CLIMATOLOGICAL REGIMES AND THEIR GOVERNING MECHANISMS OVER THE SULTANATE OF OMAN

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Inscription

To my beloved mother in her grave

To my wife who has always supported me in my life.

Abbreviations:-

1	DGCAM	Director General of Civil Aviation and Meteorology
2	ENSO	El Nino Southern Oscillation
3	EOF	Empirical Orthogonal Function
4	FFT	Fast Furrier Transformation
5	NOAA	National Oceanic and Atmospheric Administration
6	NCEP	National Centre for Environmental Prediction
7	NCAR	National Centre for Atmospheric Research
8	OLR	Outgoing Long wave Radiation
9	PCA	Principal Component Analysis
10	VIMT	Vertical Integrated Moisture Transport

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Abstract

The study of rainfall pattern over the Sultanate of Oman showed that the climatic region can be broadly divided into three climatic zones, north, central and south. Monthly rainfall over the north, central and south showed that there is a maximum rainfall during the winter months especially in the north and central zone with a double maximum in the case of the south. This study also established that the rainfall during the winter period originates from synoptic system from the Mediterranean region in the west of the country. This can be seen from the case study of a number winter storms that showed the propagation of the convection using OLR as a proxy from the Mediterranean sea to the region. Analysis of the vertically integrated moisture transport (VIMT) also demonstrated that during the winter the VIMT during both no-rain days and rain days was from the Mediterranean region. The main influence of this moisture transport is in the north and central climatic zone where the monthly rainfall during the winter period over the two region is around 20 mm. The southern zone is influenced by the Indian summer monsoon which set in from June to September. Case studies of convection during the summer using OLR, wind and VIMT showed that the main source of moisture is from the Arabian sea and the equatorial Indian ocean i.e. from the east of the country.

Spectral analysis of the rainfall long term variability exhibit of power spectrum peak four to seven years. EOF analysis of zonal wind anomaly showed a positive significant correlation between Oman and the east equatorial Pacific which is related to the ENSO anomaly in the Pacific basin. From the annual rainfall variation it is established that Oman tend to receive above normal rainfall during ENSO years.

Abstrak.

Kajian hujan di Negara Kesultanan Oman mengenalpasti tiga zon iklim umum iaitu zon utara, tengah dan selatan. Kajian hujan bulanan di utara,tengah dan selatan menunjukkan hujan máxima pada bulan-bulan musim sejuk khasnya di zon iklim utara dan tengah dengan dwi máxima untuk zon selatan pada musim sejuk dan musim panas. Kajian ini juga mendapati semasa musim sejuk, hujan di Oman berasal dari sistem sinoptik Mediterranean dari barat yang memasuki Oman. Ini dapat dipastikan melalui kajian kes ribut hujan lebat di Oman semasa musim sejuk melalui "outgoing long wave radiation" OLR ynag digunakan sebagai "proxy" perolakan yang menunjuk perolakan menular masuk ke Oman dari kawasan Mediterranean. Analisis "vertical integrated moisture transport" (VIMT) untuk kes ribut juga memberi gambaran yang sama dan menunjukkan semasa musim sejuk pengangkutan utama kelembaban adalah dari kawasan Mediterranean ke Oman. Pengaruh utama pengangkutan kelembaban ialah di zon iklim utara dan tengah di mana jumlah hujan bulanan semasa musim sejuk ialah lebih kurang 20mm/sebulan. Zon iklim selatan lebih dipengaruhi oleh monsun musim panas India yang terjadi dari Jun ke September. Kajian kes kejadian hujan semasa musim panas melalui OLR dan VIMT mendapati asal kelembaban ialah dari lautan Arab dan kawasan khatulistiwa lautan India iaitu dari timur Oman. Kajian analisis spectral jangka panjang hujan menunjukkan satu máxima kuasa pada kitaran empat ke tujuh tahun. Analisis EOF anomali angin zonal pula menunjukkan kaitan significan dan positif diantara kawasan Oman dan kawasan di timur khatulistiwa Pasifik yang dikaitkan secara langsung kepada anamali ENSO di basin Pasifik. Dari tabulan tahunan hujan pula ianya menunjukkan bahawa Oman menerima hujan yana lebih dari biasa semasa tahun-tahun ENSO.

Chapter 1: Introduction

The Sultanate of Oman is located in the south-eastern part of the Arabian peninsularr in both arid and semi arid environments. It is located between latitudes 16.40º N and 26.20º N and longitudes 51.50º E and 59.40º E with a total area of 309500 km^2 and divided into four governorates and five administrative regions as illustrated in Figure. 1.1. The country has a coastline which stretches over 1,700 kms, from the Arabian sea and the entrance to the Indian ocean at its south-western extremity, to the Gulf of Oman and Musandam in the north, where it overlooks the Strait of Hormuz and the entrance to the Arabian Gulf. The land area is very diversified and can be divided into three principal physiographic i.e. mountain ranges, coastal plains and desert.

Figure1. 1 Location map of the Sultanate of Oman and its neighboring regions.

Mountain ranges encompasses northern Oman or Al Hajar mountains and the Dhofar or Qara mountains which occupies 15% of the area of the country. Mountains in northern Oman extend in an arc form for 700 km from Musandam in the north and curve eastward towards the coast to the Ras Al Hadd, the easternmost part of Oman. Jabal Shams with the highest peak of 3075 m above mean sea level, is part of Al Jabal Al Akhdar that forms the central part of the northern Oman mountains. The Dhofar mountains, located in southwestern Oman, have peaks from 1000 to 2000 m above mean sea level.

Coastal plains comprise of Batinah in the north and Salalah in the south which account for 3% of the land mass. These plains, which serve as the main agricultural areas, have elevations ranging from 0 to 500 m above mean sea level.

The interior region occupies the area between the mountain ranges in the north and the south, and consists of sandy wasteland desert. The area has elevations not exceeding 500 m and accounts for 82% of the country.

In addition to the above principal classifications, Oman has a complex topographical orientation with different types of geographical terrain such as coastal areas, mountains, wadies and desert as illustrated in Figure 1.2.

Around 82% of the Sultanate of Oman consists of desert (Ministry of Education, 2005). The arid and semi arid desert regions are characterised by rainfall, which is highly variable in space, time, quantity and duration(Noy-Meir, 1973). Like most of the Arabian Peninsular, Oman is characterized by hyper arid (rainfall <100 mm/year), arid (100-250 mm/year) and semi arid (250-500 mm/year) environments that are experienced in different parts of the country (Fleitmann et al, 2003; Kwarteng et al 2009). However the long coastline and high mountains of Oman, cause significant rainfall over some elevated areas of the country (Al-Barashdi, 2007).

Figure1.2 Geographical map of Sultanate of Oman showing different topographical terrains

In general, Oman has two broad seasons, the summer season which consists of five months (May to September) and winter season which consists of seven months (October to April (Al-Barashdi, 2007). The empty quarter of Oman is characterized by a hyper arid climate with an annual rainfall of less than 50 mm. The coastal area is characterized by arid climate, where the annual rainfall is between 100-150 mm. The rainfall over the region is controlled by different weather system such as the Indian monsoon, frontal intrusion; local thunder storms etc. As an example the southern most areas of Oman such as Salalah, is influence by the Indian summer monsoon and has an annual rainfall of around 250 mm ((Ministry of Education, 2005).

1.1 General Climatology over Oman

The complex and diverse topographic regions in Oman result in a wide range of spatial and temporal climatic variations. The average temperature in northern Oman from May to September is between 32 and 48° C, and that for October to April is between 26 and 36° C. Coastal regions are hot and humid in summer with high temperature of 46° C and more than 90% relative humidity. In the interior plain or empty quarters, high temperature in summer season sometimes exceed 50° C. The temperature in winter season is reasonably mild and remains between 15 and 23 °C. The temperature in the highlands and southern Dhofar regions are moderate throughout the year. The Dhofar mountain region has a fairly steady year-round temperature of 30–35 °C.

1.2 Major mechanisms of rainfall over Sultanate of Oman

The variety of the topography along with the extent of the country provides different types of precipitation and vary both spatially and temporarily. The main synoptic systems producing rainfall in Oman is caused by four principal mechanisms (Roberts and Wright, 1993; Ministry of Water Resources, 1995; Al-Barashadi, 2007)

1. ***The Passage of the Troughs during Winter***

   Cold frontal troughs in the upper level of the atmosphere are most common from November to April and originate from north Atlantic or the Mediterranean sea. The troughs transport rainfall to the northern parts of Oman and possibly to central and southern parts of Oman. Rainfall in these areas generally depends on the physiographic location e.g. an average annual rainfall in Muscat which is located at coast is 75 mm whereas it is between 250 and 400 mm in the Al Jabal Al Akhdar which is located at elevation between 400 and 3000 m above mean sea level.

2. *Local development of thunderstorms during summer*

Convective development takes place over the Al-Hajar Mountains during the summer season. The average maximum temperature exceeds 45°C in the country with high relative humidity in the coastal areas (> 95%) during summer season. The phenomenon of thermal low develops in the empty quarter of Oman and these thermal lows contribute to the periodic oscillation of the Inter Tropical Convergence Zone (ITCZ). Further, ITCZ moves towards the southwest coast of Oman which oscillates between land and sea and develop instability which leads to the triggering of convective clouds and showers.

3. *Indian summer monsoon*

The south-west monsoon currents occur from June to September and brings humid conditions accompanied by regular drizzle, fog, mist and rain (khareef) in the Dhofar coast and neighboring mountain areas. The schematic diagram of the monsoon currents and apparent position of the ITCZ during the southwest monsoon season in India is shown in Figure 1.3. These monsoon currents penetrate occasionally more inland to create convective storms.Parts of the Dhofar region are transformed into lush landscapes of green field and verdant vegetation during the khareef season . The monsoon season in the Dhofar region brings about 100–400 mm of rainfall.

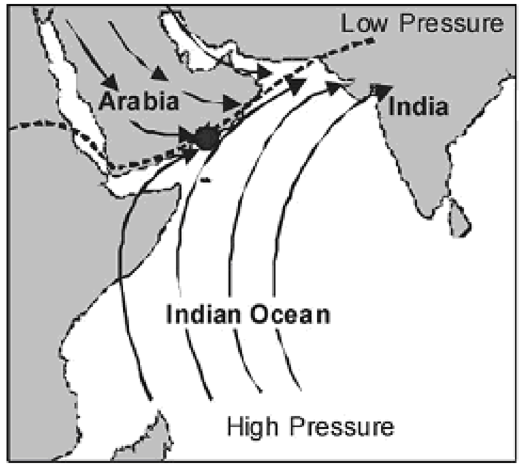


Figure1. 3 The generalized summer surface wind pattern, dashed line indicates the approximate position of the ITCZ (Fleitmann,2006).

4. The tropical cyclones and easterly waves

Tropical cyclones affect the northern and southern coast of the Oman. These cyclones originate from the Arabian Sea and tend to be distributed equally between the two main cyclone seasons i.e. May to June and October to November (Bruintjes and Yates, 2003)

However, cyclones occasionally take place outside the two periods. In general, the Arabian coast of Oman is affected by a frequency of cyclones. These cyclones forms intense storms and crop up once in every 5 years in Dhofar Governorate and once out of 10 years in Muscat. Even though these storms are rare they could result in heavy rain to the Arabian coast of Oman. One of such storms traversed Masirah Island in 1977 where 430.6 mm of rain was recorded in 24 hours (Watts, 1978), whereas the average annual rainfall in Masirah Island is only 70 mm.

1.3 General Climatology of the Middle East

The Middle East region is generally under the influence of frontal activity due to the occlusion of different air masses that form over Euro-Asia and move toward the south, southwest and southeast. One of the air masses that affect the Middle East is continental polar air mass which forms over Siberia in Euro-Asia which is extremely cold during the winter (Nurten, 2003). It moves towards south and southwest due to the increase in pressure gradient. The cooler air mass is blocked by the mountains in the northeast of Middle East resulting an anticyclonic feature and thus preventing the adverting of low pressure system from the west resulting in a decrease in winter precipitation. Continental polar air mass loses its influence over Middle East in summers due to the retreat of the Siberian high to the north. Monsoonal air mass affects the southern part of Iran and south-southwest part of the Arabian Peninsular in the Middle East region.

The climate in the UAE is sub-tropical, arid and rainfall is occasional and normally takes place during November to March with an average annual rainfall of 152 mm. The Siberian high pressure is considered to be the most dominant surface pressure system, some time extending to the south of the Arabian Peninsularr. It is usually associated with strong north-westerly wind depending on the location of the high pressure extension within the country that causes inflow of cold air which results in a drop in the surface air temperature. The minimum temperature is less than 1^{o}C at such locations. In summer the prevailing synoptic situation is the thermal low centred over the Arabian Peninsularr (April- September), this low plays an important role in raising the surface air temperature that reaches more than 50^{o} C. The prevailing wind associated with this situation is usually south-easterly and the surface condition is generally dry and hot.

1.4 Scope of the study

The Sultanate of Oman has an arid, hyper arid, and semi arid environment and thus the rainfall over the country has a wide fluctuation in both temporal and spatial scales. More over, rainfall is scarce and is an important hydrological variable in dry land areas. The need for water in the country is growing rapidly due to population growth, economic developments and urbanization. Water management has become a critical issue in natural resources management. It is essential to understand the general pattern and its variability in different time scale to assess the impact on the ecosystem in order to develop an effective management strategy. These variability need to be properly studied and documented. The present research study will help to understand the variability of the rainfall and its controlling mechanism in Oman. The findings could be utilized in hydrological survey and agricultural planning as well as climate research in the future.

1.5 Objective of the study

The key objectives of the study are listed below:-

1. To study the annual rainfall Study and its departure from the mean for different stations.
2. To study the monthly rainfall climatology in different stations and regions of the Oman such as the Northern, Central and Southern regions.
3. To study the rainfall trend using the available rainfall data set for different categories of rainfall such as low intensity, medium and high intensity range.
4. To investigate the linkage between the rainfall with wind and temperature pattern for different regions of Oman on monthly basis.
5. To investigate the mechanism for the rainfall occurrences during summer and winter season and the moisture source.
6. To study the linkages of rainfall in the Oman with ENSO events.

Chapter 2: Literature review:

The proper study of long-term rainfall data and its documentation are inadequate particularly in Oman and generally in most of the arid zones of the Arabian peninsular. This may be due to lack of adequate network of rain gauges, inaccessibility and uninhabitable nature of the area, poor data quality and lack of the personnel for effective maintenance and archival of the rainfall data. Research activities in Oman are primarily focused on climate change and its mitigation strategies but long term analysis and studies of rainfall are sporadic and seldom reported. A more systematic observation of rainfall and other meteorological parameters are essential to overcome this problem. Moreover, it is essential to increase training and capacity building in the field of meteorology and climatology in this region.

This chapter reviews some of the previous research studies that have been carried out in Oman by various climate scientists. The present climate of the area is hyper arid to arid to semiarid with an annual precipitation ranging from 50 to 255 mm (DGCAM, 1996)

The climatic zone of Oman covers a wide range with mean annual rainfall of less than 50 mm in the interior of the Rub al- Khali desert and at some high altitudes over the northeastern Al-Hajar mountains (>3000 m) the annual rainfall is 350 mm with an occasional snow falls. Rainfall occurs in summer due to the southwest monsoon circulation and also in winter due to the penetration of eastern Mediterranean troughs in the Persian Gulf following the Zagros topographical barrier (Lezine et al, 2002). Mean monthly temperatures ranges 33 to 35° C during the summer months and 20 to 25° C during the winter months. Precipitation in northern Oman is extremely variable and originates from different sources. The main sources of rainfall in Oman have been described in detail in the introduction chapter. Tropical cyclones reach northern Oman once every 5 to 10 years between the summer and the winter season (May–June and

October–November) and are associated with heavy rainfalls of several days duration (Dominik, et al, 2002; Weyhenmeyer, 2002)

In contrast to northern Oman, southern Oman receives more than 80% of its total annual rainfall ranging between 200-600 mm/year during the summer monsoon season, which lasts between July and September (Fleitmann and Burns, 2006).

Earlier studies reported that monthly average rainfall over the northern stations and the coastal stations of the Gulf of Oman receive the highest rainfall during November to March. The Al-Hajar mountains and adjoining areas receive the maximum rainfall during summer (July-September) due to the local thunderstorms (DGCAM, 1996)

The southern stations are affected by the Indian summer monsoon and receive maximum rainfall during July and August. In general, the annual mean rainfall reaches the maximum over Al-Hajar mountains (350 mm/year) and the minimum rainfall occurs over the desert areas (4 mm/year) (Al-Barashdi, 2007).

Fleitmann et al 2006 reported that Oman is an area that is more sensitive to change in the mean meridional transition of the ITCZ and hence this area is prone to convective activity. The cloud development is currently prevented by a temperature inversion located over southern Oman as shown in the Figure 2.1, whereas the height of this temperature inversion is dynamically linked to the mean latitudinal summer position of the ITCZ and to the monsoon wind pattern over southern Arabia (Fleitmann, et al, 2006).

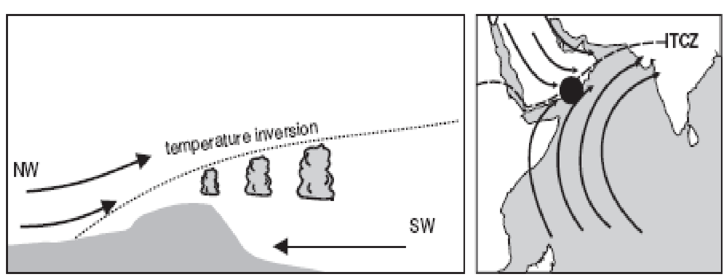


Figure 2. 1 a) wind flow over heterogeneous surface that create temperature inversion, dashed line is the zone of temperature inversion. b) means southwest monsoon circulation and approximate position of the ITCZ given as the dashed line.

Studies of Radies et al (2004) revealed that the climate in Oman is hyper arid with rainfall less than 100 mm/year. The rainfall is caused by the influence of tropical cyclones during the winter months. Over southern Arabia the ITCZ is a chain of low pressure cells that marks the convergence of the northerly wind regime and southwesterly monsoon winds. Southwesterly monsoon winds are deflected into southerly and even easterly directions over the Oman deserts as shown in Figure 2.1 b.

It is important here to note about the paleo-climate of Oman and it is very important to be conscious about the present climate and how much it has changed in the past. Evidence of past changes in monsoon dynamics comes from sedimentary archives of the dust and pollen input into the Arabian sea and the upwelling intensity induced by summer and winter monsoons. A stronger monsoon circulation causing significantly higher precipitation over the Arabian peninsular during the Holocene climatic optimum was identified in marine sediment cores and in terrestrial geoarchives of southern Arabia (Preusser, et al, 2002). They argued that the present day southern circulation over the Arabian sea was substituted or at least strongly influenced by an increase of northwesterly winds. Radies et al (2004) reported that the precipitation during the early Holocene wet period was apparently monsoon derived and the northern boundary of the monsoon system was probably pushed further to the north. Consequently the rainfall belt associated with the ITCZ moved northward and therefore the conditions become fully arid again around 2000 years ago (Preusser, 2002).

The recent knowledge of the Indian monsoon dynamics remains limited due to the lack of high resolution and long term records. The longest instrumental data of monsoon rainfall variability cover the last 150 years and are thus too short to fully reveal monsoon variability on century time scale (Dominik and Stephen, 2003)

Today southern Oman is mainly dependant on the Indian summer monsoon for precipitation, where more than 80% of total annual precipitation falls during this period

(June to August). From annual to decadal time scale monsoon variability is influenced by changes such as internal boundary conditions, tropical sea surface temperatures in the Indian ocean (Burns, 2002; Goswami et al) variation in Eurasian snow cover (Barnett, 1988) and linkages with ENSO in the Pacific ocean (Webster, 1998

In southern Oman monsoon rainfall occurs as fine drizzle, seldom exceeding more than 5mm/day. During the southwest monsoon season, the amount of rainfall increases with altitude, varying from 150 mm at the coastal plain to 500 mm in the Dhofar mountains (Dominik and Stephen, 2003; Kwarteng et al 2009).

At present, northern Oman is not affected by the Indian ocean monsoon, because the ITCZ and the associated monsoon rainfall belt remains generally in the south of the Arabian Peninsular (Hastenrath, 1985). However in the past centuries, the monsoon precipitation recharged groundwater during peak interglacial periods, because early to middle Holocene paleolake records from throughout north Africa and India indicate that the ITCZ and the associated monsoon rainfall belt were located much further north of its present- day position (Dominik, et al, 2002).

Concetanze (2000) reported that the water recharge in the catchment occurs mainly during the winter months as a result of Mediterranean frontal system passing through the Arabian peninsular from the northwest. The other source of rainfall is the local convective storm cells that form during the very hot summer. Tropical cyclones occasionally approach the area, originating either in the south eastern Arabian sea or in the bay of Bengal.

Recent studies showed that the Indian summer monsoon (ISM) is an integral part of the ITCZ and the manifestation of the seasonal migration of the ITCZ (Gadgil, 2003)

The annual migration of the ITCZ and seasonal progress of the monsoon winds are key components of the climatology in the Indian ocean and the surrounding areas. In spring the ITCZ migrate northward across the Indian ocean and reaches its northernmost position during boreal summer. From June to September a strong low level monsoonal air flow (low level jetstream) is generated (Findlater, 1967; Joseph and Raman 1969) by a strong pressure gradient between the Tibetan Plateau and a high pressure cell over the southern Indian ocean (Rao, 1976; Fleitmann, et al, 2007), which transports large quantities of moisture to bring monsoon precipitation over some parts of southern Arabia and the Indian subcontinents. In autumn the ITCZ then retreats southward and reaches its southernmost position in January. The reversed pressure gradient during the winter months generates the moderate and dry northeast monsoon (Fleitmann, et al, 2007)

One significant issue is, if there any correlation between the amount of monsoon precipitation in Oman and the intensity of the Indian summer monsoon or to the latitudinal position of the ITCZ and convective activity within it. Webster (1998) proposed that both features have an important influence for the amounts of monsoon precipitation for the following two reasons. First the low level monsoon winds transport large amounts of moisture from the southern Indian Ocean, which fuel the convective cells within or along the ITCZ. Second, the release of latent heat during the monsoon months is an important driving force for the intensity of the monsoon. Moreover stronger monsoon circulation enhances cross equatorial transport of moisture, which in turn intensifies convection within the summer ITCZ and ISM circulation due to the greater release of latent heat. This feedback mechanism leads to higher monsoon precipitation in Oman and other areas located close to the summer ITCZ (Fleitmann, et al, 2007).

