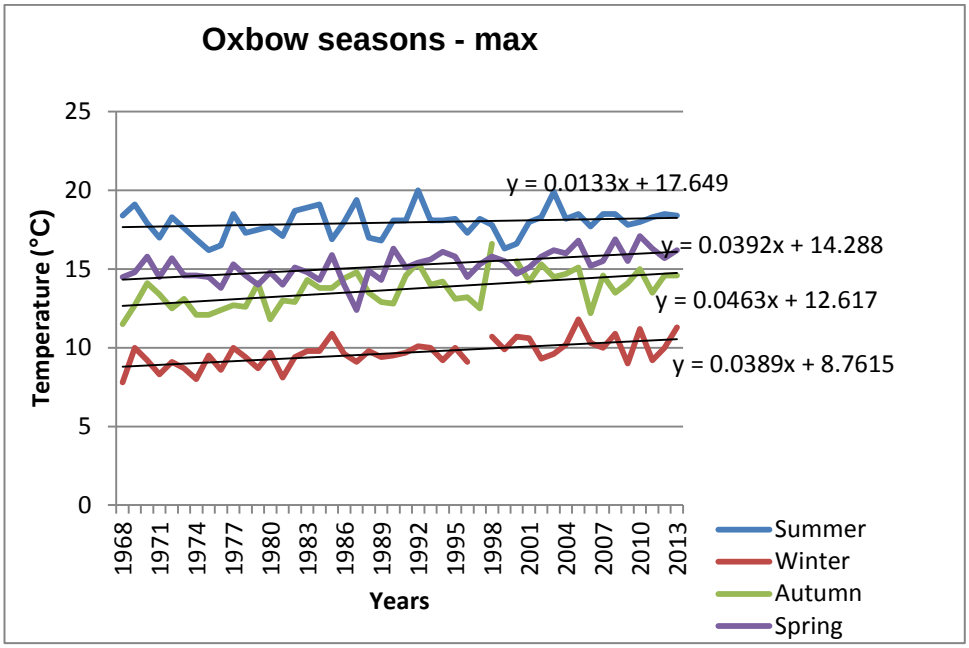


Figure 4.13(a)

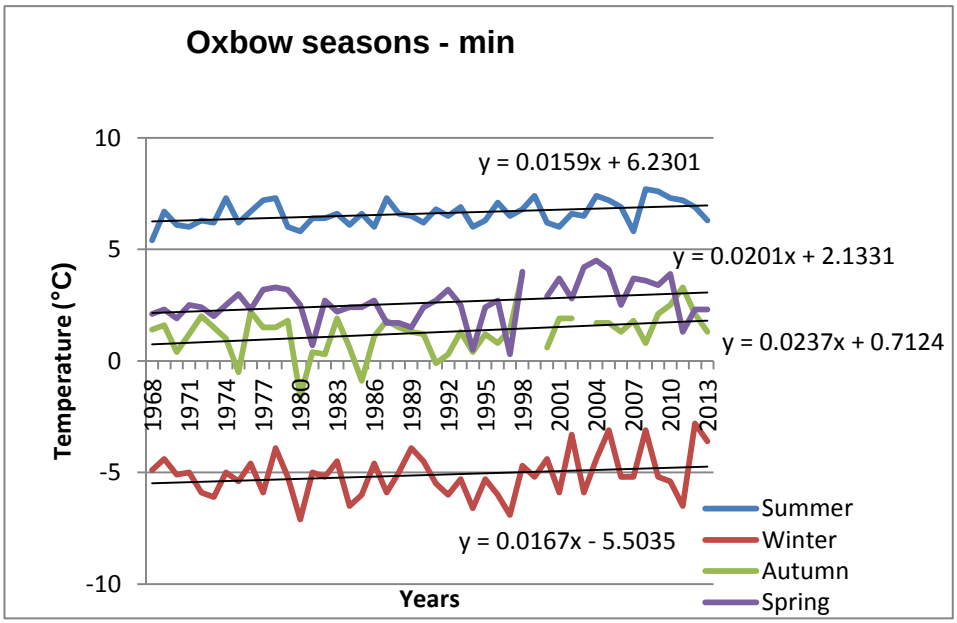


Figure 4.13(b)

Figure 4.13(a-b): Trends for seasonal maximum and minimum temperatures for Oxbow for the period 1968 – 2013.

For Qachasnek, which is also located in the highlands, the results show a positive trend for both maximum and minimum temperatures for all the seasons (Figure 4.14 a-b). The trends for maximum temperatures are higher than the trends for minimum temperatures for all the seasons except the summer season where trend for minimum temperature is higher than the trend for maximum temperature (0.37 and 0.28 °C/decade for minimum and maximum temperature respectively). The trend for mean temperature is positive for all the seasons.

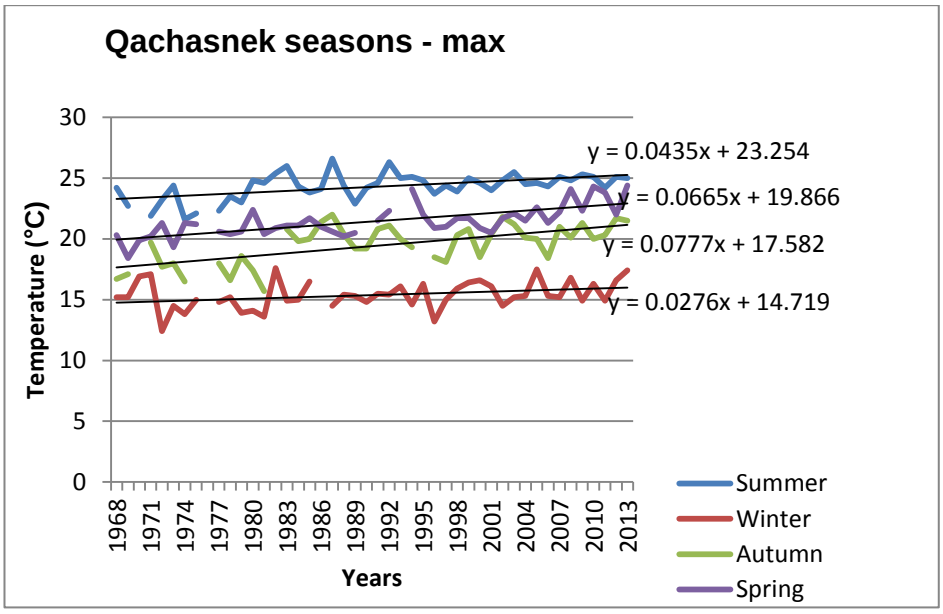


Figure 4.14(a)

