SYNOPTIC AND ATMOSPHERIC STABILITY CLASSIFICATION FOR THE UNITED ARAB EMIRATES

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A Dissertation submitted to the Faculty of Science,

University of the Witwatersrand, Johannesburg

for the Degree of Master of Science

February 2005

Abstract

The United Arab Emirates (UAE) is a country that has developed rapidly over the past thirty years. Future development is going to be hampered by the enormous shortage of fresh water in the country. It is critically important that a strategic management plan for water resource management be developed to avoid a water crisis for the population and environment. The first step in managing water resources is to understand the sources and sinks of fresh water.

Clearly, one of the most important sources of water to any environment is precipitation and the atmospheric processes and characteristics that promote or diminish the likelihood of rainfall over an area.

The synoptic circulation of a region, as well as the thermodynamic structure of the atmosphere, are important for both frontal and convectively activated rainfall. In the past little detailed research has been conducted over the UAE and surrounding regions to classify and characterise atmospheric processes. This study represents the first attempt to develop a synoptic circulation climatology for the region. Synoptic circulation patterns have been classified at both the surface and 500 hPa layer over a period of seven years (1995-2001). In addition, the UAE is located under the descending limb of the Hadley circulation. As in other parts of the globe, this has severe implications for the vertical thermodynamic structure of the atmosphere. Atmospheric stability over the UAE has been evaluated for the period of seven years. The implications of descending air have been determined with respect to the thermodynamic structure of the atmosphere as a function of time and space. Vertical Radiosonde data collected over the same seven year period at the Abu Dhabi International Airport have been analysed to determine the frequency of occurrence and nature of absolutely stable layers in the atmosphere.

Six circulation patterns that dominate the flow at both the surface and in the upper atmosphere at 500 hPa have been identified from the synoptic climatology. The dominant circulation pattern at the surface and upper atmosphere are the Siberian high and the Subtropical high, respectively. The Siberian high occurs at the surface predominantly during the winter season with a maximum frequency of occurrence in January (48%). The Subtropical high occurs in the upper atmosphere throughout the year, however, it is dominant during the summer months occurring 80 % of the time in August.

Absolute stable layers are a permanent feature of the atmosphere over the UAE. A maximum of six layers have been identified in the atmosphere at a given time. Surface inversions occur throughout the year. Absolute stable layers have been identified at 850, 700, 600, 500 and 400 hPa. The surface inversions as well as the layers at 850 and 700 hPa have a distinctly seasonal pattern of occurrence. The absolute stable layers at the remaining pressure layers do not vary significantly with season. The surface and 600 hPa layers are by far the most dominant in the atmosphere and certainly have the most important control on vertical movement and accumulation of pollutants in the atmosphere.

Declaration

This dissertation is dedicated to Sheik Mansour Al Nayan

and

My Family

Preface

Understanding the nature and characteristics of atmospheric circulation and the thermodynamic structure of the atmosphere form the basis for any research in precipitation and atmospheric pollutants. Little research has yet been undertaken to classify the nature of atmospheric circulation over the United Arab Emirates (UAE) and to summarise these patterns into a synoptic climatology for the region. Despite the fact that there are several weather forecasting offices in the UAE, no standard documentation of the synoptic circulation patterns over the region, and their seasonal variation and impacts, exists. In addition, the UAE is known to be located in a region dominated by anticyclonic circulation. Descending air associated with anticyclonic pressure systems has indicated, in other parts of the world, highly stable atmospheres. This stability effectively suppresses convective activity, as well as creating stagnant conditions conducive to the accumulation of pollutants in the atmosphere.

The aim of this study is to classify the synoptic circulation patterns over the UAE and evaluate each circulation pattern's influence on rainfall. In order to accomplish this, an analysis of the atmospheric stability over the UAE will also be undertaken. The specific objectives of this dissertation are:

1. To classify the synoptic circulation patterns over the UAE in categories
2. To evaluate the contribution of each identified synoptic category to rainfall production over the UAE
3. To determine atmospheric stability conditions over the UAE and to evaluate if these conditions could act to inhibit or suppress rainfall

Chapter 1 introduces the research aims and objectives within the context of the current understanding of atmospheric circulation over the UAE. Chapter 2 clarifies the data types and sources used, as well as the methodologies used in this study. In Chapter 3, the dominant synoptic scale pressure systems affecting the weather of the UAE, at both the surface and at the 500 hPa pressure level are identified and classified. Rainfall records from UAE weather stations are analyzed in order to link the spatial distribution of rainfall to particular synoptic patterns. In Chapter 4 the nature of atmospheric stability is presented and discussed. Finally, the conclusions are outlined in detail in Chapter 5, and references are listed in Chapter 6.

Data used in this dissertation have been obtained from the Abu Dhabi International Airport. Synoptic circulation patterns over seven years (1995-2001) were used to classify synoptic systems, at both the surface and upper atmosphere (500 hPa), into categories. Radiosonde data (1995-2001) from the Abu Dhabi International Airport were plotted on tephigrams and analysed in regions of absolute stability. Aircraft data have been obtained from the atmospheric chemistry and cloud seeding project conducted over the UAE between 2000 and 2002.

The Meteorology section of the Department of Water Resources Studies (DWRS) and the Office of H.H. the President, Abu Dhabi, assisted in analysing the synoptic charts and the hundreds of tephigrams used to determine seasonal variations for this study. The research has been supervised by Dr Stuart Piketh of the Climatology Research Group (CRG) at the University of the Witwatersrand, Johannesburg. Dr Roelof Bruintjes from the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA, is thanked for his advice during this study. Mr Roelof Burger of the CRG, previously with the South African Weather Services (SAWS), is thanked for his help in analysing the long-term radiosonde data. Dr Kristy Ross of the CRG assisted in analysing the vertical temperature data collected with the aircraft. The graphics section of the DWRS is also thanked for their help in preparing figures used in this dissertation. Sheik Mansour Al Nayan is thanked for the continued financial support that his office has given to the DWRS, which has facilitated the research. Mr Abdullah Al Mangoosh is thanked for his support and friendship during the time of completing the study. I would also like to thank my family for their support and encouragement.

List of Abbreviations

UAE - United Arab Emirates
DWRS – Department of Water Resources Studies
CRG – Climatology Research Group
masl - meter above the mean sea level
GMT – Greenwich meridian time
hPa – hectare Pascal
SH - Siberian high
RST - Red Sea trough
MT - Mediterranean trough
SH/IH - Siberian high/Indian high
ET - Easterly trough
IH - Indian Ocean high
TL - Thermal low
ET/SH - Easterly trough/Siberian high
RST/MT - Red Sea trough/Mediterranean troughs
RST/ET - Red Sea trough/Easterly trough
TL/IH - Indian Ocean high/Thermal low
ET/TL - Easterly trough/Thermal low
SAWS – South African Weather Services
NCAR – National Center for Atmospheric Research
WT - Westerly trough
WR - Westerly ridge
STH - Subtropical high
ZF - Zonal flow
WCL - Westerly cut-off low

Table of Contents

CHAPTER 1

OVERVIEW

A detailed discussion of the state of knowledge of atmospheric circulation and stability in general and specifically over the United Arab Emirates (UAE) will be given in this chapter. The research goals are also outlined

Introduction

Knowledge of the frequency and average positions of synoptic weather systems over large areas is an important element in the synoptic climatology of any area (Makrogiannis and Giles, 1980). There are many synoptic climatological studies of individual storms, fronts, depressions and anticyclone storm tracks in the literature (Reiter, 1971; 1975; Flocas, 1984). An excellent account of the early history of synoptic climatology was given by Riehl (1944). A comprehensive discussion of the frequency of cyclones and anticyclones in relation to the mean circulation was given by Klein (1956). Continuing the studies for the Northern Hemisphere, Klein (1957) considered the history of synoptic meteorology and climatology with reference to the tracking and frequency of cyclones and anticyclones. By the beginning of the 1990's some excellent studies of monthly anticyclonic and cyclonic circulation in the Southern Hemisphere had been conducted by Leighton (1992; 1994).

At present climate variability and change is an important scientific, social and political topic around the world (IPCC, 2001). Changing climates might have important implications for many parts of the world. Impacts relate to sea level rise, available water and food resources and, eventually, national security (IPCC, 2001). It is therefore important to understand the atmospheric circulation processes in different regions of the world so that the consequence or impact of the climate change can be properly evaluated.

The interaction between different scale motions has been a subject of intensive theoretical studies. A tendency of the atmosphere to be stable for a particular range of motion and at the same time be unstable for the others opened an interesting and exciting field in the science of meteorology under the title of "hydrostatic instability" (Lorenz, 1955; Kuo, 1965; Eliassen, 1652; Charney, 1959). High static stability suppresses the growth of atmospheric convection and effective dispersion and dilution of atmospheric constituents. Regional-scale atmospheric circulation plays a key role in determining the nature of the weather over any given region as well as the nature of atmospheric stability.

This dissertation focuses on two main subjects. The first is the development of a synoptic climatology for the UAE and the second is the evaluation of the nature of atmospheric stability over UAE. In addition, rainfall over UAE is analyzed in association with the aforementioned atmospheric conditions.

Position and topography of UAE

The UAE is situated between 21.5º and 26.5º N and 51.5º and 56.5ºE and covers an area of 77, 700 km^2. It is located in the south western part of Asia and is boarded by the Arabian Gulf to the north, the Arabian Sea and Oman to the east, Saudi Arabia to the south, and Qatar and Saudi Arabia to the West (Figure 1.1). In general the weather in this region is very hot in summer and warm in winter. The geographical location of the UAE with respect to the Arabian Gulf and the Arabian Sea plays an important role in the climate of the area. Climatically, the UAE is part of the "desert" zone, covering North Africa, and Western Asia.

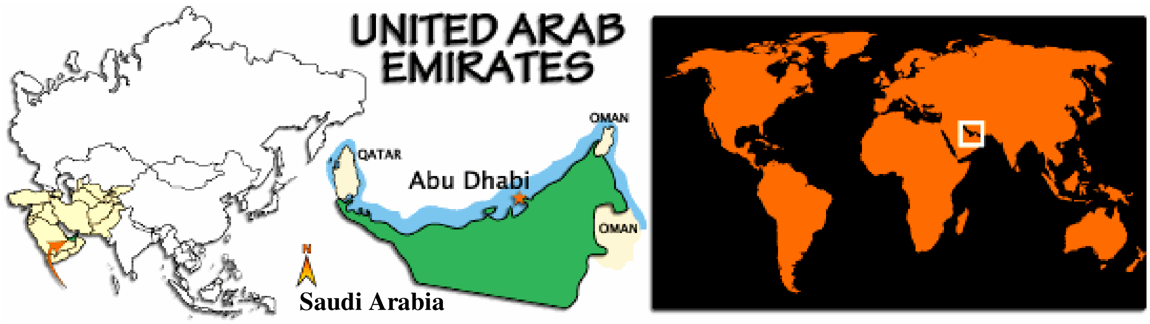

Figure 1.1. The geographical location of the UAE with respect to the Arabian Gulf and Arabian Sea, which play an important role in influencing the climate of the region.

Topography of the area

Generally, the UAE has two main elevation zones. The first is a large sandy desert zone, which covers about ninety percent of the country's surface area, extending from the Oman Mountains in the east to the coast line of the Arabian Gulf. The second zone is the mountain ranges themselves, which extend from north to south in the eastern part of the country, with a peak of 2438 amsl (Figure 1.2). The topography plays a vital role in determining the weather and climate over the UAE. The relative position of the UAE, with respect to the coastal regions also means that the country is affected by land-sea breeze circulation from both the western and eastern side of the country. The Oman Mountains also have an influence on the nature of these local wind patterns.

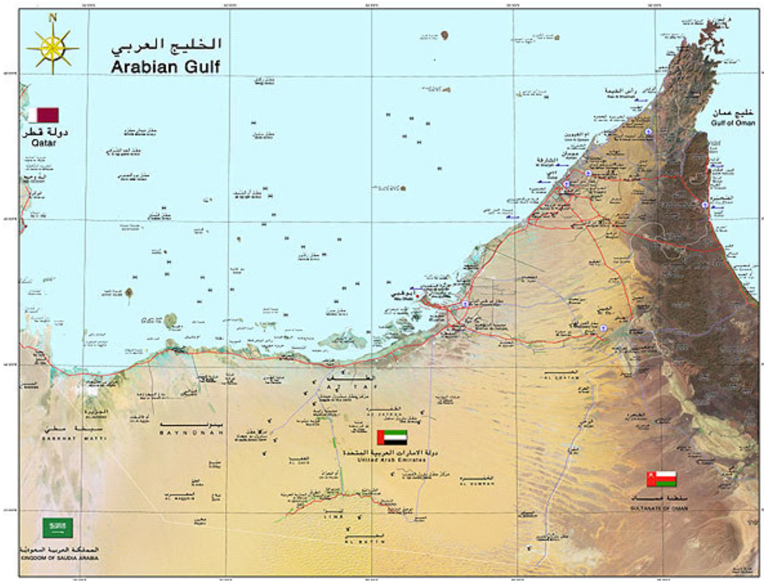

Figure 1.2. The topography of UAE with the sandy desert to the east of the Oman Mountains which bound the entire eastern side of the country.

Review of the previous studies on the weather of UAE

Although the UAE has a well developed infrastructure for weather prediction and forecasting, little has been done to summarize the most important aspects of synoptic scale circulation of the country. Weather systems over the UAE are distinguished by their characteristic scales and circulation patterns. These patterns result from global energy imbalances that produce temperature gradients and therefore pressure variations, which are complex in the subtropical latitudes. The UAE is centred on the Tropic of Cancer, which is located below the descending limb of the Hadley cell. As a result, the region is dominated by subtropical anticyclones and thus provides this region with a subtropical desert climate (UAE Climate, 1996; Barry and Chorley, 1982). The position of the UAE relative to the Arabian Gulf and the Indian Ocean also exerts an important influence on the creation of the large desert zone extending from North Africa to Western

Asia. In addition mountain barriers can act as important forcing mechanisms on a smaller scale (Tyson and Preston-Whyte, 2000).

In general the weather for much of the year shows a ridge of high pressure extending southward into central Saudi Arabia, with lower pressure over the eastern Gulf (Del LA Mare, 1978). Prevailing light to moderate north westerly winds, known by in Arabic as Shamal, meaning north, are associated with mid-latitude disturbances (Oil Companies Weather, 1976; Perrone, 1981; Ali, 1992). Along the western coastal plain, sea breezes tend to dominate with light south to south easterlies at night being replaced by moderate north westerlies during daytime. This pattern changes along the east coast where the proximity of the mountains results in gusty and less predictable wind shifts. A good strong blast of the northerly Shamal is usually preceded in the UAE by strong southerly winds, raising desert sands and reduced visibility for a few kilometres or less (Perrone, 1981, Brower *et al.*, 1992). The shift to northerly winds may be quite sudden and may be accompanied by rain, thunderstorms, or dust storms. In summer, the weather is usually influenced by a broad area of low pressure, extending from the Western Sahara, across the Arabian Peninsula and Asia, to China. Local pressure variations over the Gulf combine with the latter to create weather conditions over the UAE. Steady north-westerlies, predominatly over in the central and northern regions of the Gulf, do not generally extend as far south as the UAE. When they do, sea conditions around Abu Dhabi become unsettled and rough, while the rest of the UAE's coastal waters experience only small swells (Naval Environmental Prediction Research Facility, 1980).

General circulation of the Atmosphere

Local winds vary considerably from day to day and from season to season. These winds form part of a much larger circulation pattern. When winds throughout the world are averaged over long periods of time it is possible to discern a general circulation pattern or climate of the atmosphere over specific regions. The average circulation can also reveal the driving mechanism behind hemispheric scale winds. In general these large-scale winds are driven by heat and momentum being exchanged between the equatorial regions and the poles (Donald, 2001). The underlying cause of the general circulation is firstly the unequal heating of the earth's surface. Also, averaged over the entire earth, incoming solar radiation is roughly equal to outgoing earth radiation. However, this energy balance is not maintained for each latitude, since the tropics experience a net gain in energy, while the polar regions suffer a net loss. To balance these inequalities, the atmosphere transports warm air poleward and cool air equatorward. In addition to thermally driven winds, the rotation rate of the Earth is a second major driving force for large-scale circulation. Although it seems simple, the actual flow of air is fairly complex (Barry and Chorely, 1982).

Single-Cell Model

Two conceptual models, developed in the eighteenth century, have been used to describe the heat transfer mentioned above. The first model is known as the single-cell model which assumes that the earth's surface is uniformly covered with water and that the sun is directly over the equator. The first condition was defined in such a way that differential heating between land and water does not come into play, and the second condition was defined in such a way that the winds do not shift seasonally. Finally, the model assumes that the earth does not rotate, so that the major horizontal force remaining is the pressure gradient force. With these assumptions the general circulation of the atmosphere can broadly be represented by the circulation depicted in Figure 1.3, which illustrates a huge thermally driven meridional convection cell in each hemisphere.

These convection cells are known as Hadley cells (named after the eighteenth-century English meteorologist George Hadley (1735), who first proposed this idea). The cells are driven by energy from the sun. Excessive heating of the equatorial area produces broad region of surface low pressures, while at the poles excessive cooling creates a region of surface high pressure. In response to the horizontal pressure gradient, cold surface polar air flows equatorward, while at higher levels air flows toward the poles. The entire circulation consists of rising air near the equator, sinking air over the poles, an equatorward flow of air near the surface, with a return flow aloft. In this manner, some of the excess energy of the tropics is transported as sensible and latent heat to the regions of energy deficit at the poles.

This first model illustrates a simple cellular circulation that does not actually exist on the earth. Observations alone indicate that a closed circulation of air between the equator and the poles is not the proper model for a rotating earth which is a condition for the second model (Chamberlain and Hunten, 1987).

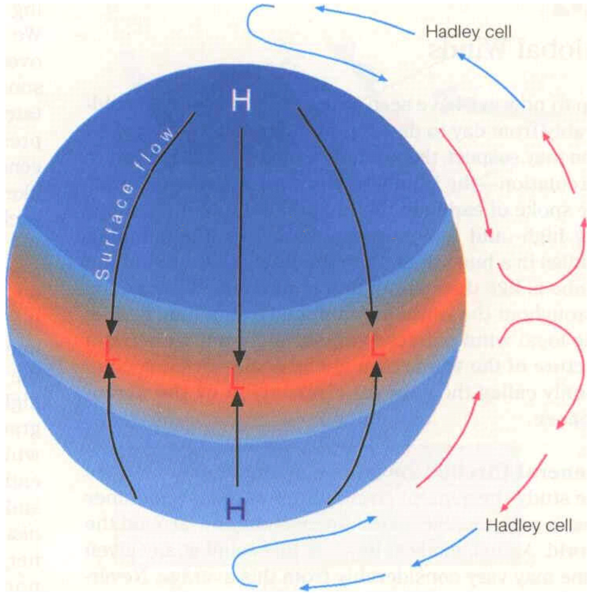

Figure 1.3. The general circulation of air on a non-rotating sphere (earth) uniformly covered with water with the sun directly above the equator. (Donald, 2001).

Three-Cell Model

If the earth in the single cell model is allowed to spin, the simple convection system considered in the fist model breaks up into a number of meridional cells, as shown in Figure 1.4. Although this model is considerably more complex than the single-cell model, there are some similarities (Donald, 2001). The tropical regions still receive an excess of heat while the poles receive a deficit of heat. However, in each hemisphere, a three-cell structure, instead of one, is now governing energy redistribution. A surface high-pressure area is located at the poles, while a broad trough of surface low pressure still appears at the equator. From the equator to latitude 30°, the circulation is thermally driven and closely resembles that of a Hadley cell. As a result of the earth's rotation a second cell circulates in the opposite direction that stretches from approximately 30°-60° latitude. A third thermally driven cell completes the circuit by rising at 60° and descending at 90° latitude.

Over equatorial waters, the air is warm, horizontal pressure gradients are weak, and winds are light. This zonal region is referred to as the doldrums (Figure 1.4). Here, warm air rises, often condensing into huge cumulus clouds and thunderstorms called convective "hot" towers because of the enormous amount of latent heat they liberate. The heat makes the air more buoyant and provides additional energy to drive the Hadley cell. The rising air reaches the tropopause, which acts like a barrier, causing the air to move laterally toward the poles. The Coriolis force deflects this poleward flow toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere, providing easterly winds aloft in both hemispheres (Donald, 2001).

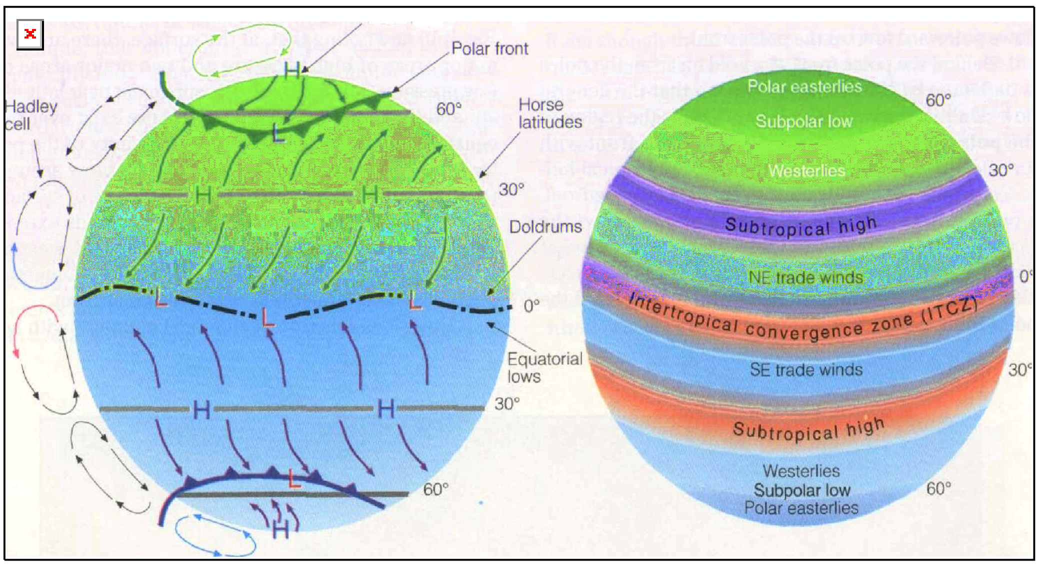

Figure 1.4. Schematic representation of the three cell conceptual model. Diagram (a) shows the idealized wind and surface pressure distribution over a uniformly water- covered rotating earth while diagram (b) gives the names of the surface winds and pressure systems over a uniformly water- covered rotating earth. (Donald, 2001).

Air moving poleward from the tropics constantly cools as a result of less radiation per area, and at the same time it also begins to converge, especially as it approaches the mid latitudes (Figure 1.4). This convergence (piling up) of air aloft increases the mass of air above the surface, which in turn causes the air pressure at the surface to increase. Hence, at latitudes near 30°, the convergence of air aloft produces zonal belts of high pressure called subtropical highs (or anticyclones). As the converging, relatively dry air above the highs slowly descends, it warms adiabatically. The subsiding air produces general clear skies and warm surface temperatures. It is in this zonal band at 30° that we find the major deserts of the world. Over the ocean, the weak pressure gradients associated with the high pressure systems produce only weak winds.

From the 30° N latitude, a fraction of the surface air moves back toward the equator. However, it does not flow directly back, because the Coriolis force deflects the air, causing it to flow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. These winds are known as trade winds or monsoon winds. Near the equator, the northeast winds converge with the southeast winds along a boundary called the intertropical convergence zone (ITCZ). In this region of surface convergence, air rises and continues its cellular journey.

Meanwhile, at latitude 30°, not all of the surface air moves equatorward. Some air moves toward the poles and deflects toward the east in the Northern Hemisphere,, resulting in a more or less westerly air flow called the prevailing westerlies, or, simply, westerlies in both hemispheres. The westerly flow is not constant since migrating systems of high and low pressure break the surface flow pattern from time to time.

As this air travels poleward, it encounters cold air moving down from the poles. These two air masses of contrasting temperature do not readily mix. They are separated by a boundary called the polar front, a zone of low pressure (the subpolar low) where surface air converges and rises. Some of the rising air returns at high levels to the 30° N latitude, where it sinks back to the surface in the vicinity of the subtropical high.

Polewards of the polar front, the cold air from the poles is deflected by the Coriolis force, so that the general flow of air is north easterly in the Northern Hemisphere (polar easterlies). In winter, the polar front with its cold air may propagate towards middle and subtropical latitudes, producing cold polar outbreaks. Along the polar front, a portion of the rising air moves poleward, and the Coriolis force deflects the air into a westerly wind at high levels in the Northern Hemisphere. Air aloft eventually reaches the poles, slowly sinks to the surface, and flows back toward the polar front, completing the weak polar cell.

Referring back to Figure 1.4, there are two major areas of high pressure and two major areas of low pressure at the surface. Areas of high pressure exist near latitude 30° and the poles, while areas of low pressure exist over the equator and near 60° latitude (in the vicinity of the polar front).

Average Surface Winds and Pressure

Donald (2001) discussed the average distribution of sea level pressure and winds for January and July (which are illustrated in Figure 1.5). One finds regions where pressure systems appear to persist throughout the year. These systems are referred to as semi permanent highs and lows because they move only slightly during the course of a year.

In Figure 1.5a, there are four semi-permanent pressure systems in the Northern Hemisphere during January. One is located in the eastern Atlantic Ocean, between latitudes 25° and 35°N and in the Pacific Ocean is its counterpart. These are the subtropical anticyclones that develop in response to the Hadley cell convergence of air aloft. Since surface winds rotate clockwise around these systems, the trade winds are found to be to the south and the prevailing westerlies to the north. In the Southern Hemisphere, where there is relatively less land area and as a result less contrast between land and water the subtropical highs show up as well-developed systems with a clearly defined circulation (Barry and Chorley, 1986; Tyson and Preston-Whyte, 2000 and Donald 2001)

The polar front (between latitudes 40° and 65°), is identified by two semi permanent subpolar lows. In the North Atlantic, there is a low covering Iceland and southern Greenland, and another centre over the Aleutian Islands in the North Pacific. These zones of cyclonic activity actually represent regions where numerous storms, having travelled eastward, tend to converge, especially in winter. In the Southern Hemisphere, the subpolar low forms a continuous trough that completely encircles the globe (Donald, 2001).