Chapter 3:- Data and Methods

3.1 Introduction

This chapter deals with the data and the methods used for the present study. Daily and monthly rainfall data for different meteorological stations distributed all over Oman are utilised to understand the monthly and annual distribution of the rainfall. The data were collected from various agencies of Oman. In addition to the station data, NCEP/NCAR reanalysis data set was also utilised. The details of the data sets will be described in the forthcoming sections. The meteorological data obtained from these stations covers a period of more than 31 years (1977-2007), but the station Marmmul covers only a period of 22 years. The analysis of rainfall variabilities in these stations were carried out and variabilities in different time scales were discussed based on the rainfall data set.

3.2 Rainfall Station Data

Monthly and daily meteorological data of 12 stations for the available period from 1977 to 2007 over Oman region have been published by the Director General of Civil Aviation and Meteorology (GDCAM). The selection of stations for building the rainfall regimes over Oman has been made using the following criteria:-

1- The stations should have long and continuous daily rainfall records.
2- The stations should be spread throughout the country, giving good spatial representation.

Twelve representative meteorological stations which are generating continuous data from the year 1977 to 2007 were selected on the basis of the above mentioned criteria. They cover more than 30 years of data set to study the climatology of the stations. The station name, location and their altitudes are given in Table 3.1. The stations are given in the table as an orientation form north to south and locations are marked in the map of Oman as shown in the Figure 3.1. Five of these stations (Saiq, Ibri, Buraimi, Thamrait and Marmmul) are located in the interior part of the Oman. The station Saiq among them is located at an altitude of 1755 m above mean sea level (MSL). The other six stations are coastal stations and located along the coast of Oman from north to south. Masirah station is an island located in the Arabian Sea.

Table 3.1 Shows the Meteorological Stations from North to South.

No.	Name of the Station	Starting year	Total period up to 2007 (yrs)	Location	Elevation (m)
1	Khasab	1974	31	20.10ºN 54.14ºE	30.36
2	Shinas	1977	31	24.93ºN 56.45ºE	5.4
3	Buraimi	1977	31	24.14ºN 55.47ºE	298.89
4	Sohar	1977	31	24.28ºN 56.38ºE	3.63
5	Ibri	1977	30	23.25ºN 56.31ºE	244
6	Seeb	1975	33	23.35ºN 58.17ºE	8.4
7	Saiq	1979	29	23.04ºN 57.38ºE	1754.86
8	Sur	1977	31	22.32ºN 59.28ºE	13.77
9	Masirah	1977	31	20.40ºN 58.54ºE	18.8
10	Marmmul	1985	22	18.08ºN 55.10ºE	269
11	Thamrait	1980	28	17.40ºN 54.01ºE	466.9
12	Salalah	1977	31	17.02ºN 54.05ºE	20

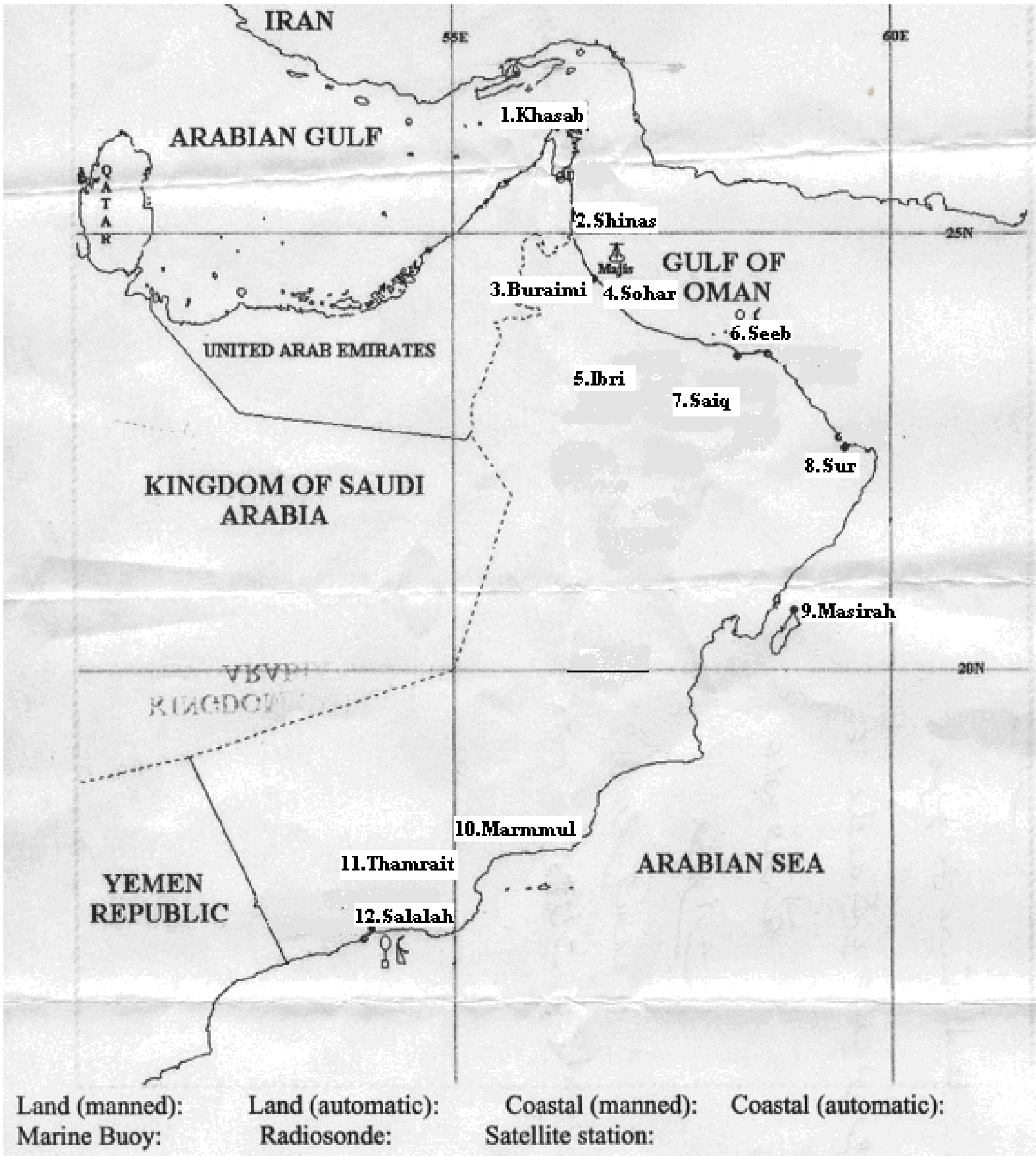


Figure3. 1 The location map of the meteorological stations in Oman

3.3 Meteorological Gridded Data

The NCEP-NCAR reanalysis data of wind fields at different pressure levels has been used in addition to the station data, on a spatial resolution of 2.5 X 2.5 latitude–longitude grid (Kalnay et al. 1996)

Daily as well as monthly data sets were used to identify the relation between the rainfall and the wind fields for a period of 48 years (1960-2007). Daily National Oceanic and Atmospheric Administration (NOAA) interpolated Outgoing Long wave Radiation

(OLR) with the same spatial resolution (Liebmann and Smith, 1996) was also used to study the pattern and propagation of convection from the Mediterranean sea and Asian monsoon climate systems during the rain spells over Oman in the winter and summer seasons. The interpolated OLR can be used as a proxy of convection and the values of OLR < 220 Wm-2 can be considered to indicate convection and thus precipitation in the tropics (Arkin and Meisner, 1987)

3.4 Homogeneity Testing for Station Rainfall Data

One should be aware that the data collected over a long period and different stations may not reflect uniform conditions when analyzing rainfall series for a considerable number of years. This could be due to changes in instrumentation, sensor calibration, maintenance procedure, change of site, observation methods, personal and codes (Mebrhatu, et al, 2007). The homogeneity of observed data with respect to non-climatic influence must therefore be assessed prior to performing different analyses. A homogeneous climate time series is defined as one where variations are caused only by variation in weather and climate (Conrad and Pollak, 1950). Most homogeneity testing techniques are primarily used in comparisons with neighbouring stations (Peterson, 1998)

As often happens, however, the homogeneity of rainfall series of neighbouring stations is also doubtful or as in this particular study, that there is no independent close neighbouring rainfall station which has long-term rainfall data for comparison purposes. A first indication of departure from homogeneity due to different changes can be obtained by plotting the partial sum of the departures from the mean (Mebrhatu, et al, 2007).

3.5 Time series analysis

A time series is a collection of observations made sequentially in time, which constitute an important area of statistics (Chatfield, 1984). Traditional methods of time series analysis are mainly concerned with decomposing a series into a trend, a seasonal variation and other irregular fluctuation (Kendall and Stuart, 1966). The review of historical data over time provides the decision maker with a better understanding on what has happened in the past, and how to estimates for the future (Mebrhatu, et al, 2007). The first step in analyzing a time series is to plot the observations against time. This will show important features such as trend, seasonality and discontinuities. Plotting the data is not as easy as it sounds. The choice of scale, the size of the intercept, and the way the points are plotted may substantially affect the way the plot look and so the analyst must exercise care and judgment (Chatfield, 1984).

3.6 Empirical Orthogonal Function (EOF) Analysis

An EOF analysis of the zonal wind anomaly at 850 hPa was undertaken to understand the major mode of variabilities. A brief description of EOFs is given below. The anomaly data matrix X' is determined, and then its covariance matrix is defined by:

$$\sum = \frac{1}{n-1} X'^{T} X'$$

which contains the covariance between any pair of grid points (Randal, 2003). The aim of EOF/PCA is to find out the linear combination of all the variables, i.e. grid points, that explains maximum variance. That is to find a direction $a = (a_1, a_2, ...a_p)^T$ such that $X'a$ has maximum variability (Lorenz, 1956). Now the variance of the (centered) time series $X'a$ is

$$\mathrm{var}(X'a) = \frac{1}{n-1} \|X'a\|^2 = \frac{1}{n-1} (X'a)^T (X'a) = a^T \sum a$$

To make the problem bounded we normally require the vector to be unitary. Hence the problem readily yields: $\max\left(a^T \sum a\right)$, such that $a^T a = 1$

The solution of this problem is a simple eigen value problem (EVP):

$$\sum a = \lambda a$$

By definition the covariance matrix $\sum$ is symmetrical and therefore diagonalizable. The k^{th} EOF is simply the k^{th} eigenvector a_k of $\sum$ after the eigen values, and the corresponding eigenvectors, have been sorted in decreasing order. The covariance matrix is also semi definite, hence all its eigen values are positive. The eigen value λ_k corresponding to the k^{th} EOF gives a measure of the explained variance by a_k, k = 1, p. It is usual to write the explained variance in percentage as:

$$\frac{100\lambda_k}{\sum_{k=1}^{p}\lambda_k}\%$$

The projection of the anomaly field X' onto the k^{th} EOF a_k, i.e. $c_k = X' a_k$ is the k^{th} principal component (PC)

$$c_k(t) = \sum_{s=1}^{p} x'(t,s)a_k(s)$$

3.7 Selection of software programs

There are many software programs that can be used in the time series data analysis. The MATLAB and GrADS software have been used in the present study due to their wide use for data analysis and display of graphical outputs. MATLAB has a numerical programming language and it allows easy matrix manipulation, plotting of functions and data implementation of algorithms, including the capability to display the information graphically. MATLAB can call functions and subroutines written in C programming language and Fortran. A wrapper functions allow MATLAB data types to be passed and returned. The dynamically loadable object files created by compiling such functions are termed MEX-files, although the file name extension depends on the operating system and processor. MATLAB also provides a number of features for documenting and sharing works like high level language for technical computing, development environment for managing code, files and data and mathematical functions for linear algebra, statistics and Fourier analysis.

The other software is the Grid Analysis and Display System (GrADS). It is an interactive desktop tool used for easy access manipulation and visualization of earth science data. This software is widely used by the meteorological and oceanographical community. The format of the data may be either be binary, GRiB, NetCDF or HDF-SDS. GrADS has been implemented worldwide on a variety of commonly used operating system and is freely distributed over the internet. It uses a 4-dimensional data environment: longitude, latitude, altitude and time. Data set are placed within the 4-D space by use of a data descriptor file.

Chapter 4: Climatology of Rainfall in the Sultanate of Oman.

4.1 Introduction:

There are 25 surface meteorological stations are located in the country that have been collecting daily rainfall records. This data set allows the study of seasonal, annual and inter annual variations of rainfall for different regions of Oman. The 31 years daily rainfall data from 1977 to 2007 were available only for 12 stations which have been used for the present study. The monthly and yearly rainfall data from the daily rainfall records were derived., Daily rainfall data is available from all the 12 stations for the 31 year period except for the stations Saiq, Marmmul, and Thamrait where the data period were 29, 22 and 28 years respectively.

4.2 Annual Rainfall.

4.2.1 Khasab station

Khasab station is located in northeast part of Oman near the coast of the gulf of Oman (20.10º N, 54.14º E) at an altitude of 30.36 m MSL. Figure 4.1 shows the time series of annual rainfall over the station from 1977 to 2007 (31 years). The average annual rainfall for this station is 184 mm with a standard deviation of 137.1 mm. This high value of standard deviation indicates a good amount of variability in rainfall from year to year. The rainfall in certain years is low but the immediate next year it is high e.g. 1994 and 1995. However the station received a high amount of rainfall for a few number of years such as 1995 to 1998 where average annual rainfall exceed 350 mm/year. The inverse condition is also noticed in the station from the year 2002 to 2004 when average rainfall was less than 50 mm/year.

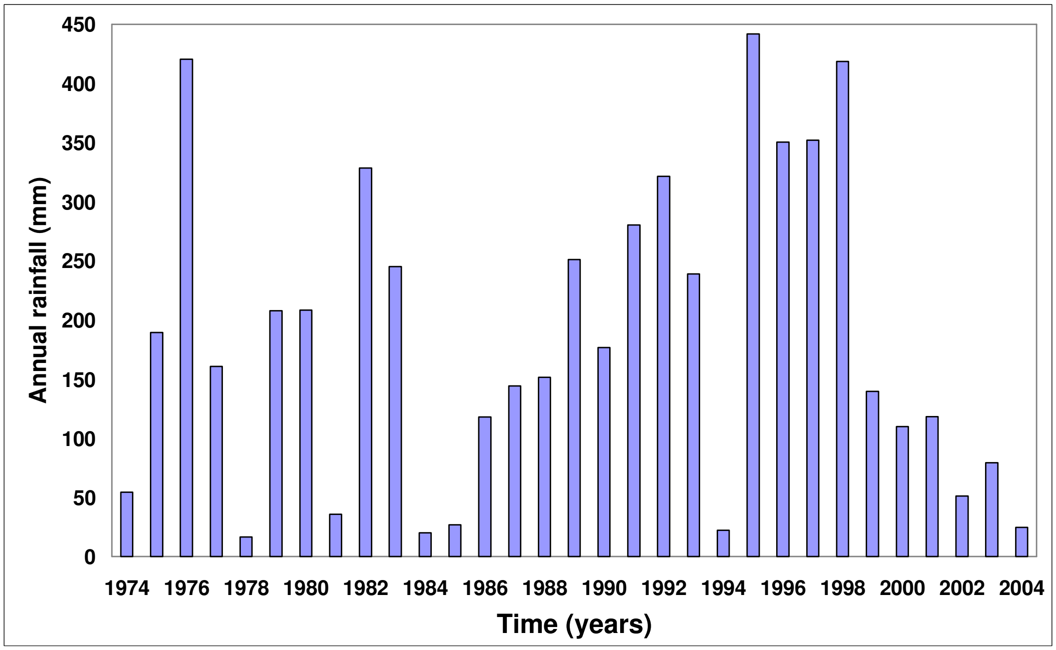


Figure- 4. 1 The annual rainfall fo Khasab station for the last 31 years.

This station received maximum rainfall of 441.8 mm in the year 1995 and minimum amount of less than 17 mm of rainfall in the year 1978. The Figure 4.2 represents the rainfall departure from the mean value for Khasab station in the study period., Wet and dry years were arbitrarily selected on the basis of the standard deviation. The wet year is known when rainfall amount is more than one standard deviation from the mean value of rainfall and the dry year, when the rainfall amount is less than one standard deviation from the mean value. The years 1976, 1982, 1992, 1996, 1997, 1998 and 1999 are wet years and 1978, 1979, 1980, 1981, 1984, 1985, 1994, 2002, 2003 and 2004 are dry years during the period study based on this definition. It shows that 23% of the years are wet and 32% are dry years. The rest of the years are normal years (45%). Number of dry years occurred continuously for four years and that for wet years are also four years.

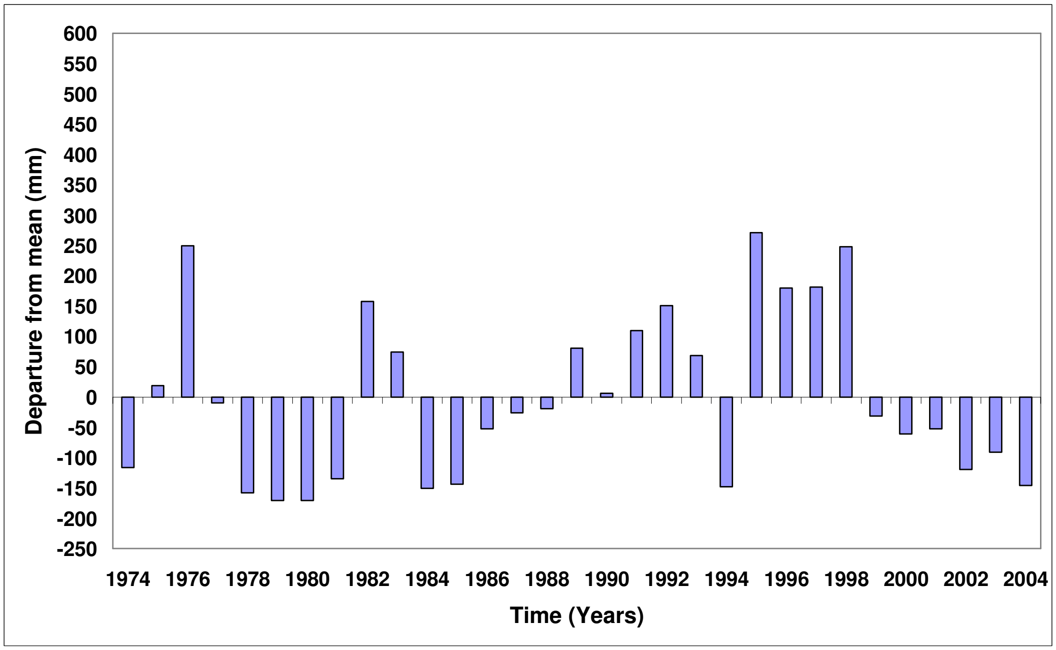


Figure 4. 2 The departure from mean of annual rainfall in Khasab.

4.2.2 Shinas station

Shinas station is one of the coastal stations which is located in the vicinity of the coast of gulf of Oman (24.93º N, 56.45º E and 5.4 m amsl). The average annual rainfall for Shinas station is 99 mm with a standard deviation of 93.4 mm as shown in the figure 4.3. The maximum rainfall of 336 mm and minimum amount of rainfall is less than 19 mm were observed in the year 1996 and 1980 respectively. The year to year variability of rainfall is almost similar to that of the Khasab station. The station received high amount of rainfall for a few years such as 1995 to 1997, with an average annual rainfall of 280 mm. Continuous dry years (1984-1985) were also observed with an average annual rainfall of about 13 mm.

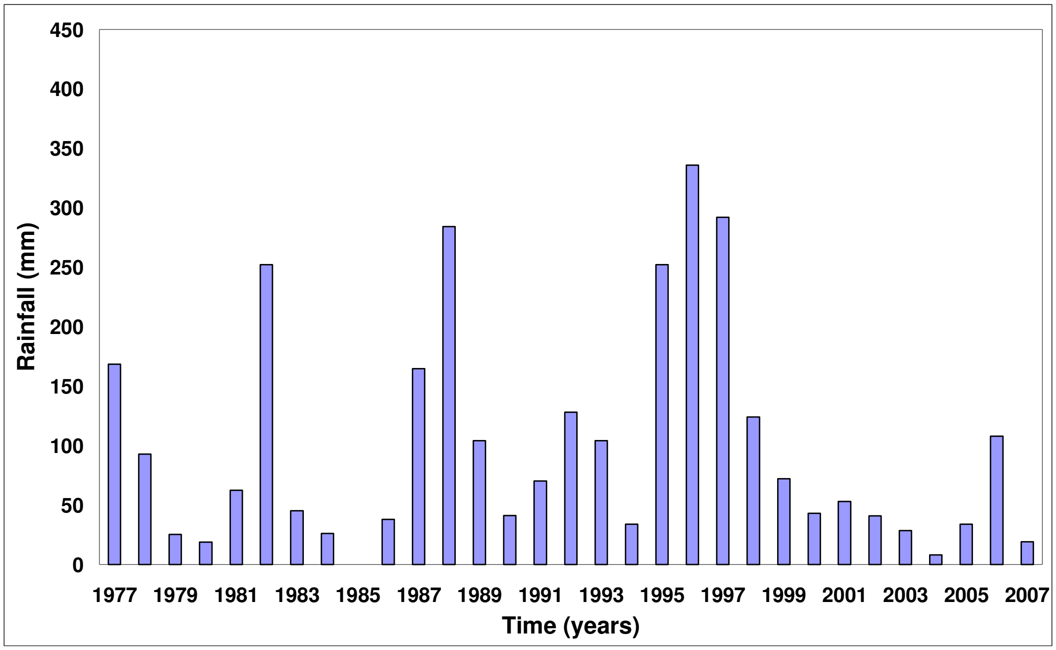


Figure 4. 3 The annual rainfall recorded in Shinas station during last 31 years.

The years 1982, 1988, 1996 and 1997 were observed as wet years and the year 1985 as dry year on the basis of wet dry criteria as detailed above. The departure from the mean for this station for the same period is shown in Figure 4.4. Annual rainfall in this station is comparatively less than that of the Khasab station. The rainfall departure patterns at this station is almost similar to the previous one e.g. clustering of low rainfall years and high rainfall years though rainfall is less.