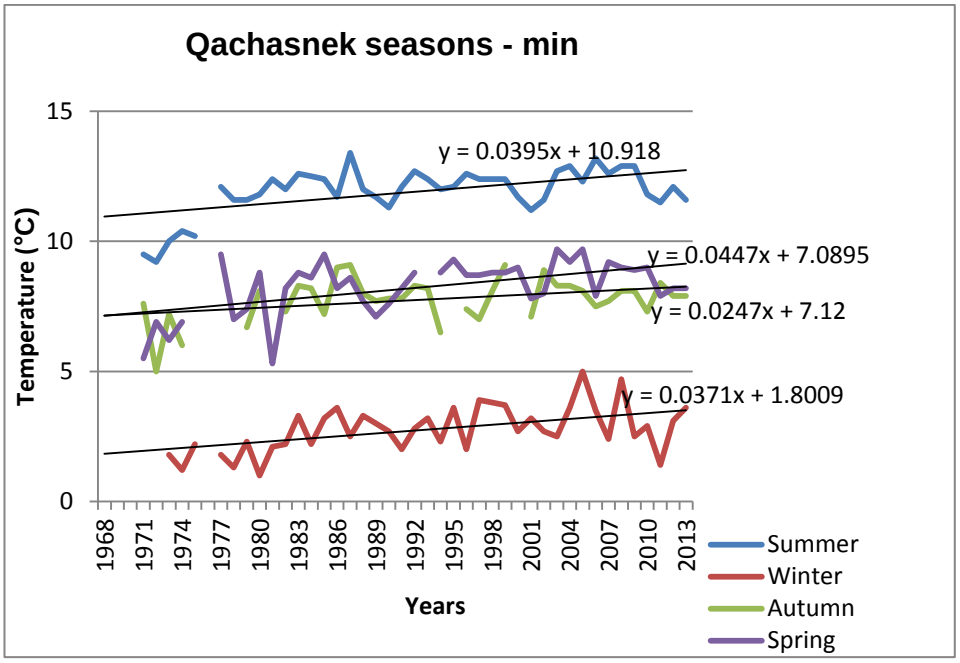


Figure 4.14(b)

Figure 4.14(a-b): Trends for seasonal maximum and minimum temperatures for Qachasnek for the period 1968 – 2013.

Table 4.11: Trends for seasonal maximum temperatures at various stations in Lesotho for the period 1968 – 2013. Red values indicate the rate at which maximum temperature is increasing is higher than for minimum temperature while bold values indicate equal rates for maximum and minimum temperatures for that particular month.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	0.01	0.18	0.26	0.21	0.28	**0.27**	0.30
Summer	0.24	-0.12	-0.19	-0.19	0.44	0.02	**0.16**
Autumn	0.08	0.17	0.08	0.20	0.78	0.20	0.40
Spring	0.07	0.25	0.26	0.33	0.67	0.24	0.26

Table 4.12: Trends for seasonal minimum temperatures at various stations in Lesotho for the period 1968 – 2013. Red values indicate the rate at which maximum temperature is increasing is higher than for minimum temperature while bold values indicate equal rates for maximum and minimum temperatures for that particular month.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	0.64	0.65	-0.18	0.29	0.37	**0.27**	0.16
Summer	0.40	0.28	-0.05	0.26	0.40	0.32	**0.16**
Autumn	0.29	0.26	-0.04	0.21	0.25	0.22	0.22
Spring	0.44	0.50	-0.07	0.40	0.45	0.28	0.10

Table 4.13: Trends for seasonal mean temperatures at various stations in Lesotho for the period 1968 – 2013.

	Rates of change (°C/decade)						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	0.34	0.36	-0.01	0.29	0.33	0.25	0.30
Summer	-0.12	0.04	-0.09	0.26	0.44	0.13	0.13
Autumn	0.16	0.23	0.01	0.21	0.43	0.19	0.31
Spring	0.16	0.32	0.27	0.40	0.54	0.28	0.29

Overall, there is a positive trend for both maximum and minimum temperatures with the exception of the summer season maximum temperatures in the lowlands (Maseru and Mejametalana), the foothills (Butha Buthe) and in the Senqu river valley (Mohaleshoesk) where the trend is negative. Warming in both maximum and minimum temperatures was also found in studies by Bhutyani et. al. (2007) and also by Grab & Linde (2014). The trend is also negative for minimum temperature in Mohaleshoek in the Senqu river valley. The trends for minimum temperatures are higher than the trends for maximum temperatures in the lowlands as well as in the foothills while the trends for maximum temperatures are higher than the trends for minimum temperatures in the highlands. The trend for mean temperatures are positive for all the seasons except for Maseru during the summer season where the trend is negative (-0.12 °C/decade).

The trends for maximum temperatures are significant in high lying areas (Mokhotlong (p=0.012), Oxbow (p=0.000) and Qachasnek (p=<0.0001)) for most of the seasons, except for the summer season in Mokhotlong and Oxbow. These findings are similar to the findings by Katell & Yao (2013) in their study over the Himalayas, in which they found warming of maximum temperatures at higher altitude. The significant trends are also observed at Mohaleshoek (p=0.028) and Butha Buthe (p=0.027) in the winter season while at Mejametalana the trend is only significant in spring (p=0.037)

(Table 4.14). The trends for minimum temperatures are significant in both low-lying areas (Maseru (winter: p<0.0001), Mejametalana (summer: p=0.001), Butha Buthe (autumn: p=0.013) and high-lying areas (Mokhotlong (summer: p<0.0001), Oxbow (spring: p=0.032), Qachasnek (winter: p=0.001)) except for the autumn season in high lying areas (Table 4.15). This is consistent with findings by Diaz & Eischeid (2007) who found significant warming during cooler period as opposed to warmer periods. The mean temperature trends are significant in the high lying areas (Mokhotlong (p=0.002), Oxbow (p<0.0001) and Qachasnek (p<0.0001)) as well as the foothills (Butha Buthe (p=0.000), while in the lowlands only winter (Maseru (p=0.000), Mejametalana (p=000)) and spring (Maseru (p=0.016) seasons are significant (Table 4.16).

Table 4.14: Mann-Kendall test statistics for seasonal trends for maximum temperatures at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	0.810	0.173	**0.028**	**0.027**	**0.022**	**0.004**	**<0.0001**
Summer	0.199	0.357	0.311	0.753	**<0.0001**	0.483	0.111
Autumn	0.497	0.224	0.243	0.036	**0.000**	**0.031**	**0.000**
Spring	0.906	**0.037**	0.059	0.007	**<0.0001**	**0.012**	**<0.0001**

Table 4.15: Mann-Kendall test statistics for seasonal trends for minimum temperatures at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

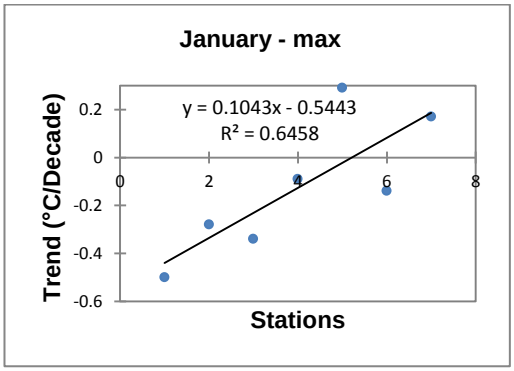
	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	**<0.0001**	**<0.0001**	0.402	**0.002**	**0.001**	**0.005**	0.014
Summer	**0.044**	**0.001**	0.976	**0.001**	**0.001**	**<0.0001**	**0.011**
Autumn	**0.000**	**0.001**	0.820	**0.013**	0.140	0.061	0.053
Spring	**<0.0001**	**<0.0001**	0.636	**0.001**	**0.001**	**0.007**	**0.032**