On the January map (Figure 1.5a), there are other pressure systems, which are not semi permanent in nature. Over Asia, for example, there is a huge (but shallow) thermal anticyclone called the Siberian high, which forms because of the intense cooling of the land. South of this system, the winter monsoon shows up clearly, as air flows away from the high across Asia and out over the ocean. A similar (but less intense) anticyclone is evident over North America (Donald, 2001). As summer approaches in the Northern Hemisphere, the land warms and the cold, shallow highs disappear. In some regions, areas of surface low pressure replace areas of high pressure. The lows that form over the warm land are normally thermal lows.

On the July map (Figure 1.5b), warm thermal lows are found over the desert southwest of the United States, over the plateau of Iran and over India. As the thermal low over India intensifies, warm, moist air from the ocean is drawn into it, producing the wet summer monsoons of India and southeast Asia. Comparing the January and July maps, several changes in the semi permanent pressure systems can be seen. The strong sub-polar lows that are well developed in January over the Northern Hemisphere are hardly discernible on the July map. The subtropical highs, however, remain dominant in both seasons. Because the sun is overhead in the Northern Hemisphere during July and overhead in the Southern Hemisphere during January, the zone of maximum surface heating shifts seasonally. In response to this, the major pressure systems, wind belts, and ITCZ (heavy red line) shift toward the north in July and toward the south in January (Donald, 2001). The continents have an important influence on the location of the ITCZ. This increases the complexity of the circulation compared to the three cell conceptual model (F`figure 1.4).

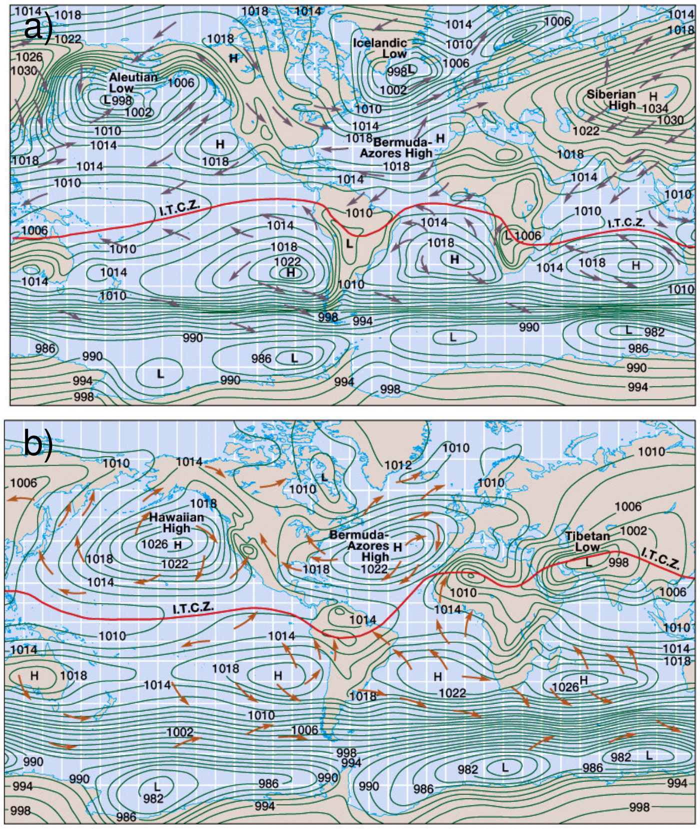

Figure 1.5. Average sea level pressure distribution and surface wind flow pattern for a) January and b) July. The heavy red line represents the position of the ITCZ. (After Donald 2001).

The General Circulation and Precipitation Patterns

The position of the major circulation cells and their latitudinal displacement (which annually averages about 10° to 15°) strongly influence the climates of many areas (Donald, 2001). For example, on the global scale, abundant rainfall is expected where the air rises (low pressure zones) and very little where air sinks (high pressure zones). Consequently, areas of high rainfall exist in the tropics, where humid air rises in conjunction with the ITCZ, and between 40° and 55° latitude, where middle latitude storms and the polar front force air upward. Areas of low rainfall are found near 30°

latitude in the vicinity of the subtropical highs and in the polar regions where the air is cold and dry (Figure 6).

Poleward of the equator, between the 10° and 30° latitude the general circulation, is influenced by both the ITCZ and the subtropical high. In summer (high sun period), the subtropical high moves poleward and the ITCZ might invade areas normally identified as subtropical, bringing with it ample rainfall. In winter (low sun period), the subtropical high moves equatorward, bringing with it clear, dry weather.

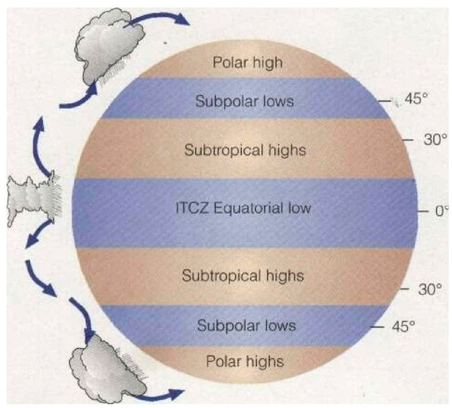

Figure 1.6. Major pressure systems and idealized air motions and precipitation patterns of the general circulation. Areas shaded blue represent abundant rainfall (after Donald, 2001).

Westerly Winds and the Jet Stream

The winds above the middle latitudes in both hemispheres blow in a more or less west to east direction. The reason for these westerly winds is that higher pressure over equatorial regions and lower pressures over polar regions are generally found aloft, (Donald, 2001). Where these upper-level winds tend to concentrate into narrow bands, streams of fast flowing air, called jet streams, are found.

Atmospheric jet streams are swiftly flowing air currents hundreds of miles long, normally less than several hundred miles wide, and typically less than a mile thick (Figure 1.7). Wind speeds in the central core of a jet stream often exceed 100 knots and occasionally 250 knots. Jet streams are usually found at the tropopause at elevations between 10 and 14 km (33,000 and 46,000 ft), although they may occur at both higher and lower altitudes.

Since jet streams are bands of strong winds, they must form in the same manner as all winds - due to horizontal differences in pressure. In Figure 1.7, notice that the jet stream is situated along the boundary where cold polar air lies to the north and milder subtropical air lies to the south in the Northern Hemisphere. The jet streams are important mechanisms in the atmosphere, driving atmospheric circulation along due to the vast amount of momentum and energy they provide. The jet stream is an important atmospheric feature for the UAE weather. In the winter it is especially important in driving westerly troughs over the Middle East region. These troughs are usually associated with precipitation.

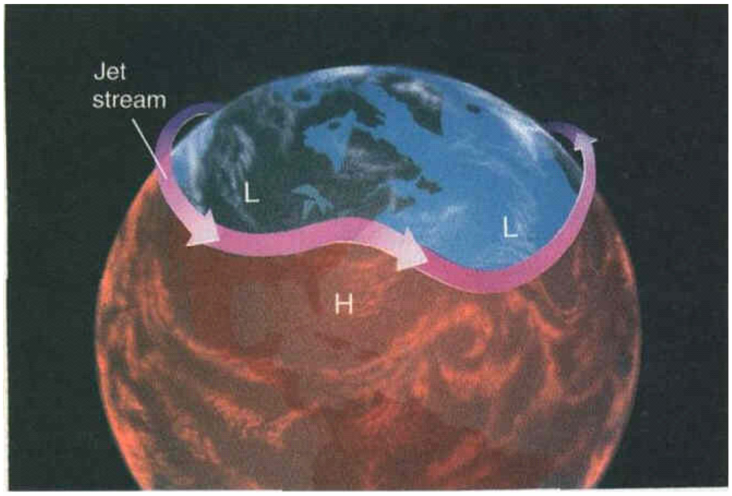

Figure 1.7. A jet stream is a swiftly flowing current of air that moves in a wavy west-to east direction. It forms between warmer and colder air (after Donald, 2001).

Atmospheric stability

Meteorologists are concerned with static stability parameters in order to understand convective weather patterns and the dispersion potential of the atmosphere. If the atmosphere is unstable, with abundant low-level moisture and a mechanism exists to lift the air (thereby releasing the potential instability), convective weather and rainfall can develop. Conditions favourable for these events are warm moist air at low levels; cool dry air aloft and surface convergence coupled with upper-level divergence. A study done by Wilson and Scoggins (1976) reports that convective activity exist "in areas where the low and middle troposphere is moist, air is potentially and convectively unstable, and has upward motion, in combination with positive moisture advection, at either the surface or within the boundary layer."

Static stability is defined as the stability of the atmosphere in hydrostatic equilibrium with respect to vertical displacements. These displacements are explained by using the parcel method. The parcel is a hypothetical box that does not allow for any transfer of heat energy into or out of the box, but allows for adiabatic temperature or internal energychanges. The stability of the parcel is dependent upon the vertical parcel's motion after a forced displacement from an original location. As the parcel undergoes adiabatic change, its temperature is compared to that of the surrounding environment so as to relate differences in density. A parcel that returns to its original position is considered stable while one that will continue upwards from its original position is unstable. One that is displaced and remains at its new position is considered neutral. Given the importance of the stability in producing severe convection (Doswell et al. 1985; Johns and Doswell 1992; Tyson and Preston-Whyte 2000), knowing the climatology of this parameter is a step toward understanding the complex relationship between the environmental stability and the formation of severe storms. Previous climatological studies about stability have shown that tropospheric stability is not temporally and spatially homogeneous (Gates 1961; Havonec and Horn 1983; Lee and Mak 1994).

Four basic stability profiles

How quickly the atmosphere cools with height, known as the environmental temperature lapse rate, determines the atmosphere's stability. The four main classifications are as follows.

1. Absolutely stable: Environmental temperature lapse rate (Γ) is less than the moist adiabatic temperature lapse rate (Γm), and less than the dry adiabatic temperature lapse rate (Γd) i.e $\Gamma d > \Gamma m > \Gamma$. Any air parcel rising in this atmosphere will eventually become cooler than its environment and begin to sink. Very few, if any, clouds form in an absolutely stable atmosphere.

2. Neutral stability: Exists when the environmental temperature lapse rate (Γ) is equal to the dry adiabatic temperature lapse rate (Γd), i.e $\Gamma d = \Gamma$. The rising air parcel is cooling at the same rate as the environment so the temperature difference between the parcel and its environment remains constant with height. In other words, the atmosphere will not help an air parcel to rise, but it will not cause it to sink either.

3. Conditionally Unstable: Environmental temperature lapse rate (Γ) is less than the dry adiabatic temperature lapse rate (Γd), but greater than the moist adiabatic temperature lapse rate (Γm), i.e $\Gamma d > \Gamma > \Gamma m$. This profile would be stable for an unsaturated air parcel, but unstable for a saturated air parcel. This is the state that the atmosphere most commonly exists in. Clouds and precipitation usually form as a result of unsaturated air being forced to rise by heating, fronts, topography, etc. If enough moisture is present in the unsaturated air parcels, they become saturated and unstable and continue to rise and form clouds and precipitation. This process causes many of summer's showers and thunderstorms.

4. Absolutely unstable: Environmental temperature lapse rate (Γ) is greater than the dry adiabatic temperature lapse rate (Γd), i.e $\Gamma > \Gamma d > \Gamma m$. Any air parcel in this atmosphere will quickly rise since it would always be warmer than its environment. Absolute instability is usually limited to only a shallow layer of air near the surface on a hot, sunny day.

How the atmosphere becomes stable

Any process that causes warmer conditions aloft relative to cooler conditions at the surface will increase the atmosphere's stability. Some of the processes are as follows:

1. Radiational cooling: Occurs on clear skies, calm wind nights. Air near the surface cools more quickly than air above it, and as a result, cooler air is located near the surface and the temperature increases with height (inversion)

2. Cold advection at surface: Cold air filters into region at the surface and causes temperatures to drop faster at the surface than at higher altitudes. This also enhances a stable cold air at surface to warm air at higher altitudes scenario
3. Warm advection aloft: Warm air moves into the higher altitudes and causes temperatures to rise faster than at the surface
4. Air moving over cold surface: The air closest to the surface cools and again creates cold air under warm air conditions
5. Large scale sinking of the air: A thick layer of air is compressed by the weight of the atmosphere and becomes a thinner layer of air as it sinks. As a result, the upper part of the layer sinks farther than the bottom and warms more. This causes the air aloft to warm more than the air at the surface, and hence, increases stability

How the atmosphere becomes unstable

Any process that causes colder conditions aloft relative to warmer conditions at the surface will cause the atmosphere to become more unstable. Some of the processes are as follows:

1. Heating of the surface: Sunshine heats the surface, and the air near it, and causes warmer conditions at the surface, which makes the atmosphere more unstable
2. Warm advection at surface: Warm air moves into region at the surface and warms temperatures at the surface more quickly than at higher altitudes. This causes warmer conditions at the surface relative to higher altitudes and therefore makes the atmosphere more unstable
3. Cold advection aloft: Cold air moves into the higher altitudes and causes temperatures to cool faster than at the surface
4. Air moving over warm surface: Air closest to the surface warms up and enhances the unstable cold air over warm air scenario

5. Mixing of the air: Rising air lowers the temperatures toward the top of the layer while sinking air warms temperatures toward the bottom
6. Large scale rising of the air: A thick layer of air expands and becomes thicker as it rises. The upper part of the layer rises more than the bottom and cools more as a result. This creates colder temperatures aloft relative to the surface and causes the atmosphere to become more unstable

Research goals

The aim of this study is to classify the synoptic circulation patterns over the UAE and evaluate each circulation patterns influence on rainfall. In order to accomplish this, an analysis of the atmospheric stability over the UAE will also be undertaken. The specific objectives of this dissertation are:

1. To classify the synoptic circulation patterns over the UAE
2. To evaluate the contribution of each identified category to rainfall production over the UAE
3. To determine the atmospheric stability conditions over the UAE and evaluate if it could act to inhibit rainfall

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> The basis of all good atmospheric science starts with advanced knowledge of the circulation systems influencing the region of interest. The importance large scale circulations have been discussed. Synoptic scale circulation has not been formally classified over the UAE previously. The aims of this dissertation have been outlined. The methods that are used to achieve the aforementioned will be discussed in detail in Chapter 2.

CHAPTER 2

DATA AND METHODOLOGY

A large and diverse data set has been employed in this study to obtain an inclusive and accurate understanding of atmospheric processes over the UAE as they relate to synoptic circulation, rainfall and atmospheric stability. The purpose of this chapter is to outline the data and methodologies utilized in this study to achieve the objectives outlined in the previous chapter

Data

The Synoptic Charts (Surface and Upper air Charts at 500 hPa)

Surface (sea level pressure) and upper air (500 hPa) synoptic charts have been obtained from the Weather Office at Abu Dhabi International Airport for a period of seven years (1995-2001). Abu Dhabi International Airport has the largest data record in the UAE, as well as having the most experienced forecasting office in the country. Synoptic charts were provided in hard copy form and scanned to be archived in electronic form. The synoptic charts are produced daily in the forecast office at the airport at 00h00 GMT and 12h00 GMT, and are representative of the atmospheric circulations at the surface and at 500 hPa. Data used to compile the information were obtained from ground based monitoring stations as well as radiosonde ascents.

Rainfall Data

The rainfall data has been obtained from the Ministry of Agriculture, Ministry of Communication and from all the weather offices at the International Airports in the UAE. The rainfall data records are expressed as daily totals in millimetres. The period of available rainfall records varied significantly between stations. All relevant information regarding the rainfall data have been summarized in Table 2.1.

One difficulty with the rainfall data is that it is a mixture of automatic rain gauges with high temporal resolution measurements and manual rain gauges read only once per day. Data obtained from the Ministry of Agriculture were collected using automatic tipping bucket rain gauges. Rainfall data collected at the International Airports are mostly manual stations. The concentration of surface stations is skewed to the east of the UAE (Figure 2.1). This is due to the sparse population densities west of Abu Dhabi. Rainfall data are most representative of the eastern portion of the UAE.

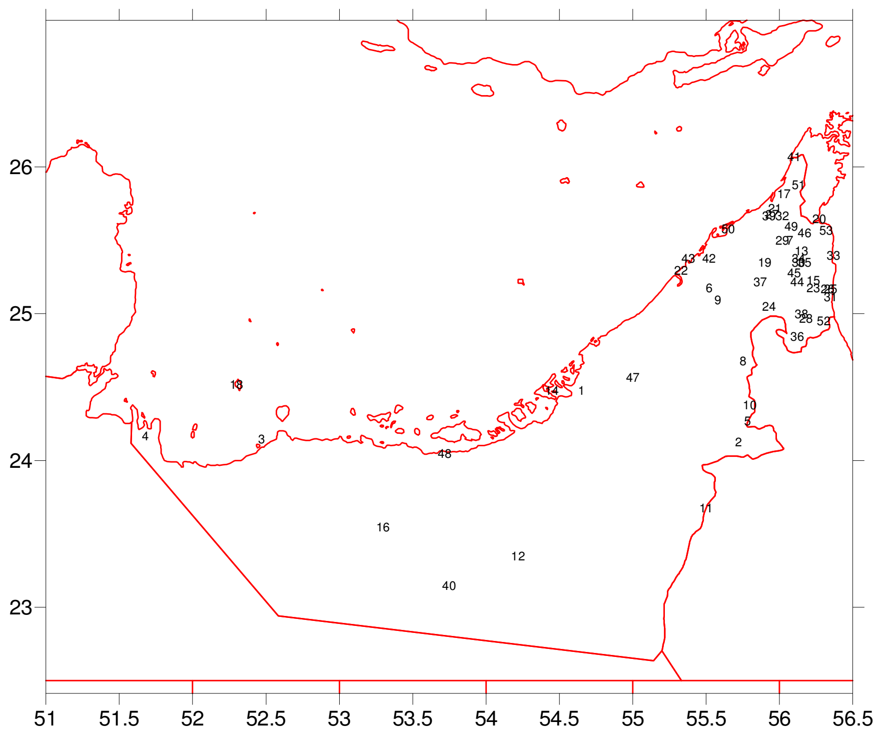

Figure 2.1 Location of rainfall stations in the UAE used in this research project. The numbers on the map coincide with the numbers and names of stations in Table 2.1.

Table 2.1. Location and period of measurement of rainfall measurements in the UAE

Stations Name	Longitude	Latitude	Observation period
Ab D.A.P.	54.65	24.43	1991-2002
An Sukhnah	55.72	24.08	1980-2001
AL Hamra	52.47	24.10	1986-2000
Al Sila	51.68	24.12	1988-1995
AL Ain	55.78	24.22	1991-2002
AL Awir	55.52	25.13	1980-2001
Al Ghail	56.07	25.45	1979-2002
AL Haiyir	55.75	24.63	1979-2002
AL Haibab	55.58	25.05	1991-2002
Al Oha	55.80	24.33	1991-2002
Al wagan	55.50	23.63	1979-2002
Asab	54.22	23.30	1979-2002
Asimah	56.15	25.38	1979-2002
Bateen A.P.	54.45	24.43	1979-2001
BITHNA	56.23	25.18	1976-2001
Bu Hasa	53.30	23.50	1979-2002
Burairat	56.03	25.77	1979-2002
Delma	52.30	24.47	1984-2000
Dhaid	55.90	25.30	1979-2002
Dibba	56.27	25.60	1979-2002
Digdaga	55.97	25.67	1979-2002
Dubai A.P.	55.33	25.25	1979-2002
Farah	56.23	25.13	1979-2002
FILI	55.93	25.00	1979-2002
FUJAIRAH	56.35	25.12	1979-2002
Fujaira A.P.	56.33	25.12	1979-2002
Hamraniyah	55.95	25.63	1979-2002
Howeilat	56.18	24.92	1976-2002
IDHN	56.02	25.45	1979-2002
J. Sharmah	56.13	25.30	1979-2002
Kalba	56.35	25.07	1979-2002
KHATT	56.02	25.62	1979-2002
Khorfakkan	56.37	25.35	1979-2002
Marbad	56.13	25.33	1979-2002
Masafi	56.17	25.30	1979-2002
Masfut	56.12	24.80	1979-2002
Meleiha	55.87	25.17	1979-2002
MUNAI	56.15	24.95	1976-2002
R.K.A.P.	55.93	25.62	1979-2002
Radom	53.75	23.10	1987-1995
Shaam	56.10	26.02	1979-2002
Sharjah A.P.	55.52	25.33	1979-1997
Sharjah T. A.p	55.38	25.33	1979-2002
SIFUNI	56.12	25.17	1976-2002
Siji	56.10	25.23	1976-2002
SINNAH	56.17	25.5	1977-2002
Swehan	55.00	24.52	1989-1995
Tarif	53.72	24.00	1986-1995
Tawiyn	56.08	25.55	1982-2002
Umm Al Quwain	55.65	25.53	1979-2002
Wadi Bih	56.13	25.83	1979-2002
Wahala	56.30	24.90	1979-2002
Zikat	56.32	25.52	1979-2002

Radar and Rain Enhancement Aircraft

During 2001 to 2003 the UAE implemented a network of five weather radars (Figure 2.2). Data from five radars are now available that satisfy the stringent requirements for obtaining rainfall amounts with good spatial and temporal resolution across the UAE. Table 2.2 gives the location and specification for each radar. For this study the radar images have been used qualitatively to evaluate historical rainfall data and to assess how representative these are for the UAE. Quantitative techniques for extracting rainfall data from radar networks do exist but fall beyond the scope of this study.

Radar data (2001-2004) was used to evaluate spatial classification of rainfall data over the UAE. Using data from the rainfall enhancement aircraft, it was found that there were many convective clouds and precipitation over regions of the UAE where no rain gauges were located. This is especially true for the mountainous regions of the UAE, along the border with Oman, as well as the south-western parts. An example is presented in Figure 2.3. Rainfall over the mountainous region and in the south-western parts occurs frequently during the summer but has never been captured in the rainfall measured by the rain gauges.

Table 2.2. Weather Radar locations and specifications

Radars	Latitude	Longitude	Wavelength (cm)	Transmitter power (kW)	Antenna gain (dB)
Al Dhafra	54 33.2	24 15.16	5.32	250	43
Dubai	55 21.94	25 15.65	5.36	300	46
Mobile (Alain)	55 37.11	24 15.56	5.36	300	38
Mezaira	53 45.28	23 06.19	5.36	300	45
Delma	52 19.54	55 21.94	5.36	300	45

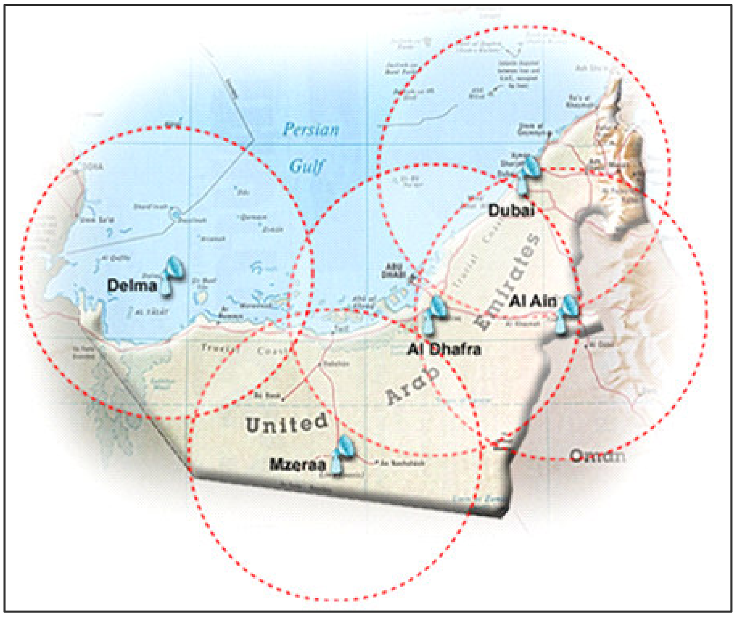

Figure 2.2. Radar coverage over the UAE. The dashed red lines indicate the coverage area of each radar.

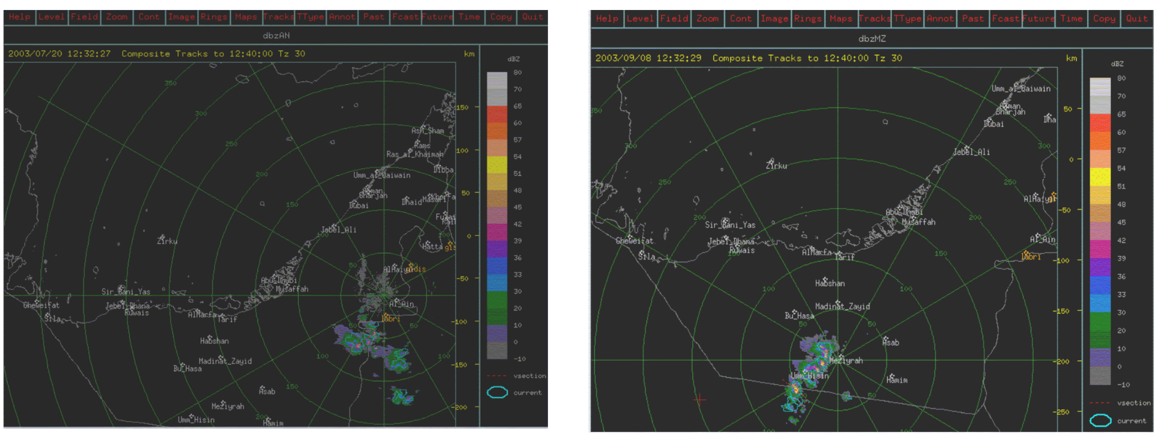

Figure 2.3. Radar images for 20-7-2003 and 8-9-2003 showing how rainfall can fall between rain gauges and therefore not be accurately recorded.

Upper Air Data

The upper air data have been obtained from 00h00 and 12h00 GMT radiosonde ascents at Abu Dhabi International Airport. These data have been analyzed for the period from 1995-2001. The radiosonde data are assumed to be representative of upper air conditions for the entire country. These data have been re-formatted so that they can easily be input into the NCAR SUDS Software package, which generates Tephigram plots for further analysis.

Methodology

Each of the above mentioned data sets have been analyzed in order to achieve the objectives of this study outlined in Chapter 1. In most instances an attempt has been made to collect sufficiently long data sets to be able to infer climatological trends. The procedures used to summarize and analyze the respective data are outlined in detail below.