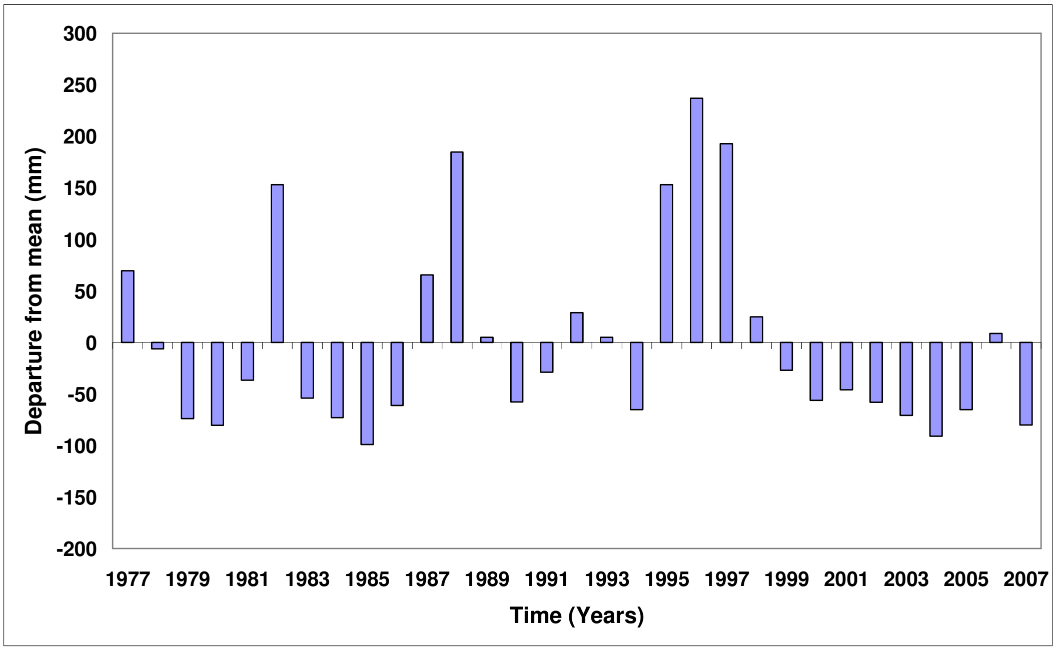


Figure 4. 4 The departure from mean of annual rainfall records of Shinas station.

4.2.3 Sohar station

Sohar Station is located in the northern part of Oman in the vicinity of the coast of Gulf of Oman (24.28º N, 56.38º E and 3.6 m above MSL). The average annual rainfall at this station is 96.5 mm with a standard deviation of 78.2 mm which means significant amount of variability in rainfall from year to year. The maximum annual rainfall of 306 mm has observed in 1997 and the minimum annual rainfall less than 1 mm (trace amount) was in the year 1985 as depicted in the figure 4.5. The years 1982, 1988, 1995, 1996 and 1997 were observed as wet years and the years 1978, 1979, 1984, 1985 and the period from 2000 to 2005 were found as dry years on basis of we and dry classification as shown in the Figure 4.6. The rest of the years were noticed as normal years.

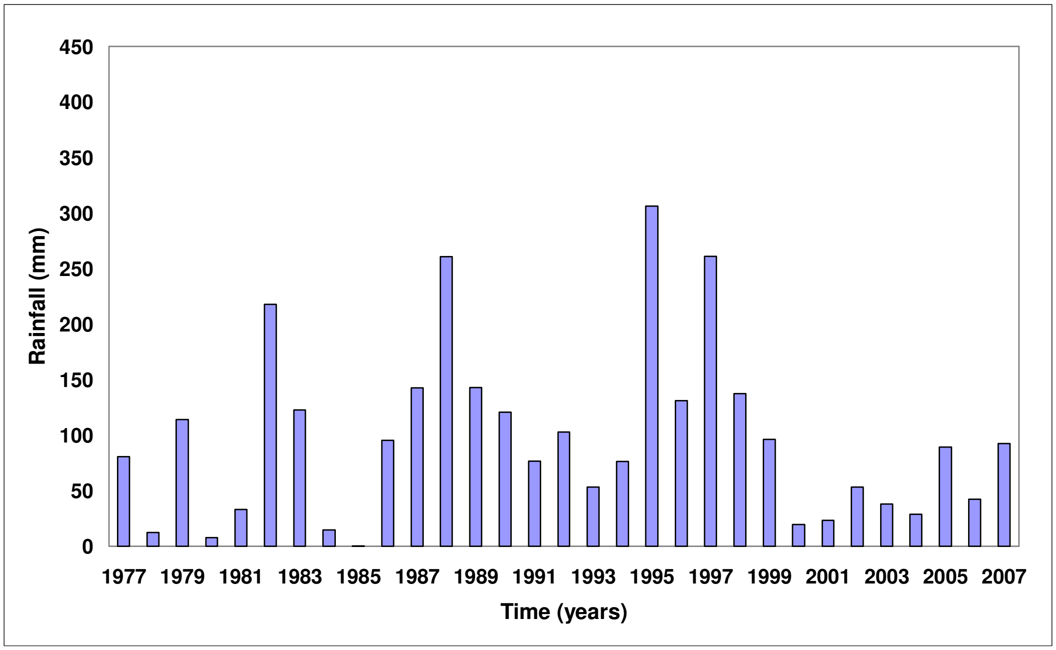


Figure 4. 5 The annual rainfall recorded in Sohar station during last 31 Years.

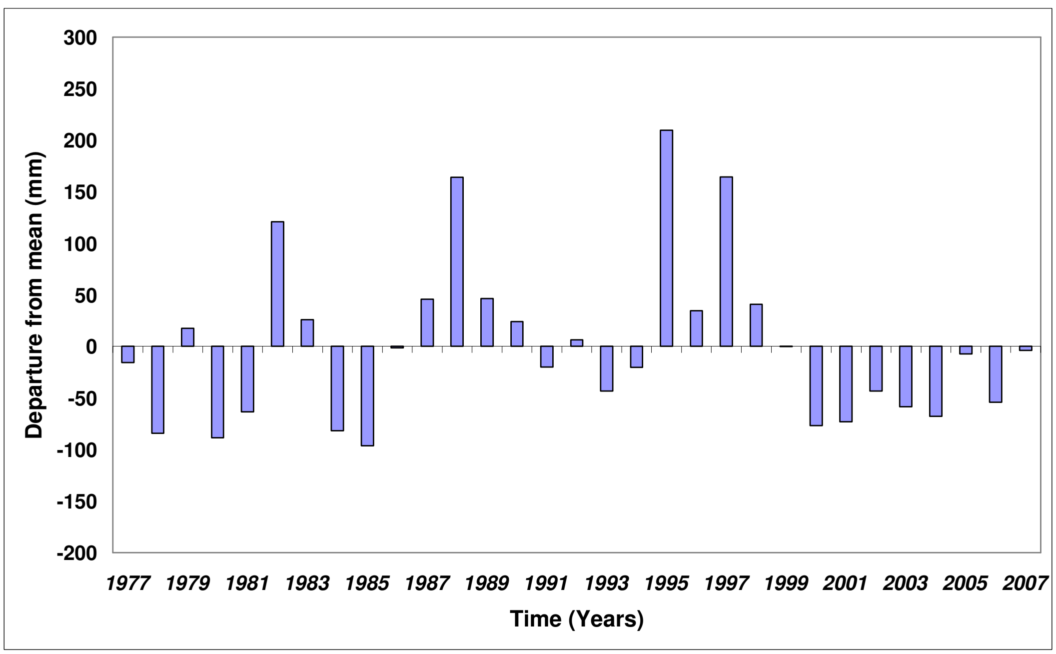


Figure 4. 6 The departure from mean of average annual rainfall records
in Sohar station

4.2.4 Buraimi Station

Buraimi station is located in the northern part of Oman around 180 km from the coast (24.14º N, 55.47º E and 298.89 m above MSL). The average annual rainfall for this station is 87.6 mm with a standard deviation of 92.3 mm. The maximum rainfall of 423 mm and the minimum amount of rainfall of 9 mm was observed in 1995 and 1984 respectively as shown in the Figure 4.7. It shows that the station received high amount of rainfall for a few years such as 1995 and 1996 and low amount of rainfall in other years such as 1991 and 1992 with an average annual rainfall less than 18 mm.

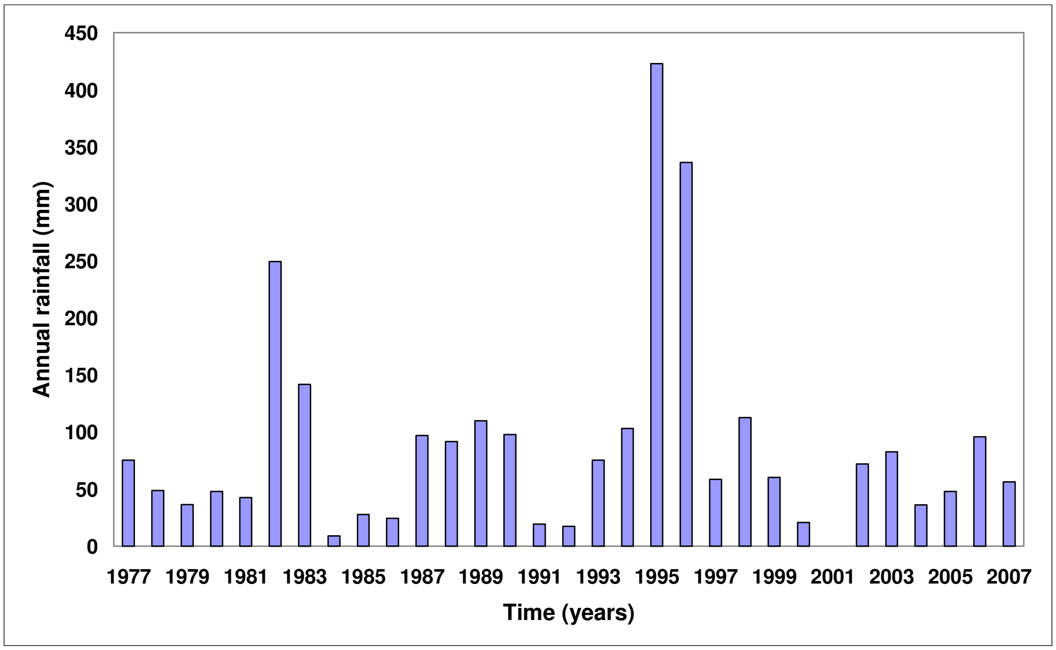


Figure 4. 7 The annual rainfall recorded in Buraimi station during last 31 years.

Figure 4.8 shows the annual rainfall departure from the mean over the station from 1977 to 2007. The years 1982, 1995 and 1996 were found as wet years according to the wet-dry criteria. On the other hand, year 2001 was noticed as dry year out of entire study period. The annual rainfall in this station is less comparison to Shinas and Sohar stations, but rainfall pattern is almost similar for example, the clustering of low rainfall years and high rainfall years.

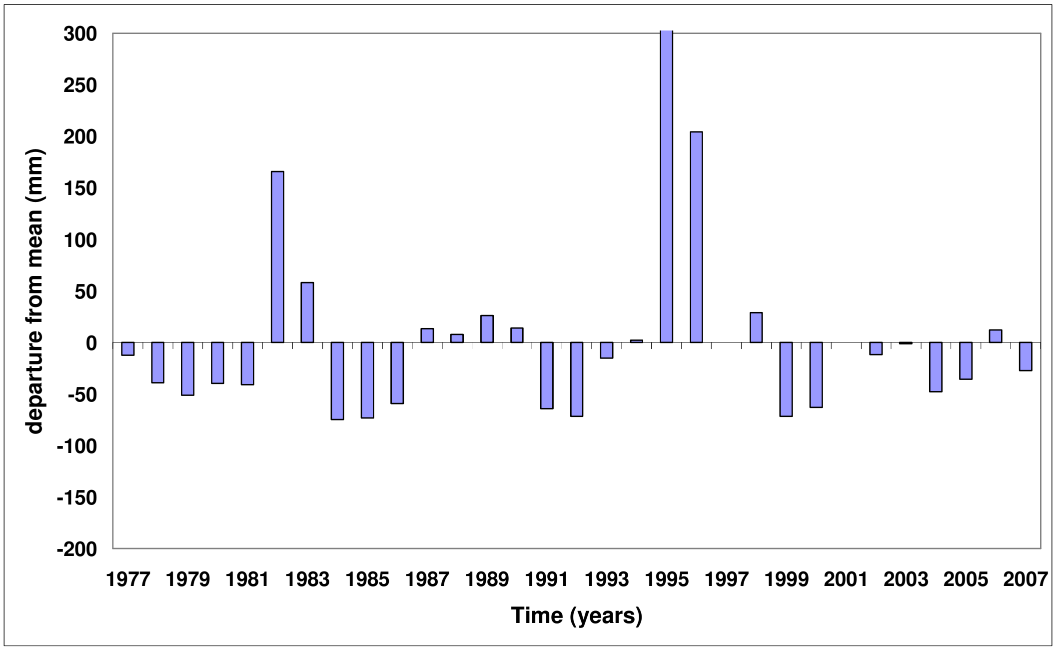


Figure 4. 8 The departure from mean of annual rainfall records of Buraimi station.

4.2.5 Ibri station

Ibri station, located in Al-Dahera region, it is one of the interior parts of Oman. It is located more than 200 km away from the Arabian sea coast (23.25º N, 56.31º E and 244 m amsl). Figure 4.9 shows the time series of annual rainfall over this station from 1977 to 2006 (30 years). The average annual rainfall for this station is 77.6 mm with a standard deviation of 78.2 mm. In certain years the rainfall is high but immediate next year it is low e.g. 1997 and 1998. The station received a maximum rainfall in 1982 of 347.1 mm and minimum rainfall in 2004 was 2 mm. The wet years are 1982 and 1997. The years 1980, 1984, 1991 and the period from 1999 to 2005 was observed as dry years as detailed in the figure 4.10.

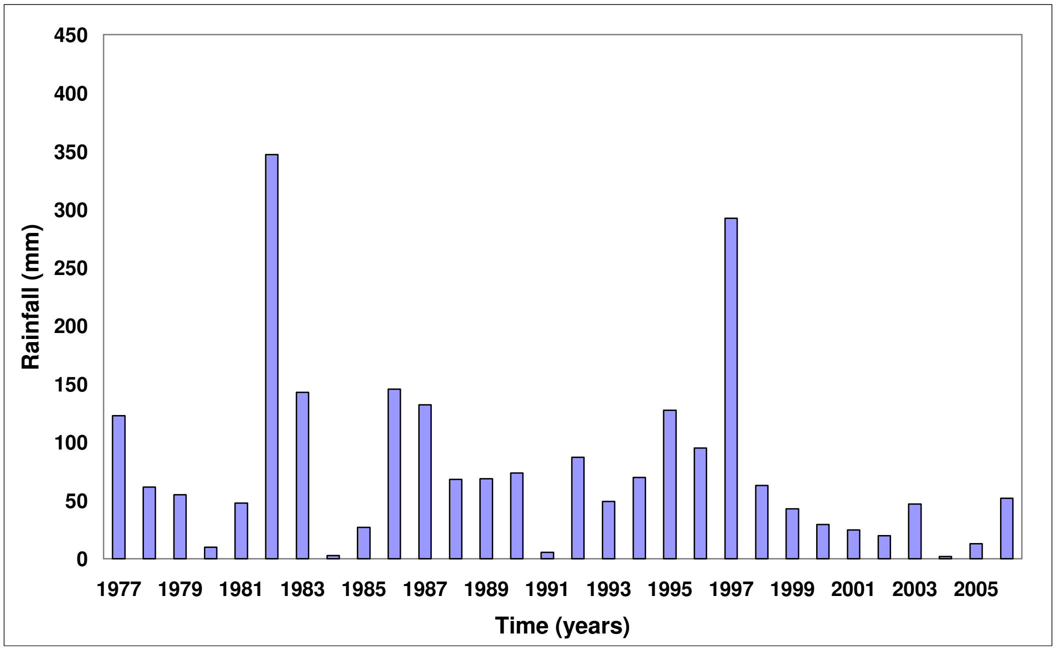


Figure 4.9 The annual rainfall recorded in Ibri station during last 30 years.

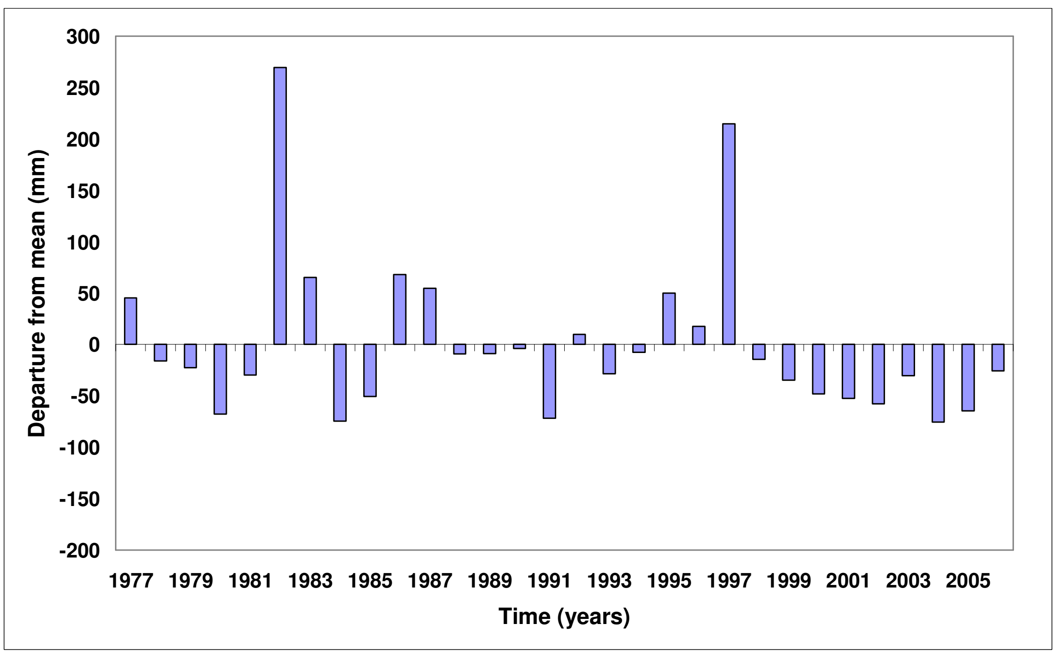


Figure 4. 10 The departure from mean of annual rainfall records of Ibri station.

4.2.6 Seeb station

Seeb station is located in the central part of Oman at the Muscat international airport, in the close vicinity of the Gulf of Oman (23.35º N, 58.17º E and 8.4 m above MSL). The average annual rainfall at Seeb station is 85.1 mm with a standard deviation of 73.4 as shown in the Figure 4.11. The maximum and minimum recorded annual rainfall was 307.6 mm in the year 2007 and less than 2 mm 1985respectively. The station received high amount of rainfall in the certain years such as 1995, 1997 and 2007 with annual rainfall above 228 mm. However in some other years the recorded annual rainfall was very less e.g. years 1984 and 1985, with average annual rainfall less than 3 mm.

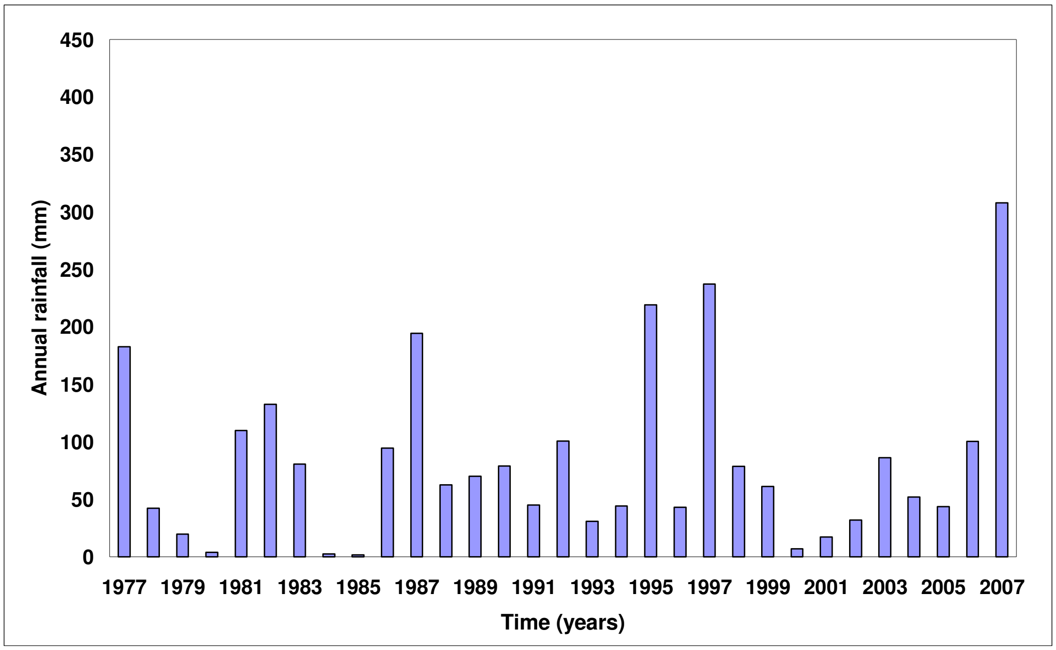


Figure 4. 11 The annual rainfall recorded at Seeb station during last 31 years.

It has been observed that the years 1976, 1977, 1987, 1995, 1997 and 2007 were the wet years whereas the years1979, 1980, 1984, 1985 and the period from 1999 to 2002 were found as dry years. Annual rainfall at this station is comparatively less than at the Ibri station which is also located in the central part of the Oman. Though, rainfall is less, the rainfall departure pattern looks similar for the wet and dry years.