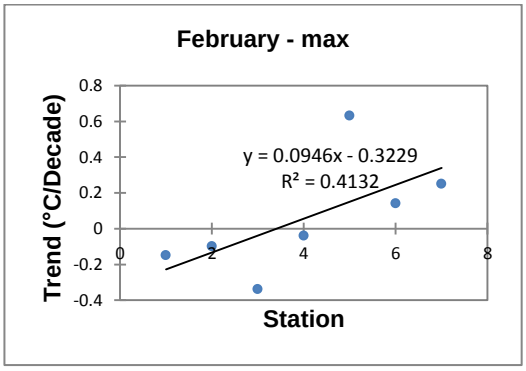
Table 4.16: Mann-Kendall test statistics for monthly, annual and seasonal trends for mean temperatures at various station in Lesotho for the period 1968 – 2013. Bold values indicate significant trends.

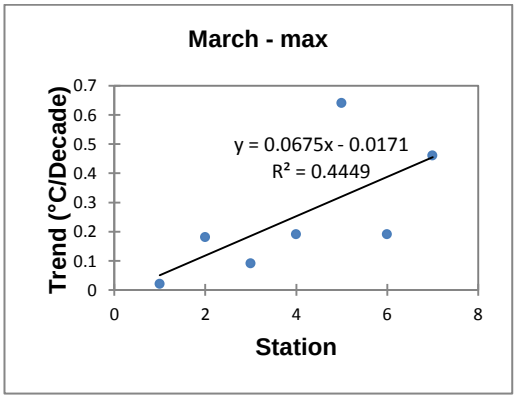
	Mann-Kendall test statistics p-values at α = 0.05						
	Maseru	Mejametalana	Mohaleshoek	Butha Buthe	Qachasnek	Mokhotlong	Oxbow
Winter	**0.000**	**0.000**	0.900	**0.001**	**0.005**	**0.002**	**0.000**
Summer	0.255	0.723	0.687	**0.005**	**<0.0001**	**0.040**	**0.022**
Autumn	0.059	**0.006**	0.379	**0.009**	**0.005**	**0.024**	**0.000**
Spring	**0.016**	**<0.0001**	**0.025**	**0.000**	**<0.0001**	**0.002**	**<0.0001**

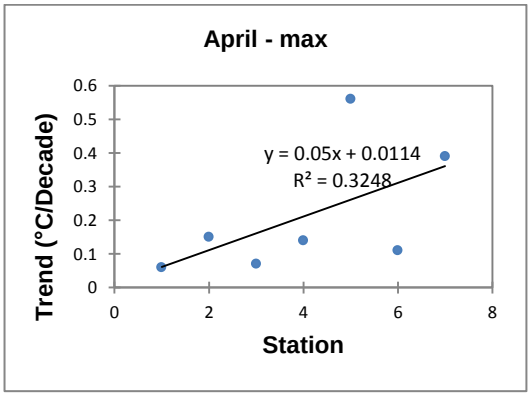
4.2.3 Relationship between temperature trends and altitude for maximum, minimum and mean temperatures for the period 1968 – 2013.

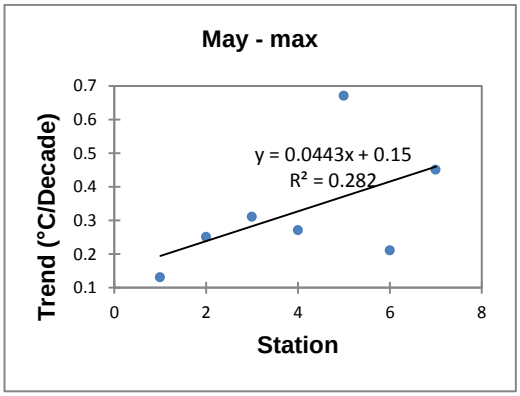
The results for the regression analysis for the relationship between the trends and the altitude for maximum and minimum temperatures on monthly and annual scale are presented in Figures 4.15 and 4.16 below. For the period 1968 – 2013, the results show that there is a positive relationship between monthly trends for maximum temperature and height. However the positive relationship between the trend for maximum temperature and height is only significant in March as well as in the winter season (Table 4.17).