Synoptic circulation patterns over the UAE

Surface synoptic scale circulation

The prevailing surface synoptic circulations have been classified into twelve possible circulation patterns impacting the UAE region. The classification was based on the surface pressure fields that covered an area extending between 51º and 57ºN, 22.5º and 27.5ºE (Figure 2.4). The twelve possible categories of surface synoptic circulation are provided in Table 2.3. The synoptic circulation for every day over a period of seven years has been classified into one of the categories. The classification was done manually comparing the pattern of circulation for each day. The frequency of occurrence of each category has been calculated over the study period (1995-2001). In addition the seasonal variation of each circulation type has also been determined as a percentage of days of occurrence. From these data, it is possible to evaluate the seasonal variability and importance of each category to the overall circulation. An average circulation category pressure field has been constructed and represented schematically for each system. An example is shown in Figure 2.5. The results are presented in the Chapter 3.

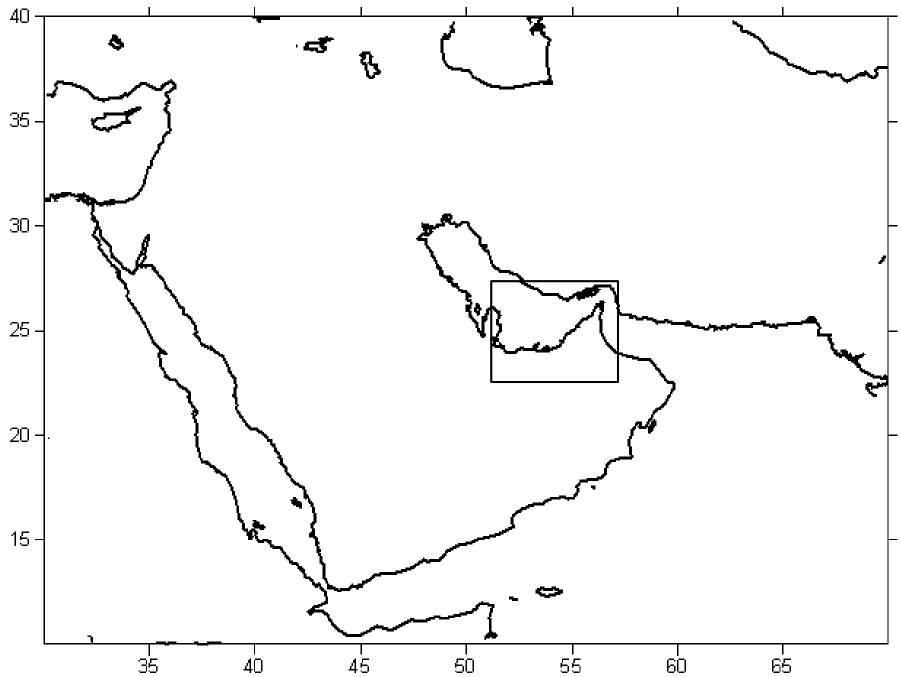

Figure 2.4. Map showing the Middle East including the region of interest. The box represents the region for which synoptic circulations have been classified.

Table 2.3. Classification of the different surface pressure systems identified as affecting the circulation over the UAE.

Surface pressure systems	Abbreviation
Siberian high	SH
Red Sea trough	RST
Mediterranean trough	MT
Siberian high Indian high	SH/IH
Easterly trough	ET
Indian Ocean high	IH
Thermal low	TL
Easterly trough/Siberian high	ET/SH
Red Sea/Mediterranean troughs	RST/MT
Red Sea/Easterly trough	RST/ET
Indian high/Thermal low	TLIH
Easterly trough/Thermal low	ET TL

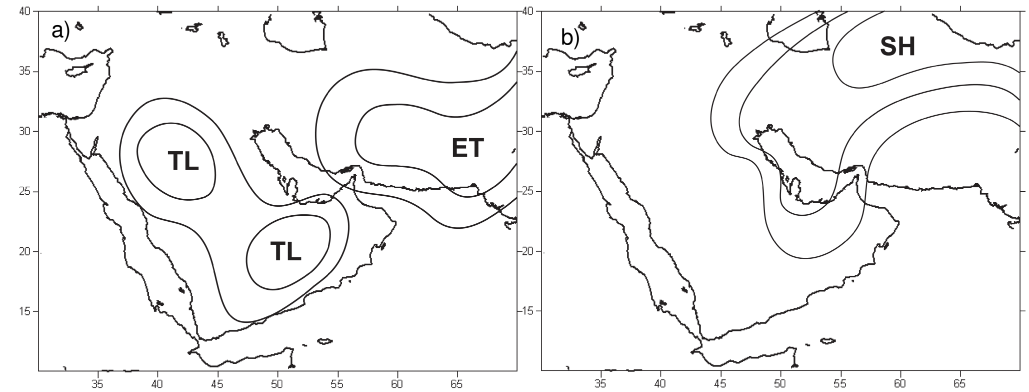

Figure 2.5. Examples of a) easterly trough with thermal low circulation(ET/TL), and b) Siberian high pressure (SH) circulation at the surface over the UAE.

Upper Air Charts (500 hPa)

Synoptic circulation charts at 500 hPa have also been evaluated and classified into different categories for the period 1995-2001. Each pressure system in the upper atmosphere was assigned to a category according to the location of the system and the air mass associated with the system. Also, the classification used in this study for the upper air systems was conducted according Tyson *et al.,* (1996). Table 2.4 shows the classifications and assigned codes for the different upper pressure systems. An example is shown in Figure 2.6. The surface and the upper air pressure systems were combined for seven years period and were related to the rain events that occurred during different synoptic situations.

Table 2.4. Categories of upper air synoptic circulation patterns identified for this study with respective codes of occurrence, which have been used throughout the study.

Upper pressure systems	Classification Code
Westerly trough	WT
Westerly ridge	WR
Easterly trough	ET
Subtropical high	STH
Zonal flow	ZF
Westerly cut-off low	WCL

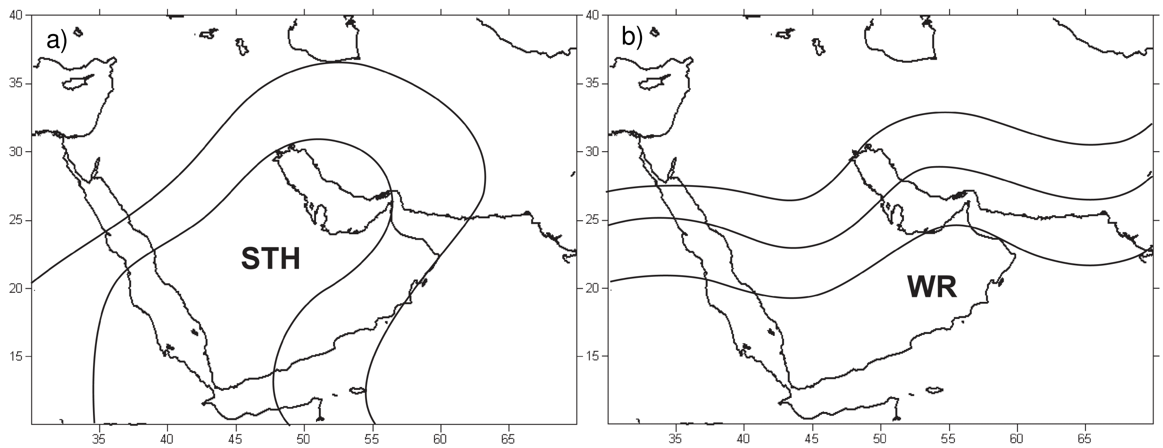

Figure 2.6. Examples of a) subtropical high pressure circulation (STH), b) and westerly ridge circulation (WR) at 500hPa over the UAE.

Rainfall

Rainfall data was quality checked for consistency and accuracy. A major problem with rainfall data over the UAE is that it is highly variable in time and space. The variability of rainfall over the UAE is shown in Figure 2.7 for the period 1980-2002. Rainfall over the UAE is clearly highly variable with annual values ranging between 25 $mm.annum^{-1}$ and 375 $mm.annum^{-1}$. The variability on the UAE rainfall has not previously been investigated in any detail. An extensive study of rainfall variability in relation to other global teleconnections is needed; however, it is beyond the scope of this study.

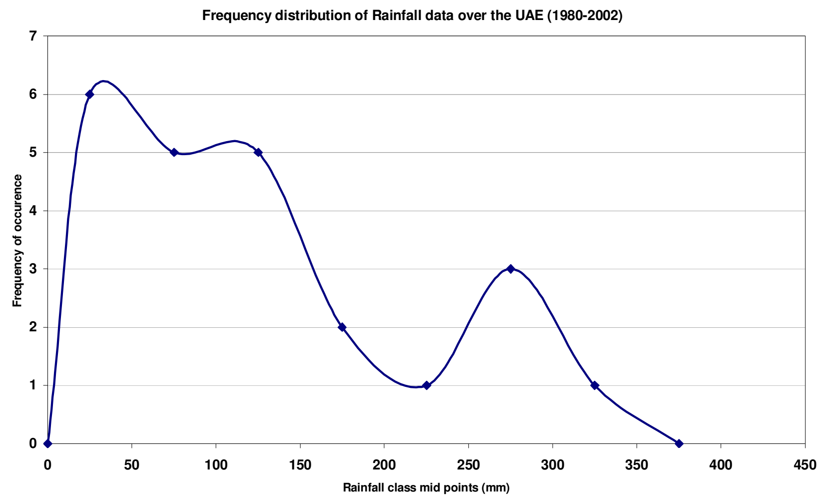

Figure 2.7. Frequency distribution of annual average rainfall data over the UAE (1980-2002)

The relation between the dominant pressure systems and the rainfall over the UAE.

The surface and upper air pressure systems have been linked together day by day for a seven year period in order to establish the weather situation which could be correlated to the rainfall over the UAE. The number of rainy days and non rainy days associated with the weather synoptic situation has been obtained on a daily basis throughout the period 1995 to 2001. The total amount of rainfall over different parts of the UAE has also been obtained daily. The total number of rainy days was 721 days, which represents 30% of the study period. The total amount of rainfall was calculated and correlated to the pressure systems (Surface + Upper), to determine and resolve the active pressure systems with respect to the intensive rainfall. These systems and resultant rainfall are discussed in Chapter 3.

Atmospheric stability

The thermodynamic structure of the atmosphere is an important consideration for all meteorological studies. In the middle latitudes the prevalence of high pressure systems leads to the extreme and constant atmospheric stability that inhibits vertical mixing in the atmosphere. The UAE's position in the northern hemisphere determines that it is widely affected by predominantly high pressure systems with a net downward vertical flow. These conditions are ideal for the formation of extensive subsidence inversion layers in the atmosphere. There are important degrees of atmospheric stability. Inversion layers represent the most extreme stability conditions. Absolute stability is a more conservative measure of atmospheric stability and is defined in the atmosphere where the environmental temperature lapse rate is less than the saturated adiabatic temperature lapse rate (Figure 2.8). An attempt has been made in this study to explore the nature of atmospheric stability over the United Arab Emirates. A climatology of atmospheric absolutely stability derived from seven years of radiosonde soundings over Abu Dhabi Airport has been developed. Radiosonde soundings are conducted at Abu Dhabi airport at midday and midnight GMT (09h00 and 21h00 local time respectively).

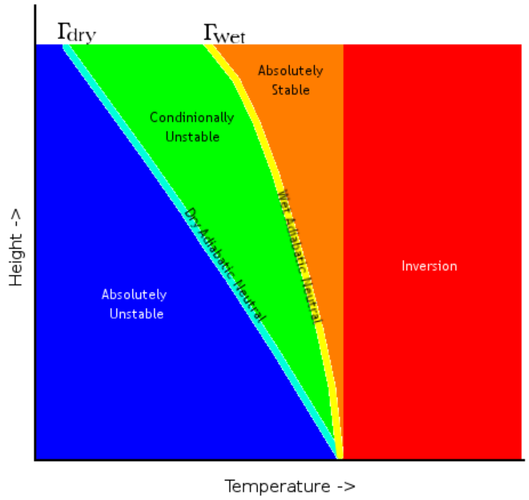

Figure 2.8. The dry adiabatic - Γ_{dry} (turquoise) and wet adiabatic - Γ_{wet} (yellow) temperature lapse rate are used to stratify the atmospheric temperature lapse rate into absolutely unstable (blue), conditional unstable (green), absolutely stable (orange) and inversion (red). When the environmental temperature lapse rate is equal to the adiabatic temperature lapse rate, it will be neutral.

Atmospheric stable layers form in the atmosphere as a result of several factors such as surface radiation cooling, katabatic flow of cold air into valleys or low points of irregular terrain or advection of cold air under less dense warmer air and adiabatic heating of air as it descends in the atmosphere (Tyson and Preston-Whyte, 2002 and Oke, 1987). The first two mechanisms mentioned above are associated with surface inversions or stability. The air close to the surface is colder than the layers above causing an inversion. Studies of atmospheric stability over the UAE have not been studied previously in any detail. Absolutely stable layers have been shown to be significant over southern Africa. It has been shown that absolutely stable layers in this environment have a profound impact on convective activity, long-range transport of atmospheric constituents and pollution, the severity of local air pollution and the transport of water vapour over the southern African subcontinent (Garstang *et al.*, 1996; Cosijn and Tyson, 1996; Swap and Tyson, 1999 and D'Abreton and Tyson, 1999). The main field of interest for this analysis was the environmental temperature lapse rate with height as measured by the radiosonde balloons.

Dry adiabatic temperature lapse rate describes the temperature changes that a parcel of air will experience when undergoing vertical motion in an adiabatic environment (not exchanging heat with its environment).

$-[dT/dz] = g/C_p = \Gamma_{dry}$ --- (Equation 2.)

Equation 2 expresses the dry adiabatic lapse rate in terms of the first law of thermodynamics. This has a constant value of about 9.8 ºC km^{-1}.

$$-[dT/dz] = g/C_p = \Gamma_{dry} \quad \text{--- (Equation 2.2)}$$

where, T – temperature; z – height; g – gravitation; C_p – specific heat of air at constant temperature

When no condensation is taking place, the dry adiabatic temperature lapse rate can be used to describe vertical motions in the atmosphere. However, the latent heat release associated with condensation will alter the temperature lapse rate depending on the variation of the saturated humidity mixing ratio with height. This temperature lapse rate is known as the saturated or wet adiabatic temperature lapse rate, Γ_{wet}, and is defined in Equation 2.2.

$$-[dT/dz] = \Gamma_{dry} + L/C_p \cdot [dx_s/dz] = \Gamma_{wet} \quad \text{--- (Equation 2.1)}$$

where, T – temperature; z – height; g – gravitation; C_p – specific heat of air at constant temperature; L – latent heat; x_s – saturated mixing ration

Figure 2.8 is a graphic presentation of the temperature lapse rate with height. The turquoise line illustrates the dry adiabatic temperature lapse rate. The yellow line illustrates the wet adiabatic temperature lapse rate. The equilibrium or stability of the atmosphere can be described in reference to the dry and wet adiabatic temperature lapse rates.

A climatology of absolutely stable layers

Vertical sounding or radiosonde data have been obtained for a period of seven years from Abu Dhabi Airport (1997-2002). Abu Dhabi was selected as the most appropriate site as a result of the fairly long-term reliable data set available from this site. Radiosonde data are available at other sites in the UAE, Aldhfra and Dubai. Missing data from these two sites was perceived to be a problem at the aforementioned upper air stations.

Daily soundings at both midnight (00h00) and midday (12h00) have been analysed by hand on Skewed-T graphs to identify all absolutely stable layers present in the atmosphere. Approximately 5000 vertical soundings were analysed for the study period. Absolute stability as mentioned above, is been defined as all regions in the atmosphere where the recorded environmental lapse is less than the gradient of the saturated adiabatic lapse rate. The radiosonde data were plotted on skewed tephigrams for analysis purposes. The identified layers were recorded for each day for the two soundings. Layers above 300 hPa were not considered for this study. Figure 2.9 gives an example of a skewed-T plot on 18 June 1999. These data were downloaded from the University of Wyoming (http://www.weather.uwyo.edu/upperair/sounding.html) web page. An initial analysis of one year's data showed that six possible absolutely layers could form in the atmosphere over the UAE at the surface, 850, 700, 500, 400 and 300 hPa. Absolutely stable layers identified in each temperature profile over Abu Dhabi were classified in one of these six layers. The bottom and top pressure surface of each of these layers was recorded. The details of each layer has been characterised in detail for summer (May to October) and winter (November to April) respectively.

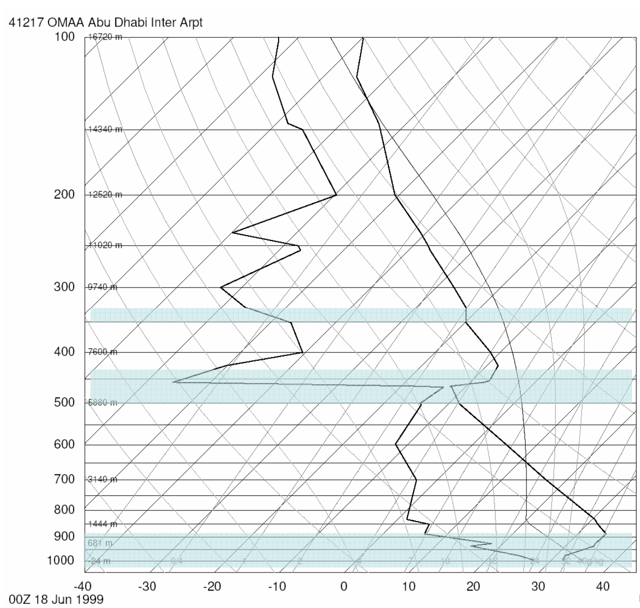

Figure 2.9. A Skewed-T of vertical dry bulb (right line) and wet bulb (left line) temperature against pressure (hPa) for 18 June 1999 at Abu Dhabi Airport. The blue shaded areas show the absolutely stable layers for this day at midnight below 300 hPa.

The long term data sets of thermodynamic profiles have also been used to automatically calculate the atmospheric stability at Abu Dhabi (station code 41217) and Muscat (station code 41256) for the period 1989 to 2002. The purpose of the additional analysis was to confirm the aforementioned results. Periods of atmospheric stability were identified according to the above mentioned criteria as described in Figure 2.8. An example the results obtained from automatic analysis in shown in Figure 2.10.

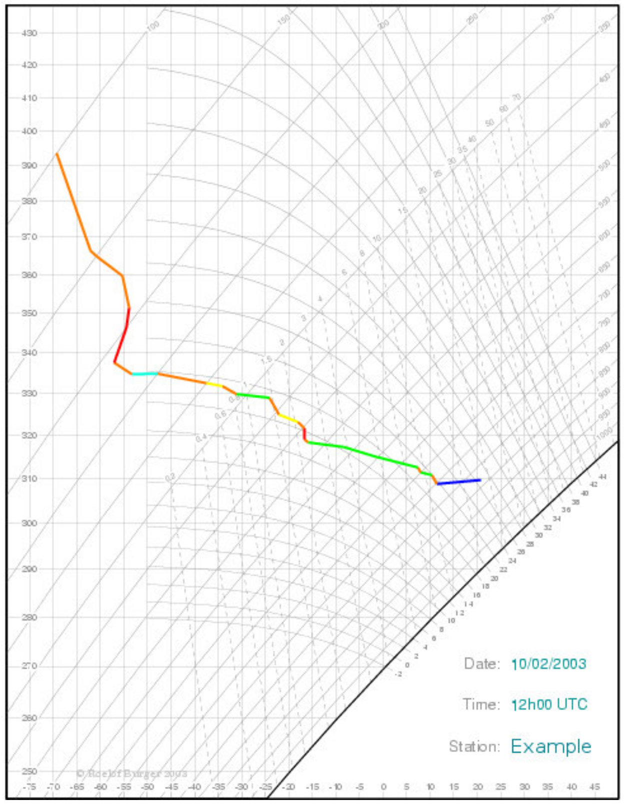

Figure 2.10. An example of the environmental lapse rate that is stratified according to the colour scheme explained in Figure 2.8.

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The data and methodologies used in this dissertation have been summarised. Synoptic circulation classifications at the surface and in the upper atmosphere have been based on daily charts obtained from Abu Dhabi International Airport. Rainfall data have been obtained from the entire UAE with a bias to the eastern parts of the country. Atmospheric stability has been evaluated using radiosonde sounding from Abu Dhabi International Airport for a ten year period.

CHAPTER 3

SYNOPTIC CIRCULATION AND RAINFALL OVER THE UAE

In order to obtain a clear understanding of the nature of large scale circulation over the UAE a climatological classification of synoptic circulation patterns has been undertaken. Results of the classification are presented in this chapter. In addition, each synoptic circulation type has specific implication on atmospheric conditions that impact the rainfall potential over the UAE. Rainfall patterns related to each synoptic classification will be discussed.

Synoptic climatology for the UAE

Surface synoptic circulation

Synoptic charts of the region surrounding the UAE have been analyzed on a day to day basis to quantify the frequency of the occurrence of each pressure systems and the effects on the weather of the UAE. The synoptic circulations that govern weather and climate in the UAE are complicated and difficult to identify unambiguously. Weather patterns frequently result from a combination of pressure changes, and dynamic air movements that vary both horizontally and vertically in time.

An analysis of the surface pressure charts between 1995 to 2001 show that the region around the UAE is affected by the following surface pressure systems: Siberian High (SH), Red Sea Trough (RST), Easterly Trough (ET), Indian Ocean High (IH), Thermal Low (TL) (Table 2.3). The other systems that effect the weather over the area are combinations of the aforementioned systems such as: Easterly Trough and Siberian High (ET/SH), Red Sea Trough and Easterly Trough (RST/ET), the Mediterranean Trough, Red Sea Trough and Easterly Trough (MT/RST/ET), Thermal Low and Indian

High (TL/IH), Siberian High and Indian High (SH/IH), Easterly Trough and Indian High (ET/IH), and Easterly Trough and Thermal Low (ET/TL).

A strong seasonal signal is evident in the occurrence of synoptic circulation patterns over the UAE. During winter months SH is the most dominant over the region occurring up to 48 % of the time in January. During the summer months the centre of the high pressure systems shifts towards the north and a combination of the easterly trough and a thermal low is evident (up to 44 %) (Table 3.1). Each identified category of synoptic scale circulation will be discussed in detail.

Table 3.1. The average of the total frequency of occurrence (%) of each surface pressure systems at each month of the year between 1995 and 2001.

Month	SH	ET	TL	RST	IH	ET/SH	ET/TL	RST/ET	T/IH	MT/RST/ET	SH/IH	ET/IH
January	48.4	11.1	0.0	6.0	1.4	23.5	0.0	5.5	0.0	4.6	0.0	0.0
February	41.3	9.7	0.0	12.2	3.6	19.4	0.0	14.3	0.0	0.5	0.0	0.0
March	33.2	6.0	0.0	6.5	2.8	22.6	0.0	24.0	0.0	4.1	0.0	0.0
April	30.0	14.8	0.0	3.8	4.3	24.7	0.5	19.0	0.0	2.4	1.9	0.3
May	12.4	31.8	11.5	0.9	1.8	29.5	5.5	6.5	0.0	0.0	0.0	0.9
Jun	1.9	32.9	22.4	0.0	3.3	11.9	27.1	0.5	0.0	0.0	0.0	0.0
July	0.0	18.9	27.2	0.0	1.4	1.4	44.2	0.0	6.9	0.0	0.0	0.3
August	0.0	17.1	28.1	0.5	0.9	3.2	41.0	0.9	7.7	0.0	0.0	0.0
September	2.9	18.1	24.8	1.4	0.5	5.2	22.9	3.8	20.5	0.0	0.3	0.3
October	16.1	20.3	11.5	4.1	2.3	26.3	6.0	7.4	3.7	0.0	2.3	0.0
November	26.7	22.4	2.4	7.6	1.4	33.8	0.5	3.3	0.0	0.3	1.0	0.3
December	32.7	15.7	0.0	4.6	1.4	32.3	0.0	9.2	0.0	0.3	0.0	0.3

Siberian high (SH)

In winter the dominant system over the region is SH which is centred over Iran (Figure 3.1) (Browe Jr, 1992). It starts to appear at the beginning of November (27%) and it reaches its maximum impact during January (48%), and decreases again in April to (30%). The atmospheric conditions associated with the SH are fresh cold and dry with dominant northerly to north-westerly winds.

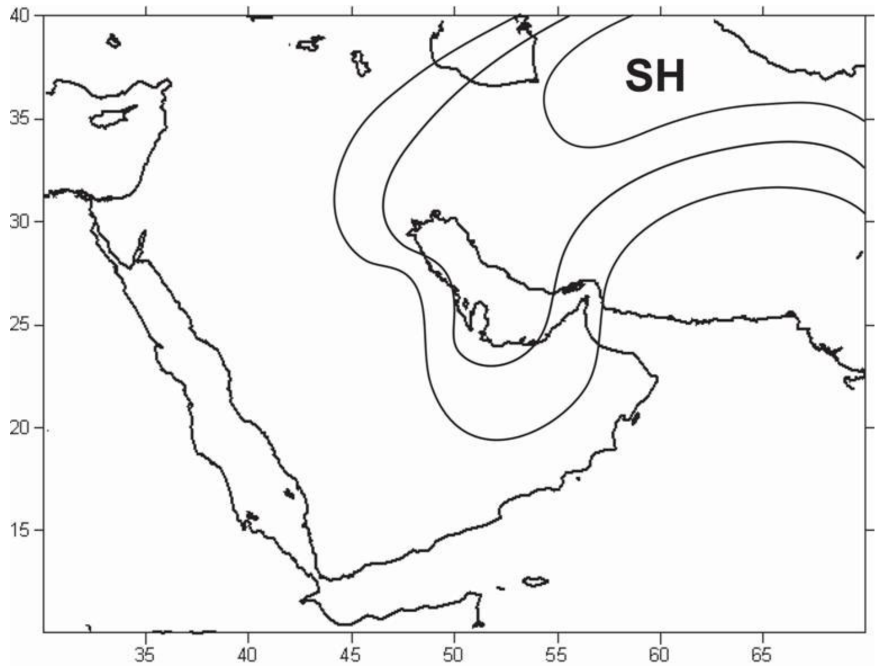


Figure 3.1. An average surface synoptic chart associated with the Siberian high (SH) pressure over the UAE region.