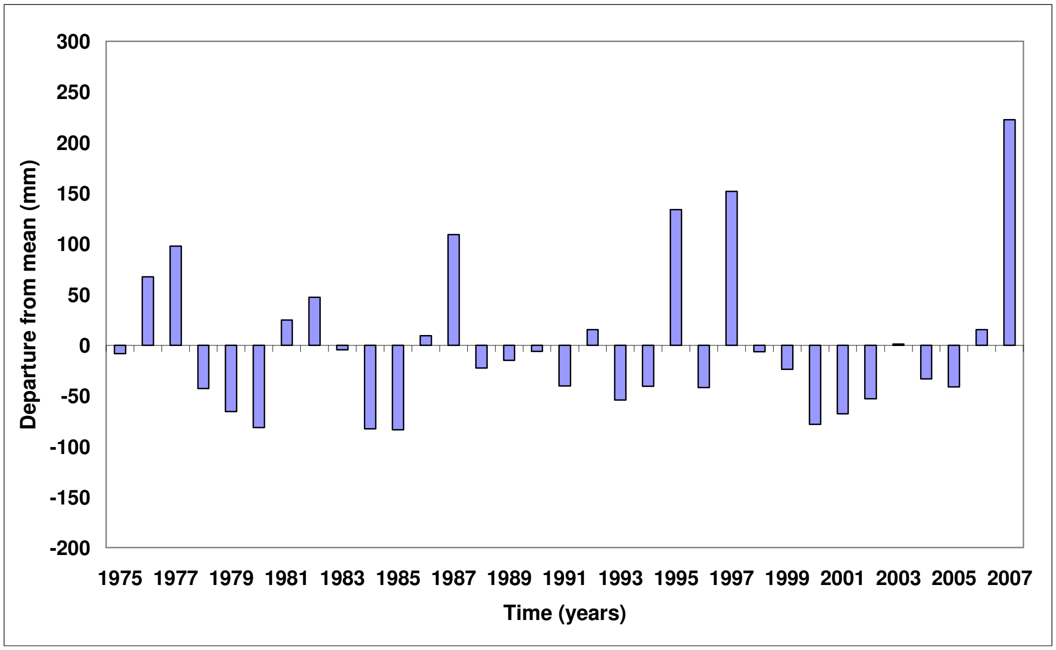


Figure 4. 12 The departure from mean of annual rainfall records of Seeb station.

4.2.7 Saiq station

Saiq Station is one of the inland and is located at the highest altitude at Jabal Akdar mountain at a height of 1654.86 m above MSL (23.04º N, 57.38º E). Figure 4.13 represents the time series of annual rainfall at the station from the year 1979 to 2007 (29 years). The average annual rainfall at this station is 315.9 mm with a standard deviation of 173.4 mm. This value of standard deviation is almost 55% of the annual mean. This standard deviation is low in comparison to other stations. The maximum annual rainfall of 900.9 mm was observed in 1997 whareas the minimum rainfall recorded was 127.7 mm in 1985. The annual rainfall is comparatively higher than other stations, though rainfall departure pattern is almost similar to other stations.

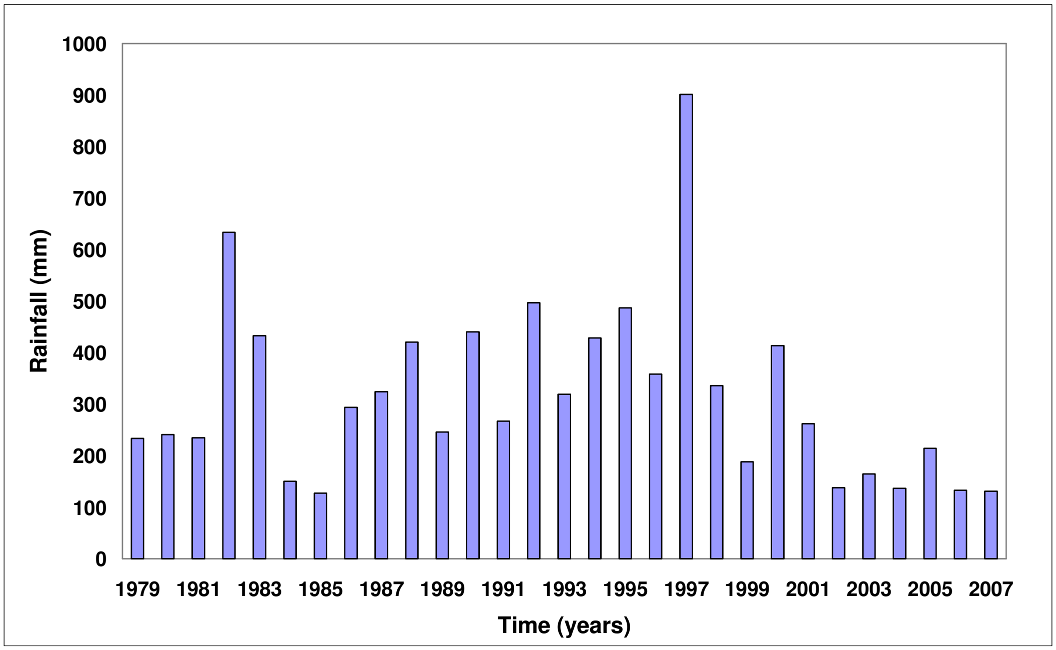


Figure 4. 13 The annual rainfall recorded in Saiq station during last 29 years.

The years 1982, 1992 and 1997 were identified as wet years and the years 1984, 1985 and the period from 2002 to 2007 as dry years on the basis of wet-dry criteria, The departure from the mean at this station for the same period is shown in Figure 4.14.

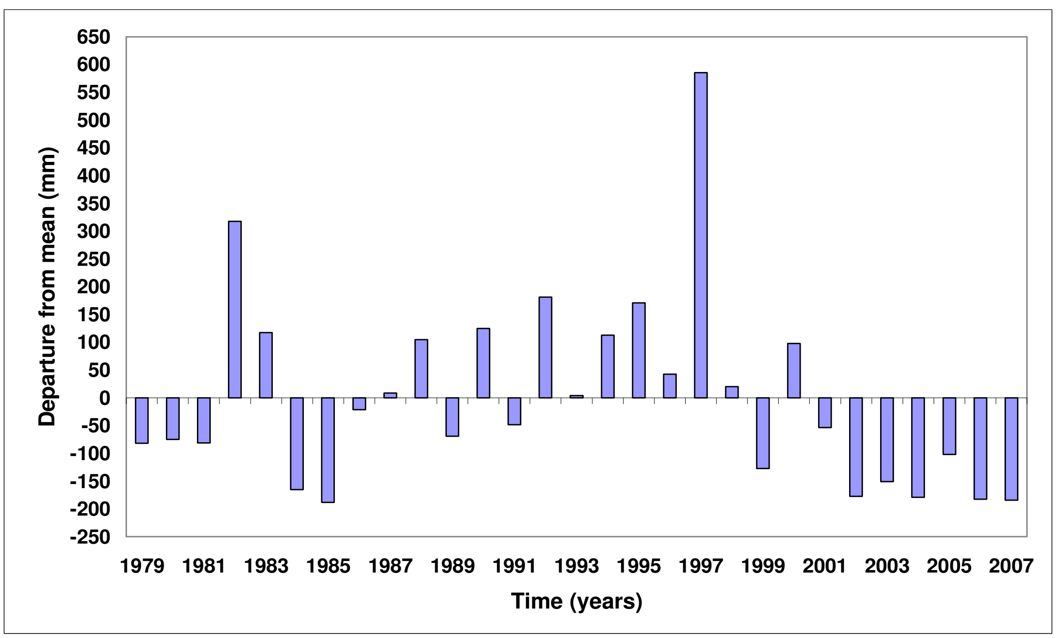


Figure 4. 14 The departure from mean of annual rainfall records of Saiq station.

4.2.8 Sur station

Sur station is one of the coastal stations, located in the vicinity of the Arabian Sea coast in Al-Sharqia region (22.32º N, 59.28º E and 13.77 m above MSL). The average annual rainfall at this station is 89.8 mm with a standard deviation of 78.0 mm as illustrated in the Figure 4.15. The maximum annual rainfall of 284.9 mm was in 2007 whereas the minimum rainfall was observed as 3.2 mm and 3.1 mm in 1980 and 2004 respectively.

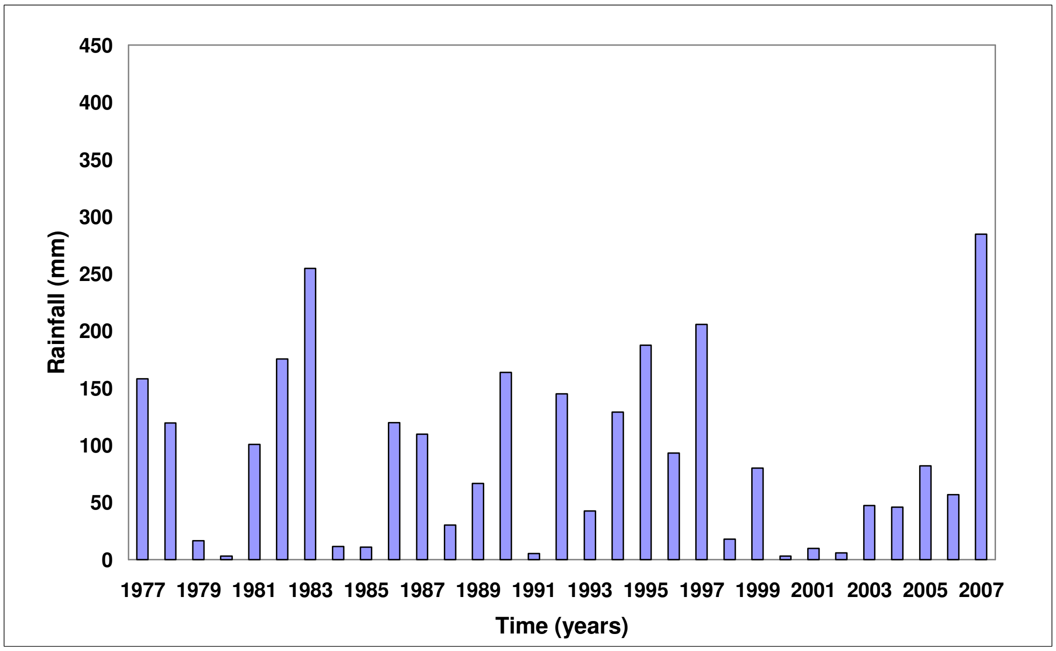


Figure 4. 15 The annual rainfall recorded in Sur station during last 31 years.

The years 1982, 1983, 1995, 1997 and 2007 were observed as wet years on the basis of wet-dry criteria, which depend on the departure from the mean and were mentioned above. On the other hand, years 1980, 1984, 1985, 1991, 2000, 2001 and 2002 were found as dry years during the last 31 years as illustrated in the Figure 4.16. This station receive more rainfall but less than Saiq station in comparision to stations Ibri and Seeb, Meanwhile all these stations have similar rainfall departure pattern for example as years of low and high rainfall.

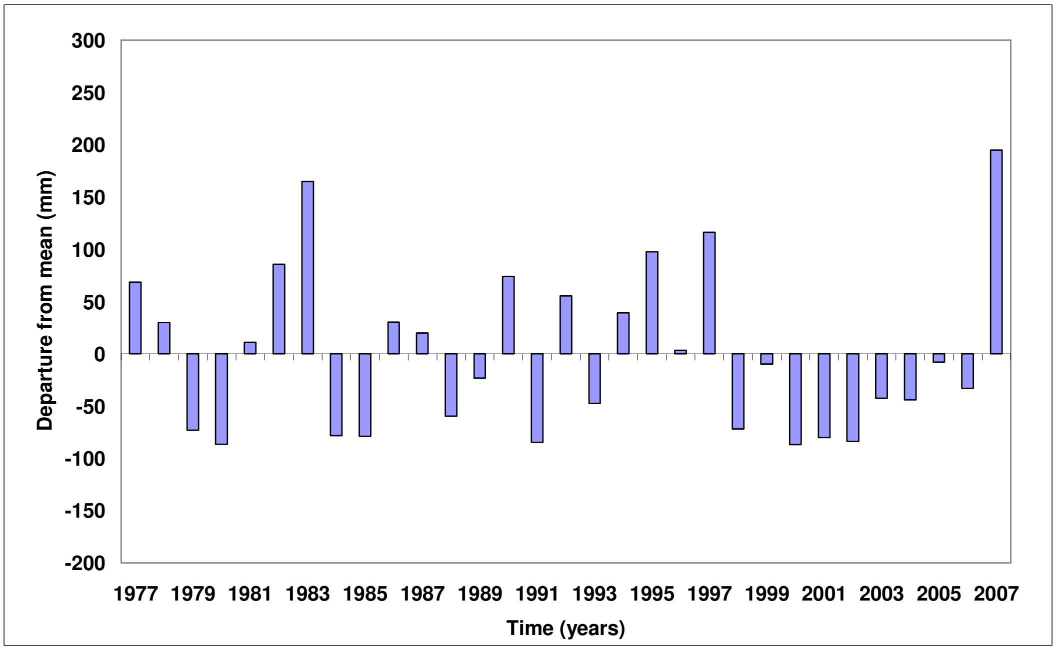


Figure 4. 16 The departure from mean of annual rainfall records of Sur station.

4.2.9 Masirah station

Masirah station is the only island station in Oman. It is located in the Arabian sea (20.40ºN, 58.54ºE). This station has an elevation of 18.8m above msl The figure 4.17 shows the annual rainfall at the station from 1977 to 2007 (31 years).The average annual rainfall at this station is 61.9 mm with an standard deviation of 82.3 mm. This value of standard deviation indicates a high variability in rainfall from year to year. There is no distinct variability in the rainfall. More over, in certain years the rainfall is high but immediately in next year it is low such as 1977 and 1978. The station received maximum rainfall of 441.0 mm in 1977 and minimum amount of rainfall was noticed in 1985 when it was less than 1 mm. This station was identified as the station with the least amount of rainfall in central Oman.

The years 1977, 1983 and 1992 were identified as wet years and years 1980, 1984, 1985, 1991, 1999, 2000, 2001 and 2004 as dry years during the period 1977-

2007 as illustrated in the Figure 4.18. The rest of the years are identified as normal years.

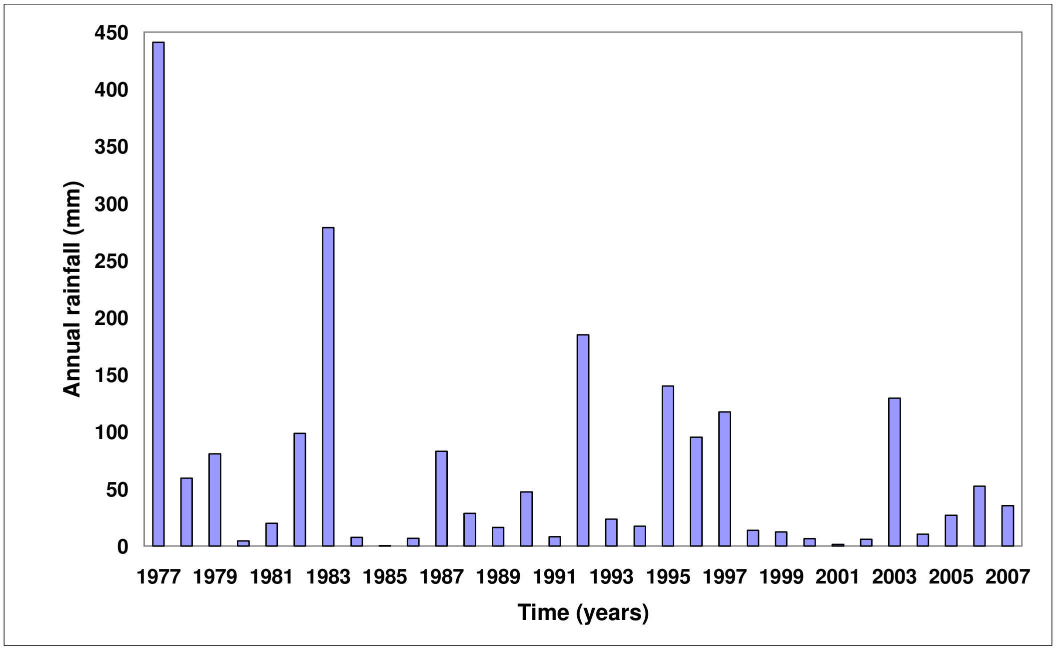


Figure 4. 17 The annual rainfall recorded in Masirah station during last 31 years.

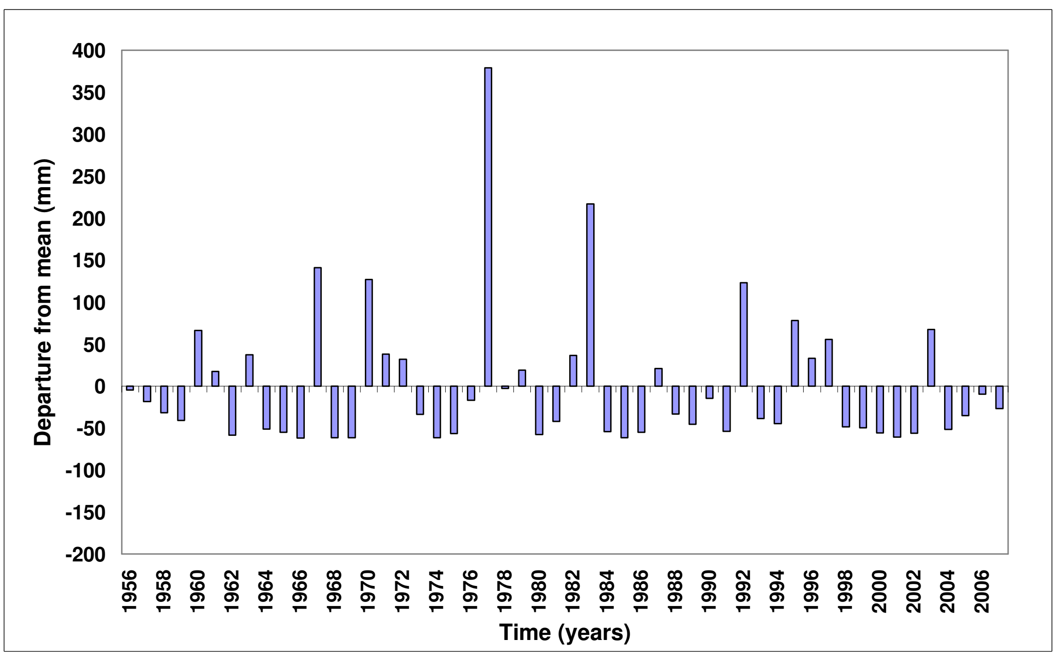


Figure 4. 18 The departure from mean of annual rainfall records of Masirah station.

4.2.10 Marmmul station

Marmmul station is located in the desert area close to the Empty Quarter (more than 300 km away from the Arabian Sea (18.08º N, 55.10º E and 269 m above MSL). The average annual rainfall at this station is 24 mm as shown in the Figure 4.19 with a standard deviation of 46.4 mm. As depicted in the figure 4.18, the standard deviation is almost twice of the annual mean rainfall which shows a large year to year fluctuation. The maximum annual rainfall of 203 mm was observed in the year 1995 and there was no rainfall in few years such as in 1994 and 2001. There is variability in rainfall pattern seem not be similar to the other stations. In addition, The station received high annual rainfall of 203 mm in a year such as 1995 but no rainfall in other years such as 1994 and 2001.

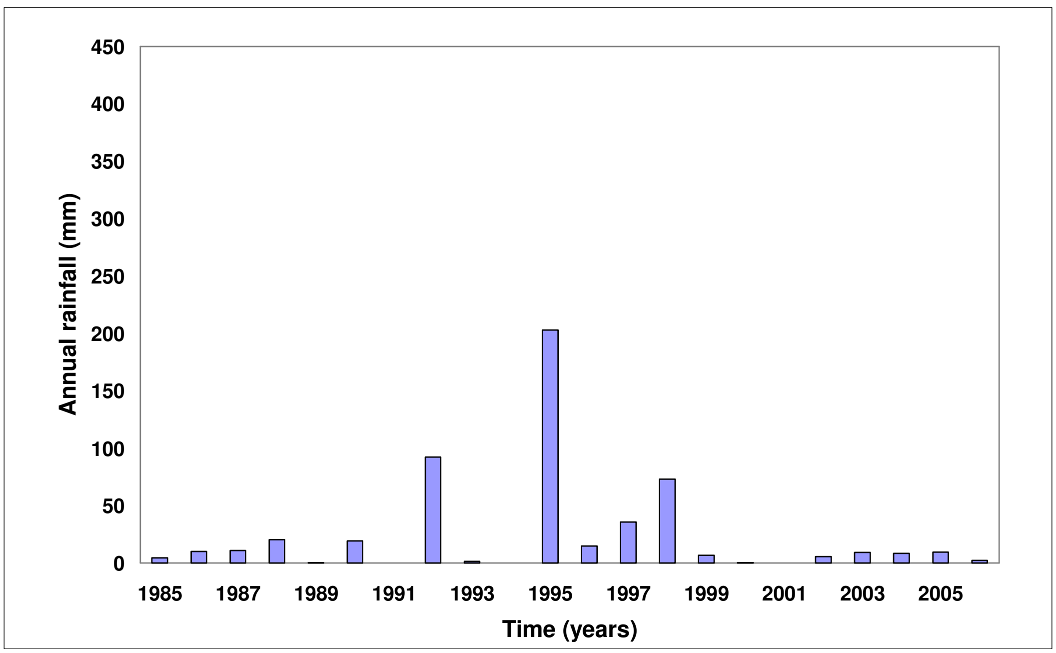


Figure 4. 19 The annual rainfall recorded in Marmmul station during last 22 years.

The years 1992, 1995 and 1998 were observed as wet years and years 1985, 1986, 1987, 1988, 1989, 1990, 1991, 1993, 1994, 1996 and 1999- 2006 were observed as dry years during the last 22 years. The annual rainfall at this station is very low compare to other stations in the Oman. Further, rainfall departure pattern of this station is also different from other stations as shown in the Figure 4.20.