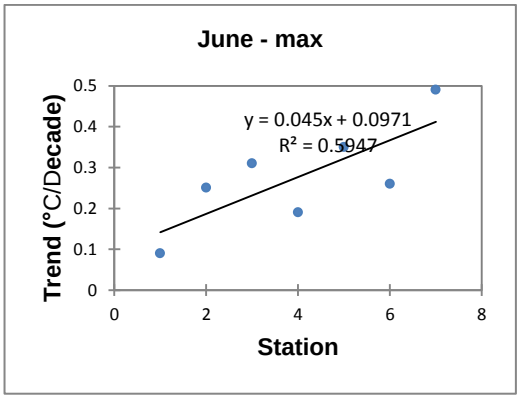


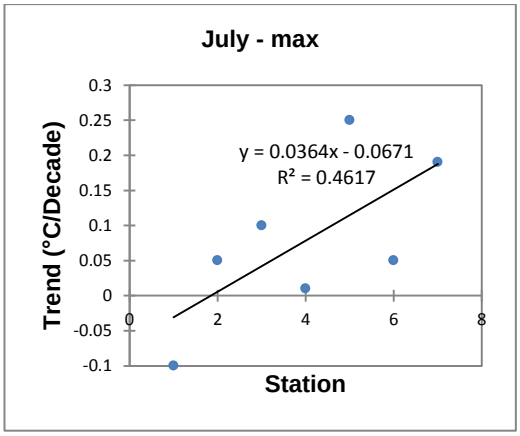


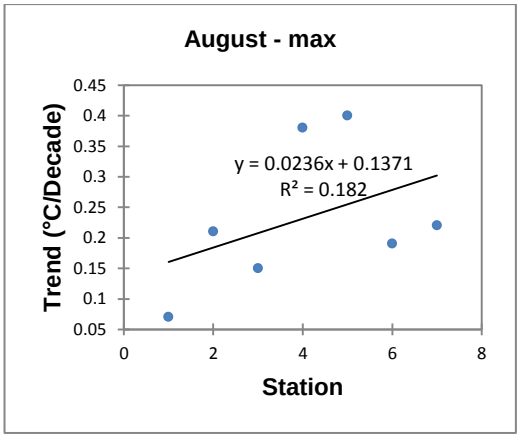


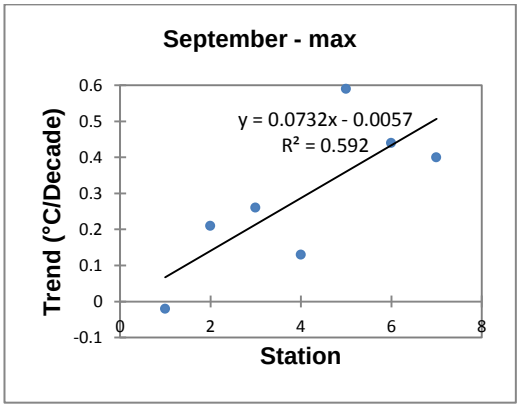


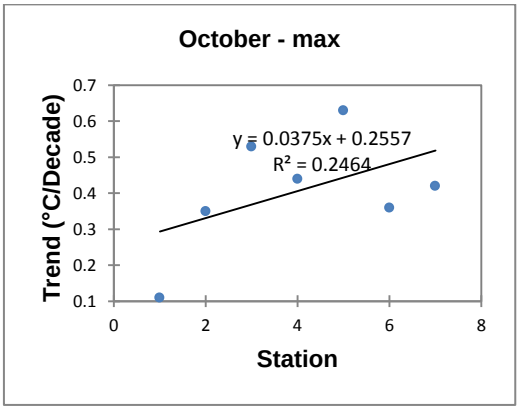

May - max
Trend (°C/Decade)
y = 0.0443x + 0.15
R² = 0.282
Station

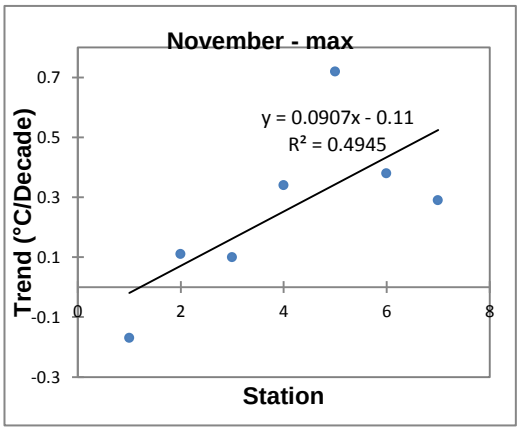

June - max
Trend (°C/Decade)
y = 0.045x + 0.0971
R² = 0.5947
Station

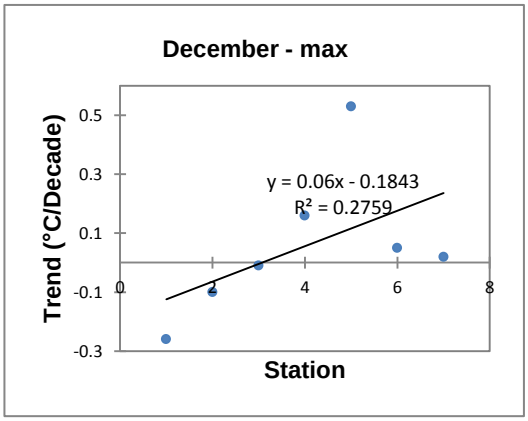

July - max
Trend (°C/Decade)
y = 0.0364x - 0.0671
R² = 0.4617
Station


August - max
Trend (°C/Decade)
y = 0.0236x + 0.1371
R² = 0.182
Station


September - max
Trend (°C/Decade)
y = 0.0732x - 0.0057
R² = 0.592
Station


October - max
Trend (°C/Decade)
y = 0.0375x + 0.2557
R² = 0.2464
Station


November - max
Trend (°C/Decade)
y = 0.0907x - 0.11
R² = 0.4945
Station


December - max
Trend (°C/Decade)
y = 0.06x - 0.1843
R² = 0.2759
Station

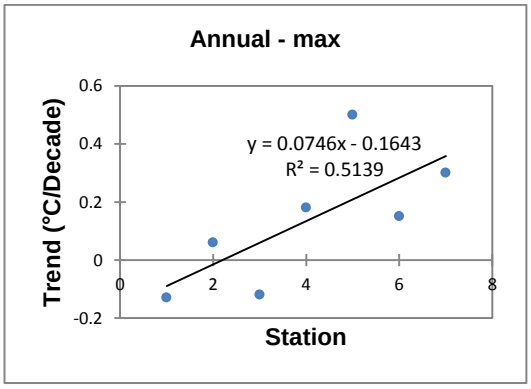
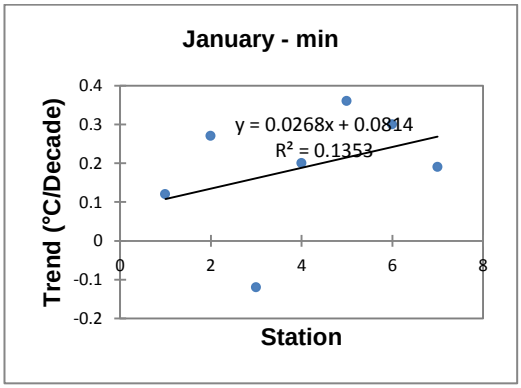
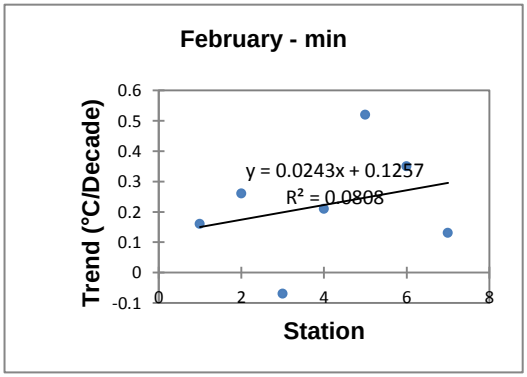
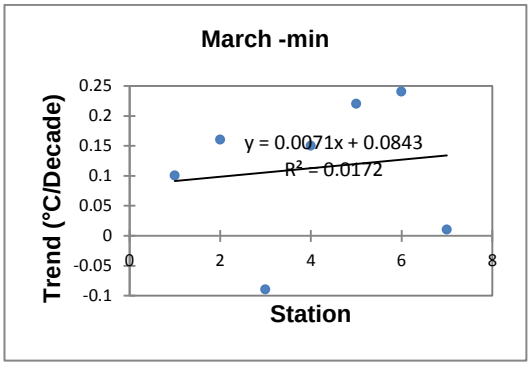


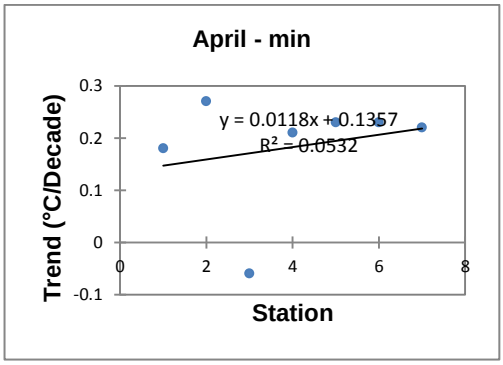
Figure 4.15: The relationship between trends for monthly and annual maximum temperature at various stations in Lesotho for the period 1968-2013. Stations in ascending order of altitudes (1. Maseru 1528m; 2. Mohaleshoek 1530m, 3. Mejametalana 1600m; 4. Butha Buthe 1768m; 5. Qachasnek 1972m; 6. Mokhotlong 2375 and 7. Oxbow 2591).