Easterly Trough (ET)

The ET persists over the region throughout the year. The ET is an extension of the Indian Monsoon Low, and is often associated with the advection of warm, moist air over the UAE (Figure 3.2). Rain occurs as a result of the formation and development of cumuliform clouds over the mountain areas. The highest frequency of occurrence occurs in the months of May (32%) and June (33%) respectively. This synoptic situation results from the extension of depressions from the east and depends on the ridging of the SH at the end of the winter season and a decline in the thermal depressions at the end of the summer season. The wind associated with these depressions is easterly to south easterly or north easterly depending on the location of the depression in relation to the UAE.

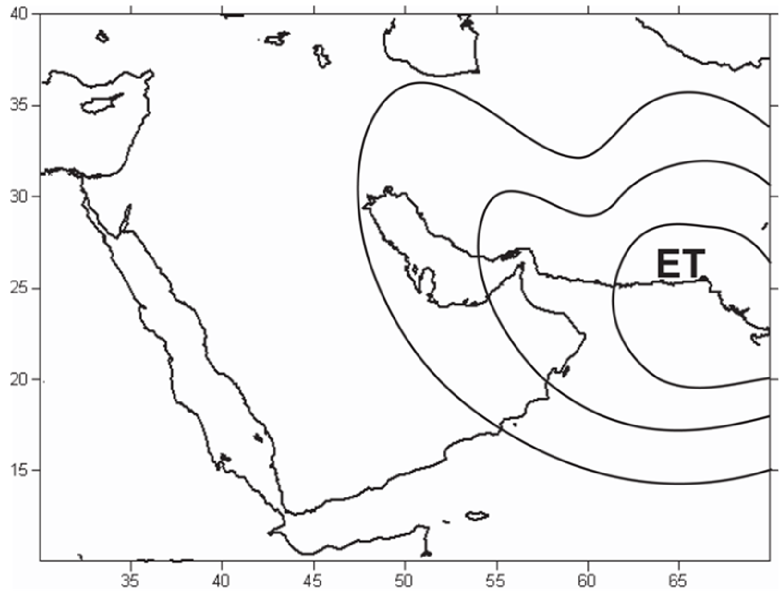


Figure 3.2. An average surface synoptic chart associated with the Easterly trough (ET) pressure over the UAE region.

Thermal Low (TL)

This type of depressions develops due to the high insulation of the solar radiation over the interior parts of the Arabian Peninsular. The Thermal low (TL) depression is mostly centred over the Arabian Peninsula (Figure 3.3). During the summer months starting from June to September, the thermal low is a common feature and occurs on approximately 28 % of all days. The wind associated with this system is usually southerly and is normally hot and dry. Under the influence of the TL ambient temperatures over the central UAE can rise to as high as 50ºC.

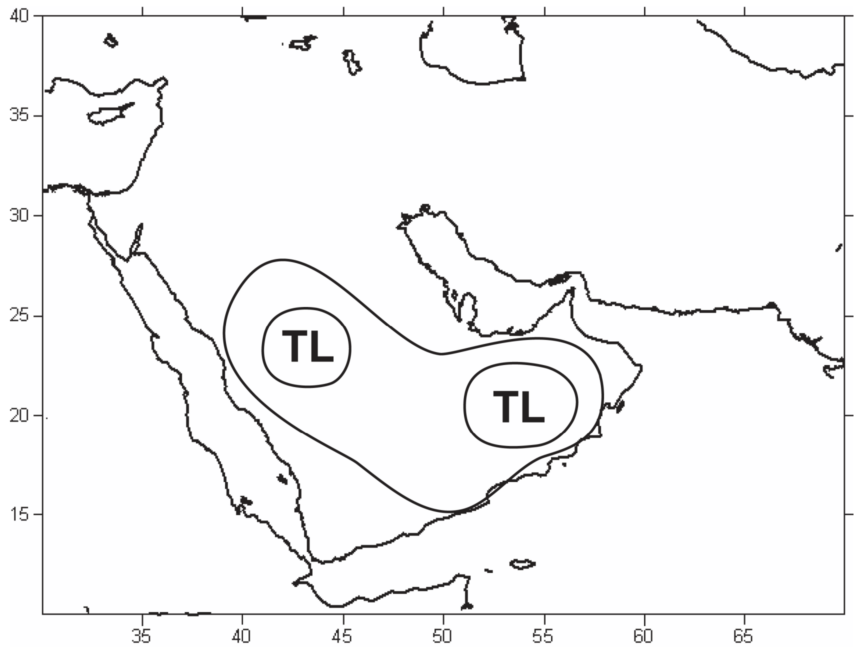


Figure 3.3. An average surface synoptic chart associated with the Thermal low (TL) pressure over the UAE region.

Easterly Trough and Siberian High (ET/SH)

The combination between the ET and the SH has the highest frequency of occurrence throughout the year although it does decrease somewhat in the summer. The combination of circulation patterns interacting with one another often causes cloudy weather and precipitation. This is a result of the interface between the cold air and moist air.

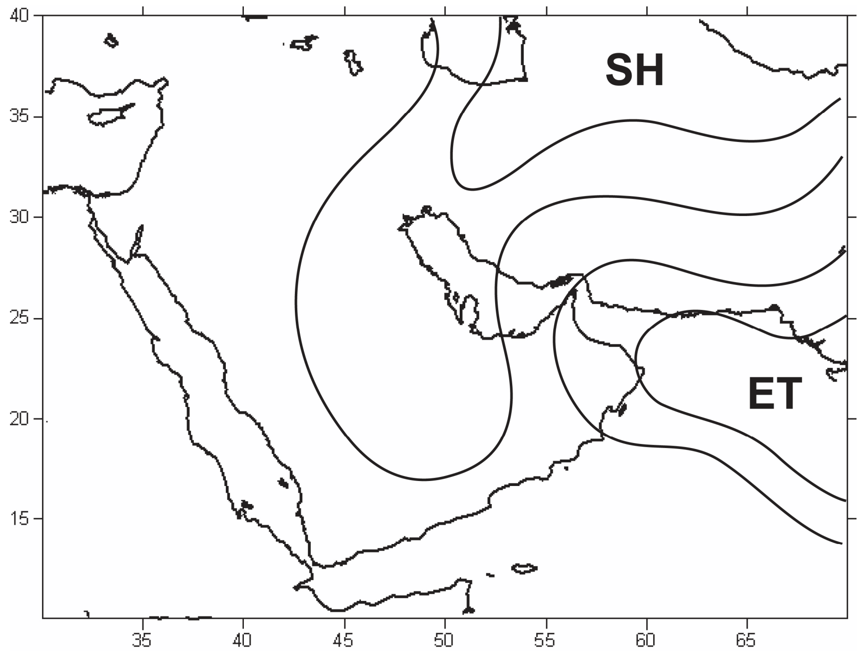


Figure 3.4. An average surface synoptic chart associated with the Easterly Trough and Siberian High (ET/SH) pressure over the UAE region.

Easterly Trough and Thermal Low (ET/TL)

The combination of an ET and a TL over the study region constitutes a further pattern of circulation (Figure 3.5). This combined system represents an extension of the TL which is centred over the interior of the Arabian Peninsula with an extension of the ET centred over the Arabian Gulf. The combination of the two systems can cause convective clouds and thunder storms over the mountains as a result of the on shore flow from the Arabian Sea and the unstable atmospheric conditions. It has been found that the frequency of this system increases at the beginning of the summer season which starts in the month of June (27%). This frequency increases throughout the months of July and August (up to 44 %)

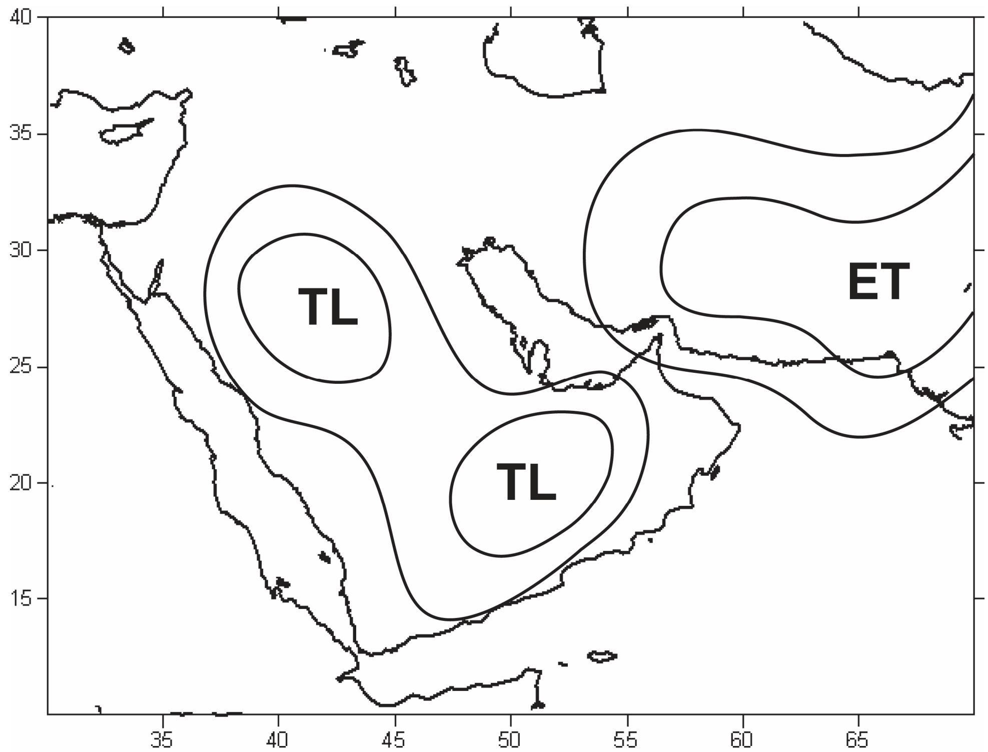


Figure 3.5. An average surface synoptic chart associated with the Easterly Trough and Thermal Low (ETTL) pressure over the UAE region.

Red Sea Trough (RST)

The Red Sea trough (RST) is an extension of the Tropical Sudan Monsoon Low over the Red Sea that reaches towards the Arabian Gulf regions. The effect of this type of depression over the UAE region is noticeable in winter season and the two transitional periods with the highest frequency of occurrence in February (12%). Unstable weather conditions usually associated with this type of depressions brings warm and moist air from the south or from the south west to the UAE.

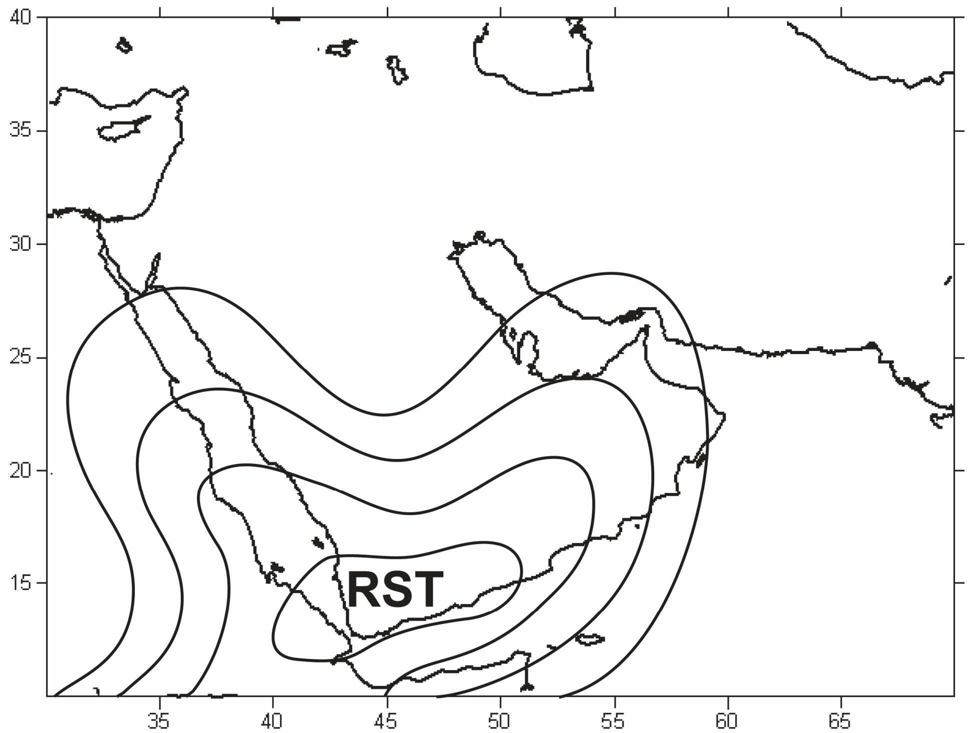


Figure 3.6. An average surface synoptic chart associated with the Red Sea trough (RST) pressure over the UAE region.

Indian High (IH)

The region of the Arabian Gulf including the UAE is occasionally affected by the ridge of the IH Pressure. This high pressure usually dominates over the Indian Ocean throughout the year, while the effect of its extension to the region occurs mostly during the summer and the two transitional periods, April and October respectively. Usually this system brings moist air from the Indian Ocean to the area which helps to form clouds, especially over the mountainous terrain in the eastern part of the UAE. The wind associated with this system is mostly south or the south westerly.

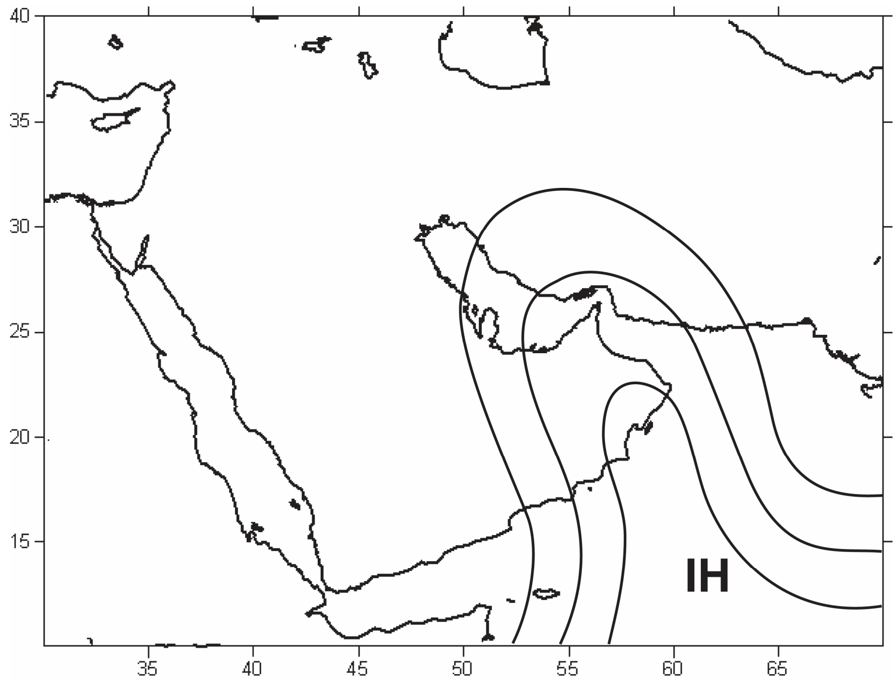


Figure 3.7. An average surface synoptic chart associated with the Indian Ocean high (IH) pressure over the UAE region.

Mediterranean Trough, Red Sea Trough and Easterly Trough (MT/RST/ET)

The complex relationship of synoptic circulation associated with the MT/RST/ET) synoptic governs and affect the UAE weather over the infrequently (Figure 3.8). The interaction of these depressions is characterized by heavy rainfall over the area when associated with upper air trough.

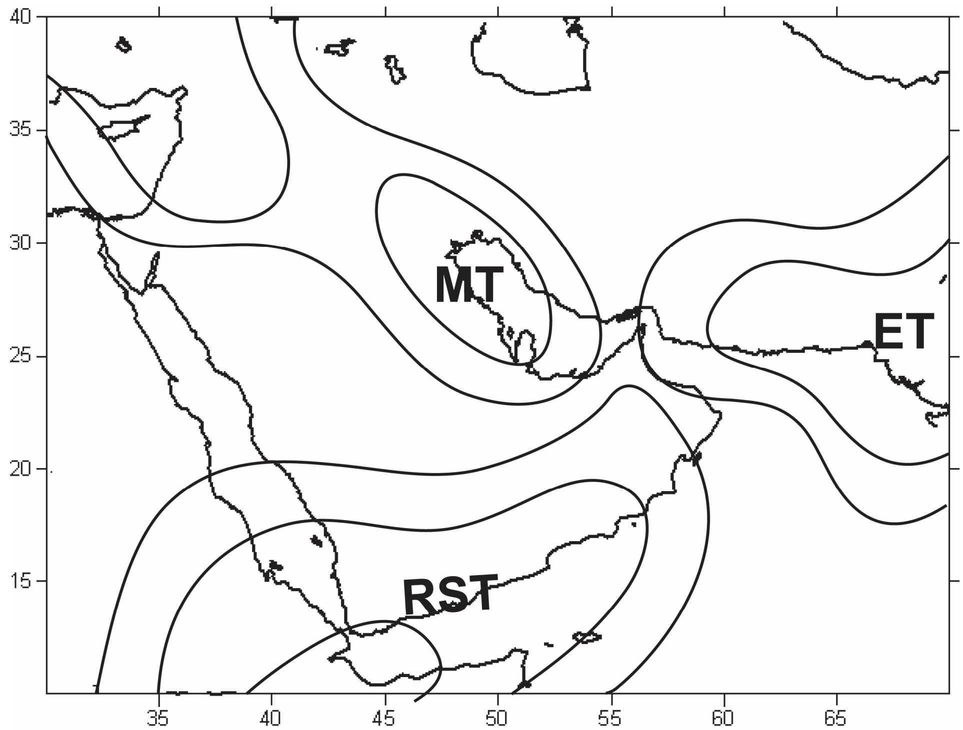


Figure 3.8. An average surface synoptic chart associated with the Mediterranean trough, Red Sea trough and Easterly trough (MT/RST/ET) pressure over the UAE region.

Thermal Low and Indian High (TL/IH)

The IH pressure system centred over the Indian Ocean in the summer season can combine with the TL over the central parts of the Arabian Peninsula. This affects the weather by advecting moisture from the Arabian Sea over the Peninsula. The advection of moisture over the mountains results in topographically induced convection over the eastern parts of the UAE and Oman. The highest frequency of occurrence for this synoptic circulation is in the summer (September 20.5%). Surface wind is mostly easterly to south easterly over the UAE.

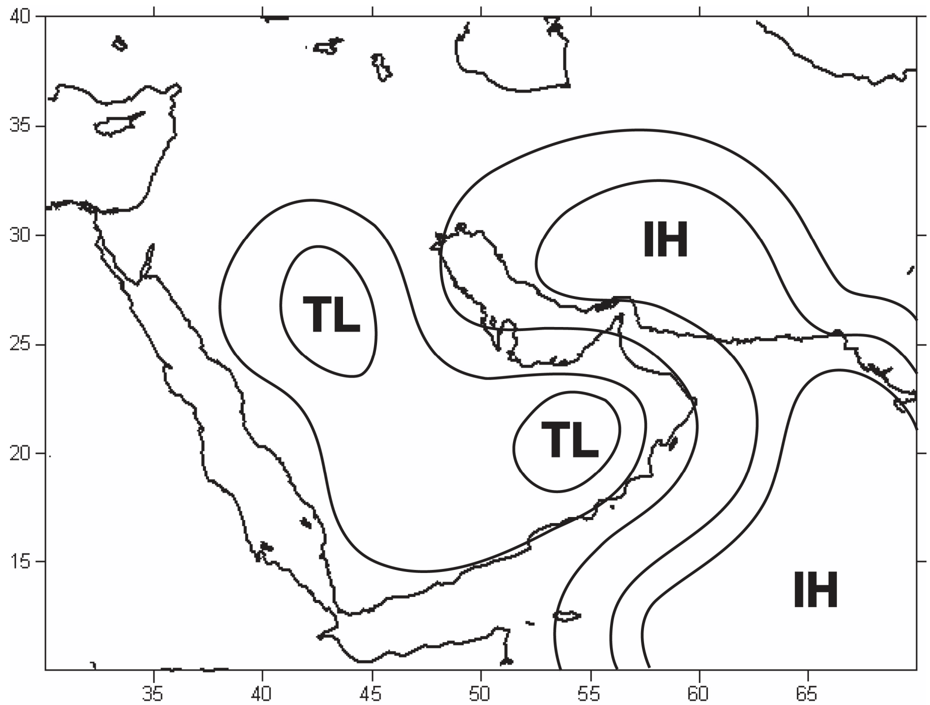


Figure 3.9. An average surface synoptic chart associated with the Thermal low trough and Indian high (TL IH) pressure over the UAE region.

Red Sea trough and Easterly trough (RST ET)

In a synoptic circulation scenario an extension of the Tropical Red sea depression moves towards the east and interfaces with an Easterly trough coming from the east. This combination of systems may cause unstable weather conditions over the area. This circulation pattern is most likely to occur in the system's two transitional periods and, to a lesser extent, during the winter

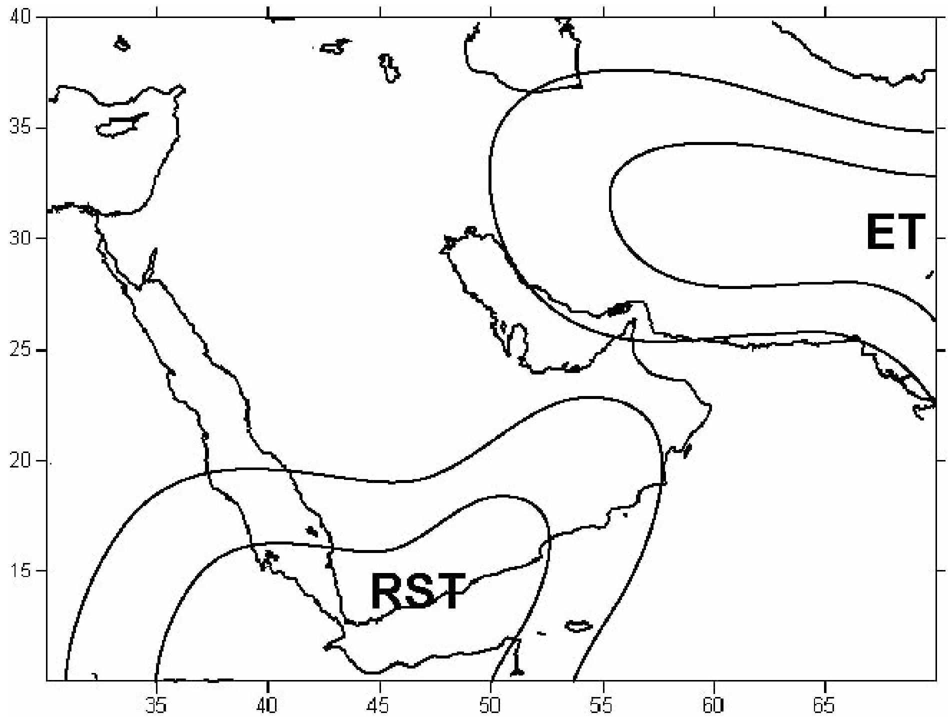


Figure 3.10. An average surface synoptic chart associated with the Red Sea Trough and Easterly Trough (RST ET) pressure over the UAE region.

Other

The combinations of circulation patterns between the SH with the extension of IH centred over the Indian Ocean (Figure 3.11) and ET accompanied with the IH (Figure 3.12) have a very small impact on the weather of the UAE and surrounding region. They have been included in the classification for completeness only. Their occurrence over the study region is associated with the advection of moisture to the mountains. Both synoptic circulation patterns mentioned above occur most frequently in the summer and the two transitional periods of the year.

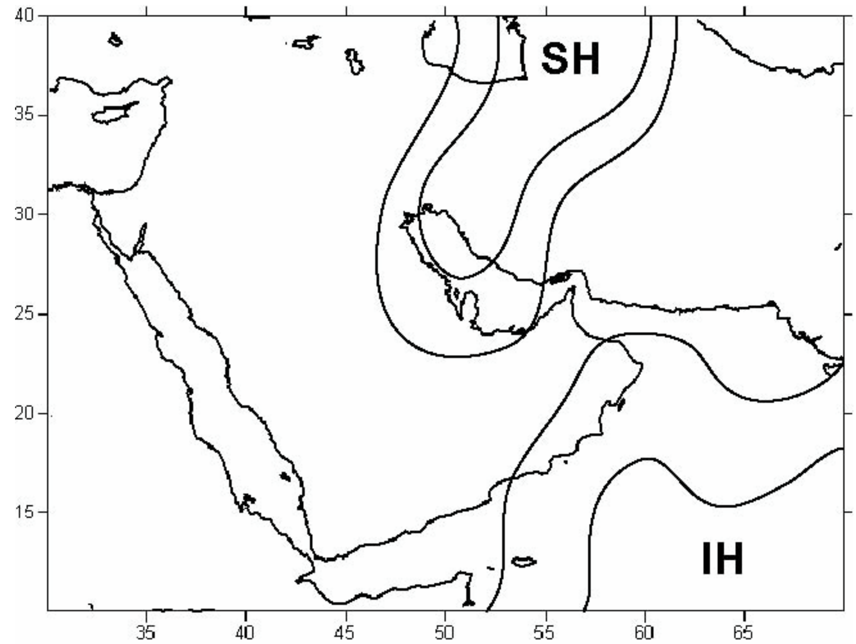


Figure 3.11. An average surface synoptic chart associated with the Siberian High and Indian High (SH/IH) pressure over the UAE region.