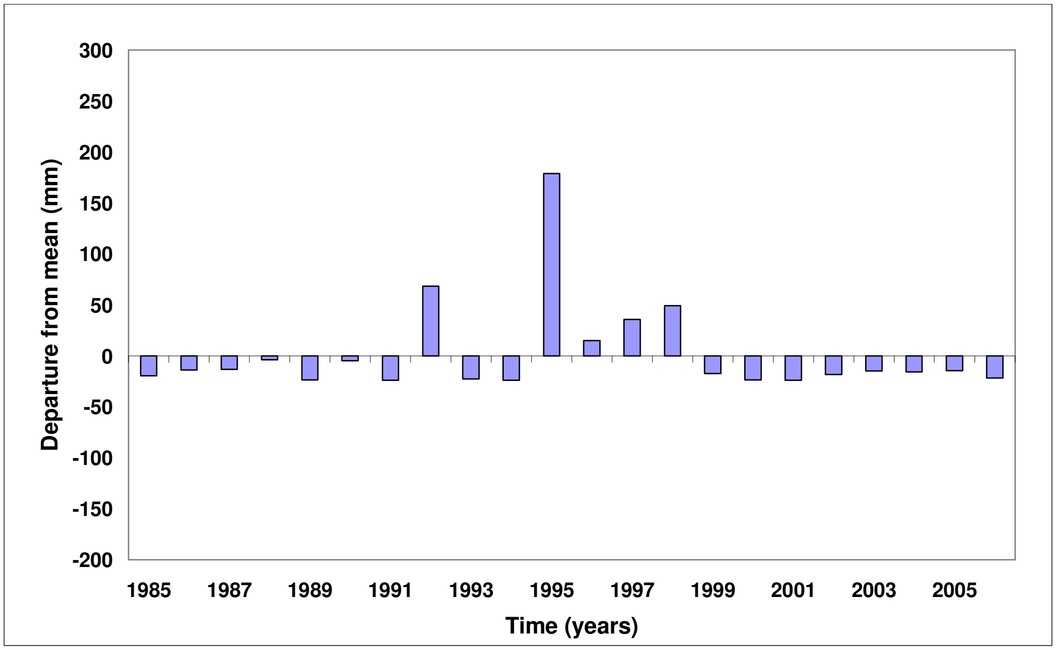


Figure 4. 20 The departure from mean of annual rainfall records of Marmmul station

4.2.11 Thamrait station

Thamrait Station is one of the inland stations and located in the southern part of Oman around 200 km from the coast of the Arabian sea (17.40ºN, 54.01ºE). The station is located at a height of about 466.9 m above MSL The Figure 4.21 shows the time series of annual rainfall over the station from 1980 to 2007 (28 years). The average annual rainfall for this station is 31.2 mm with a standard deviation of 53.4. The rainfall is high in certain year but immediate next year it is very low such as 1989 and 1990. The variability at this station did not show a regular pattern of wet and dry years.

This station received maximum rainfall of 272 mm in the year 1989 and did not receive any rainfall in years 1984, 1991, 2000 and 2001. The Figure 4.22 shows the rainfall departure from the mean value at Thamrait station in the study period. The years 1983, 1989 and 1992 were identified as wet years and years 1980, 1982, 1984, 1985, 1993, 1995, 1997, 1998, 1999, 2000 and 2001 as dry years during the period of last 28 years. The rainfall at this station is more than at Marmmul station.

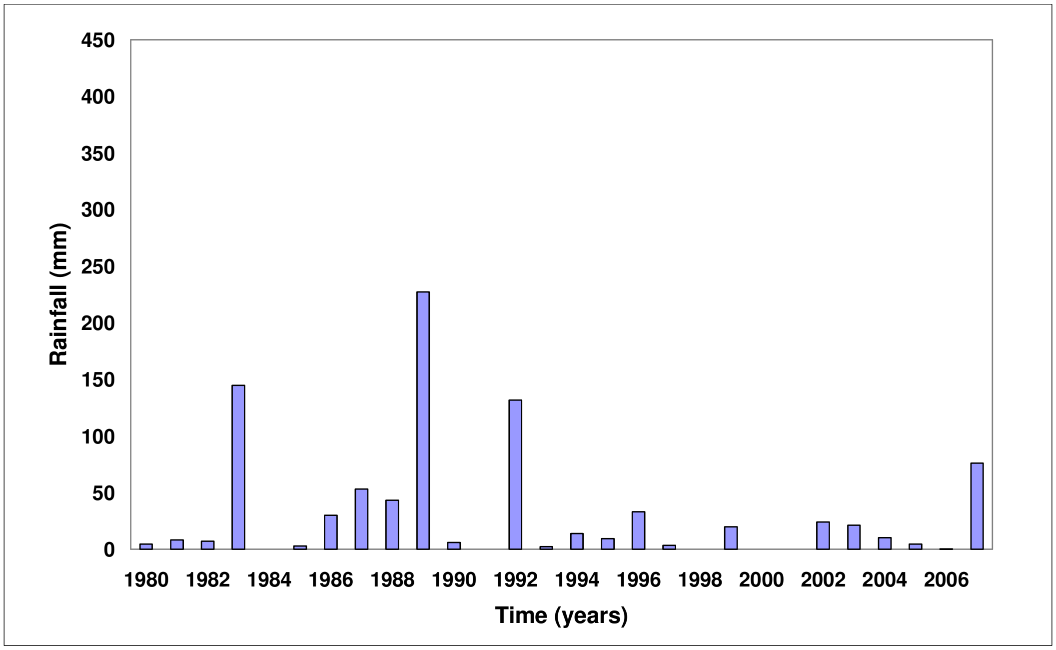


Figure 4. 21 The annual rainfall recorded in Thamrait station during last 28 years.

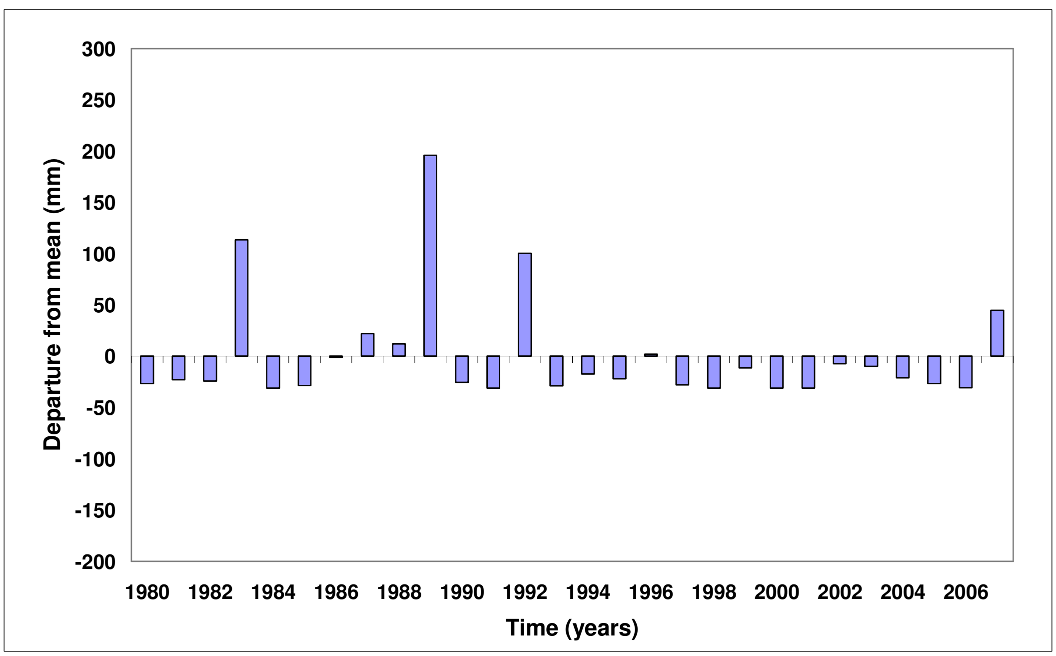


Figure 4. 22 The departure from mean of annual rainfall records of Thamrait station.

4.2.12 Salalah station

Salalah station is the oldest station where meteorological observations are regularly taken. It is located at the most southern part of Oman near the coast of the Arabian sea on the border of Yemen (17.02º N, 54.05º E and 20 m above MSL). This station is located at Salalah international airport. The average annual rainfall at this station is 99.6 mm with a standard deviation of 76.5 mm at shown in the Figure 4.23. The maximum annual rainfall of 409.9 mm observed in the year 1977 and the minimum amount of annual rainfall in the year 1985 and 1986 which was less than 2 mm. No distinct variability in rainfall pattern could not be identified. The station received a high rainfall with annual average of 201.7 mm in one year such as 1977 and received less rainfall with annual average less than 2 mm in other year such as in 1985.

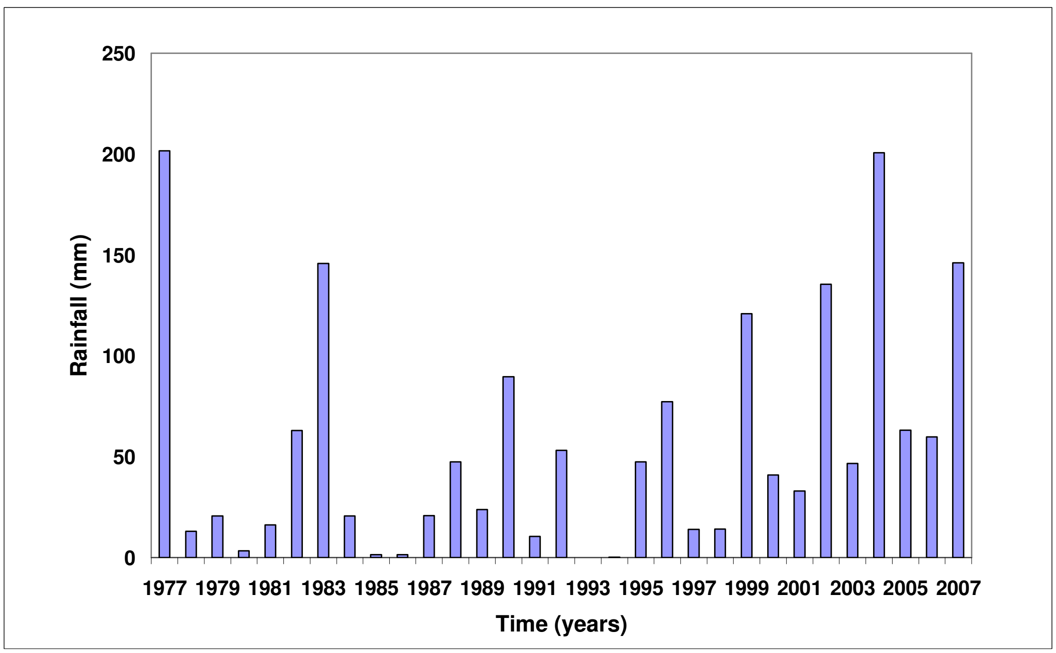


Figure 4. 23 The annual rainfall recorded in Salalah station during last 31 years.

The years 1977, 1983, 1996 and 2004 were identified as wet years and the year 1974, 1975 and 2001 were as dry years during the last 31 years. The departure from the mean for Salalah station for the study period is shown in Figure 4.24. The annual rainfall at this station is relatively more than the other two stations in the south part of

Oman i.e. Marmmul and Thamrait. The rainfall departure pattern is different and it is almost similar to the observatories in the north and middle part of Oman.

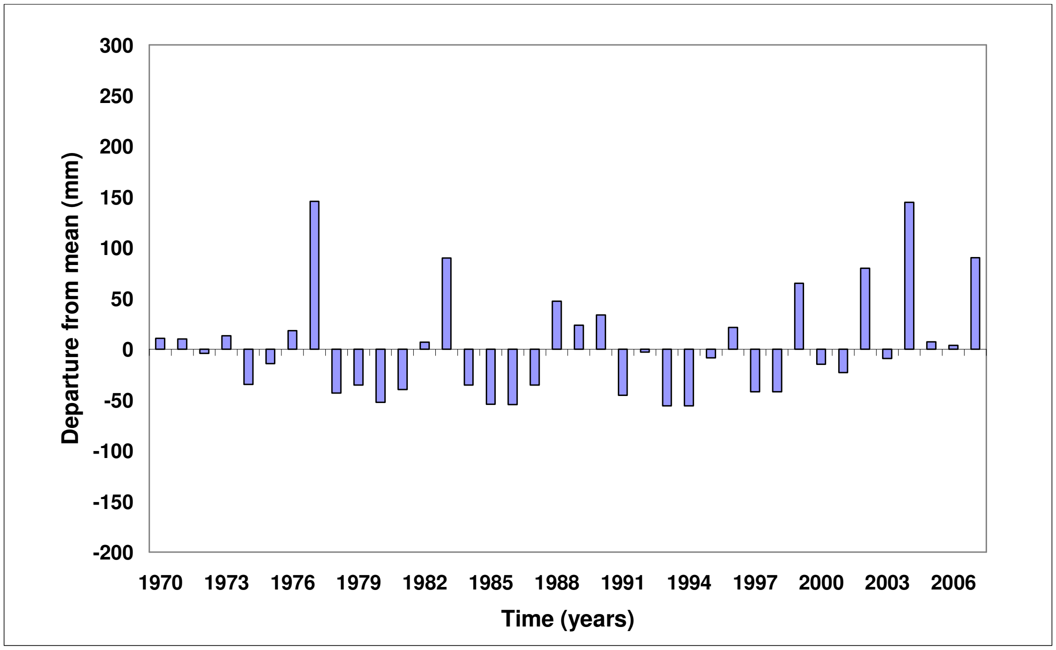


Figure 4. 24 The departure from mean of annual rainfall records of Salalah station.

4.3 General Observations

It could be identified from the table 4.1 that the average rainfall at the most of observatories ranges between 50-100 mm/year except at Saiq station where the average rainfall is more than the other stations (315.8 mm/year). It could also be concluded that station Marmmul and Masirah got the lowest rainfall i.e. 24 mm/year and 31.2 mm/year respectively due to its location in the desert region. The standard deviation at Saiq station has maximum value of 173.4 mm, whereas it is least at Marmmul station with a value of 46.4 mm.

Masirah received the maximum rainfall of 430 mm/year which is more than at Saiq station of 401.9 mm/year. On the other hand Thamrait station received the lowest amount of rainfall of 130.2 mm/year compare to rest stations. All the stations did not receive rainfall in few of months in the year.

The mountain station Saiq has the highest annual average rainfall of 315.8 mm/year whereas the minimum annual rainfall of 20 mm/year was observed at inland station Marmul. In general, average annual rainfall is high in the regions of northern Oman mountains followed by coastal stations and least in the interior parts of Oman. There is a big variation in the annual average as indicated by the standard deviation which is more than 55% at all the stations. The variability of the average annual rainfall is more at the island station of Masirah with standard deviation of 132%. The lowest annual average is recorded in the interior of Oman and these regions are mainly in the dry sandy desert.

Table 4.1 General Observations from Annual Average Rainfall of all Stations

Name of the Station	Total number of years	Average rainfall (mm)	Standard deviation (mm)	Maximum rainfall (mm)	Minimum rainfall (mm)
Khasab	31	184	130.7	269.7	0.0
Shinas	31	99	93.4	252	0.0
Buraimi	31	87.8	92.3	286	0.0
Sohar	31	96.5	78.2	235.3	0.0
Ibri	30	77.6	78.2	258.1	0.0
Seeb	33	85.1	73.4	257	0.0
Saiq	29	315.8	173.4	401.9	0.0
Sur	31	89.8	78	240	0.0
Masirah	31	61.9	82.3	430.6	0.0
Marmmul	22	24	46.4	144	0.0
Thamrait	28	31.2	53.7	130.2	0.0
Salalah	31	55.9	79.5	148.6	0.0

4.4 Monthly Distribution of Rainfall

It could be identify from the Figure 4.25 that monthly distribution of rainfall occurs in Khasab is largely during the winter season i.e. from December to March. The rainfall begins in December with an amount of more than 30 mm/month and increase in January to more than 45 mm/month. After which, the rainfall drop off in the subsequent three months (February-April). The station received a negligible amount of rainfall in the summer season i.e. from May to September.

The Shinas station has the similar rainfall pattern as of Khasab station but with a drop in rainfall. The maximum annual rainfall takes place in the month of February and March i.e. 25 mm/month. This station receives only trace amount of rainfall in the summer monsoon season.

On the other hand Buraimi station receives rainfall during the month of December to April with rainfall ranging between 5 and 30 mm/month. The rainfall increase gradually from October to February and then it decreases in the subsequent months.

Sohar station has also similar monthly rainfall distribution to the previous three stations discussed. These four stations are included in the northern part of Oman with similar rainfall characteristics.

The rainfall at Ibri station is more during the winter period ranging between 2 and 20 mm/month, and then increases gradually from December to March. But this station receive reasonable amount of rainfall during summer season (2-10 mm/month).

Seeb station has monthly distribution of rainfall similar to Ibri station and almost the same amount of rainfall during winter and summer. The winter rainfall at Seeb is slightly higher than that of Ibri station ranging between 12 to 20 mm/month.

Saiq station is entirely different than other stations due to its high altitude where the influence of orographic rainfall is significant. This station gets more rainfall than other stations. The rainfall amount during winter and summer is almost equal indicating consistency throughout the year. The rainfall amount increases gradually in the winter season (November-April) from December (10 mm/month) to March (>45 mm/month) then decreases from April to July. Subsequently, rainfall amount increases further in the months of July and August (~45 mm/month). The rainfall amount decreases in the month of September and October and reach its minimum in November.

The rainfall distribution in Sur station appears similar to that of Ibri and Seeb stations. It starts in winter season from November (6 mm/month) and increases gradually in each month and reaches a peak in February. It decreases during March to May and increases again in the month of June. After which it decreases and reaches the minimum amount in September where the rainfall is less than 1 mm/month.

Masirah station receives less rainfall when compared to Sur station even though it is close to Sur station, indicating a high spatial variability of the rain. However, the monthly pattern is almost similar to that of Sur station. The rainfall during winter starts to increase from November (7 mm/month) to March and then decreases till the month of June. The rainfall is highest in the summer season (June-October).

Marmmul station which is located in the desert of southern region receives the lowest amount of rainfall compared to other stations. This station receives rainfall from December to April. The maximum rainfall of 8 mm/month takes place during March and April., the station receives negligible amount of rainfall during the summer season except in the month of June (~5 mm/month).

The rainfall in Thamrait station has a different monthly distribution. The rainfall starts in January (8 mm/month) and decreases gradually in each month and reaches its minimum in November and December.

Salalah station which is located in southern region of Oman is affected mainly by the Indian summer monsoon. it also receives reasonable amount of rainfall during winter. The rainfall begins in November (<1 mm/month) and increases gradually until it reaches its maximum during April and May (10 mm/month). Then it decreases in June and increases again from July to September (>7 mm/month) and decreases again in October (<4 mm/month).

The stations Khasab, Shinas, Buraimi and Sohar could be grouped as representative of the northern region due to their similar monthly distributions.

Whereas, the central part is represented by stations Ibri, Seeb, Saiq, Sur and Masirah. The remaining stations can be grouped under the southern region. The mechanisms of influencing the rainfall in these different climatic regimes could be discussed on the basis of above mentioned classification.

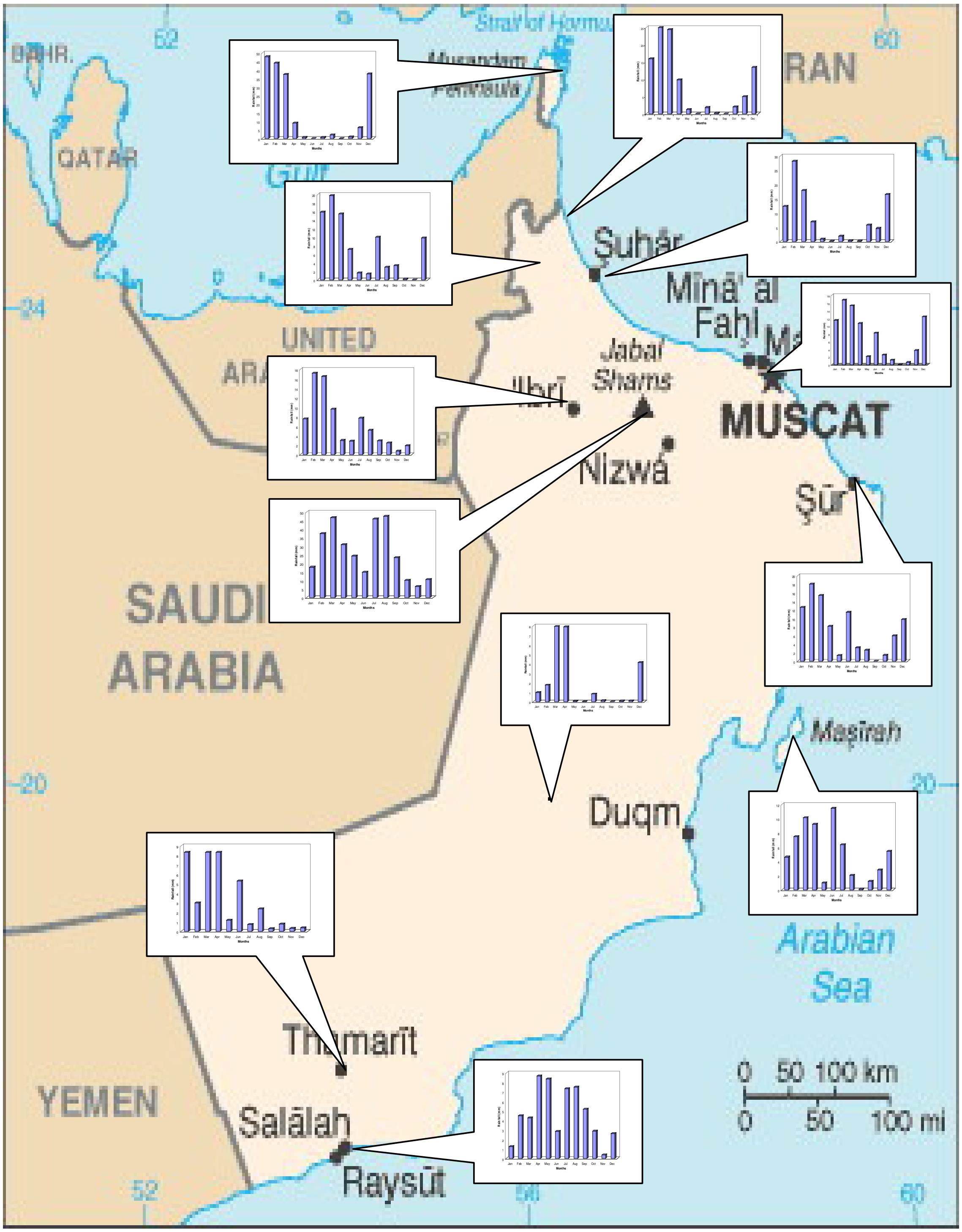


Figure 4. 25 The average monthly rainfall of the all stations.