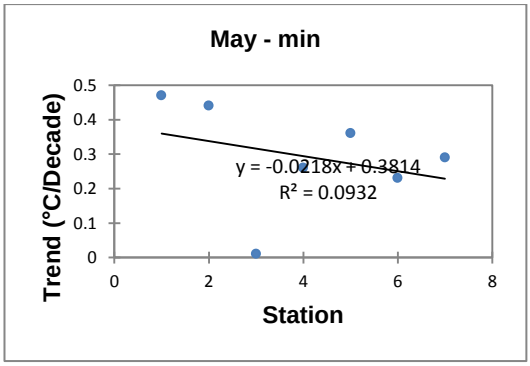
For minimum temperatures, for the period 1968-2013, the results show a negative relationship between the rate of change and altitude for monthly rate of change for colder months (i.e. May to October) while a positive relationship can be seen in warmer months (i.e. December to April). However, none of the relationships between minimum temperature and altitude are significant (Table 4.17).

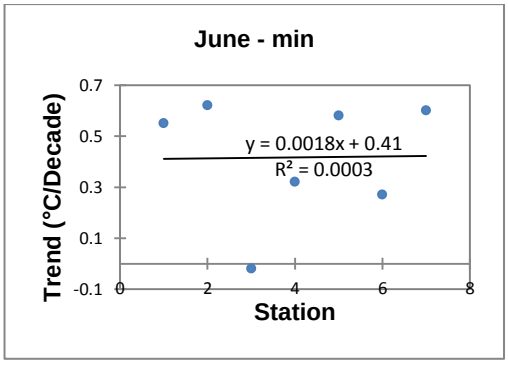


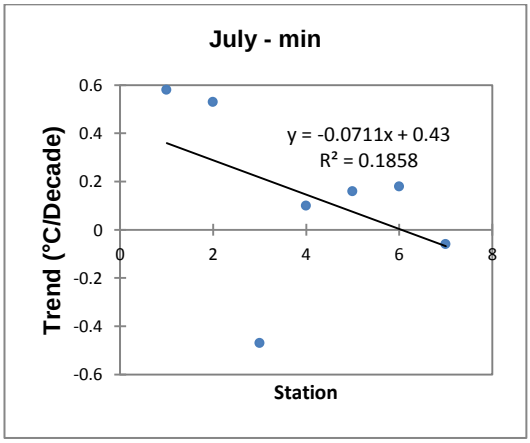


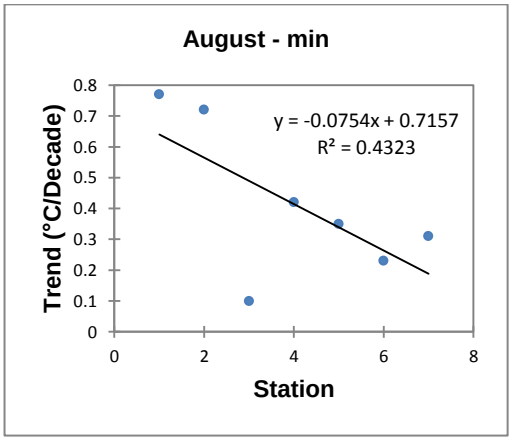

March -min
Trend (°C/Decade)
y = 0.0071x + 0.0843
R² = 0.0172
Station

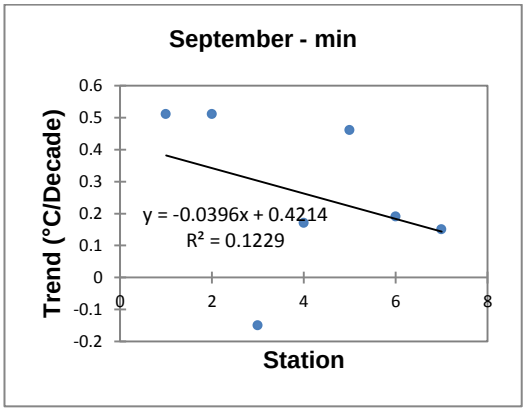

April - min
Trend (°C/Decade)
y = 0.0118x + 0.1357
R² = 0.0532
Station

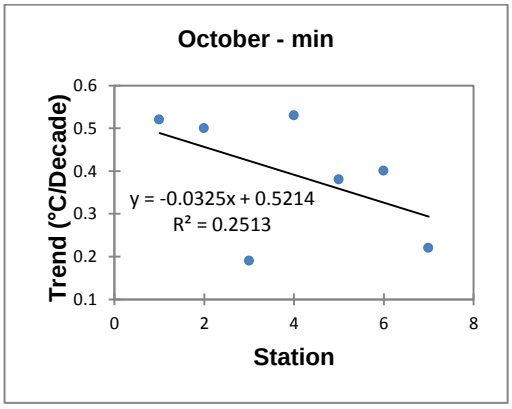

May - min
Trend (°C/Decade)
y = -0.0218x + 0.3814
R² = 0.0932
Station


June - min
Trend (°C/Decade)
y = 0.0018x + 0.41
R² = 0.0003
Station


July - min
Trend (°C/Decade)
y = -0.0711x + 0.43
R² = 0.1858
Station


August - min
Trend (°C/Decade)
y = -0.0754x + 0.7157
R² = 0.4323
Station


September - min
Trend (°C/Decade)
y = -0.0396x + 0.4214
R² = 0.1229
Station


October - min
Trend (°C/Decade)
y = -0.0325x + 0.5214
R² = 0.2513
Station

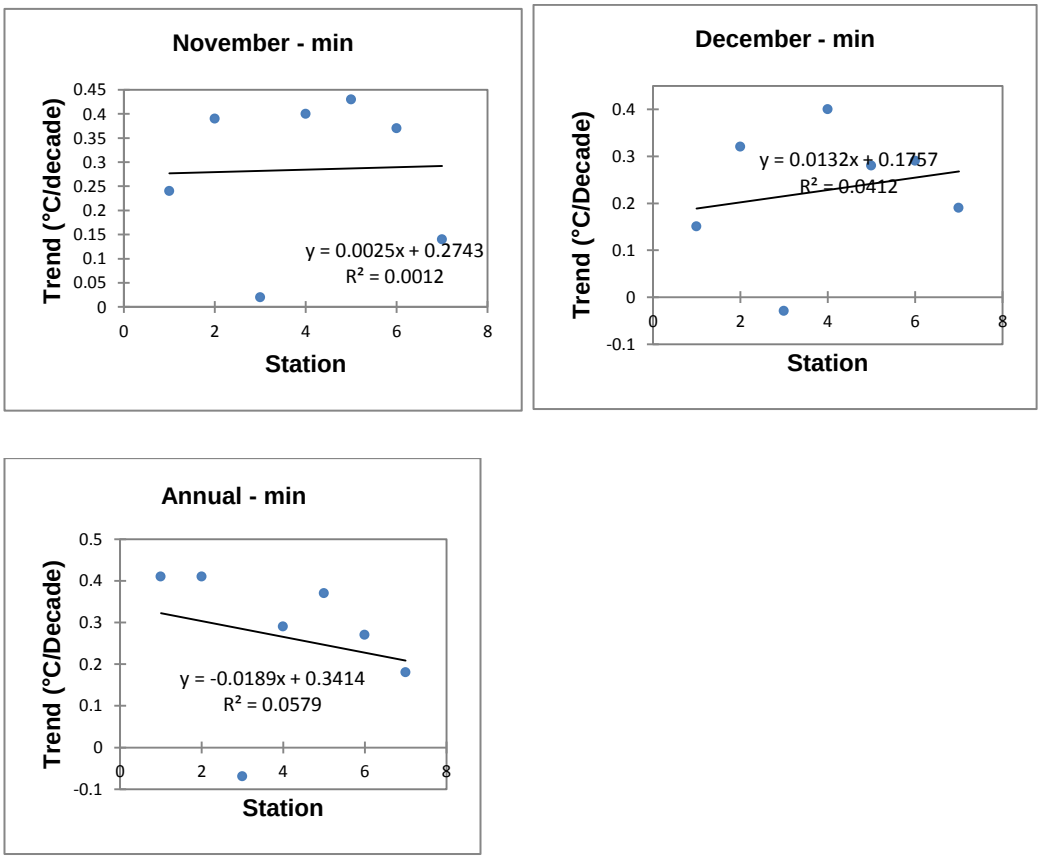


Figure 4.16: The relationship between trends for monthly and annual minimum temperature at various stations in Lesotho for the period 1968-2013. Stations in ascending order of altitudes. Stations in ascending order of altitudes (1. Maseru 1528m; 2. Mohaleshoek 1530m, 3. Mejametalana 1600m; 4. Butha Buthe 1768m; 5. Qachasnek 1972m; 6. Mokhotlong 2375 and 7. Oxbow 2591).

Table 4.17: Mann-Kendall test statistics for monthly, annual and seasonal trends with altitude at various stations in Lesotho for the period 1968 – 2013. Bold values indicate significant relationship.

	Mann-Kendall test statistics p-values at α = 0.05			**Kendall's tau test statistics at α=0.05**		
	Maximum	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**
January	0.069	0.562	0.069	0.619	0.238	0.619
February	0.069	0.773	0.136	0.619	0.143	0.524
March	**0.048**	0.562	0.095	0.683	0.238	0.586
April	0.239	0.649	0.239	0.429	0.195	0.429
May	0.239	0.381	1.000	0.429	-0.333	0.048
June	0.069	1.000	0.239	0.619	0.048	0.429
July	0.172	0.381	0.562	0.488	-0.333	-0.238
August	0.239	0.136	0.239	0.429	-0.524	-0.429