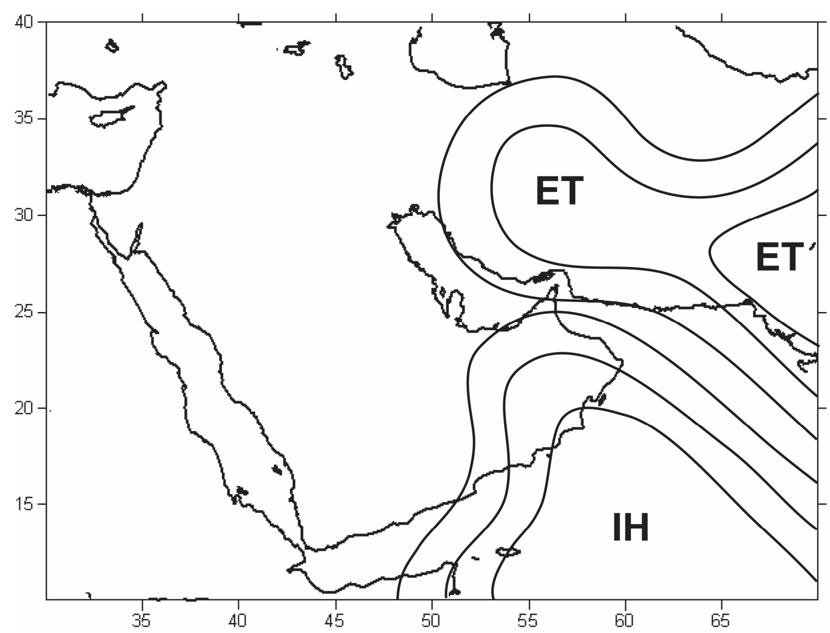


Figure 3.12. An average surface synoptic chart associated with the Easterly Trough Indian High (ET/IH) pressure over the UAE region.

Annual occurrence of surface synoptic circulation

The SH occurs most frequently over the study region (74.3 days per annum) followed by the ET/SH (71 days per year). This clearly indicates that the SH is by far the most prevalent and important pattern of atmospheric flow. Six basic circulation types can be said to effectively summarise the synoptic circulation over the UAE. (These include the aforementioned systems and the ET, ET/TL, TL and the RS/ET.) Together these systems account for 326 days of the year on average.

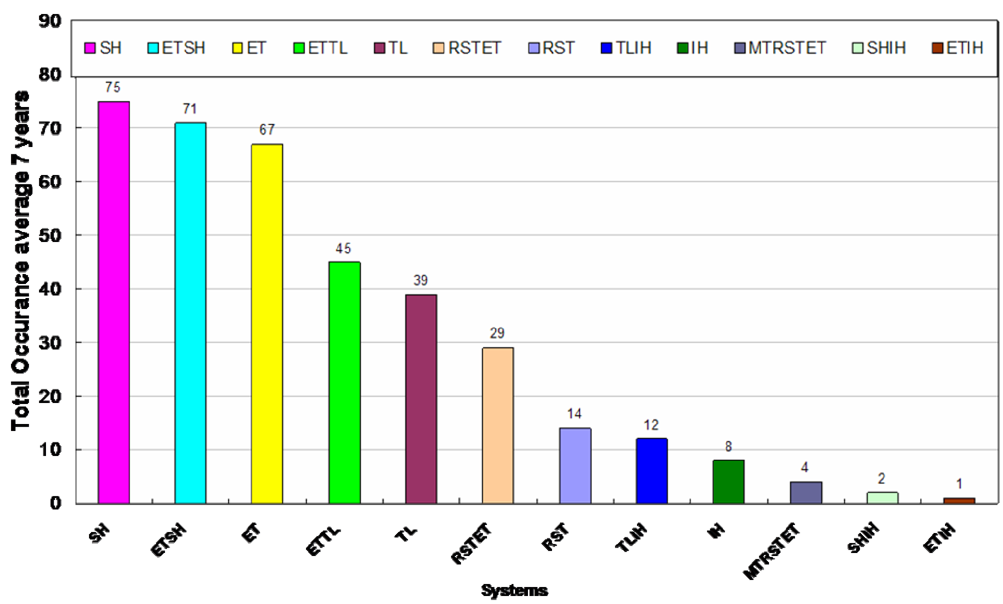


Figure 3.13. The average number of days that each category of synoptic circulation identified in this study occurred through a year (1995-2001)

Impact of the Indian Monsoon on synoptic circulation over the UAE

The Indian Monsoon is an important system affecting the weather of the UAE. As mentioned earlier, the ET is considered to be an extension of the Indian Monsoon to the study area. This is a seasonal oscillation and supports the formation of convective clouds and precipitation in the summer season months.

In a true monsoon climate, seasonal wind shifts typically cause a drastic change in the general precipitation and temperature patterns. The prime cause of monsoon circulation is the thermally induced cell to pressure system resulting from surface temperature differences (Figure 3.14). This type of circulation can only become well established in approximately barotropic conditions and where there is a favourable distribution of land and sea. The movement and oscillation of the Indian monsoon is well documented and represented in Figure 3.15. A westward extension of the Indian low occurs in April. It deepens and extends westward from May to September, the maximum deepening occurring July over the UAE. The maximum temperature and moisture associated with the movement and oscillation of the Indian monsoon occurs in July and August over the Gulf area including the UAE.

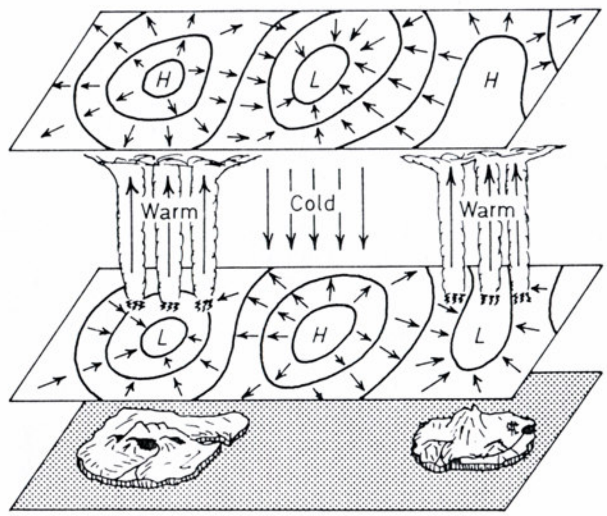


Figure 3.14. Idealised representation of the monsoon circulations. The islands in the Figure represent the tropical continents in the summer hemisphere. Solid lines represent isobars or geopotential height contours near 1000 hPa (lower plane) and 14 km or~ 200 hPa (upper plane). Short solid arrows indicate the cross-isobaric flow. Vertical arrows indicate the sense of the vertical motions in the Middle troposphere. (After Wallace and Hobbs, 1977).

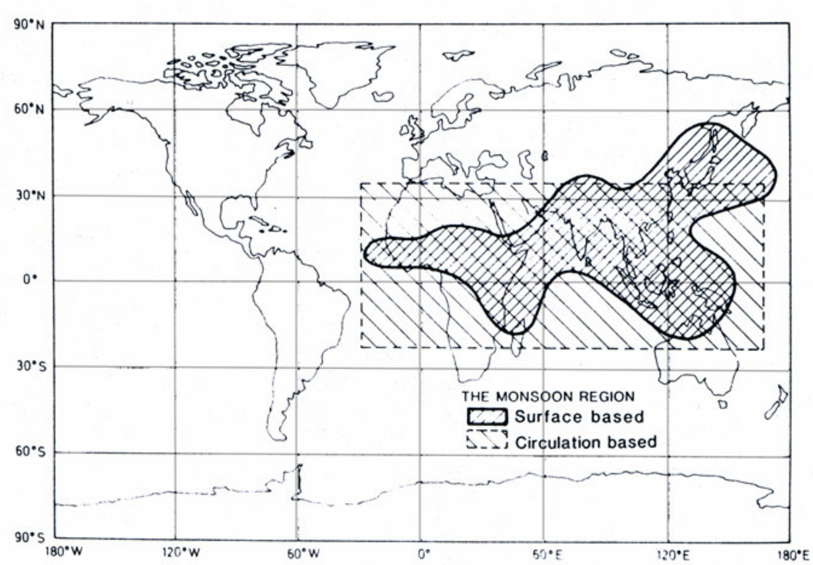


Figure 3.15. The monsoon region: the area of monsoon climate differs depending on whether the area is defined by surface-based observations or by consideration of the atmospheric circulation pattern.

Upper Air Pressure Systems

The analysis of the synoptic charts at the 500 hPa level shows that the pressure systems affecting the weather of the UAE in the upper atmosphere are as follows : Westerly trough (WT), Westerly ridge (WR), Easterly trough (ET), Subtropical high (STH), Zonal flow (ZF) and a Westerly cut-off low (WCL). These systems will be defined and discussed in this section.

The analysis of the upper atmospheric circulation shows a strong seasonal variation between the winter and summer months. STH pressure systems completely dominate the upper atmosphere over the UAE during the summer months (May-September).

Figure 3.16 and Table 3.2). During the winter the influence of the STH diminishes significantly reaching a minimum during January. The influence of the STH is increased with the northward displacement of the general circulation during the summer months. This is highlighted by the fact that the ET is only detected over the UAE region during the summer months. During winter the WT and WR circulation dominate with some influence from ZF over the UAE (Figure 3.16).

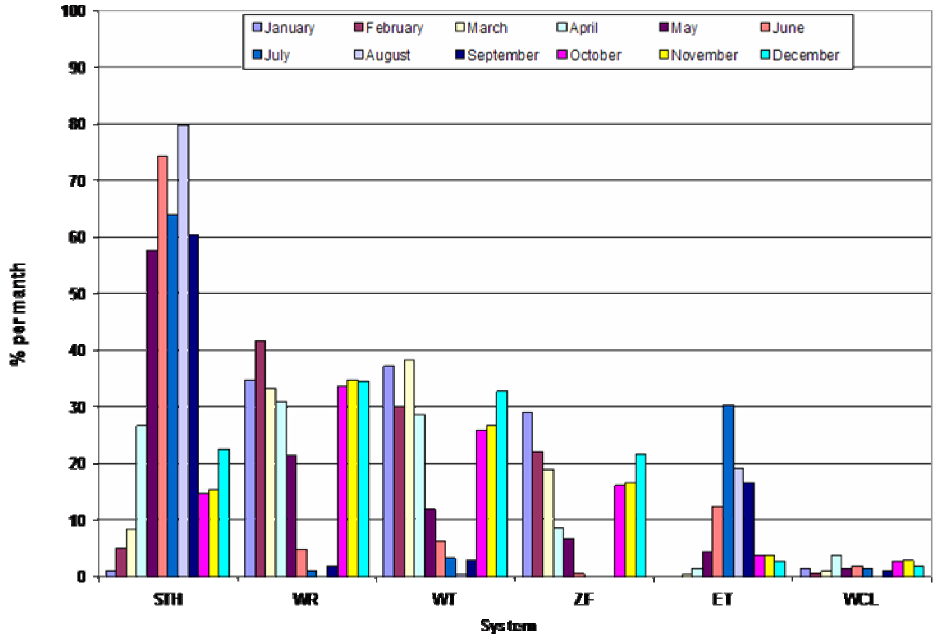


Figure 3.16. The average monthly frequency of occurrence (%) for each of the identified circulation categories that influence the upper atmosphere over the UAE region between 1995-2001.

Table 3.2. The monthly frequency of the average of the 500 hPa pressure systems for the period 1995-2001.

SYSTEM	STH	WR	WT	ZF	ET	WCL
% Month						
January	1.0	34.8	37.1	29.0	0.0	1.4
February	5.0	41.6	30.1	22.1	0.0	0.5
March	8.3	33.2	38.2	18.9	0.5	0.9
April	26.7	31.0	28.6	8.6	1.4	3.8
May	57.6	21.4	11.9	6.7	4.3	1.4
June	74.3	4.8	6.2	0.5	12.4	1.9
July	64.1	0.9	3.2	0.0	30.3	1.4
August	79.7	0.0	0.5	0.0	19.0	0.1
September	60.4	1.9	2.9	0.0	16.7	1.0
October	14.7	33.6	25.8	16.1	3.7	2.8
November	15.2	34.8	26.7	16.7	3.8	2.9
December	22.6	34.6	32.7	21.7	2.8	1.8

On an annual basis the STH has the highest total number of occurrences (143 days per annum) over the study period (Figure 3.17). WR and WT occur nearly an equal number of times on average through the year (81 and 73 days per annum respectively).

The WCL occurs only 7 days per annum. The importance of this circulation pattern is its persistence over the region, associated with significant surface upper air convergence and uplift.

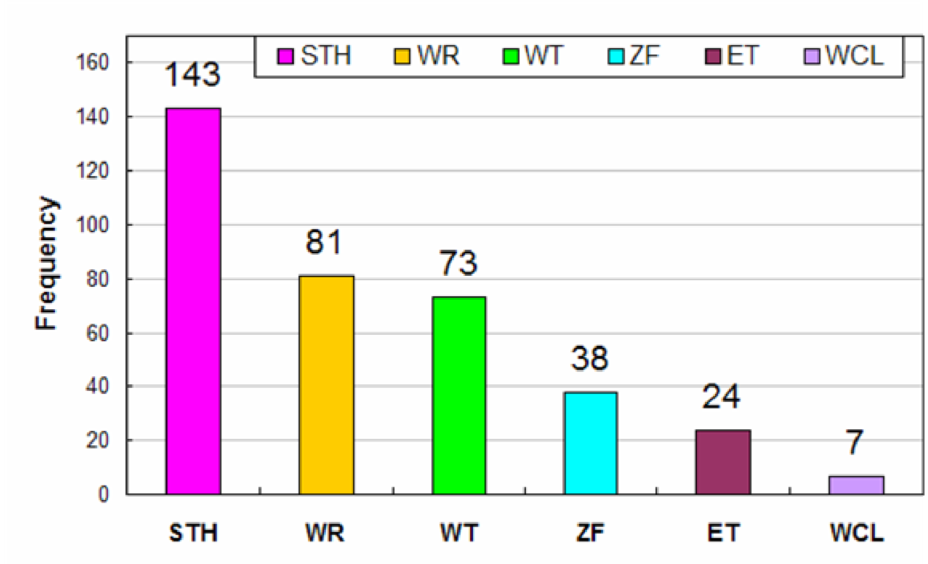


Figure 3.17. The average of the total frequency of the dominant upper air pressure systems during the period 1995-2001.

Sub-tropical High Pressure (STH)

The STH is an upper air high pressure system that in general extends from the south west over the region causing subsidence over the UAE (Figure 3.18). The dominant nature of this circulation pattern is responsible for the overall stable atmospheric conditions that characterise the atmospheric conditions over the UAE. The STH in the upper atmosphere is also frequently associated with the SH at the surface. Under these conditions the formation of surface inversions and elevated absolutely stable layers will be maximised.

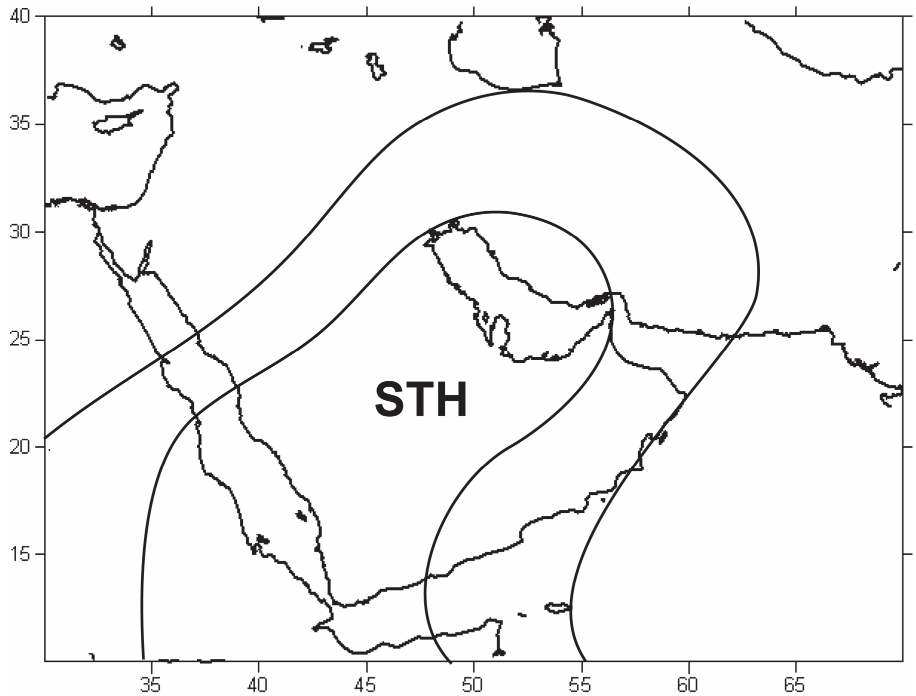


Figure 3.18. An average upper air isobaric chart indicating the dominance of the Sub-tropical high pressure (STH) system over the UAE and surrounding regions.

Westerly ridge (WR)

This system is characterized by north westerly flow at 500 hPa and plays an important role to in stabilising the weather in the region associated when combined with a high pressure at the surface. Sometimes this situation is conducive to the formation of mist or fog. It has been noticed that the WR affects the area mostly in winter season and during the two transitional periods. It does not inhibit rainfall when associated with favourable conditions at the surface. The effect decreases during the summer due to the sub-tropical high pressure which dominates at this time of the year. The highest frequency of occurrence was recorded in the month of February (42%).

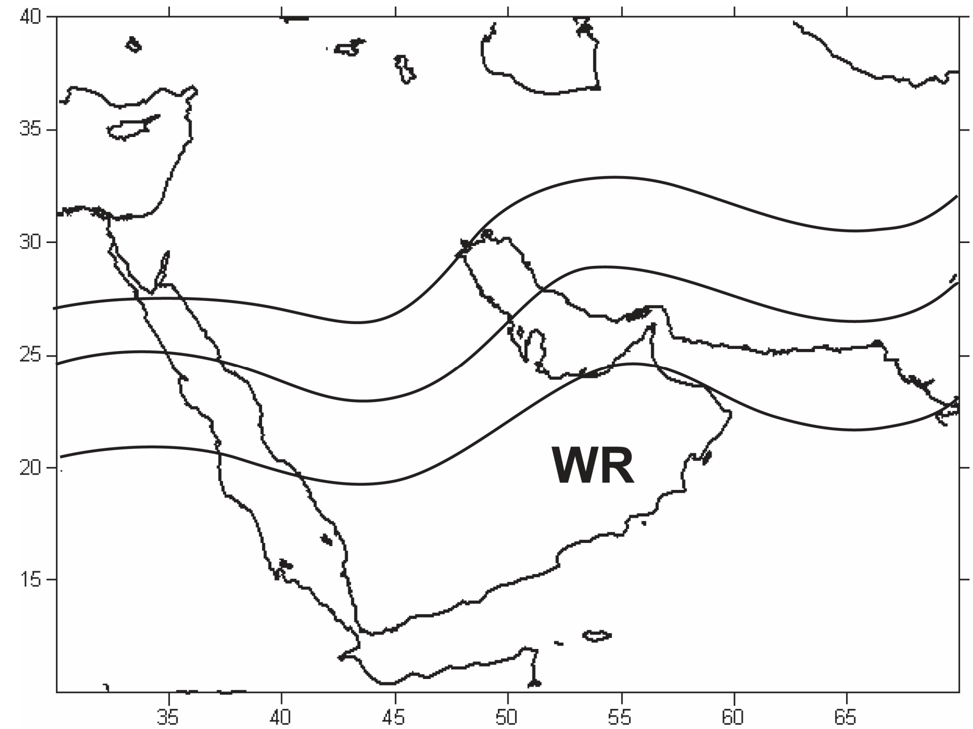


Figure 3.19. An average upper air isobaric chart indicating the dominance of the Westerly ridge (WR) system over the UAE and surrounding regions.

Westerly trough (WT)

This system acts on the region throughout the year but with different frequency of occurrence (Figure 3.20). The WT circulation plays an important role in precipitation during the winter. Unstable conditions associated with reasonable atmospheric moisture that result in cyclo-genesis at the surface bring precipitation. Cyclo-genesis accelerates the surface wind and the WT is always associated with a jet steam.

Figure 3.20. An average upper air isobaric chart indicating the dominance of the Westerly trough (WT) system over the UAE and surrounding regions.

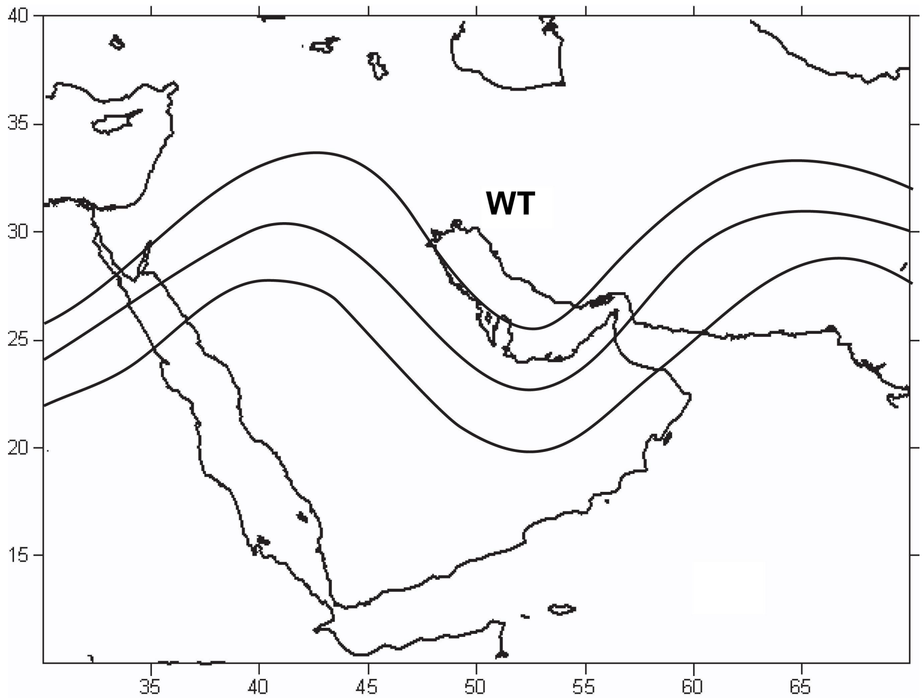
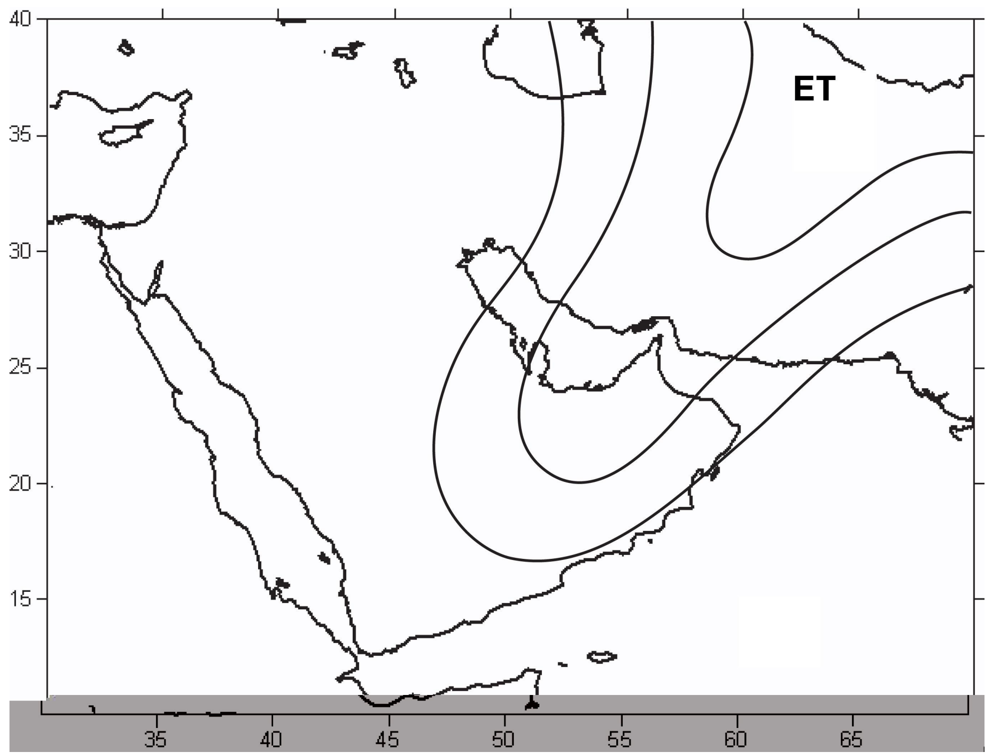


Figure 3.21. An average upper air isobaric chart indicating the dominance of the Easterly Trough (ET) system over the UAE and surrounding regions.



Easterly trough (ET)

This system extends from the east at 500 hPa and is frequently associated with easterly jet stream (Figure 3.21) which acts as an engine for the development of the convective clouds and unstable weather condition, especially over the high mountainous terrain. It is noticed that this type of system occurs most frequently in summer.

Zonal flow (ZF)

Zonal flow in the upper atmosphere is common during the winter (January 29%). This type of circulation usually proceeds or follows the other two westerly flow patterns. ZF does not exert an important influence on the weather of the UAE irrespective of the circulation occurring at the surface.

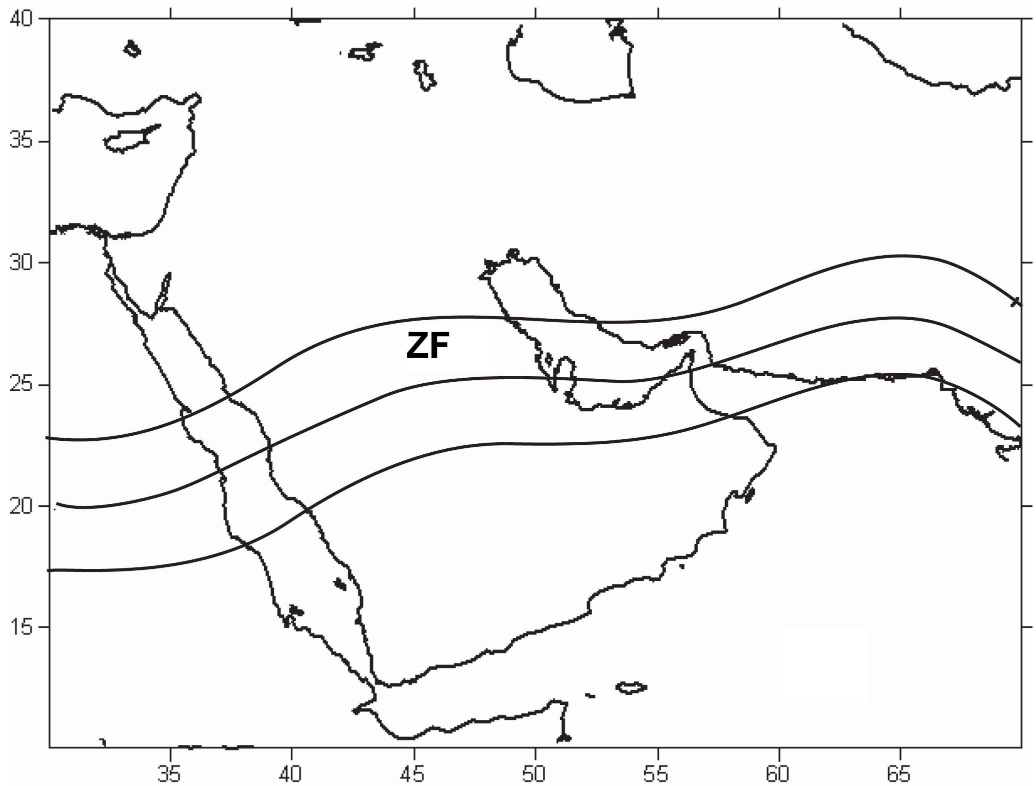


Figure 3.22. An average upper air isobaric chart indicating the dominance of the Zonal flow (ZF) system over the UAE and surrounding regions.