4.5 Monthly Average Rainfall Observations in the Oman.

The northern part of Sultanate of Oman which consists of four stations namely Khasab, Shinas, Buraimi and Sohar gets rainfall mostly during winter season i.e.December, January, February and March. The rainfall range more than 15 mm to 30 mm/ month during these 4 months and each rain event can continue for couple of days (Al-Barashdi, 2007). On the other hand this part of Oman has no or little rainfall from May to November as shown Figure 4.26. One of the issues that need investigation is why this region is not influenced by local convective system in summer.

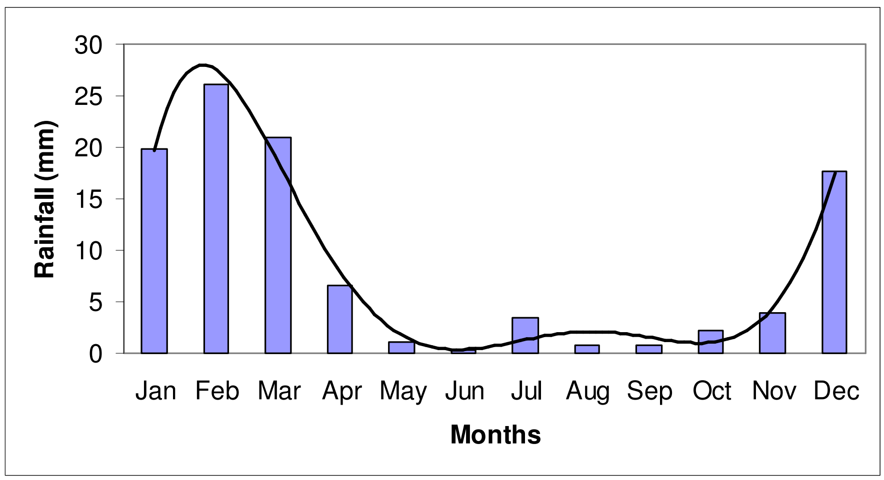


Figure 4. 26 The monthly average rainfall in the northern part of Oman.

The monthly rainfall in the central part of Oman, which is represented by the stations Ibri, Saiq, Seeb, Sur and Masirah, is shown in the Figure 4.27. The amount of rainfall received by this region ranges between less than 5 mm to 20 mm/month. There are two rainy periods in the region, one from February to March and the other from June to July. The rainfall increases from January to March and decreases thereafter till May. The rainfall then increases again in June and July and decreases gradually until November during the summer season.

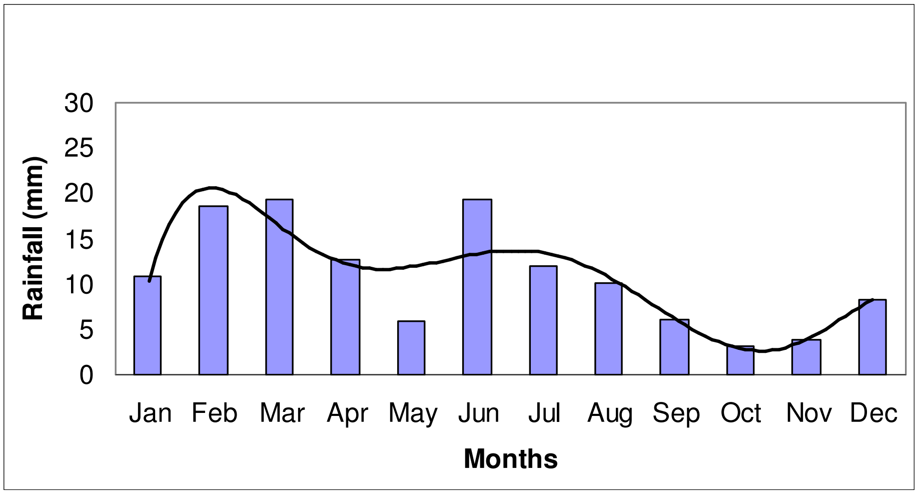


Figure 4. 27 The monthly average rainfall in the central part of Oman.

The southern region of Oman is swept by the southwest monsoon affecting the Arabian sea from June to September. The amount of rainfall during this period is less than 10 mm/month. This part also receive a reasonable amount of rain during the winter season especially in March and April as described in the Figure 4.28 with rainfall exceeding 5 mm/month.

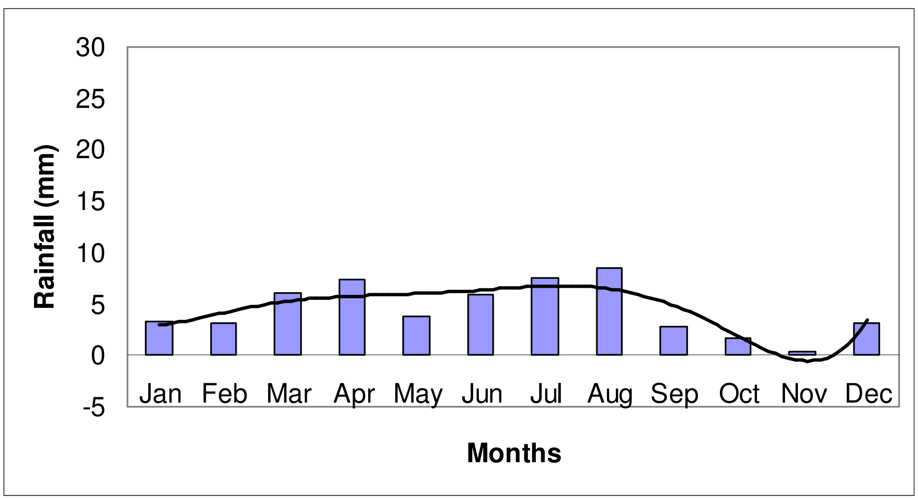
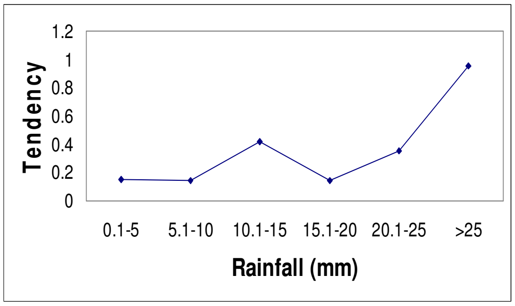


Figure 4. 28 The monthly average rainfall received by the southern part of the Oman.

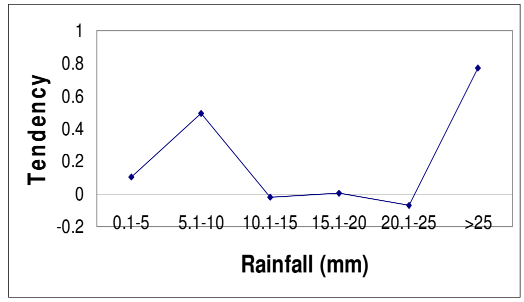
4.6 Rainfall Tendency Analysis

The amount of rainfall in Sultanate of Oman shows variability on different time and spatial scale. This increases the complexity in the prediction of rainfall. Tendency analysis of rainfall from light to heavy rains for the last 30 years will be discussed under this section. Linear trend of individual intensity classes of rainfall was established to show the tendency analysis of the different classes of daily rainfall, A trend line is drawn and its slope has been calculated using linear regression. This tendency represents a trend, the long-term movement in time series data of rainfall. The intensity of rainfall is classified into six categories, which are 0.1-5, 5.1-10, 10.1-15, 15.1-20, 20.1-25 and >25 mm. The linear trend of the individual classes are plotted to show their tendency. this study is important in forecasting the climate change scenario. The trend analysis is undertaken to find out the characteristics of the linear trends in the individual intensity classes of the rainfall, especially for very high (>25 mm) and very low (<5 mm) intensity. It has been explained in the subsequent section about the variation of trend in each intensity classes for different stations classified as the northern, central and southern stations.

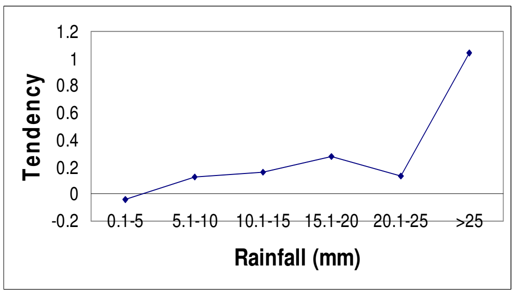
It is observed as shown in the figure 4.29 that the amount of rainfall increases in the northern part of Oman e.g. tendency of heavy rains (>25 mm) increases for stations Khasab, Shinas and Buraimi, but it decreases in Sohar. On the other hand, the tendency of light to moderate rain (0-25 mm) increases in all stations. However. the rainfall intensity of 1.5 mm is constant at Khasab station whereas it is growing each year as shown in the figure 4.29. The rainfall types for Shinas station showed an increase except for the rainfall of 5.1-10 mm which decreased rapidly during the last 31 years. Also rainfall range increase in Buraimi and Sohar station except the heavy rain events which decreased in Sohar station only.



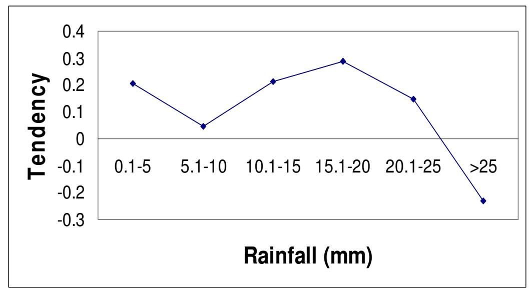
(a)



(b)



(c)



(d)

Figure 4. 29 The trends of average rainfall in northern part of Oman (a) Khasab, (b) Shinas, (c) Buraimi (d) Sohar

The tendency analysis of rainfall in the central part of Oman is shown in the Figure 4.30. The tendency of all rain bins of rainfall increases in most of the stations. The similar tendency for all rainfall amount (i.e. 0.1-5 to >25 mm) also established from the figure. The stations Ibri, Sur and Masirah show a large increase in the amount of heavy rains (> 25 mm) more than other stations (Saiq and Seeb). It could also be noticed that the rainfall of 5.1-10 mm and 10.1-15 mm increased rapidly in Saiq station more than other stations. The tendency of rainfall in Masirah station shows different trend than other stations. On other hand it decreased to extremely low tendency except the rainfall of >25 mm which shows increase in the study period.

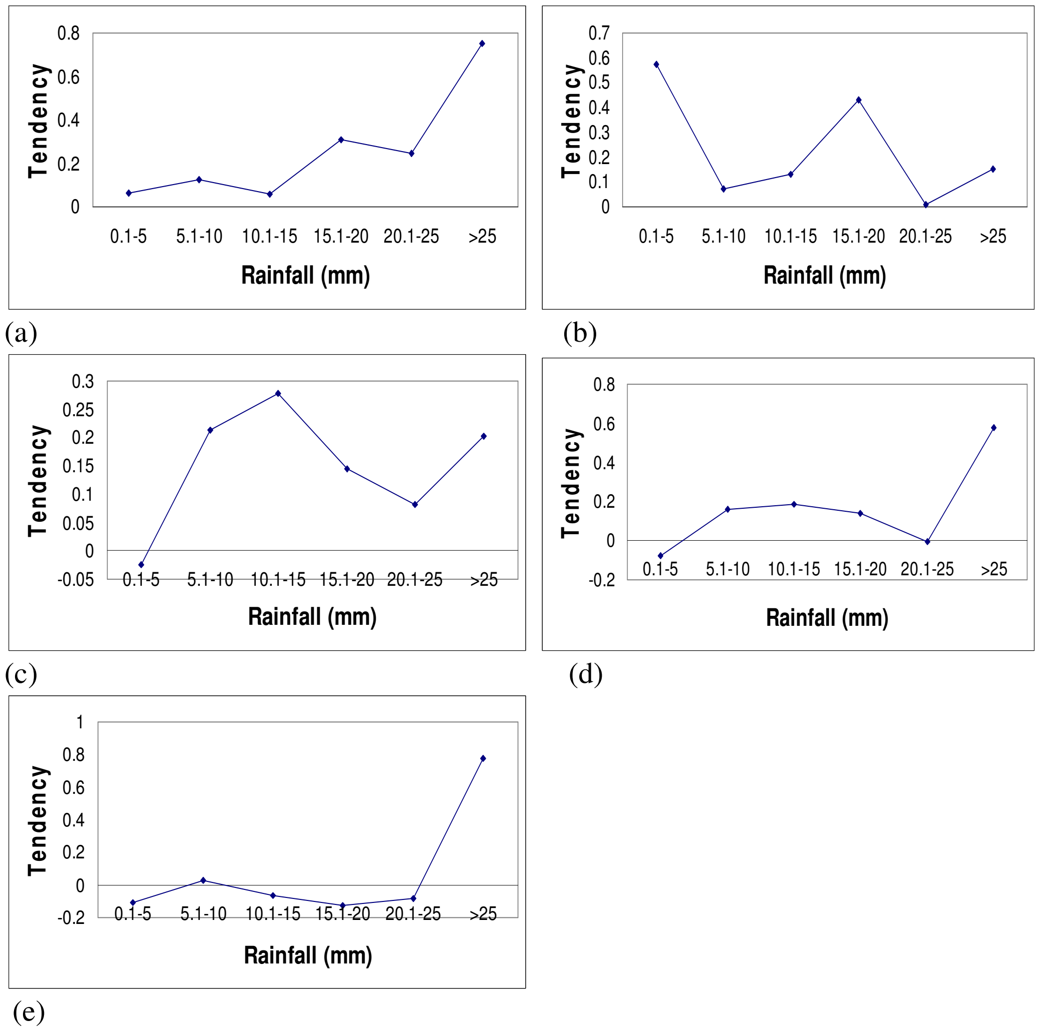
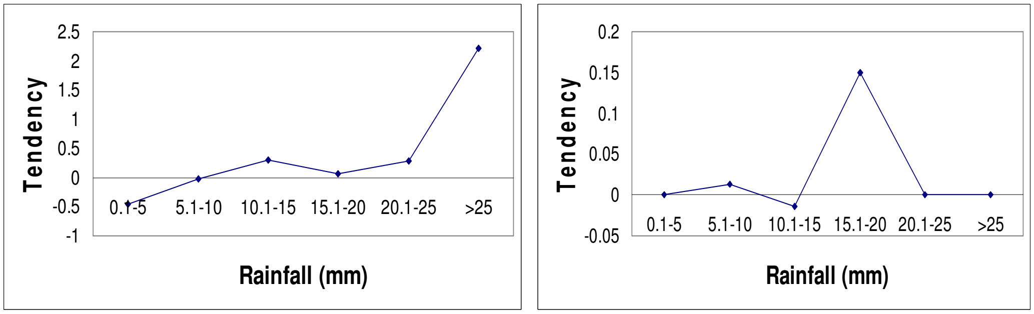


Figure 4. 30 The trends of average rainfall in central part of Oman (a) Ibri, (b) Saiq, (c) Seeb, (d) Sur, (e) Masirah

The tendency of the rainfall in the southern part of the Oman, which is affected largely by the southwest monsoon season as shown in figure 4.31, shows an increase in the amount of rainfall at Salalah station except the intensity of 0-1.5 mm which only decreases in the last 30 years as described in the Figure 4.31a. On the other hand the amount of rainfall in Thamrait shows slight increase in the amount of rainfall intensity compared to Salalah station except the rainfall intensity of 20.1-25 mm which decreases rapidly in the last 30 years. However, the rainfall intensity of >25 mm remains constant during the same period (Figure 4.31b).



(a) (b)

Figure 4. 31 The trends of average rainfall in southern part of Oman (a) Salalah, (b) Thamrait

Chapter 5: Mechanisms for climatic Regimes in the Oman

An attempt was made to interpret the mechanism of the climatic regimes in the northern, central and southern parts of Oman in the different seasons in this chapter. The monthly climatology of rainfall for the above mentioned regions has been discussed and to provide explanation of the seasonal rainfall on the basis of wind, OLR and relative humidity. The monthly rainfall derived from daily data of four stations from the north, five stations from the central and three stations from the south have been utilized.

Monthly mean wind was derived at 700 hPa over the area (54ºE-60ºE, 23ºN-26ºN) representing northern part, wind at 700 hPa over the area (54ºE-60ºE, 20ºN-23ºN) representing central region and wind at 850 hPa over (52ºE-56ºE, 17ºN-20ºN) representing southern regions to understand the interrelation between wind and rainfall. A relation between the monthly rainfall and the relative humidity for different vertical levels for the above mentioned regions was also studied.

5.1 North region of Oman

The prominent rainfall period in the northern part of the Sultanate of Oman is between December and March. Wind at 700 hPa shows a good relation with the monthly rainfall as shown in figure 5.1. The wind is high during high rainfall period and low during low rainfall period. The high wind speed during winter is mainly associated with the ITCZ and the low wind speed is due to the anticyclonic circulation in the regions. High wind speed during the winter season indicates the governing factor of rainfall as mainly wind at this level.

The Figure 5.2 which has been prepared using the data from NCEP indicates the time height structure of relative humidity over the area selected in the northern region. The relative humidity during the months from December to March is high in a layer below 700 hPa, the value exceeds 40 % and greater than 60% over the surface. In particular, the relative humidity is higher in layer below 900 hPa and mostly found during winter season. However, the relative humidity is less than 25 % during the summer monsoon season. Thus the rainfall during the southwest monsoon is rare. This can also be seen from the wind magnitude. The wind during this season is less than 2 m/s indicating advection of moist air from the ocean is low in the north.

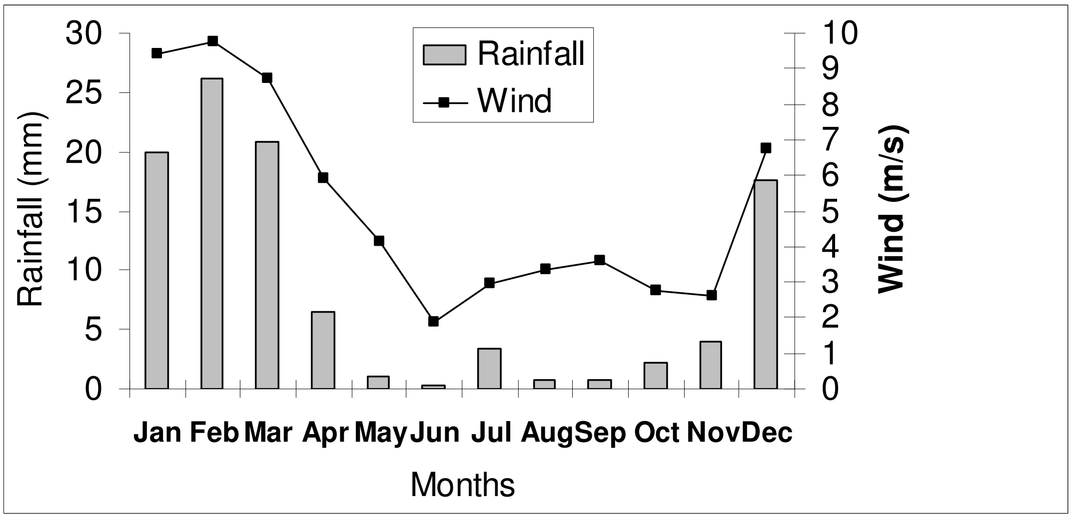


Figure 5. 1 The wind speed at 700 hPa level and the average rainfall for north part of Oman

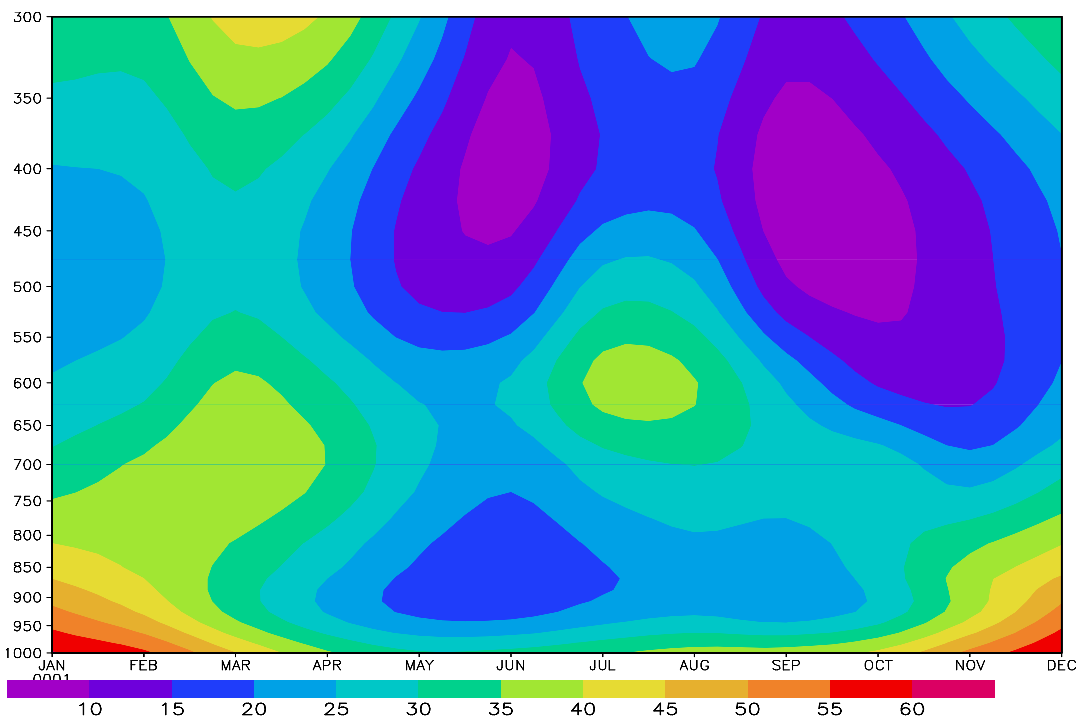


Figure 5. 2 Time-height cross section of relative humidity over the area (54ºE-60ºE, 23ºN-26ºN) presenting north region of Oman. Most of the high humidity is at the surface up to 900 hPa and most of it is in winter.

5.2 Central Part of Oman

The central part of Oman is affected by two rainy seasons (December-March and June–August). The wind at the 700 hPa reaches its maximum in late December to March and the relative humidity increase gradually between December and March in a layer below 850 hPa which exceeds 50% and even more at the surface. The wind velocity is high during high rainfall in the winter season. This situation takes place due to the effect of the high level of moisture carried out by wind as shown in the figure 5.3.