September	0.136	0.288	0.562	0.524	-0.390	0.238
October	0.381	0.381	1.000	0.333	-0.333	-0.048
November	0.136	1.000	0.288	0.524	0.048	0.390
December	0.136	1.000	0.773	0.524	0.048	0.143
Annual	0.069	0.172	0.172	0.619	-0.488	0.488
Winter	**0.011**	0.239	0.562	0.810	-0.429	-0.238
Summer	0.879	0.649	0.172	0.098	-0.195	0.488
Autumn	0.065	0.448	0.381	0.651	-0.333	0.333
Spring	0.288	0.381	0.381	0.390	-0.293	0.333

4.2.4 Trends in extreme temperatures for the period 1968 - 2013

Extreme maximum temperature refers to the daily temperatures that exceed the 90th quartile while extreme minimum temperatures refers to daily temperatures that are below the 10th quartile. There is an increase in the total number of days per year with extreme maximum temperatures in most of the stations, except for Maseru (-0.217 days/year) and Mejametalana (-0.166 days/year) where the number of days with extreme maximum temperatures are declining (Table 4.18). The numbers of days

with extreme minimum temperatures are decreasing at all the stations, except for Mohaleshoek (0.069 days/year) which shows an increase in number of days with extreme minimum temperatures per year (Table 4.18). The trends are, however, not significant in all the stations.

Table 4.18: Trends for total number of days of extreme maximum and minimum temperatures per year for the period 1968 – 2013.

	Trend (no of days/year)	
	Maximum	Minimum
Maseru	-0.217	-0.169
Mejametalana	-0.166	-0.084
Mohaleshoek	0.059	0.069
Butha Buthe	0.035	-0.004
Mokhotlong	0.080	-0.172
Oxbow	0.023	-0.045
Qachasnek	0.170	-0.175

4.3 Temperature trends for the period 1931 – 2013

For the period 1931 – 2013, data were available for only four stations, Maseru, Mohaleshoek, Mokhotlong and Qachasnek. The results for the trends in maximum, minimum and mean annual temperatures are presented in figure 4.17 – 4.20 below.

For Maseru, for the period 1931-2013, there is a positive annual trend for maximum, minimum and mean temperatures. The annual trend for minimum temperature is higher than the annual trend for maximum temperature (Figure 4.17). However, none of the trends is significant at 95% significance limit using the Mann-Kendall's test.

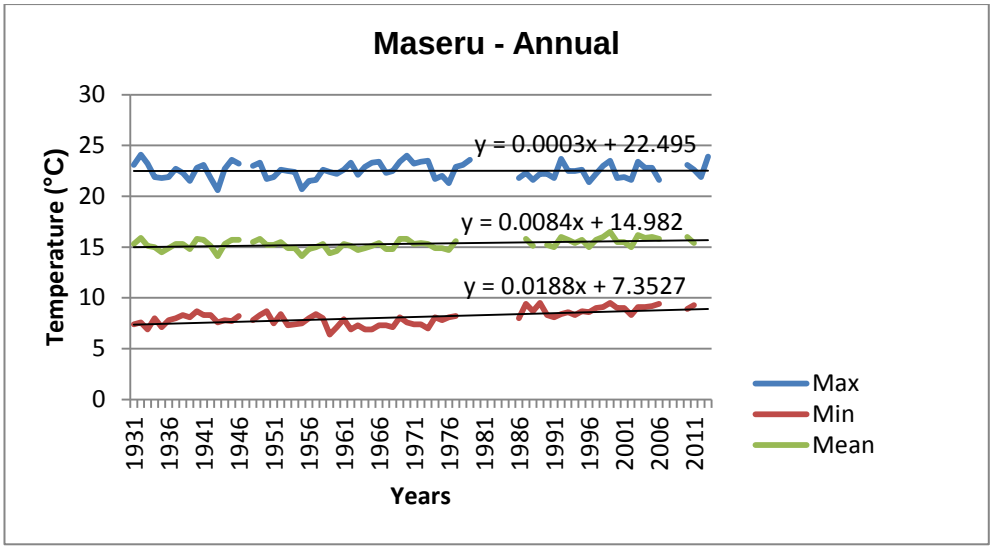


Figure 4.17: Annual temperature trends for maximum, minimum and mean temperatures at Maseru for the period 1931 – 2013.