Westerly cut-off low (WCL)

The WCL could occur during any time of the year but occurs infrequently. The system always follows a preceding WT in the upper atmosphere. The WT becomes isolated from the westerlies and stay fairly stationary over the region (Figure 3.23). Surface winds are usually highly variable and gusty.

The highest frequency of occurrence for this system is in the transitional periods such as November and April. This system can cause unstable weather conditions and is usually associated with a corresponding surface depression. Due to the fact that there is convergence in the throughout the atmosphere up to 500 hPa this circulation is often associated with heavy rainfall over the UAE.

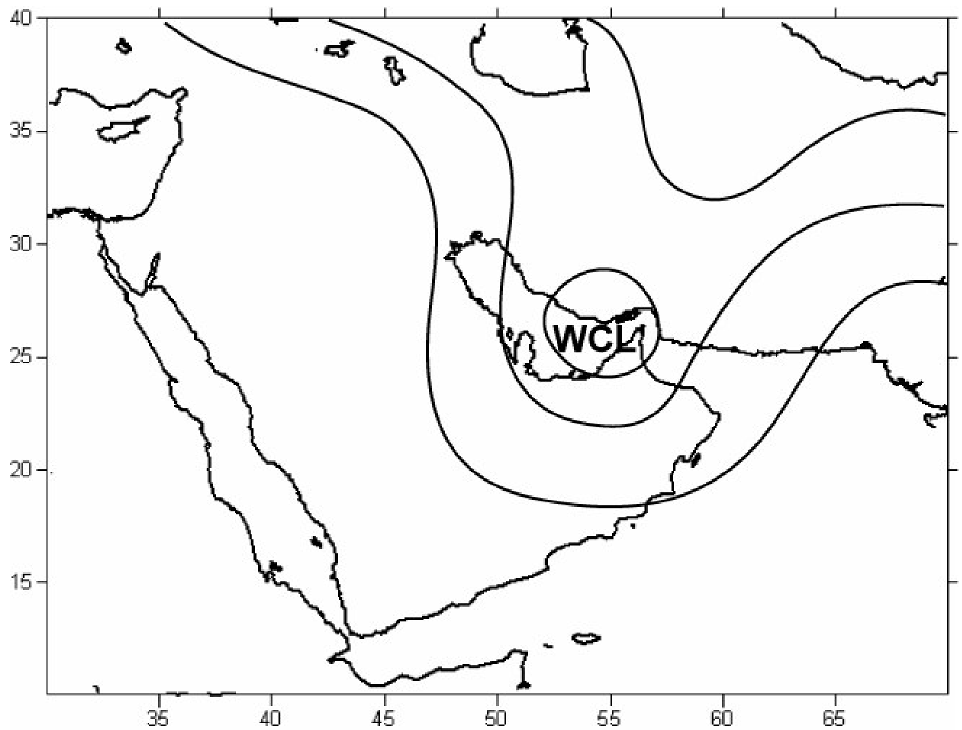


Figure 3.23. An average upper air isobaric chart indicating the dominance of the Westerly cut-off Low (WCL) system over the UAE and surrounding regions.

Rainfall over the UAE

Restricted water resources represent the single most important limiting factor to the development of the UAE in the foreseeable future. A summary of the historical records of rainfall over the UAE as well as the influence of the above mentioned synoptic circulation patterns will be discussed below.

Table 3.3 gives the total monthly rainfall at 56 stations over the UAE between 1980 and 2002. It shows that the maximum amount of rainfall occurs during the winter (December to March), while the minimum amounts of rainfall occurs between May and November (Figure 3.24).

Table 3.3. Total monthly rainfall measured at 56 weather Stations in UAE (1980-2002).

Stations Name	Lon	Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Ab D.A.P.	54.65	24.43	11.6	24.2	20.7	6.3	1.5	0.0	0.9	0.0	0.0	0.3	1.5	8.2	68.2
An Sukhnah	55.72	24.08	12.4	24.4	21.9	7.3	1.6	1.0	3.4	2.9	1.5	0.2	0.5	3.9	82.8
AL Hamra	52.47	24.10	13.9	15.7	28.1	7.2	0.2	0.0	0.2	0.0	0.0	0.4	1.7	29.6	75.8
Al Sila	51.68	24.12	4.4	26.5	20.9	7.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	27.6	66.7
AL Ain	55.78	24.22	12.6	28.7	25.4	7.1	1.9	1.1	6.7	4.8	4.6	0.4	0.7	6.0	100.9
AL Awir	55.52	25.13	21.5	39.9	35.2	10.4	1.6	0.1	3.4	1.2	1.4	3.3	3.6	18.1	139.7
Al Ghail	56.07	25.45	24.9	33.7	40.5	7.9	2.1	0.3	5.3	2.9	7.5	3.9	6.5	21.1	161.5
AL Haiyir	55.75	24.63	29.1	28.7	34.1	7.6	0.1	0.0	5.9	3.7	6.9	1.3	0.2	7.9	134.9
AL Haibab	55.58	25.05	18.0	31.9	33.6	7.8	3.2	0.2	3.9	4.0	0.9	1.5	3.1	13.8	121.3
Al Oha	55.80	24.33	16.2	34.6	30.0	4.3	1.5	3.1	9.4	9.4	2.5	0.5	1.5	7.4	116.6
Al wagan	55.50	23.63	7.5	5.8	26.9	9.6	0.0	0.0	3.5	0.0	0.1	1.8	0.2	1.7	55.0
Asab	54.22	23.30	6.0	20.6	29.8	7.5	0.2	0.0	0.9	0.5	0.0	0.1	0.0	2.6	60.8
Asimah	56.15	25.38	24.5	42.1	42.0	7.9	1.8	0.0	3.3	2.0	2.2	5.9	4.2	19.8	149.9
Bateen A.P.	54.45	24.43	10.9	28.9	20.5	7.4	0.0	0.0	0.6	0.1	0.0	0.0	2.5	9.6	80.7
BITHNA	56.23	25.18	17.5	40.6	41.7	11.9	5.7	1.9	4.1	1.9	0.3	3.8	4.8	20.4	162.7
Bu Hasa	53.30	23.50	10.9	9.2	8.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	5.4	0.6	27.0
Burairat	56.03	25.77	19.8	30.5	34.8	5.9	5.6	0.1	3.5	0.1	0.2	1.7	5.4	20.1	127.7
Delma	52.30	24.47	10.4	18.6	29.6	4.3	0.2	0.0	0.2	0.0	0.0	0.7	3.0	24.5	76.9
Dhaid	55.90	25.30	18.2	34.0	37.5	7.3	2.4	0.2	5.6	2.4	3.9	5.3	4.0	15.8	136.8
Dibba	56.27	25.60	16.6	32.4	38.7	10.4	1.9	1.1	4.3	0.7	1.9	4.8	8.4	22.5	143.5
Digdaga	55.97	25.67	20.8	36.4	42.1	6.1	1.7	0.1	1.8	0.1	0.9	2.8	5.9	20.9	135.8
Dubai A.P.	55.33	25.25	18.0	28.8	30.8	6.2	0.6	0.0	1.5	0.0	0.1	1.9	2.9	19.3	106.3
Farah	56.23	25.13	18.8	52.2	31.4	13.2	3.0	0.2	3.6	1.1	0.8	2.7	8.6	16.3	150.4
FILI	55.93	25.00	20.3	39.2	38.0	11.0	6.4	2.5	7.6	7.0	7.1	4.9	3.5	12.5	159.8
FUJAIRAH	56.35	25.12	22.3	41.9	40.1	9.0	0.3	0.1	2.5	1.0	0.0	2.8	6.2	20.5	146.7
Fujaira A.P.	56.33	25.12	38.4	5.8	52.9	4.2	0.2	0.0	0.2	5.0	0.0	4.8	6.1	42.8	149.8
Hamraniyah	55.95	25.63	18.0	34.8	34.0	5.1	1.5	0.2	1.6	0.0	0.1	1.8	8.8	17.9	118.7
Howeilat	56.18	24.92	21.2	38.8	41.5	14.2	3.5	0.5	4.6	3.1	0.8	6.2	4.5	15.6	157.5
IDHN	56.02	25.45	22.4	31.0	43.5	4.1	3.9	0.1	5.3	0.3	1.0	5.8	9.1	16.7	143.1
J. Sharmah	56.13	25.30	20.8	43.6	44.0	9.5	2.7	1.5	9.4	3.2	5.1	5.7	4.3	17.1	166.9
Kalba	56.35	25.07	19.0	44.4	31.3	11.0	1.2	0.0	3.4	0.6	0.2	2.3	4.7	18.0	141.2
KHATT	56.02	25.62	18.5	37.0	39.1	5.7	2.1	0.0	1.9	0.5	0.7	2.3	6.8	20.7	134.5
Khorfakkan	56.37	25.35	26.3	49.1	40.6	9.8	2.6	2.3	8.1	0.9	2.9	5.1	10.8	26.9	185.2
Marbad	56.13	25.33	25.4	46.2	45.6	7.5	4.2	1.1	9.8	3.6	3.0	7.2	7.0	19.8	179.7
Masafi	56.17	25.30	21.7	40.0	41.6	7.8	3.2	1.9	9.1	4.2	5.3	9.0	5.1	15.7	164.6
Masfut	56.12	24.80	21.5	37.1	41.9	13.0	4.2	1.8	9.5	3.8	2.1	6.7	3.8	12.9	160.8
Meleiha	55.87	25.17	18.5	36.6	37.2	8.7	3.6	0.1	4.8	8.1	2.7	4.7	4.1	13.2	142.1
MUNAI	56.15	24.95	19.5	38.7	34.7	9.8	3.9	1.5	4.7	1.7	2.3	6.2	6.3	14.3	141.4
R.K.A.P.	55.93	25.62	20.9	36.7	42.2	4.9	1.8	0.0	1.2	0.2	0.3	2.0	8.0	20.6	134.1
Radom	53.75	23.10	2.5	28.5	23.0	9.4	0.0	0.0	2.0	1.5	0.0	0.0	0.0	7.0	73.9
Shaam	56.10	26.02	31.3	46.7	46.6	6.5	1.5	0.0	2.7	0.3	0.1	0.3	3.1	34.8	174.0
Sharjah A.P.	55.52	25.33	17.9	31.3	34.8	7.5	1.1	0.0	3.8	0.0	0.4	2.9	3.4	17.5	122.1
Sharjah T. A.p	55.38	25.33	23.1	36.8	28.8	12.3	0.5	0.0	1.9	0.0	0.1	2.6	4.1	13.6	119.7
SIFUNI	56.12	25.17	18.8	38.1	36.0	13.6	2.4	1.5	2.6	4.5	2.1	5.9	1.8	14.3	141.5
Siji	56.10	25.23	17.4	34.7	33.0	7.7	4.9	1.6	1.4	3.9	2.8	5.8	1.9	11.4	126.4
SINNAH	56.17	25.5	21.4	39.8	40.5	6.9	1.4	1.1	3.4	1.6	0.5	5.6	7.7	19.7	152.7

Swehan	55.00	24.52	30.8	52.2	29.3	16.2	0.0	2.4	2.9	1.1	0.2	0.0	0.0	16.3	117.0
Tarif	53.72	24.00	2.0	29.4	9.0	11.7	0.0	0.0	0.5	0.0	0.0	0.0	0.0	11.1	55.2
Tawiyn	56.08	25.55	25.2	31.1	35.7	5.9	0.1	0.3	5.2	1.0	1.0	3.8	11.0	17.8	138.0
Umm Al Quwain	55.65	25.53	24.4	33.6	35.8	3.8	0.2	0.0	1.3	0.0	0.4	3.0	6.5	21.3	130.4
Wadi Bih	56.13	25.83	24.9	32.7	37.4	4.7	0.1	0.0	2.2	0.0	0.1	1.7	3.1	25.8	137.7
Wahala	56.30	24.90	22.345	35.145	34.19	8.59	0.36	0.04	3.18	0.28	0.05	6.72	2.41	18.17	131.48
Zikat	56.32	25.52	19.6	39.9	35.2	7.6	1.6	0.6	3.2	0.3	0.2	5.9	8.4	24.2	149.5
Average Total Rainfall			18.9	33.6	34.2	8.1	1.8	0.6	3.6	1.8	1.5	3.1	4.3	16.9	128.3
Max. Total Rainfall			38.4	52.2	52.9	16.2	6.4	3.1	9.8	9.4	7.5	9.0	11.0	42.8	185.2
Min. Total Rainfall			2.0	5.8	8.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	27.0

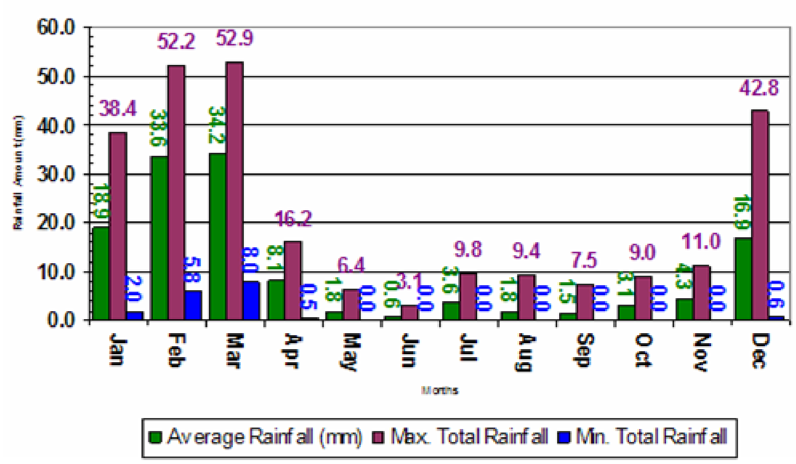


Figure 3.24. Average total monthly rainfall over the UAE between 1980 and 2002.

The highest mean annual rainfall recorded over the study period was 329.8 mm and occurred in 1982. The lowest annual rainfall (17.7 mm) was recorded in 1985. The mean annual precipitation over the UAE during this study period was 128.3 mm (Table 3.4). The UAE clearly experiences periods of above and below normal rainfall with drought type situations being a frequent occurrence over the region (Figure 3.25). No attempt has been made to explain the forcing mechanisms causing the droughts over the country.

Spatial distribution of Rainfall over the UAE

Rainfall is not evenly distributed over the UAE. The majority of the rainfall falls over the north eastern portion of the country (Figure 3.26). During the winter, rainfall is mostly associated with the passage of the WT. These troughs impact mostly on the northern parts of the UAE. This is primarily a function of the physical and spatial reach of the westerly trough systems. During the summer, rainfall is forced orographically in the north and north easterly parts of UAE. Much of the moisture available for convective activity during the summer is advected over the country from the Arabian Sea.

Table 3.4. Average total rainfall over the entire UAE (1980-2002).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
1980	5.4	26.8	14.7	0.0	0.1	0.6	2.7	0.4	2.7	0.2	2.9	1.7	58.1
1981	3.7	1.4	19.3	24.4	29.4	0.0	0.7	0.8	0.6	2.5	0.1	0.2	83.2
1982	8.1	135.2	124.0	1.5	0.2	0.5	0.5	2.1	0.6	2.4	24.1	30.4	329.8
1983	25.3	74.6	43.5	38.5	0.4	0.0	0.1	8.5	2.1	0.0	0.2	3.2	196.4
1984	1.5	0.5	14.5	0.1	2.0	0.0	3.8	2.6	2.0	0.1	0.0	16.3	43.5
1985	8.7	0.3	2.8	0.5	0.0	0.2	0.5	0.8	0.5	0.8	0.6	2.0	17.7
1986	23.5	16.3	9.1	1.4	0.0	1.3	0.9	2.4	2.8	2.4	0.8	30.1	91.1
1987	0.7	5.9	94.1	11.4	3.5	1.7	0.9	5.7	0.1	0.4	5.3	6.7	136.3
1988	6.3	164.2	1.7	18.8	0.1	0.1	8.3	0.9	0.1	0.3	0.5	4.4	205.6
1989	0.0	14.2	42.3	7.6	0.1	0.1	0.6	0.6	0.3	0.4	6.7	49.6	122.5
1990	19.0	81.6	3.5	10.3	0.2	1.3	1.9	2.8	0.1	0.9	0.4	0.2	122.1
1991	14.5	12.0	35.6	0.1	0.0	0.1	0.5	0.7	0.1	0.2	4.2	17.5	85.5
1992	38.6	40.2	2.6	41.1	0.4	0.4	3.0	1.5	0.5	1.2	1.9	30.6	162.0
1993	14.7	99.0	2.7	1.6	0.2	0.0	0.8	1.8	2.3	0.6	0.3	14.4	138.3
1994	25.2	0.7	7.9	0.3	0.5	0.1	1.3	0.5	5.5	5.4	2.2	0.1	49.8
1995	0.6	18.0	71.1	2.4	2.1	0.0	47.4	1.5	0.1	4.7	0.7	126.2	274.9
1996	78.5	26.7	123.6	4.3	1.3	2.7	2.3	0.3	4.0	0.5	2.0	6.9	253.1
1997	55.6	0.2	111.9	10.7	0.1	2.2	0.3	1.5	1.1	36.9	30.8	9.0	260.1
1998	69.4	32.5	24.2	6.0	0.0	0.7	4.3	1.3	0.2	1.3	0.4	7.8	148.1
1999	9.2	22.0	14.4	0.0	0.1	0.1	0.7	1.6	2.0	0.1	0.8	0.4	51.4
2000	2.4	0.1	0.1	0.0	0.0	0.0	0.1	0.2	3.1	6.3	7.1	27.3	46.9
2001	18.0	0.1	1.6	0.1	0.0	0.3	0.4	0.0	3.4	0.6	2.0	1.1	27.5
2002	4.6	1.4	22.1	4.1	1.5	1.6	0.6	2.5	0.4	2.4	5.1	2.0	48.5
Average	18.9	33.6	34.2	8.1	1.8	0.6	3.6	1.8	1.5	3.1	4.3	16.9	128.3

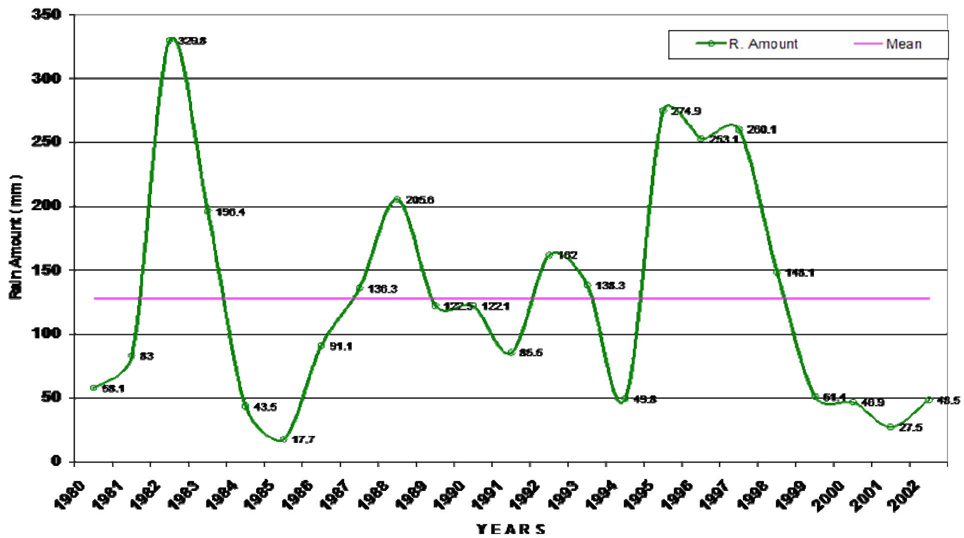


Figure 3.25. Total and mean rainfall over the entire UAE between 1980 and 2002.

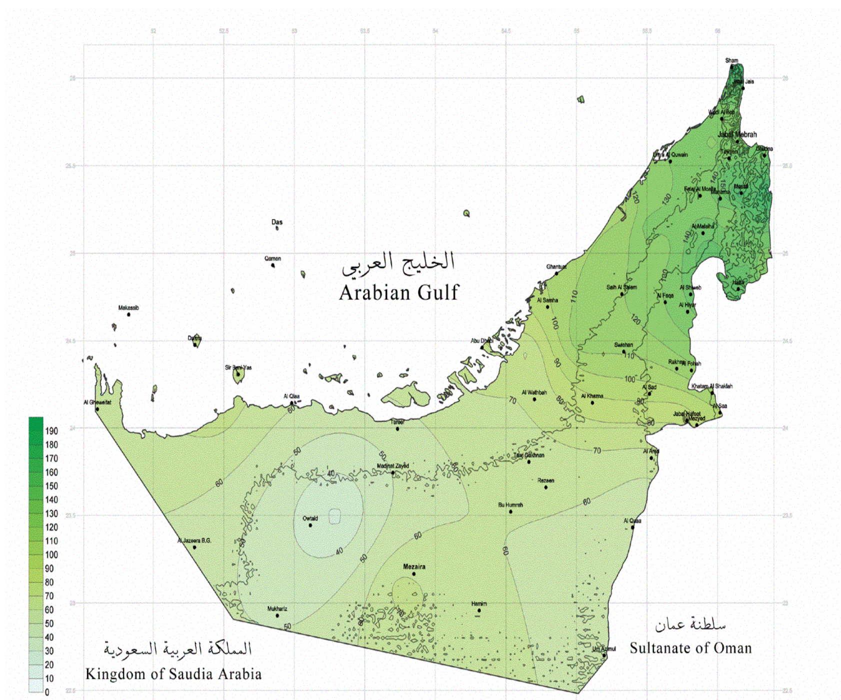


Figure 3.26. Spatial distribution of rainfall over the UAE between 1980 and 2002. Rainfall is given in mm per annum.

Synoptic circulation patterns and rainfall

Siberian high pressure (SH)

The relationship between the SH at the surface and the different synoptic scale circulation patterns at 500 hPa has been evaluated for seven years. The SH has been to be the most frequently occurring system over the UAE. A surprisingly high number of rain days occur in association with this surface high, 134 days or 5.24% of days. The highest frequency of occurrence of rainfall under SH surface flow were accompanied by a westerly high pressure ridge (WR) in the upper air extending from the west (2.3 %). A total of 58 rain days (26.5%) were found to occur under these seemingly unfavourable conditions. It seems, for the most part, that the detected rainfall is associated with onshore flow over the eastern parts of the country which is lifted by the topography in that region. Under these conditions the precipitation occurs in small quantities. Rainfall is also associated under surface SH condition with upper air westerly trough (1.6 %) and zonal flow (1.0 %). A high percentage of non-rain days also occur with all three the above upper air systems. This is clearly due to the fact that, in general, surface subsidence and divergence subdues any rainfall over the region.

Table 3.5. Analysis of the relationship between the surface SH circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	**Total no. of days of occurrence**	**% annual occurrence**	**Total non rainy days**	**Total rainy days**	**% non rainy days**	**% rainy days**
WR	219	8.6	161	58	73.5	26.5
WT	119	4.7	79	40	66.4	33.6
ZF	89	3.5	64	25	71.9	28.1
SH	74	2.9	64	10	86.5	13.5
ET	10	0.4	9	1	90.0	10.0
WCL	2	0.1	2	0	100.0	0.0

Easterly Trough and Siberian High (ET/SH)

The synoptic circulation pattern associated with the combination of a SH pressure system and an ET both impacting on the weather over the UAE is shown to give rise to the best chance for rainfall. This combination of synoptic circulation at the surface was identified on 499 days over the seven years period, thus making it the second most important circulation system for the UAE (Table 3.6). Although frequently high pressure systems are associated with subsidence, the combination of the two systems is usually associated with cold air and moisture air being advected in the SH from the Arabian Gulf and moist and warm air in the ET form the Arabian Sea and Indian Ocean. This mixture of two air masses establishes suitable conditions for the formation of rain which is greatly assisted by topographical lifting in the east of the country.

The SH/ET at the surface associated with a WT in the upper atmosphere was always associated with scattered precipitation over the country with heavy rain over the mountainous region. In addition rainfall also occurs over the region if the upper atmosphere is dominated by ET circulation. Although the WCL has low frequency of occurrence is produces extensive amounts of rainfall when overlying the SH/ET surface system. This is best explained by the extensive and deep convergence and uplift in the atmosphere if the two trough systems are aligned in the vertical.

Table 3.6. Analysis of the relationship between the surface SH/ET circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	**Total no. of days of occurrence**	**% annual occurrence**	**Total non rainy days**	**Total rainy days**	**% non rainy days**	**% rainy days**
SH	134	5.2	119	15	88.8	11.2
WT	131	5.1	56	75	42.7	57.3
WR	124	4.9	94	30	75.8	24.2
ZF	78	3.1	51	27	65.4	34.6
ET	24	0.9	14	10	58.3	41.7
WCL	8	0.3	6	2	75.0	25.0

Easterly Trough (ET)

This surface system is almost always associated with rainfall of some kind. The intensity of the rainfall is dependent on supporting convective mechanisms which may include topographical induced uplift over the mountains or and additional upper air trough, usually a westerly upper air trough (WT) at 500hpa. The resultant surface and upper air convergence that prevails throughout the atmosphere under these conditions creates significant atmospheric instability which usually results in extensive rainfall. This is evident from the fact that of the total number of days that receive rainfall, 56 % of them are associated with a surface easterly trough. The above system was found to occur on 130 days throughout the seven years period which represents 2.8 % of days. The ET system over the UAE accounted for 18.3 % of the total number of rain days (Table 3.7).