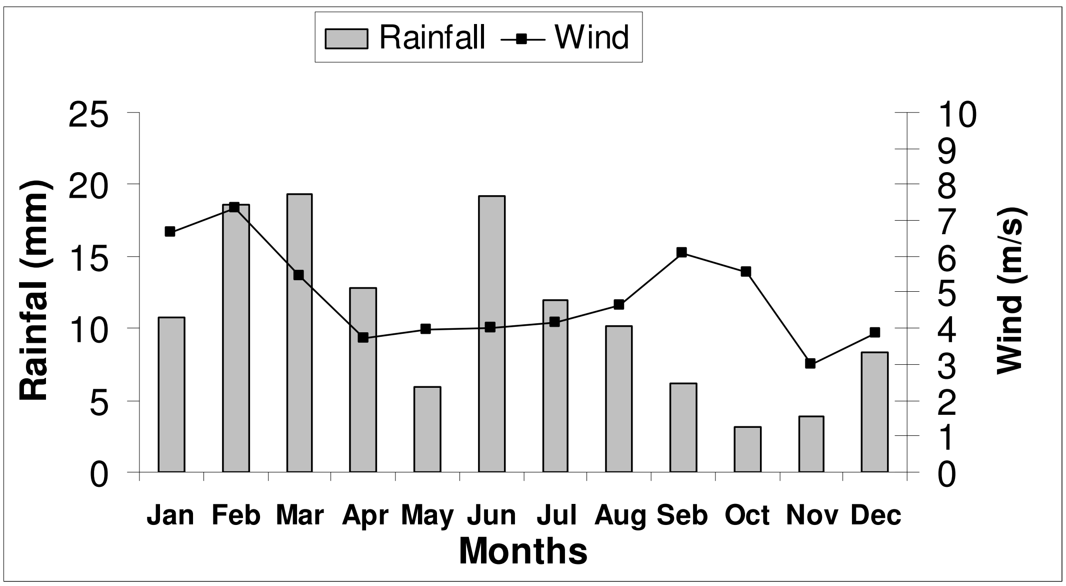


Figure 5. 3 The wind speed at 700 hPa and the monthly average rainfall for central part of Oman

The wind blows towards southeast with a speed of more than 3 m/s at 850 hPa level during the summer monsoon season as illustrated in the Figure 5.4. The relative humidity increases again at the 600 hPa level which can be related to moisture pumping from the Arabian Sea during the summer monsoon period as shown in the Figure 5.5. This condition helps in forming local convection during afternoon and causing heavy rainfall. The month of June, July and August also has surface moisture that could contribute to rainfall. The mid level high humidity could account for the higher mountain regions getting orographically induced rainfall.

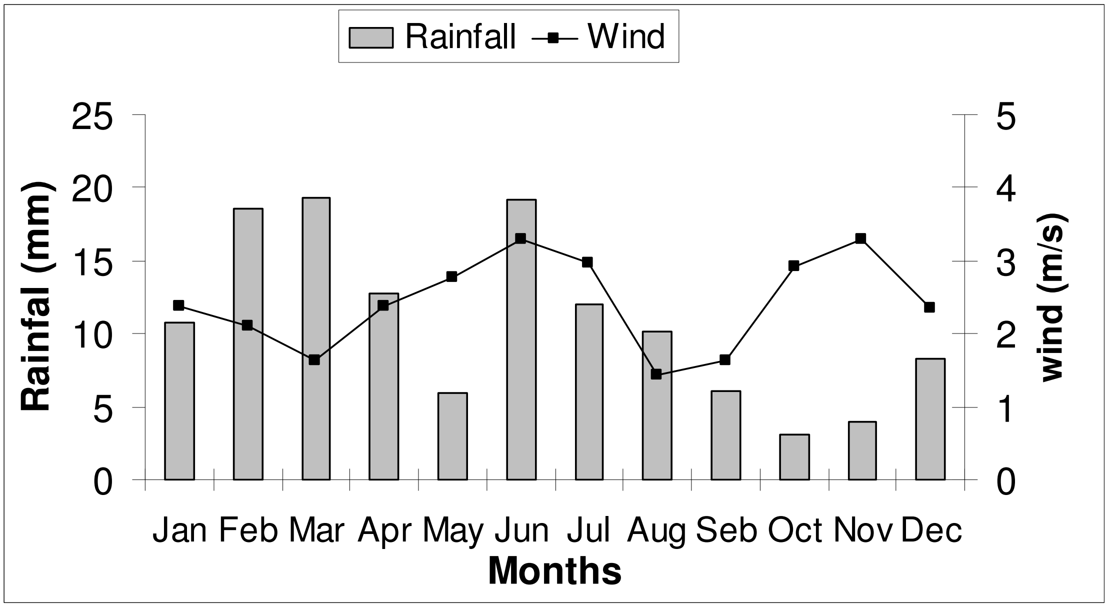


Figure 5. 4 The wind speed at 850 hPa and the monthly average rainfall for central part of Oman

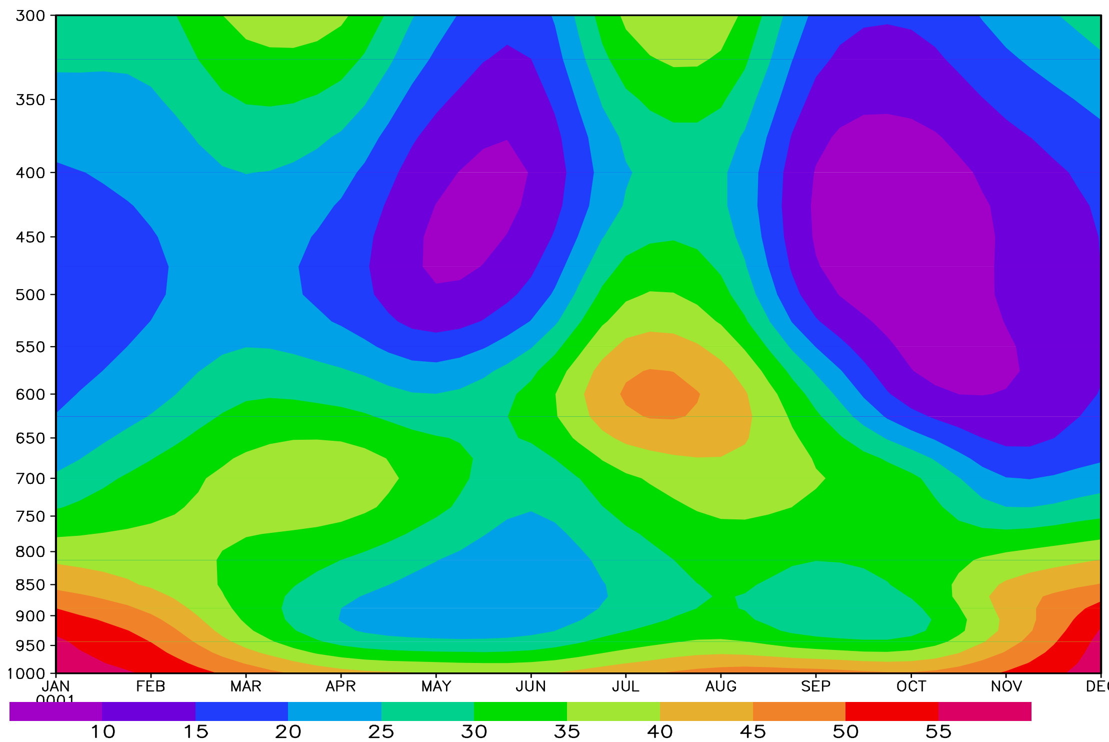


Figure 5. 5 Time-height cross section of relative humidity over the area (54ºE-60ºE, 20ºN-23ºN) representing central region of Oman

5.3 South part of Oman

The monthly rainfall increases from June to August for the stations in the southern part of the Sultanate of Oman. Figure 5.6 shows the monthly variation of rainfall with wind at 850 hPa level. The wind is low during March and April when the rainfall occurred but it is high during July and August. This indicates the wind flow from eastern region and thus the moisture source of the rainfall is the Indian ocean.

The relative humidity in the southern region of Oman during the month March and April is high in a layer shown in figure 5.7 below which is between 850 hPa and 500 hPa and it exceed 45% and caused light rainfall. However the relative humidity is more than 55% during summer monsoon season. The relative humidity reaches its peak during July and August. The source of this relative humidity suggested from the Indian ocean and Arabian sea due to high speed of easterly wind at 850 hPa level. The wind speed start to decrease from October onwards till it reaches less than 2 m/s and the relative humidity also decreases near the surface during October and November indicating the less influenced of wind during monsoon which result in less moisture adverted from the Indian ocean and the region receive less rainfall in the winter season as illustrated in the figure 5.7.

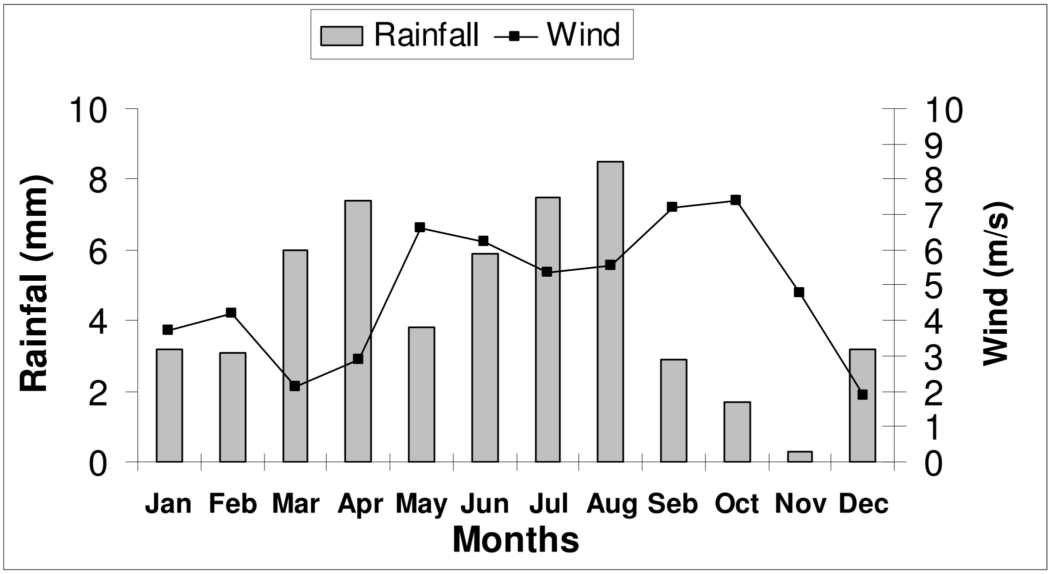


Figure 5. 6 The wind speed at 850 hPa level and the monthly average rainfall for south region of the Oman

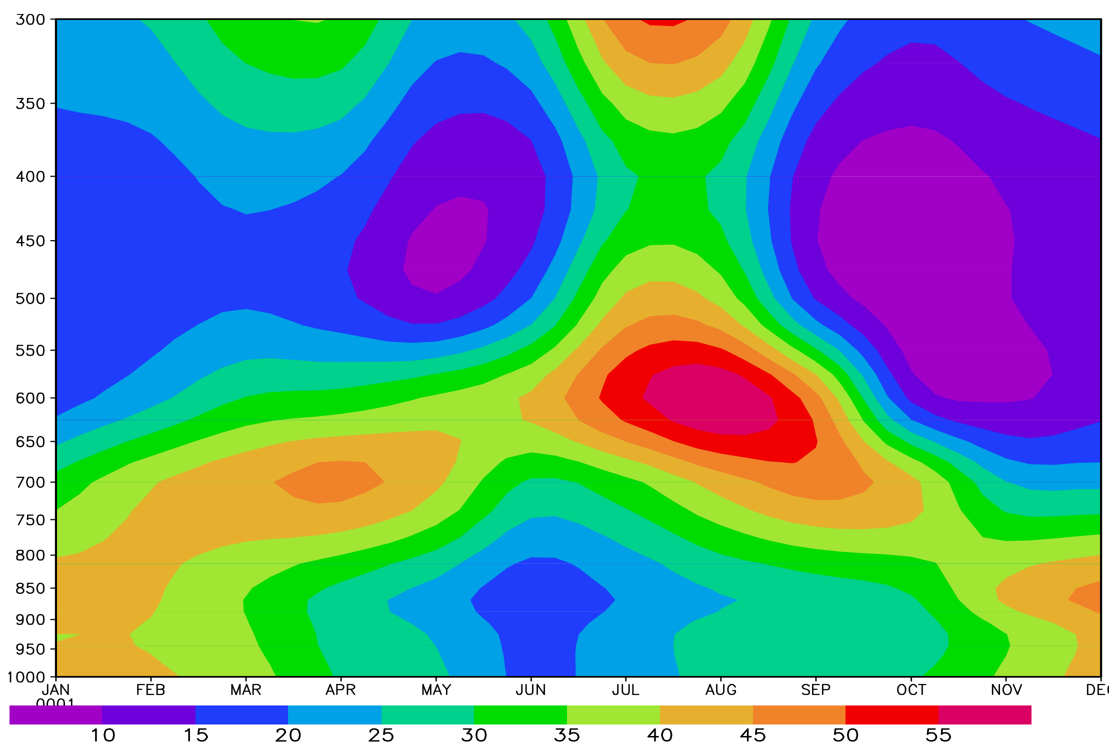


Figure 5. 7 Time-height cross section of relative humidity over the area (52ºE-56ºE, 17ºN-20ºN) representing south region of the Oman

5.4 Case Studies to Explain the Mechanism of the Rainfall

5.4.1 North Region of the Oman during Winter

A couple of days having rainfall over the region were selected to identify the mechanism of the rainfall during the winter monsoon season. The month of March in the year 1997 was selected in the northern region wherein two clusters of rainfall can be identified. One selected cluster out of two falls in the middle of the month (13 to 17) and another is at the end of the month (25 to 30). The bar chart of the daily rainfall during the month of March has been prepared as shown in the Figure 5.8. Longitudinal cross section of zonal wind at 700 hPa over the latitude belt (23ºN-26ºN) for the month of March 1997 as represented in the Figure 5.9 was created to explain the mechanisms of these rainfall episodes.

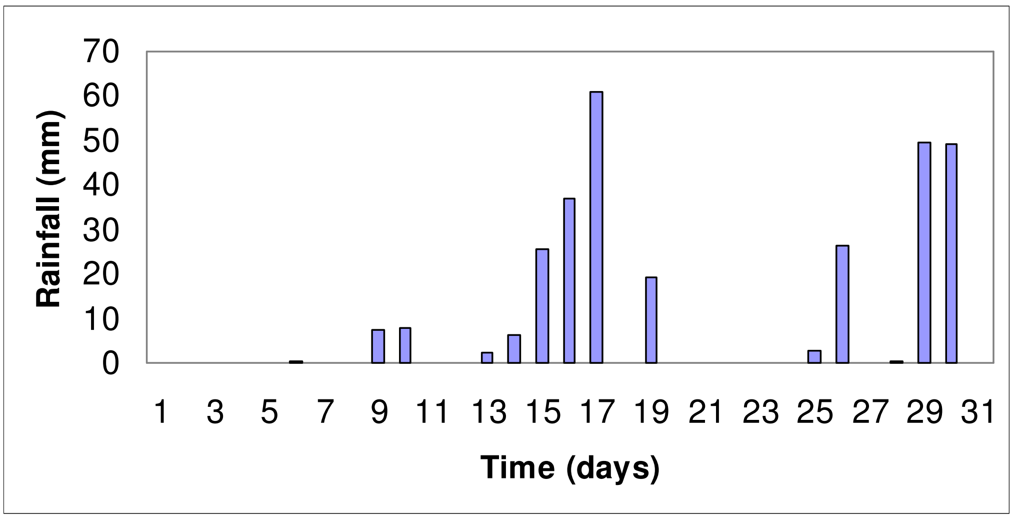


Figure 5.8 The daily average rainfall in north part of the Oman during March 1997.

A core of high winds at longitude 35ºE in the latitude belt (23ºN-26ºN) around 13th of March could be identified from the Figure 5.9. This high wind core then moves eastward through the Middle East regions and reaches the north part of Oman by 15th of March. The wind strength in the Oman region is about 24 m/s which cause rainfall ranging between 5-60 mm/day during the subsequent four days. The maximum rainfall was recorded on 17th when the wind reaches its maximum value of 24 m/s. It starts to decrease thereafter and the rainfall also decreased. This phenomenon present on the 19th of March when rainfall ceased as shown in the wind cross section mentioned above.

There was another spell between 25th to 30th March 1997. This phenomenon has less effect in the north part due to weaker wind speed (16 m/s). The zonal wind starts to move towards southeast at longitude of 30ºE at 19th of March and moves through the Middle East regions with speed ranging between 14-16 m/s. It reaches the north part on 25th March with a speed of 18 m/s as shown in the Figure 5.9. This causes rainfall amount between 5-50 mm/day. The maximum rainfall occurred on 29th and 30th of March and the amount of rainfall exceeded 50 mm/day.

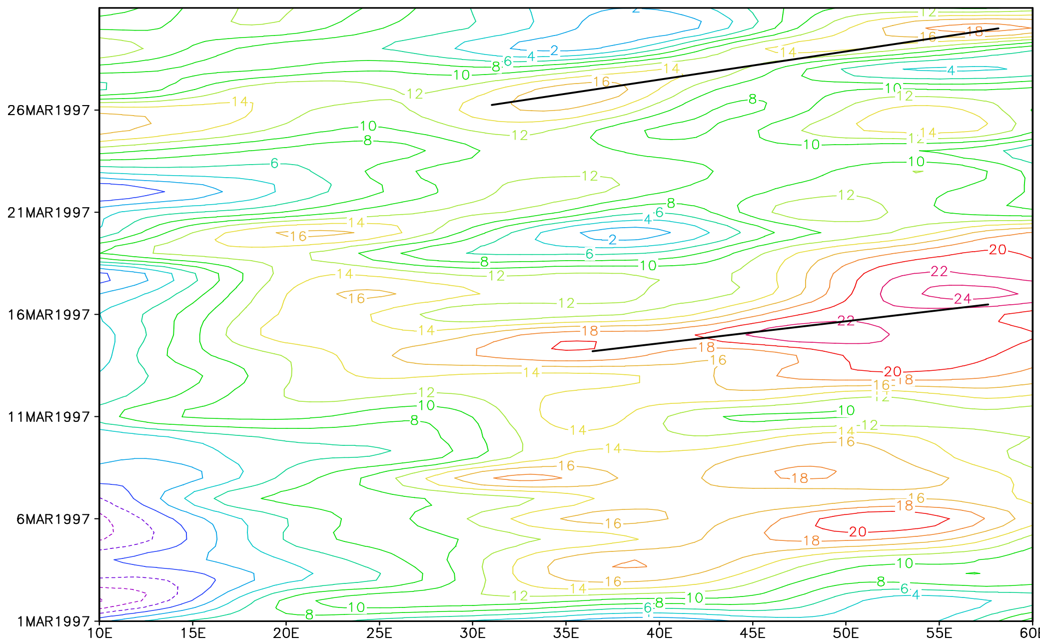


Figure 5.9 Longitudinal cross section of zonal wind at 700 hPa over the latitude area (23ºN-26ºN)

The origin and propagation of the Mediterranean system over this region can also be seen from the Outgoing Longwave Radiation (OLR). OLR is the emission to space of terrestrial radiation from the top of the earth's atmosphere (Salby, 1996). The lowest OLR value indicates high convection that was found above the northern region of the Oman during March 1997 and presence of clouds may completely block all outgoing infra-red radiation from the surface. The propagation of low value of OLR around 35º E through the Middle East can be depicted from the figure 5.10. The OLR value was around 160 W/m^2 between 15th and 17th of March when the area receive the maximum amount of rainfall. The OLR value was more than the first event during the second event of rainfall (25th -30th) due to less dense clouds over the region. The OLR during the second event was more than 210 W/m^2 which is verified by the less amount of rainfall of less than 45 mm/day.

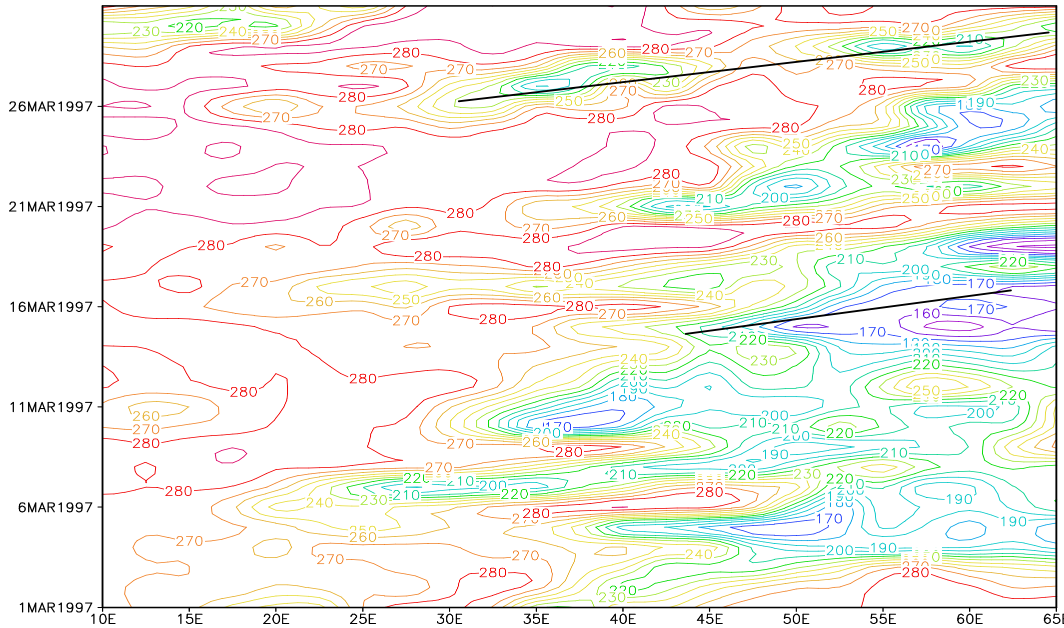


Figure 5.10 Interpolated outgoing longwave radiation over north part of Oman (23ºN-26ºN)

5.4.2 Integrated Moisture Transport Analysis during winter

Vertically integrated moisture transport (VIMT) were undertaken for three events in which one event did not show any rainfall and other two events reported considerable amount of rainfall in the northern part of Oman. The vertically integrated moisture transport was calculated based on the work undertaken by Murakami et al (1999). Vertically integrated zonal and meridional moisture flux can be drawn by following equation

$$Q_\lambda = \int_{300}^{p_s} qu \frac{dp}{g}$$

$$Q_\varphi = \int_{300}^{p_s} qv \frac{dp}{g}$$

Here q, u, v and P_s are all functions of time and they specific humidity, zonal and meridional wind fields and pressure at surface. The surface level in the equation is assumed as the 1000 hPa. Therefore the vertical integrated moisture flux is the sum of all the moisture fluxes from the surface up to height level of 300 hPa.