For Mohaleshoek in the Senqu river valley, a positive annual trend for maximum, minimum and mean temperatures is also observed for the period 1931-2013. The annual trend for minimum temperature is again higher than the annual trend for maximum temperature (Figure 4.18). However, none of the trends is significant at 95% significance limit using the Mann-Kendall's test.

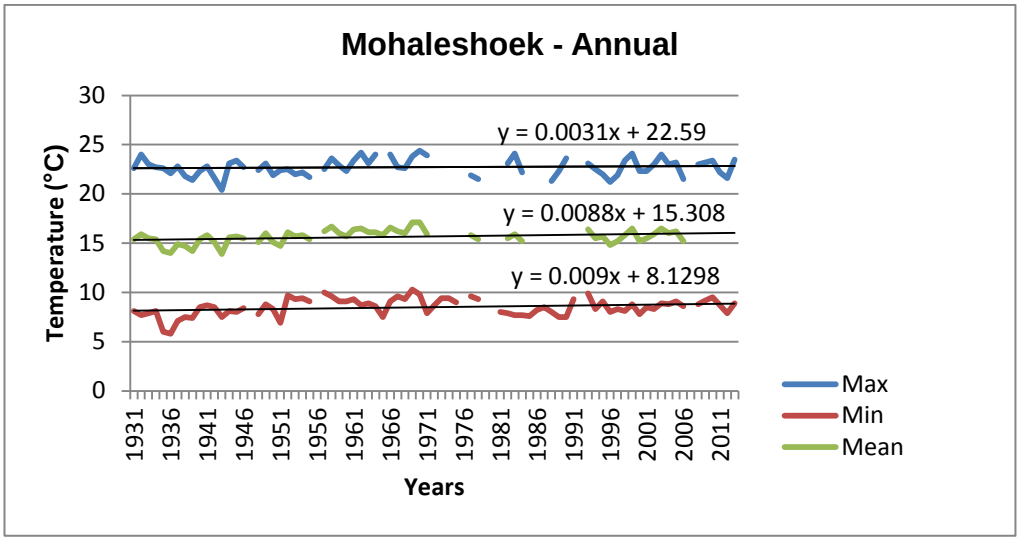


Figure 4.18: Annual temperature trends for maximum, minimum and mean temperatures at Mohaleshoek for the period 1931 – 2013.

For Mokhotlong in the highlands, a positive annual trend for maximum, minimum and mean temperatures is also observed for the period 1931-2013 (Figure 4.19). The annual trend for minimum temperature is again higher than the annual trend for maximum temperature. However, none of the trends is significant at 95% significance limit using the Mann-Kendall's test.

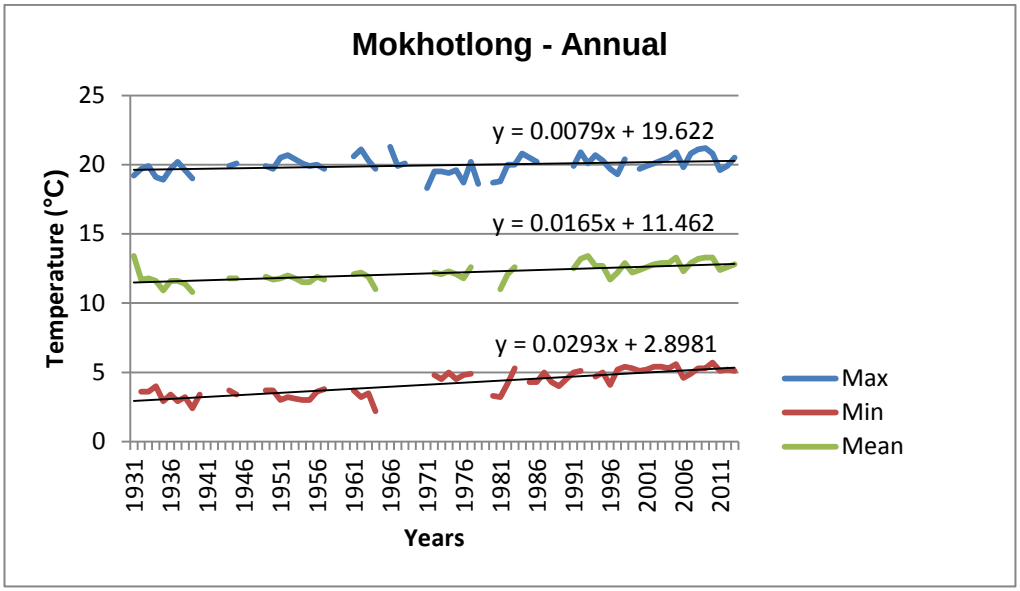


Figure 4.19: Annual temperature trends for maximum, minimum and mean temperatures at Mokhotlong for the period 1931 – 2013.

For Qachasnek also in the highlands, a positive annual trend for maximum, minimum and mean temperatures is also observed for the period 1931-2013 (Figure 4.20). The annual trend for minimum temperature is again higher than the annual trend for maximum temperature. However, none of the trends is significant at 95% significance limit using the Mann-Kendall's test.

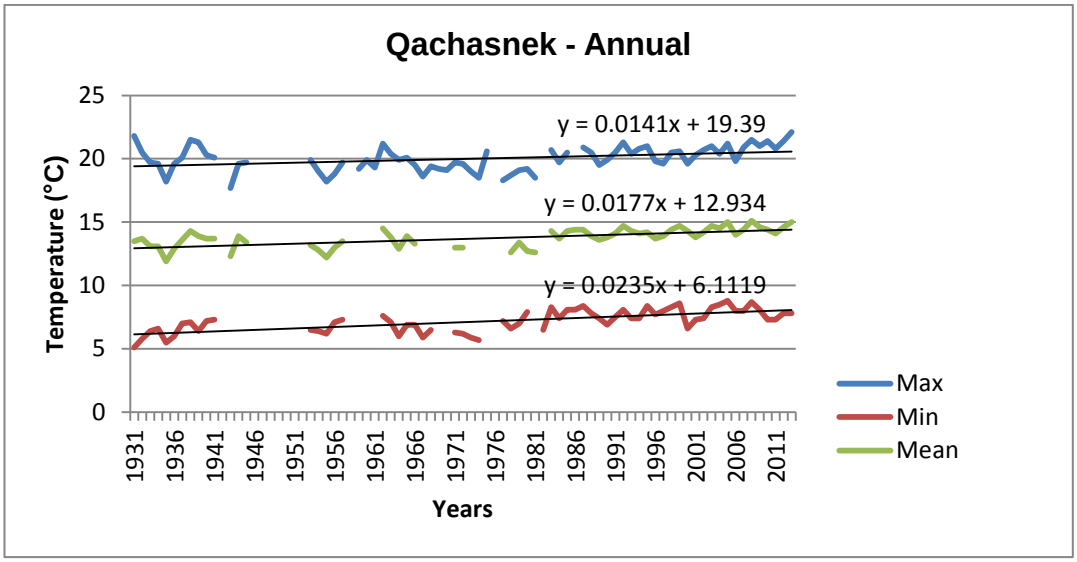


Figure 4.20: Annual temperature trends for maximum, minimum and mean temperatures at Qachasnek for the period 1931 – 2013.