The surface easterly is usually associated with either a westerly trough (WT) or a westerly ridge (WR) in the upper atmosphere (500 hPa). As was pointed out before, the highest number of rain days, also associated with some of the highest rainfall quantities, occur with the ET at the surface and a WT at 500 hPa. The combination of a surface easterly trough with an upper air WT is most likely to produce rainfall over the UAE. This surface system also occurs frequently at the surface with the subtropical high pressure (STH) in the upper air. Rainfall is not common on days when a subtropical high pressure system is present at 500 hPa. The upper air divergence associated with the high pressure system effectively suppresses any vertical motion and therefore inhibits rainfall. In fact, in general, if the STH is present at 500 hPa the likelihood of rainfall is significantly impaired. The total number of non-rain days is highest with a dominant STH at 500 hPa.

Table 3.7. Analysis of the relationship between the surface ET circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
SH	226	8.8	190	36	84.1	15.9
WR	72	2.8	49	23	68.1	31.9
WT	71	2.8	31	40	43.7	56.3
ZF	35	1.4	19	16	54.3	45.7
ET	35	1.4	22	13	62.9	37.1
WCL	12	0.5	10	2	83.3	16.7

Easterly Trough and Thermal Low (ET/TL)

A combination at the surface between a TL and an ET prevails over the area during summer. The TL is associated with hot and dry air extending from the east, while the easterly ET is associated with warm and moist air. Again the mountains in the eastern part of the UAE play an important role in convective cloud formation and rainfall under these synoptic scale circulation patterns. It has been noted the ET/TL occurs most frequently with subsiding air in the upper atmosphere as part of the STH system (9.0 % of all days) (Table 3.8). Despite expecting rainfall to be suppressed with anticyclonic flow in the upper atmosphere, the most number of rain days occurred under these conditions. Similar amounts of rainfall have been recorded with an ET in the upper air. The amount of rainfall per event with upper air convergence at hPa is enhanced, especially over the eastern mountainous region. The ET/TL at the surface and an ET at 500 hPa occur infrequently over the region and therefore has a limited impact on the total rainfall.

Table 3.8. Analysis of the relationship between the surface ET/TL circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE **between 1995 and 2001.**

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
SH	228	8.9	182	46	79.8	20.2
ET	49	1.9	39	10	79.6	20.4
WT	12	0.5	11	1	91.7	8.3
WCL	11	0.4	10	1	90.9	9.1
WR	9	0.4	8	1	88.9	11.1
ZF	0	0.0	0	0	0.0	0.0

Thermal low (TL)

The prevailing surface system during the summer season is a TL, which is characterized by extremely hot surface temperatures over the Arabian Peninsula inducing a surface low pressure system to form. Rainfall does occur under these conditions, especially over the eastern regions as a result of the mountains (1.3 %) (Table 3.9). Rainfall is most likely to occur in association with a TL surface system if it is accompanied by an easterly trough in the upper atmosphere (500 hPa) (ET), followed by zonal flow in the upper air. The TL is most likely to occur with a subtropical high pressure (STH) at the 500 hPa level. Although the likelihood of rainfall decreases under these conditions, as a result of the upper air subsidence, rainfall can occur. Extreme surface heating with a moist atmosphere, usually associated with onshore flow from Oman will result in convective activity over the mountainous regions on the eastern side of the UAE.

Table 3.9. Analysis of the relationship between the surface TL circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
SH	216	8.5	193	23	89.4	10.6
ET	27	1.1	20	7	74.1	25.9
WR	18	0.7	17	1	94.4	5.6
WT	12	0.5	11	1	91.7	8.3
ZF	4	0.2	3	1	75.0	25.0
WCL	3	0.1	3	0	100.0	0.0

Red Sea Trough Easterly Trough (RST/ET)

This surface system is a mixture of two similar air masses associated with two different surface systems, Red Sea Trough (RST) and Easterly Trough (ET) which both bring moist and warm air from the east. The combination at the surface of the two easterly flow regimes occurs almost 8 % of the time (Table 3.10). As both these systems are associated with cyclonic circulation, rainfall over the area as a result of the instability and moisture is inevitable and substantial.

In combination at the surface with a WCL in the upper air, rainfall is always recorded. When associated with WT, ZF and WR at 500hpa, high amounts of rainfall occur over the UAE. This system is responsible for more rainfall than any other combination of systems.

Table 3.10. Analysis of the relationship between the surface RST/ET circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
WT	69	2.7	21	48	30.4	69.6
WR	55	2.2	32	23	58.2	41.8
ZF	41	1.6	16	25	39.0	61.0
STH	32	1.3	28	4	87.5	12.5
WCL	3	0.1	0	3	0.0	100.0
ET	1	0.0	0	1	0.0	100.0

Read Sea Trough (RST)

The RST is associated with unstable air originating from the west. Rainfall occurs when associated with a WT or a WCL at the 500 hPa. When this system occurs simultaneously to a westerly trough in the upper atmosphere, rainfall is significantly enhanced and encouraged creating huge amounts of precipitation over the UAE (Table 3.11). When the RST is associated with STH, ZF, and WR at 500 hPa, rainfall did occur over the region but in fairly small amounts.

Table 3.11. Analysis of the relationship between the surface RST circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	**Total no. of days of occurrence**	**% annual occurrence**	**Total non rainy days**	**Total rainy days**	**% non rainy days**	**% rainy days**
WT	52	2.0	21	31	40.4	59.6
WR	34	1.3	25	9	73.5	26.5
SH	22	0.9	15	7	68.2	31.8
ZF	7	0.3	5	2	71.4	28.6
WCL	2	0.1	1	1	50.0	50.0
ET	0	0.0	0	0	0.0	0.0

Thermal Low and the Indian High (TL/IH)

This system is considered to be a summer synoptic surface system, where the total number of occurrences was 90 days, 30 days with rain and 60 days with no rain throughout the study period (Table 3.12). This persistence surface system in summer season advects moist air from the Indian Ocean, and hot dry air from the central Arabian peninsular. When this combination system is assisted by cold air at 500 hPa air (WT or ZF) it is possible to have rainfall over the region.

Table 3.12. Analysis of the relationship between the surface TL/IH circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	**Total no. of days of occurrence**	**% annual occurrence**	**Total non rainy days**	**Total rainy days**	**% non rainy days**	**% rainy days**
STH	66	2.6	45	21	68.2	31.8
ET	16	0.6	10	6	62.5	37.5
WT	5	0.2	3	2	60.0	40.0
WCL	2	0.1	2	0	100.0	0.0
ZF	1	0.0	0	1	0.0	100.0
WR	0	0.0	0	0	0.0	0.0

Indian High pressure (IH)

The IH system is an extension of the surface high, centred over the Indian Ocean. This system occurs infrequently over the United Arab Emirates and Gulf region (2.1 %) (Table 3.13). The IH systems are generally associated with warm and moist air, which is forced to rise as it ridges over the eastern mountainous terrain. The combination of moisture and orographic uplift is sufficient to cause convective cloud and precipitation (0,6 %). It is noticeable that the convection is encouraged by an upper level (at 500hpa) WT. This is probably due to deeper zones of convergence over the region. Despite this system being associated with rainfall it does not contribute to the total rainfall in a significant manner

Table 3.13. Analysis of the relationship between the surface IH circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
STH	18	0.7	14	4	77.8	22.2
WR	16	0.6	10	6	62.5	37.5
WT	11	0.4	8	3	72.7	27.3
ZF	6	0.2	5	1	83.3	16.7
WCL	1	0.0	1	0	100.0	0.0
ET	0	0.0	0	0	0.0	0.0

Mediterranean Trough, Red Sea Trough and Easterly Trough (MT/RST/ET)

The combination synoptic circulation patterns at the surface made up of a MT/RST and ET is a mixture of different unstable air masses. The UAE is exposed to this combination of surface systems most frequently in the winter. In total this combination of synoptic systems occur less than 1 % of the time (Table 3.14). When the system occurs with upper air (500hPa) ZF, WT or WR circulation rainfall is good over the UAE. Despite the low frequency of occurrence of the system in general the contribution to the total rainfall of the UAE is important.

Table 3.14. Analysis of the relationship between the surface MT/RST/ET circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
WT	10	0.4	6	4	60.0	40.0
WR	4	0.2	3	1	75.0	25.0
ZF	3	0.1	1	2	33.3	66.7
STH	1	0.0	1	0	100.0	0.0
ET	0	0.0	0	0	0.0	0.0
WCL	0	0.0	0	0	0.0	0.0

Siberian High Indian High (SH/IH)

The interaction between the warm and moist air masses coming from the Indian Ocean, associated the IH together with a cold and relatively dry air mass associated with the SH are not associated with any rainfall over the UAE.

Easterly Trough and an Indian Ocean High (ET/IH)

The ET is responsible for easterly to north easterly flow at the surface which is characterized by warm moist air. Warm and moist air masses are also transported to the region from the south as part of the IH. The moisture will only form convective precipitation if uplift is initiated by the mountains in the eastern portions of the UAE. This synoptic scale circulation pattern was found to occur less than one percent of the time. When it did occur, it was usually associated with a STH system in the upper atmosphere which is now known to inhibit rainfall of any kind over the UAE.

Table 3.15. Analysis of the relationship between the surface ET/IH circulation and the six upper circulation patterns and the occurrence of rainfall over the UAE between 1995 and 2001.

500 hPa	Total no. of days of occurrence	% annual occurrence	Total non rainy days	Total rainy days	% non rainy days	% rainy days
STH	8	0.3	7	1	87.5	12.5
WR	2	0.1	2	0	100.0	0.0
ZF	1	0.0	1	0	100.0	0.0
ET	1	0.0	1	0	100.0	0.0
WT	0	0.0	0	0	0.0	0.0
WCL	0	0.0	0	0	0.0	0.0

Unusual atmospheric conditions causing rainfall over the UAE

Infrequently unusual atmospheric circulations cause rainfall to occur over the UAE region. The circulations and events have not been included in the previous discussion of atmospheric circulation and rainfall as they are difficult to predict and occur sporadically.

Tropical Cyclone

Tropical cyclones are low pressure systems which derive energy primarily from evaporation from the sea in the presence of high winds and lowered surface pressure and the associated condensation in convective clouds concentrated near its centre (Holland 1993). Tropical cyclone formation also requires a trigger that initiates convection. One such trigger is the intertropical convergence zone (ITCZ), where warm sea-surface temperatures and convergence of surface trade winds foster convection. Tropical cyclones often develop along easterly waves. These waves, or oscillations, in the trade winds, move from east to west across the tropics

In spring and autumn the Arabian Sea is sometimes affected by tropical disturbances (GLENN, 1954), some of which develop into tropical storms. The number of tropical disturbances of all intensities, observed in the Arabian Sea during a 60-year period ending in 1950, was approximately 140 (KOTESWARM, 1962). Of this amount, 31 cases were in the pre-monsoon period (May and June), and 61 were in the post-monsoon period (October and November). It was further indicated, in the same work, that the number of occasions during which disturbances developed into tropical storms was 21 in May and June and 27 in October and November. These atmospheric disturbances over the Arabian Sea regions usually occur in the form of an easterly trough which initiates convective activity on the trailing edge of the trough. An example of a tropical cyclone that affected the eastern portion of Oman occurred on 11of May 2002 and generated 164 mm of rain over Hamim (south east of the UAE).

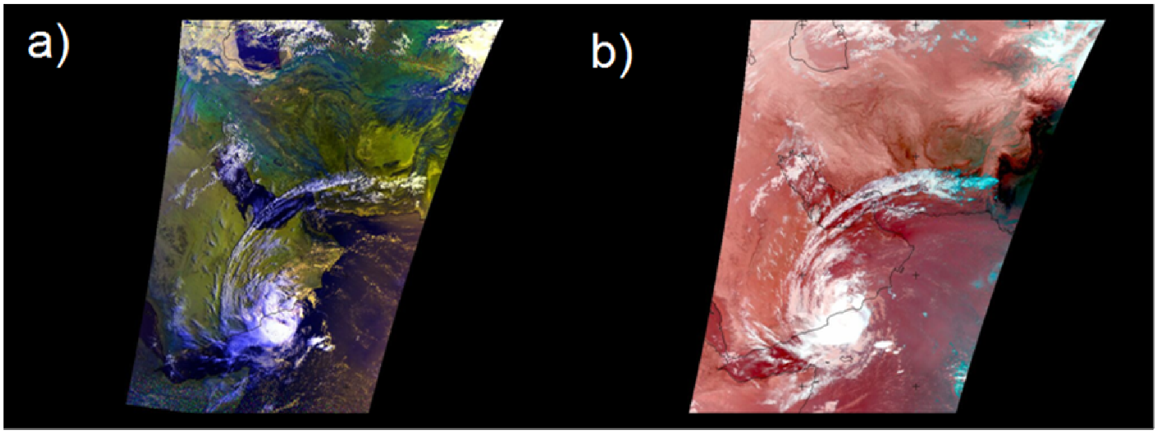


Figure 3.27. Tropical cyclone over the Arabian sea as seen by satellite as a) visible and b) infrared images on 11May 2002.

Orographic effects.

Orography is a complex source of perturbation and deformation of atmospheric flows. When airflow approaches a mountain, it is forced ascend. As the air moves up it becomes cool and initiates the formation of clouds and rainfall. Like this, orography builds up convection system and brings about precipitation or enhances rainfall.

The spatial rainfall distribution over the UAE is largely determined by orography. The complexity of the terrain produces a large spatial variability in the rainfall and often precludes generalizing the effect that a synoptic weather event may have in any given location. The mountains in the east of the UAE have an almost north-south orientation. Highest altitudes (which are about 2000 m above means sea level amsl) are found in the northern portions of the mountain ranges. During the afternoon, land heating and topographic effects combine to produce convection, and eventually rainfall, inland, and over the slopes of the mountains. Topographic uplift and land-sea differential heating, account for short-term showers often observed in the late afternoon. An example of the development of convection over the eastern mountains on the UAE and Oman, is given in Figure 3.28

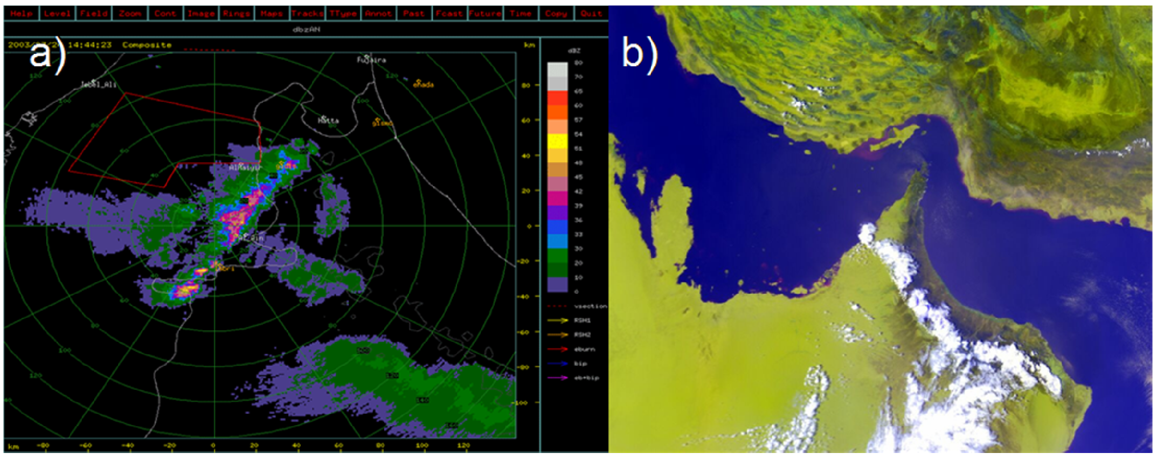


Figure 3.28. Convective clouds over the eastern mountains during the summer season (2004). a) Shows a radar image obtained from the Al Ain radar and b) is a false colour composite satellite image on the same day.

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The surface and upper atmospheric (500hPa) circulation has been characterised over the UAE region. Six major circulation types have been identified as dominating both the surface flow and the flow at 500 hPa. Combinations of synoptic circulation patterns are common over the UAE. Rainfall is produced under conditions conducive to surface and upper atmospheric convergence. The adjacent bodies of water frequently provide moisture to the UAE as a consequence of particular synoptic circulation. Atmospheric stability will be considered in detail in Chapter 4.

CHAPTER 4

ATMOSPHERIC STABILITY

Atmospheric stability is an important consideration for convective activity and the dispersion potential of the atmosphere. The characteristics of atmospheric stability over the UAE will be considered in this chapter. The prevalence of absolutely stable layers over the UAE has been evaluated and frequency of occurrence established for the stable layers identified.

Absolutely stable layers over the UAE

Surface inversions and absolute stability

At any time over the UAE it is possible to observe as many as six absolutely stable layers in the atmosphere. The first layer represents a surface inversion that forms almost every night over the UAE. The average height of the surface inversion extends up to approximately the 950 hPa (~ 525 masl) level in the atmosphere (Figure 4.1). It is a dominant feature of the UAE atmosphere throughout the years occurring in more than 60% of all soundings analysed (Figure 4.2).

The surface inversion layer plays an important role in controlling moisture availability over the region liberated from the Arabian Gulf as well as from the Gulf of Oman and Arabian Sea. The height and strength of the inversion is slightly reduced during the summer months. The surface inversion forms as a result of surface cooling over land during the evening. It can be expected to reach maximum intensities under conditions of anticyclonic circulation over the UAE, usually associated with the Siberian high pressure system. The surface inversion will start to break down over the region soon after sunrise. It will typically be completely eroded from the surface by 10h00 local time.

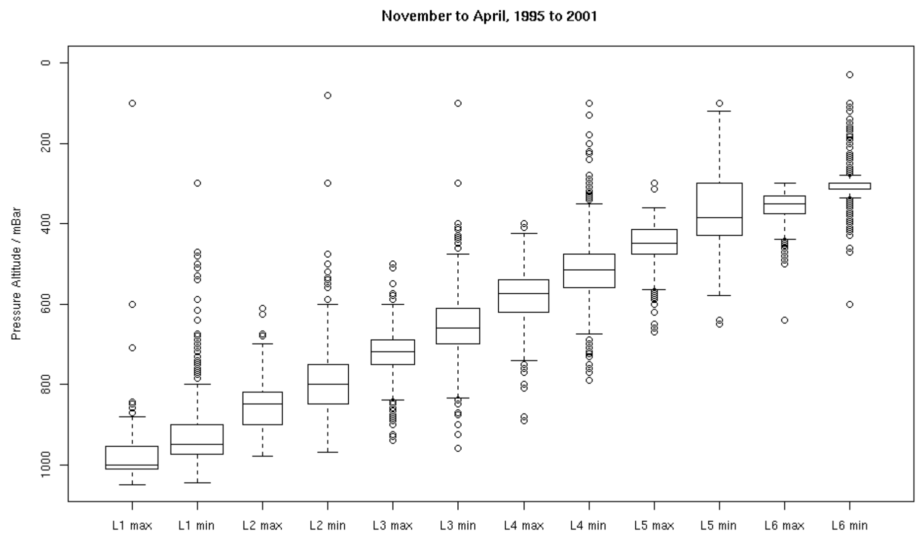

Figure 4.1. Absolutely stable layers identified over the UAE for the period 1995-2002 during the winter. The box and whisper plots give the median minimum and maximum pressure surface of each layer as well as one and two standard deviations. The empty circles indicate outliers of each layer. The width of the box indicates the persistence of each layer.

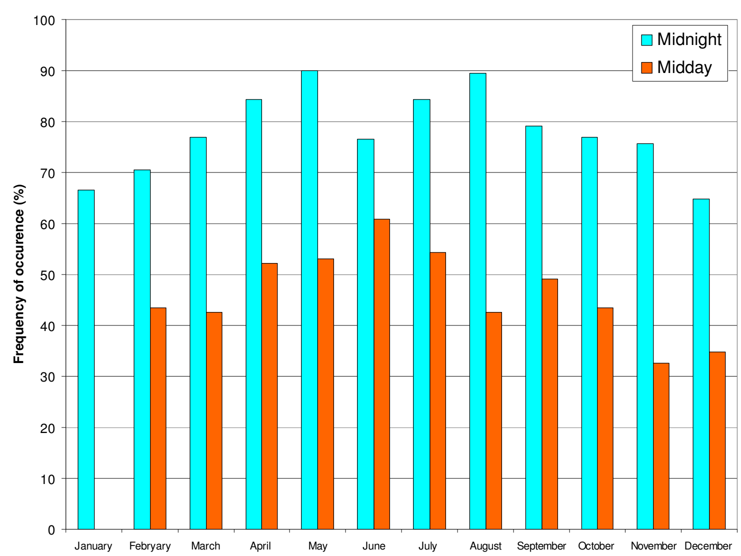

Figure 4.2. Frequency of occurrence (%) of the surface inversion layer at Abu Dhabi between 1995 and 2001.

The surface inversion is clearly detectable in both the midday and midnight soundings taken from Abu Dhabi International Airport. This results from the fact that the midday soundings occur at 09h00, local time. This is still early enough in the day for the surface inversion to be weakly developed at the surface. A comparison between the frequency of occurrence at midnight and midday reveals a sharp decline in the presence of the surface inversion by 09h00 local time (46 %). The surface inversion was found to occur over the UAE 78 % of the time at midnight on average. In both the midnight and midday data a slight increase in the frequency of occurrence of the surface absolutely stable layer is detected during the summer months. This coincides with a deepening of the layer during the summer at midnight (Figure 4.3).

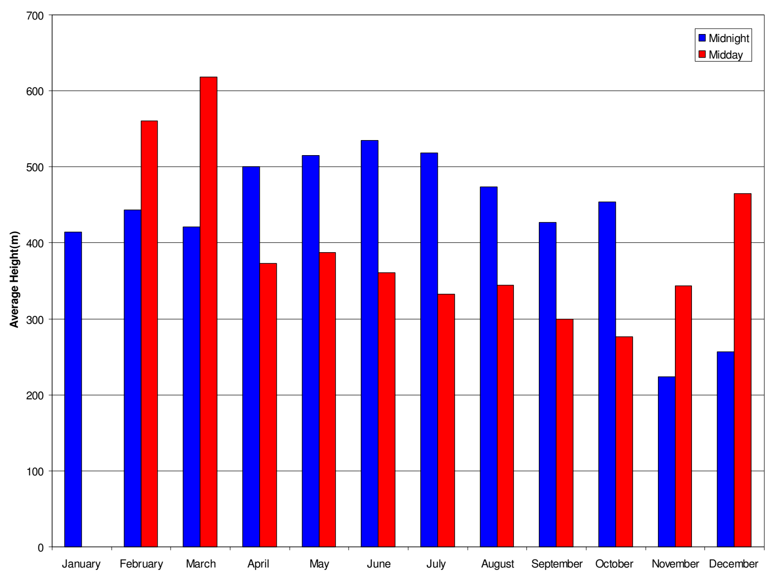

Figure 4.3. Average height above the ground of the surface inversion at midnight and midday over Abu Dhabi between 1995 and 2001.

The deepest midday inversions are found during the winter months. The development of the surface inversions is seemingly related mostly to the ability of the atmosphere to loose energy during the night. The fact that the height of the midday inversion is highest during the winter may be related to the stable conditions associated with the SH which dominates in those months. The nature of the development of the surface inversion during the summer should be studied in more detail ion eth future.

Elevated absolutely stable layers

Multiple stable layers have been identified in the atmosphere over the UAE. At any given time it is possible to identify a total of six layers simultaneously from the radiosonde data from Abu Dhabi Airport soundings (Figure 4.2 and Figure 4.3). Elevated layers of absolute stability and inversions are caused as a result of atmospheric subsidence in the upper atmosphere. The result is that descending air heats adiabatically in the atmosphere and as a result causes the formation of layers of stability. These elevated layers of absolute stability are important thermodynamic barriers in the atmosphere.

The elevated absolutely stable layers occur throughout the year over the UAE. It is clear from the composite box and whisker plots in Figure 4.2 and Figure 4.3 that the most prominent absolutely stable layers over the UAE occur at the surface and at 600 hPa. Key to the development of elevated absolutely stable layers is the presence of anticyclonic flow in the atmosphere (particularly the upper atmosphere) which promotes descending air. From the previous chapter it was established that the SH at the surface and the STH in the upper atmosphere occur frequently throughout the year. If these two systems occur simultaneously over the UAE, the atmosphere will be highly stable and it is under these conditions that as many as five elevated absolutely stable layers are identified over the region. These two layers will also be shown to exercise the most control of vertical movement in the atmosphere. None of the identified absolutely stable layers occur less frequently than 40 % of the time.

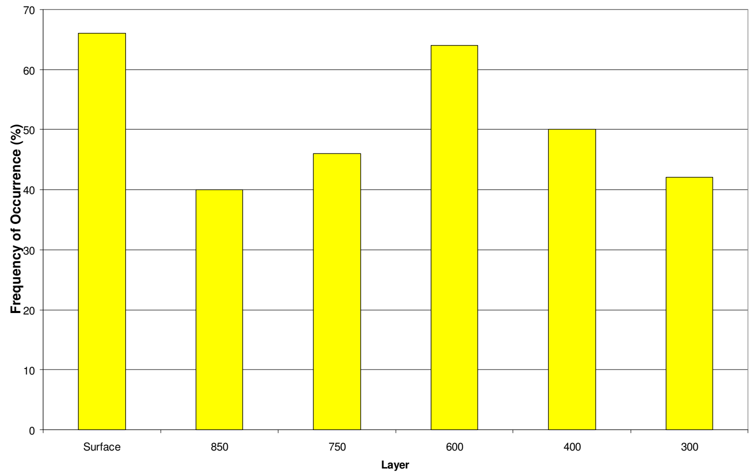

Figure 4.4. Frequency of occurrence of absolutely stable layers in the atmosphere over the UAE between 1995 and 2001

The strong seasonal signature identified in the surface inversion layer is also distinguishable in the layers occurring at 850 and 700 hPa. However, the maximum frequency of occurrence for these two layers occurs during the winter months and not the summer time, as is the case for the surface inversion layer. The seasonal pattern of occurrence is the same as observed for the SH pressure system influence over the UAE. The mechanism for the development of the 850 and 750 hPa absolutely stable layers may therefore be linked to the subsidence in the atmosphere caused by the presence of anticyclonic circulation at the surface which reaches its maximum intensity during the winter months on the northern hemisphere. The increase in the number of surface inversions during the summer does not coincide with this observation. The development of surface inversions is mostly not associated with atmospheric subsidence, but is more a function of the loss of surface radiation under clear sky conditions. This requires more detailed investigation on the future.

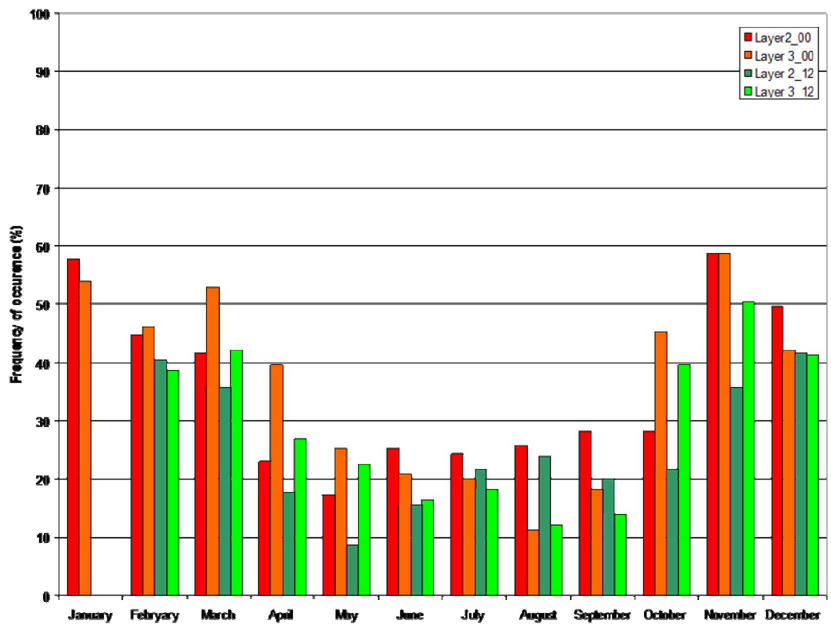

Figure 4.5. Seasonal variation of the occurrence of absolutely stable layers that occur at 850 (layer 2) and 750 hPa (layer 3) at midnight and midday between 1995 and 2001.

The variation in the frequency of occurrence of absolutely stable layers in the upper atmosphere over the UAE indicates little or no seasonal signature (Figure 4.6). The most frequently occurring absolutely stable layer in the upper atmosphere occurs at 600 hPa. This layer is present in the atmosphere up to 68 % of the time. It never occurs less frequently than 50 % of the time. The upper air absolutely stable layers are purely a function of the dominant upper atmospheric anticyclonic circulation, the STH. The absolutely stable layer at 600 hPa acts as an important thermodynamic barrier in the atmosphere over the UAE. During aircraft measurements in summer and winter, atmospheric constituents were seen to be trapped below this layer on all flying days. During the winter the 700 hPa layer may exert similar influence, reducing the height of the mixing layer slightly.

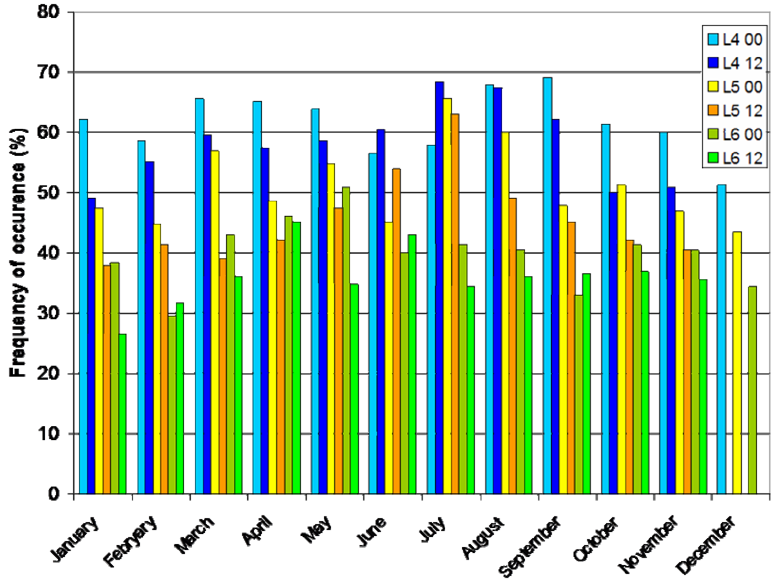

Figure 4.6. Seasonal variation of the occurrence of absolutely stable layers that occur at 600 (layer 4), 400 hPa (layer 5) and 300 hPa (layer 6) at midnight and midday between 1995 and 2001.

The nature of the atmospheric stability over the UAE for a ten year automated analysis of atmospheric stability is shown in Figure 4.7. The atmospheric stability is indicated where the environmental lapse (Γ) rate is approximately equal to the saturated lapse rate (Γs) (yellow, orange and red in Figure 4.7). Although it is more difficult to discern the six layers identified in the previous analysis, the important features of the atmospheric stability is clearly evident in this analysis. The surface inversion layer is most prominent during the summer months in the midnight soundings. Atmospheric stability is greatly increased during the winter time (evident from the predominance of yellow in the plots (Figure 4.7) between November and April. Throughout the year a thermodynamic barrier exists in the atmosphere at about 600 hPa. During the summer months the atmosphere can be unstable beneath this layer; however, the anticyclonic circulation in the upper atmosphere creates an entirely stable upper atmosphere. From these analyses the 300 hPa layer seems to be more prominent than is indicated from the tephigram analysis.

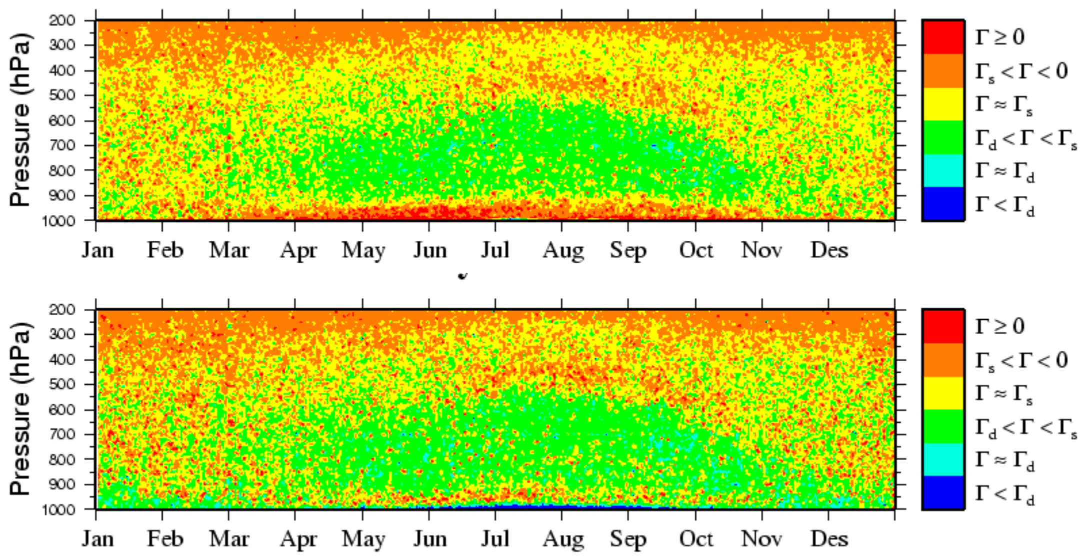

Figure 4.7. Atmospheric stability analysis for midnight (top) and midday (bottom) radiosonde data for ten years (1993-2002) at Abu Dhabi International airport. The data set was downloaded from the University of Wyoming web data base.

As was mentioned previously the prominent nature of the stability at approximately 600 hPa creates a thermodynamic barrier to atmospheric constituents. This is clearly visible in the photograph taken over the UAE during a research flight in 2001. The haze, and therefore aerosols, is clearly unable to mix above this stable layer.

Figure 4.8. Photograph of haze layer persistently present over the UAE and clearly trapped below an elevated inversion during the winter campaign of 2001.

Atmospheric Stability characteristics derived from in-situ measurements

Aircraft measurements were undertaken by the National Center for Atmospheric Research and the Climatology Research Group at the University of the Witwatersrand in an attempt to evaluate the atmospheric constituents over the UAE. These data have also clearly shown how the absolutely stable layers in the atmosphere impact on the dispersion and vertical distribution of measured species such as aerosols, SO_2, O_3 and NO_x. The constituent data has been summarised by calculating averages for all flights over given regions of the UAE. Spatially the absolutely stable layers seem to extend over the entire UAE on any given day. This is clearly demonstrated by examining data from the above mentioned in-situ aircraft data.

Trapping of emissions by absolutely stable layers over Jebel Dhanna/Ruwais

Over Jebel Dhanna and Ruwais in the summer, absolutely stable layers were recorded at ~1 200 m and at ~4 000 m (Figure 4.9). Aerosols, SO_2, O_3 and NO_x, which are presumably mainly derived from local industrial activities at Ruwais, are considerably elevated in the surface mixing layer. Their vertical dispersion is inhibited by the stable layer, and concentrations of the aerosols and trace gases drop sharply above 1 200 m.

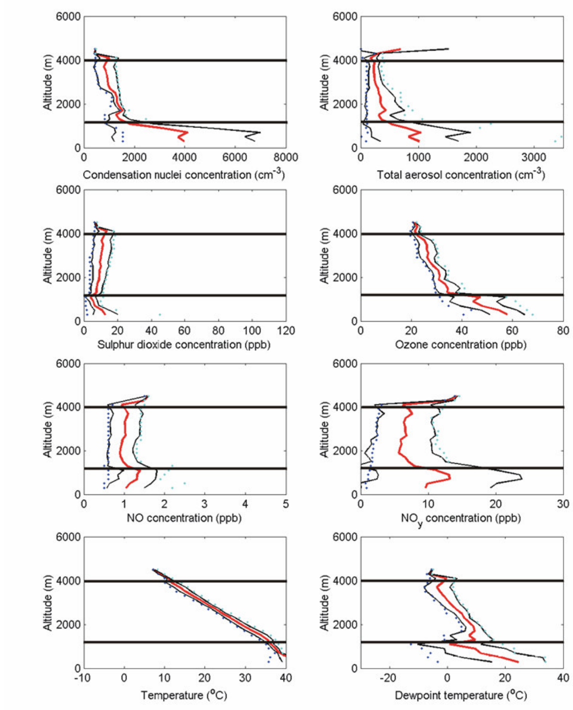

Figure 4.9. Vertical profiles of condensation nuclei, accumulation mode aerosols, sulphur dioxide, ozone, NO, NO_y concentrations, temperature and dewpoint temperature over Jebel Dhanna and Ruwais during summer 2001.

Trapping of emissions by a temperature inversion over Das Island

The stability over the UAE is not only restricted to the land. Measurements over the Arabian Gulf also show the existence of absolutely stable layers in the atmosphere. A temperature inversion, for example, was clearly detected at 1 000 m amsl over Das Island in winter 2001. It effectively trapped emissions from the refinery close to this island in the lowest kilometre of the atmosphere (Figure 4.10). Concentrations of aerosols and trace gases were considerably elevated below the inversion.

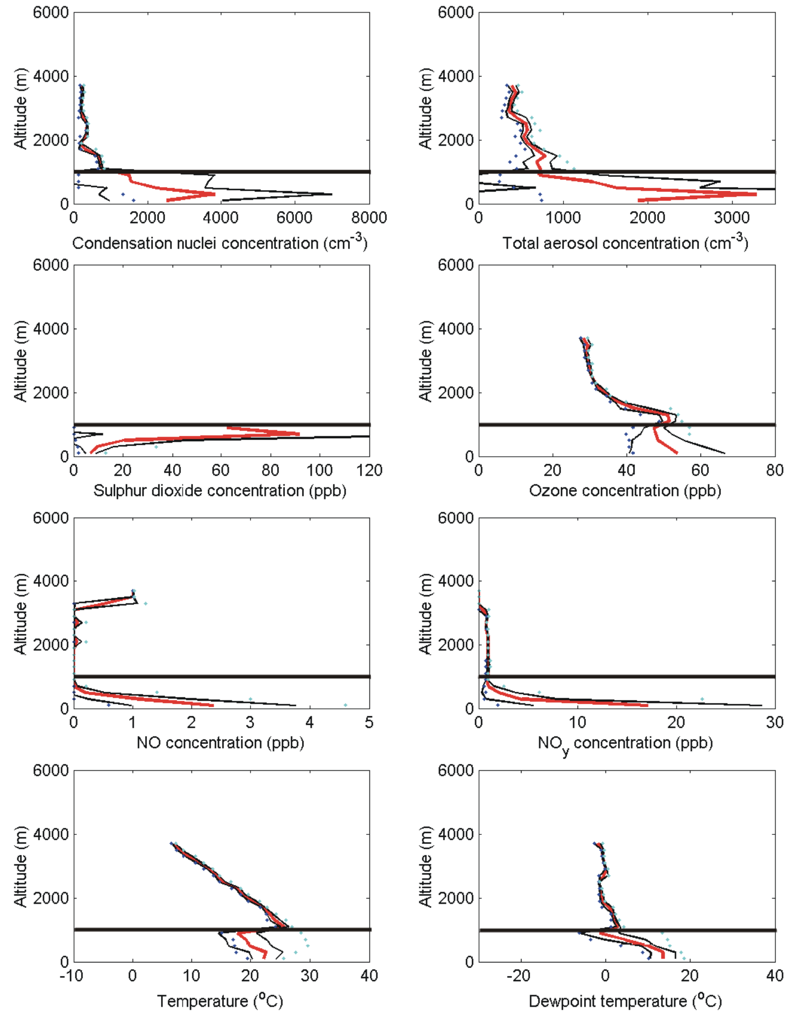

Figure 4.10. Vertical profiles over Das Island during winter 2001. These data were collected in-situ using an instrumented aircraft.

The stability over the ocean also occurs in several discrete stable layers. Over Zirku Island, for example, during summer 2001, there was a surface temperature inversion extending to 400 m, a discontinuity at ~1 500 m, and an absolutely stable layer at ~3 600 m (Figure 4.11). The surface inversion was due to the influence of the relatively cooler water at the surface, and is probably a common feature over the Arabian Gulf. The surface mixing layer extended to ~1 500 m, while the absolutely stable layer at ~3 600 m is subsidence-induced. High concentrations of aerosols, sulphur dioxide and ozone were found below 600 m, due to emissions from Zirku Island. Aerosol, ozone and sulphur dioxide levels dropped sharply above 600 m, but remain elevated up to ~1 500 m.

Five temperature inversions, centred at 800 m, 1 400 m, 1 800 m, 2 800 m and 3 700 m, were evident over Zirku Island during winter 2001 (Figure 4.12). Layering of aerosols and trace gases is related to discontinuities in the thermodynamic profile. It is hypothesised that most emissions from the refinery on Zirku Island are trapped below the ~800 m inversion. Aerosols and trace gases were able to disperse up to the ~1 400 m inversion, perhaps because the 800 m inversion broke down at an earlier stage.

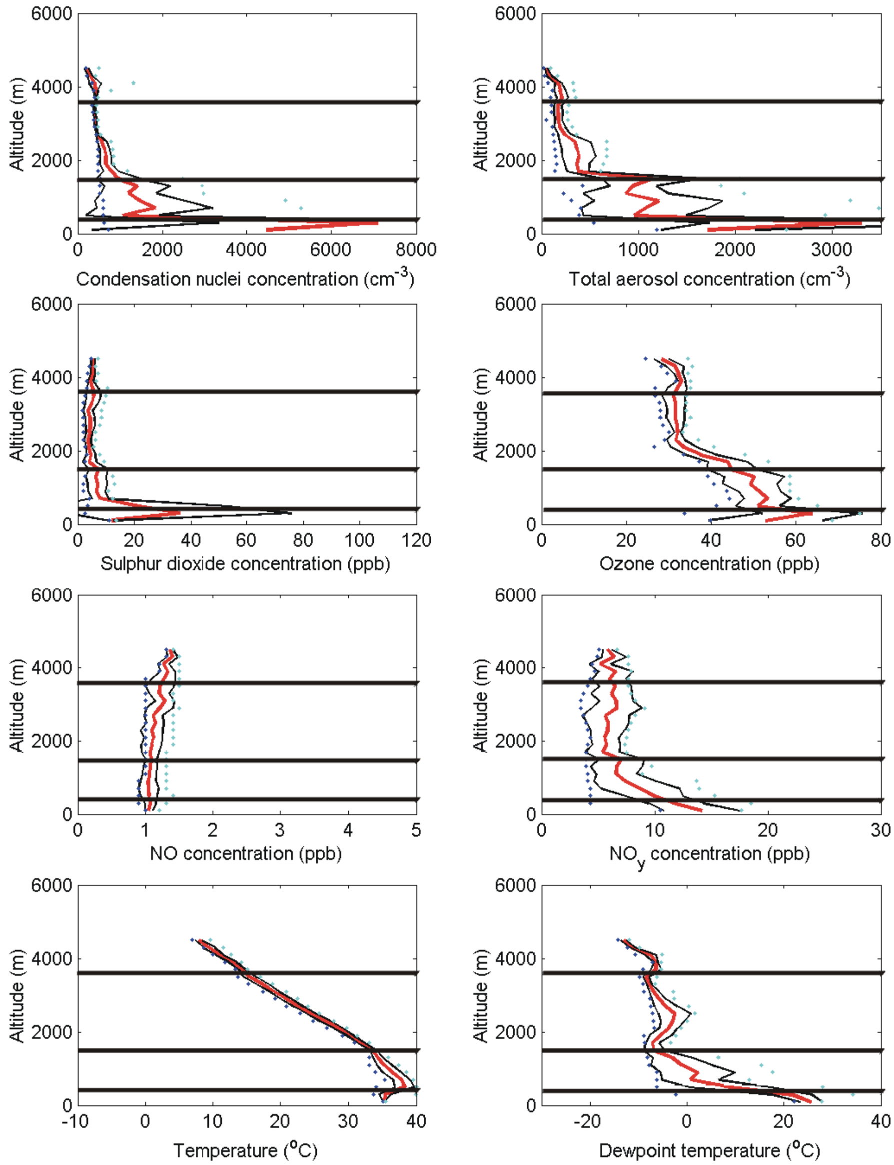

Figure 4.11. Average vertical profiles over Zirku Island during summer 2001.

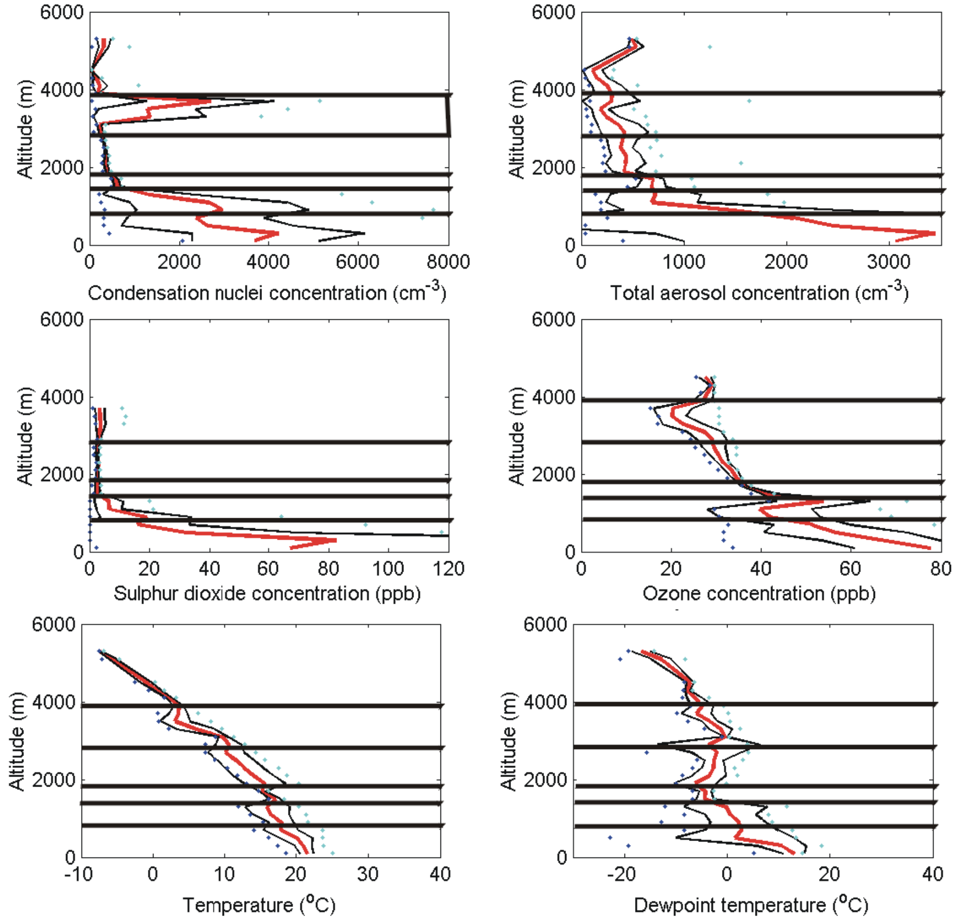

Figure 4.12. Vertical profiles of condensation nuclei, aerosol sulphur dioxide and ozone concentrations and temperature and dewpoint temperature over Zirku Island during winter 2001.

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Atmospheric stability has been shown to be an important characteristic over the UAE. Absolutely stable layers have been identified frequently at six levels in the atmosphere, surface, 850, 750, 600, 400 and 300 hPa respectively. The most frequently occurring of these layers are the surface inversion and the absolutely stable layer at 600 hPa. The absolutely stable layers act as thermodynamic barriers in the atmosphere. Atmospheric constituents are effectively trapped below these stable layers.

CHAPTER 5

CONCLUSIONS

The nature of atmospheric circulation and stability over the UAE has been evaluated in this dissertation in order to understand rainfall. The synoptic circulation has been summarised at the surface and 500 hPa. The influence of the circulation types on rainfall has been determined. Atmospheric stability has been characterised at Abu Dhabi and the influence on vertical dispersion of atmospheric constituents considered. The purpose of this chapter is to summarise the most important findings of the research conducted and presented in this dissertation.

The UAE is a country that has developed very rapidly over the past thirty years. The future development of the country is now being threatened by the lack of fresh water. In order to understand the characteristics of the natural water supply it is important to understand the atmospheric processes that influence the nature and quantity of precipitation. Previously no study had defined the major circulation patterns affecting the UAE and surrounding regions. Although studies of the region had been conducted, there was a lack of continuity in understanding of the atmospheric circulation. In addition, as a result of the fact that the UAE is positioned under the descending limb of the Hadley circulation, atmospheric stability plays an important role in the atmospheric processes associated with rainfall. The main findings of this dissertation can be summarised as follows:

Synoptic circulation climatology over the UAE

(1) The synoptic over the UAE surface circulation can be summarised by five main synoptic types, namely, Siberian high, Red Sea trough, Easterly trough, Indian Ocean high and Thermal low.

(2) In general the synoptic circulation at the surface is a combination of the of circulation types that impact the UAE. These include the Easterly trough) and Siberian high (ET/SH), Red sea trough and Easterly trough (RST/ET), the Mediterranean trough the Red Sea trough and the Easterly trough (MT/RST/ET), a Thermal low and Indian Ocean high)TL/IH), the Siberian high and the Indian ocean high (SH/IH), the Easterly trough and the Indian ocean high (ET/IH) and the Easterly trough and a Thermal low (ET/TL).

(3) All of the identified circulation patterns have a strong seasonal signature of occurrence.

(4) The Siberian high occurs most frequently during the winter season (November to April).

(5) The combination of the Easterly trough and a Thermal low most frequently during the summer months (May – October)

(6) The Easterly trough occurs frequently during the summer (May - October).

(7) The upper atmosphere circulation is completely explained by six circulation patterns, Subtropical high, Westerly ridge, Westerly trough, Zonal flow, an Easterly trough and a Westerly cut-off low.

(8) The subtropical high occurs throughout the year with the highest frequency of occurrence during August (79 %).

(9) Westerly flow, including the westerly trough, westerly ridge and zonal flow all occur most frequently during the winter months.

(10) The Easterly flow in the upper atmosphere occurs mostly during the summer (July – 30 %).

(11) The highest rainfall occurs during the winter and results from cyclonic cloud bands that pass over the UAE driven by the westerly troughs.

(12) The highest rainfall amounts occur in association with an Easterly trough at the surface and westerly flow in the upper atmosphere.

(13) Rainfall in the summer occurs over the mountains in the west of the UAE and is driven by onshore flow associated with an easterly trough, Red Sea trough or and Indian Ocean high.

(14) Tropical cyclones do affect the weather over the UAE infrequently.

Atmospheric Stability

(15) Six absolutely stable (surface, 850, 750, 600, 400 and 300 hPa) layers were identified over the UAE from radiosondes launched from Abu Dhabi International Airport.

(16) The surface inversion layer occurs throughout the year with a peak frequency of occurrence during the summer months. This inversion layer is associated with surface cooling at night.

(17) The average height of the surface inversion was approximately 400 masl. There was some seasonal variation with a maximum height of approximately 610 masl and a minimum height of 220 masl.

(18) Elevated absolutely stable layers also occur throughout the year over the UAE. The absolutely stable layer at 600 hPa occurs on average 65 % of the time.

(19) The absolutely stable layers identified at 850 and 750 hPa showed a distinct seasonal pattern of occurrence over the UAE. The highest frequency of occurrence occurs during the winter months. This coincides with the highest frequency of occurrence of the Siberian high at the surface.

(20) The upper layers of absolute stability do not show strong seasonal variations. This is due to the fact that they occur as a result of adiabatic heating from the subsiding air in the atmosphere associated with the dominant Subtropical high circulation pattern throughout the year.

(21) Absolutely stable layers have been seen to be effective thermodynamic barriers in the atmosphere, preventing the effective dispersion of pollutants. Aerosols and trace gases collect beneath these layers.

The atmospheric circulation and thermodynamic structure has been considered in detail in this dissertation. For the first time a climatological classification of surface and upper air synoptic circulation has been established. The circulation and rainfall have been linked and it has been shown that rainfall occurs under specific synoptic circulation patterns. Atmospheric stability has been found to be an important consideration in the

UAE atmosphere. Any research that involves development of convective rainfall or the dispersion of pollutant in the UAE atmosphere will have to account for the highly structured nature of the atmosphere.

CHAPTER 6

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