CHAPTER 5: CONCLUSION

5.1 Summary

The study investigated the relationship between the temperature trends and altitude at various time scales; i.e. monthly, annually and seasonally. For comparison purposes, data were divided into two periods, based on the periods of availability of data at the various stations that were used in the study. The periods included a shorter period of 45 years (1968 – 2013) and a longer period of 82 years (1931 – 2013). Data availability posed a challenge to the study as there were data gaps that could not be filled. This has an impact on the results as adding these missing values could produce different results.

Generally, for the period 1968 – 2013 (45 years), there is an observed warming over the study area; however, the rate of warming varies for the different temporal scales. The rate of warming also varies between maximum and minimum temperatures, with maximum temperatures warming at a rate much higher than minimum temperatures in the high-lying stations, Oxbow (0.63 and 0.65 °C/decade for maximum and minimum temperatures respectively for February) and Qachasnek (0.25 and 0.13 °C/decade for maximum and minimum temperatures respectively for February). This is consistent with findings by Katell and Yao (2013) for their study over the central Himalayas, in which they observed a clear warming trend for maximum temperatures. In the low-lying stations, minimum temperatures are warming at a rate much higher than for maximum temperatures (Maseru (0.02 and 0.10 °C/decade for maximum and minimum temperatures respectively for March), Mejametalana (0.15 and 0.27 °C/decade for maximum temperatures respectively for April) and Butha Buthe (0.19 and 0.32 °C/decade for maximum and minimum temperatures respectively for June), except for Mohaleshoek, located at the Senqu river valley, where minimum temperatures are decreasing at all temporal scales.

The warming trends are significant for minimum temperatures at monthly, annual and seasonal scales, for all the stations, except Mohaleshoek. This significant warming of minimum temperatures is observed at the highland stations, Mokhotlong (p=0.000), Oxbow (p=0.013) and Qachasnek (p=0.002), located on the eastern side of Lesotho, the lowlands stations, Maseru (p<0.0001) and Mejametalana (p=0.000), as well as at the foothills, Butha Buthe (p=0.017), located on the western side of Lesotho. In Mohaleshoek, located in the Senqu river valley, no significant trends were observed. For maximum temperature, however, the significant warming is limited to the highland stations (Mokhotlong (p<0.0001), Oxbow (p=0.007) and Qachasnek (p=0.000)), located in the eastern side of Lesotho. These findings are consistent with results from various studies across the globe which found warming for both maximum and minimum temperatures (Bhutiyani *et. al*., 2007; Grab & Linde, 2014; IPCC, 2014; MacKellar, 2014). Seasonally, for the period 1968 – 2013, the greatest warming in minimum temperatures is in winter in Mejametalana (0.65 °C/decade) and is significant (p<0.0001) at 95% significance limit, while for maximum temperatures, the greatest warming is in autumn at Qachasnek (0.78 °C/decade) and is significant (p=000) at 95% significance limit. This is similar to studies that found that the warming is greater for temperatures during autumn and spring than for summer temperatures (Liu & Chen, 2000; Diaz & Eisched, 2007; Wang *et. al*., 2014).

For the relationship between temperature trends and altitude for the period 1968 – 2013, a positive relationship was found for maximum temperatures, while a negative relationship was found for minimum temperature trends. A negative relationship was also observed with monthly trends for mean temperatures monthly as well as for the winter season. There was no significant relationship found for maximum, minimum and mean rates of change of temperature with altitude, except for maximum temperatures in March (a p= 0.048) and winter season (p= 0.011).

The numbers of days with extreme maximum temperatures are increasing annually and seasonally while the numbers of days with extreme minimum temperatures are decreasing with the exception of autumn where extreme minimum temperatures are increasing. However, none of the trends are significant. There is a significant decrease in the total number of days with frost at both the high lying stations (Mokhotlong (p=0.028), Oxbow (p=0.016) and Qachasnek (0.015)) as well as the low-lying stations (Maseru (p=0.000), Mejametalana (p=0.000) and Butha Buthe (p=0.022).

For the much longer period, 1931 – 2013 (82 years), the consistent positive trends for maximum, minimum and mean temperatures are still observed; however, none of the trends are significant.

The relationship between the trends for maximum temperature with altitude is positive, implying that the rate of warming increases with altitude, however, the trend is only significant in winter, similar to results from a study by Katell and Yao (2013). There is a negative trend for minimum temperatures with altitude. There is an enhanced warming for maximum temperatures at higher altitudes as compared to lower altitudes.

5.2 Implications for agriculture

Temperature is one of the major role players on how climate affects agricultural production (Wheeler *et al.,* 2000). In Lesotho, agricultural production is limited to the lowlands, due mainly to long periods of low temperatures and high frost risk at higher altitudes (Zinyengere *et. al.*, 2014). Gwimbi *et. al.* (2013), in their study on the impact of climate change in Lesotho, presented results from various global circulation models, which shows a potential for new agricultural production areas to be gained in the eastern parts of Lesotho under changing climate conditions, where agricultural production was not feasible under previous climate conditions. From the results of this study, there is significant warming for both maximum and minimum temperatures in the eastern parts (highlands) of

Lesotho. This therefore implies that there might be an increase in the potential for agricultural production in these areas where agricultural production was not previously possible.

The main crops grown in Lesotho are maize, wheat, sorghum and to a lesser extent beans and peas (Mekbib *et al.*, 2012), with maize as the staple food for most of the country's population. The productions of maize and sorghum, specifically, are expected to decline due to climate change in the western parts of Lesotho (lowlands), where it is currently produced (Gwimbi *et. al*., 2013). The positive trends in maximum and minimum temperatures in the eastern parts (highlands) of Lesotho, presents an opportunity for migration of the production of maize and sorghum in Lesotho to the new potential areas in the highlands. In addition to migration of maize and sorghum, new crops that are more suitable to a warming climate can be investigated and introduced to Lesotho lowlands where conditions are no longer suitable for maize and sorghum production (Gbetibouo & Hassan, 2005).

Different crops grow under various climate conditions; therefore adaptation strategies that are in-line with current climate conditions can maximize the potential for new opportunities presented by the changing climate (Collier *et al.*, 2008). However, temperature is not the only determining factor in agricultural production, soil content and type as well as moisture or rainfall patterns of the area, are equally important in determining the suitability of crops to grow in a specific area. Therefore, an in-depth study that will look into all the variables important for production of various crops, is required to determine whether crops can grow in the potential areas where a significant increase in temperature has been observed, as well as where potential for new areas of agricultural production potential is high.

5.3 Conclusion

For the period of 45 years, 1968 – 2013, there is a significant increase in both maximum and minimum temperatures observed in both the highlands and the lowlands of Lesotho, however, no significant relationship between these trends and altitude could be established. The observed increases in temperatures will have a negative impact on agricultural production in the lowlands as crops will reach their optimum production temperatures and therefore result in reduced production. These, however, may benefit from an increase in temperatures in the highlands. Migration of agricultural production might be possible in Lesotho as well as the introduction of new more heat tolerant crops in the lowlands.

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