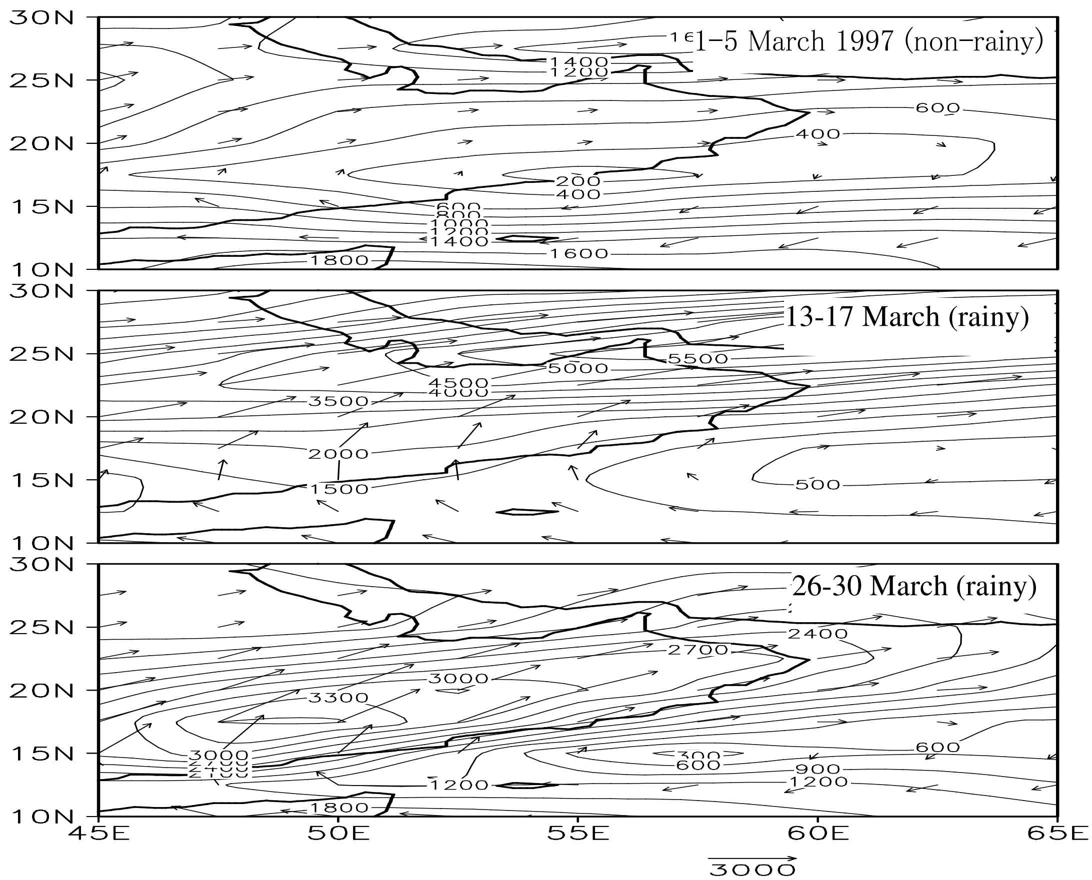


Figure 5.11: Vertically integrated moisture transport (kg/kg m/s) during three events. Upper panel of the figure indicates the VIMT for non rainy days (1-5th March 1997) and the other two panels indicates the rainy spells

The Figure 5.11 shows the VIMT from surface to a level of 300 hPa. The data for u, v and q are obtained from the NCEP/NCAR reanalysis website. The vertical level of the specific humidity is only up to 300 hPa. The specific humidity beyond this level is assumed as negligible amount and VIMT is calculated up to 300 hPa. The upper panel of the figure is the VIMT for non rainy periods (1-5 March 1997) and other two panels (13-17, 26-30 March 1997) are for the rainy events. The five day composites- were taken for all the three episodes to highlight the difference in patterns during rainy spell from that of the non-rainy periods for the analysis of the VIMT,. The VIMT during non-rainy period and the values of moisture flux are lower while comparing to that of the rainy days. Over the Oman region, the values during non-rainy period is about 200 kg/kg m/s and that for the northern part is little higher but is still less that 1500 kg/kg m/s. The direction of transport is from the eastern side indicating a predominant moisture transport from the east. The other two figures (middle panel and bottom panel) indicate the VIMT during two rain episodes. In both of the episodes we can clearly see that the values of the VIMT is very much higher than what we see during non-rainy period. In both the cases, the predominant transport of moisture is coming from the east of Oman. This gives us an indication that the moisture source is from the east is possibly be the Mediterranean sea. The values of the VIMT during rainy days are 3 to 5 time higher than that of the non rainy periods. There fore we can attribute that this abundant moisture from the Mediterranean sea was the main reason for the rainfall over the central and northern part of Oman during the winter season.

5.4.3 Central region of Oman during winter

The central part of Oman during winter receives large amount of rainfall (December-March) similar to the northern part. The March 1997 was selected to explain the mechanisms for this event as a representative case due to the significant amount of rainfall in this month. This phenomenon formed at longitude of 35° E in 13th of March with wind speed of 22 m/s. The wind blows towards west carrying moisture from the Mediterranean sea through the Middle East. The vertically integrated moisture transport is very similar to what is explained in the earlier section. The wind speed decreased when it moves towards the central part and reaches this region on 15th of March with speed of 16 m/s and causing rainfall amount less than 30 mm/day as shown in the figure 5.12. The rainfall increased rapidly while the wind moved toward the west and the amount of the rainfall rose to 140 mm/day in 19th of March. Another event could be seen from the figure 5.13 while starts to form at longitude of 30ºE on the 23rd of March along with wind speed of 16 m/s. This wind moves further to the west with a speed of 14 m/s through the Middle East and reach central part of Oman on 25th of March causing a rainfall of 80 mm/day. The maximum rainfall occured on 30th of March when wind speed decreased to 12 m/s.

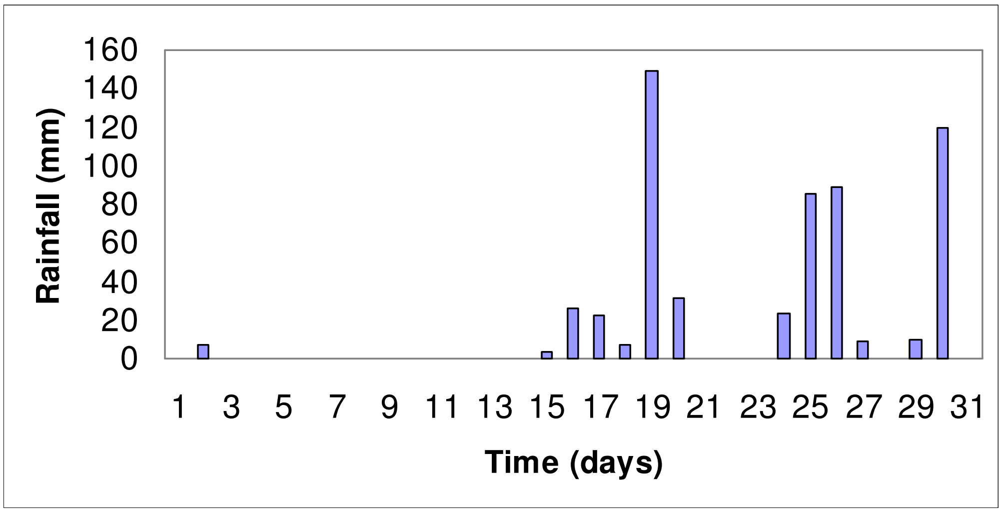


Figure 5. 12 The daily average rainfall in the central part of Oman during March 1997.

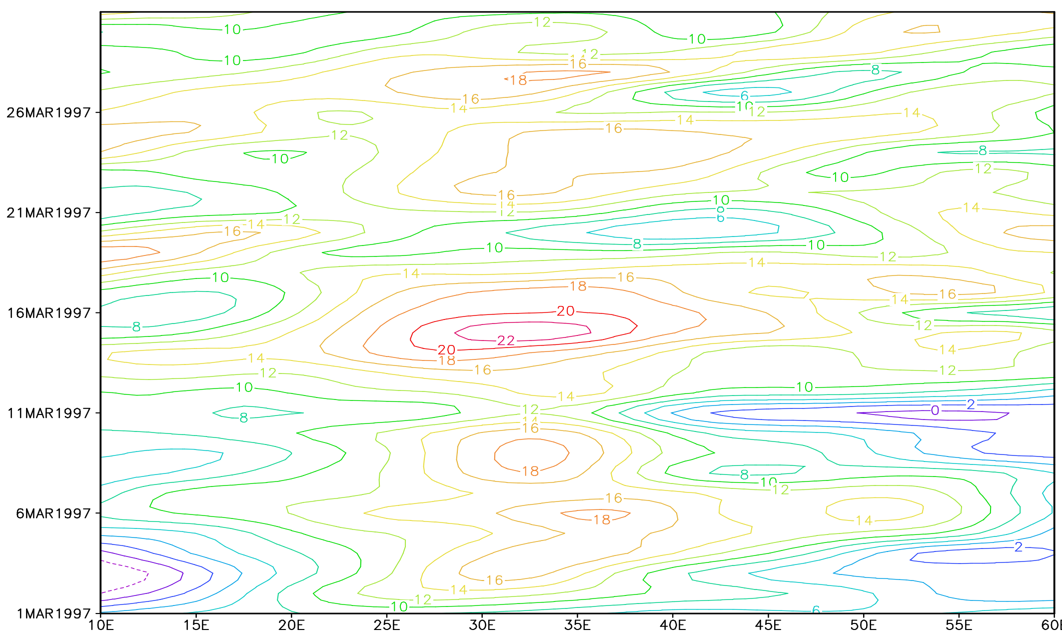


Figure 5. 13 Longitudinal cross section of zonal wind at 700 hPa over the latitude area (20º N-23º N)

The figure 5.14 shows the OLR in the middle region of Oman (20º N-23 ºN) during March 1997. The analysis of OLR over this region shows the value around 190-

200W/m^2 in 23rd to 29th of March which means dense cloud were over that region when the rainfall exceeds 140 mm/day. This observation agree with zonal wind anomalies during the same period when the wind is move westerly adverting moisture from Mediterranean region through the Middle East until it reaches the central part of Oman. This system move from 40^{0}E to 65^0 E from 21st March to 25th march. The rainfall amount during this period is varying from 40 to 140 mm/day as can be seen from figure 5.14.

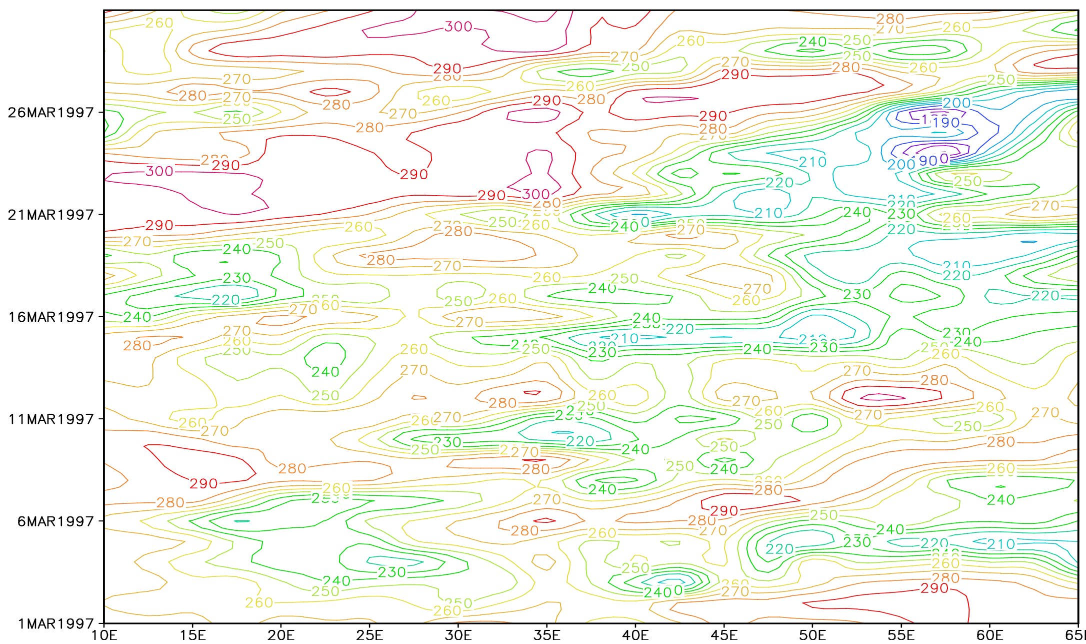


Figure 5. 14 Interpolated outgoing longwave radiation over central part of Oman (20º N-23 ºN.) the system move from 40^{0}E to 65^0 E from 21st March to 25th March.

5.4.4 Central region of Oman during summer

Central part of the Sultanate of Oman is also affected by rainy season during the summer season. This season takes place at the same time of summer monsoon which affects the southern part of Oman from late June to September. Local convection clouds which formed in afternoon time causes heavy rains during this period. Figure 5.15 shows the daily rainfall during July and August 1995 as one case to determine the mechanism that controls the rainfall in the summer period.

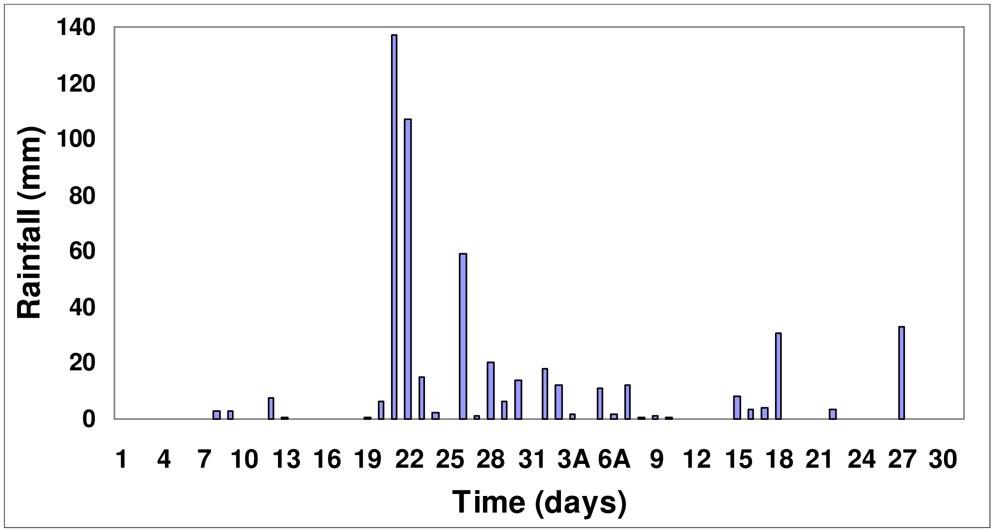


Figure 5. 15 Average daily rainfall in central part of the Oman (1 July-31 August 1995).

The meridianal wind (v-component) started to blow at 70º E with speed of 4 m/s on 3rd of July and moved towards northeast which could be seen in the Figure 5.16. Further, it has been diverted steadingly towards west at longitude 65º E on the 19th of March. It reached the central region of Oman on 21st of March and helped in formation of the local convection storm over Al-Hajar Mountains as depicted in the figure 5.16. The wind is also associated with the rainfall taking place in the central part of the Oman which moisture coming from the Arabian sea. Similar conditions started to form in the early month of July causing rainfall less than 20 mm/day. The rainfall increased till it reaches its peak on 22nd of July with an amount of 140 mm/day. The rainfall continued till the end of August ranging from 5 mm/day to 60 mm/day.

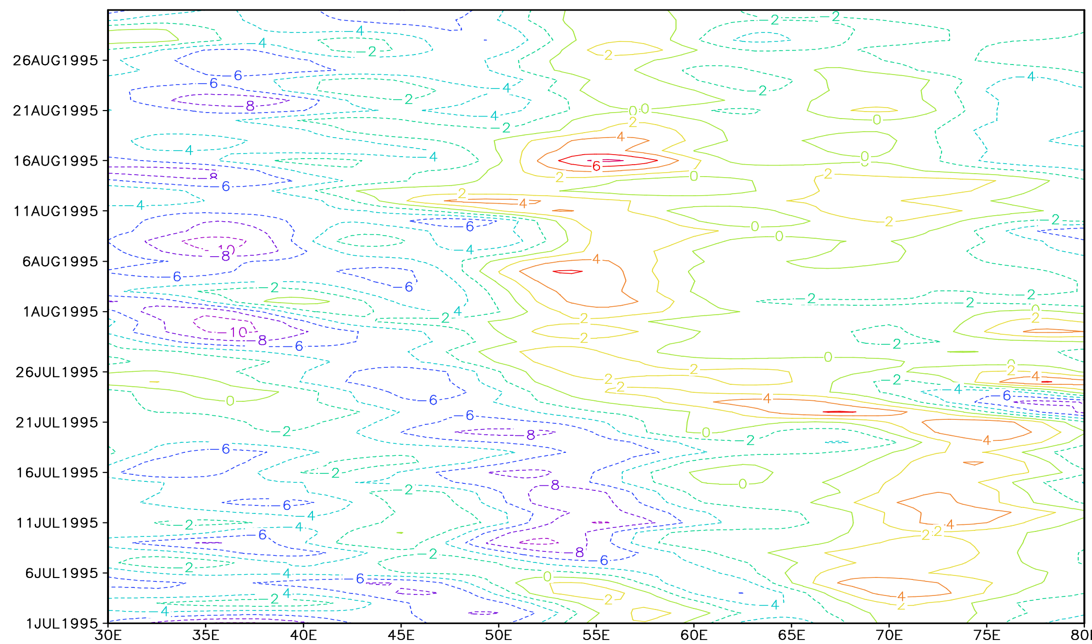


Figure 5. 16 Longitudinal cross section of meridian wind at 850 hPa over the latitude area (20º N-23º N)

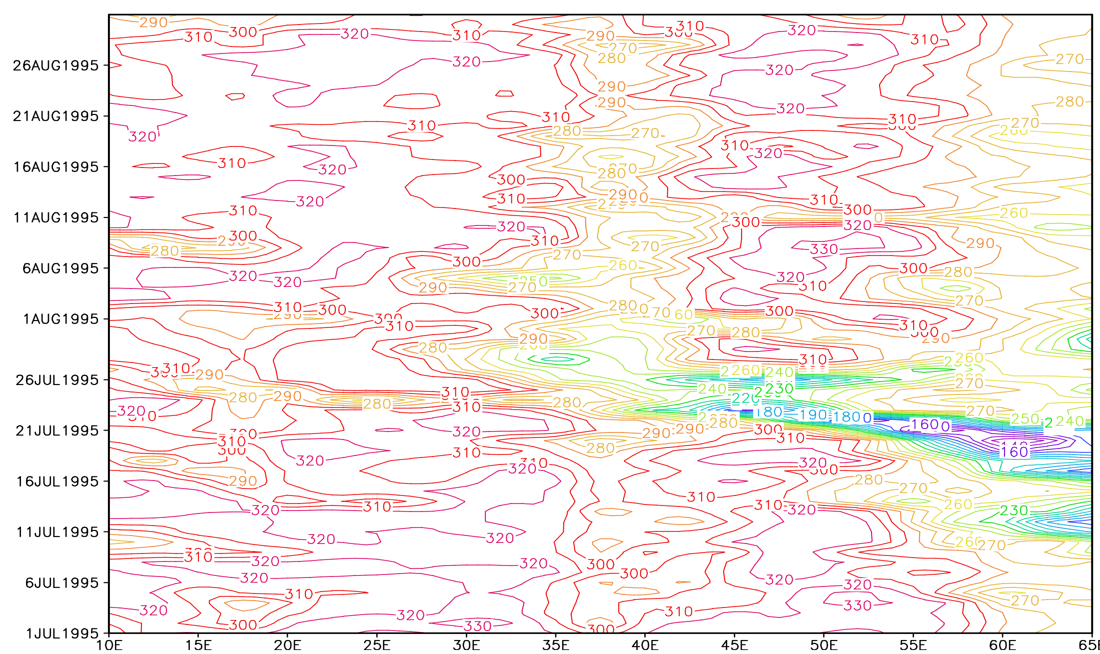


Figure 5. 17 Interpolated outgoing longwave radiation over central part of the Oman (20ºN- 23ºN). This system move from 65^0 E to 45^0 E from 21 to 26 July.

The figure 5.17 shows the OLR anomalies in the central part of the Oman from July to August 1995. The analysis shows that clouds start to move from longitude 65º E when OLR value (160 W/m^2) is minimum on 16th of July and also indicates dense clouds over that region. The system moved steadily from 65^0 E to 45^0 E from 21st to 26th

July. The OLR pattern has coincide with wind pattern that blows eastward from the Arabian sea, bringing abundant moisture to precipitate over the region. These clouds start to reach central part of Oman from the 18th of July onwards. The rainfall decreases later on and the wind become weaker, so less clouds were driven to the central part and the value of OLR become larger (>300 W/m^2).

It has been observed from the above mentioned discussion that the central part of the Oman is influenced by two seasons. One is the winter season (December-March) when wind blows westerly and brings moisture from Mediterranean region causing rainfall ranging between 20-150 mm/day. Another season occurred in summer (June-September) when rainfall in Oman is influenced by the Indian monsoon, which derive moisture from the Arabian sea and finally causing heavy rainfall in the afternoon time. The wind blows easterly from Indian ocean and cross the Arabian sea and provides moisture at 850 hPa level with speed of 6 m/s during rainy days.

5.4.5 South region of the Oman during summer

The southwest monsoon season is a climatic feature which takes place in the southern part of the Oman. The monsoon starts in late June and last in late September each year without significant fluctuation in the rainfall amount which ranges between light rains to showers in the summer monsoon season as depicted in Figure 5.18. Duration of July-August 1995 was selected as a study case to understand the mechanism which controls this phenomenon.

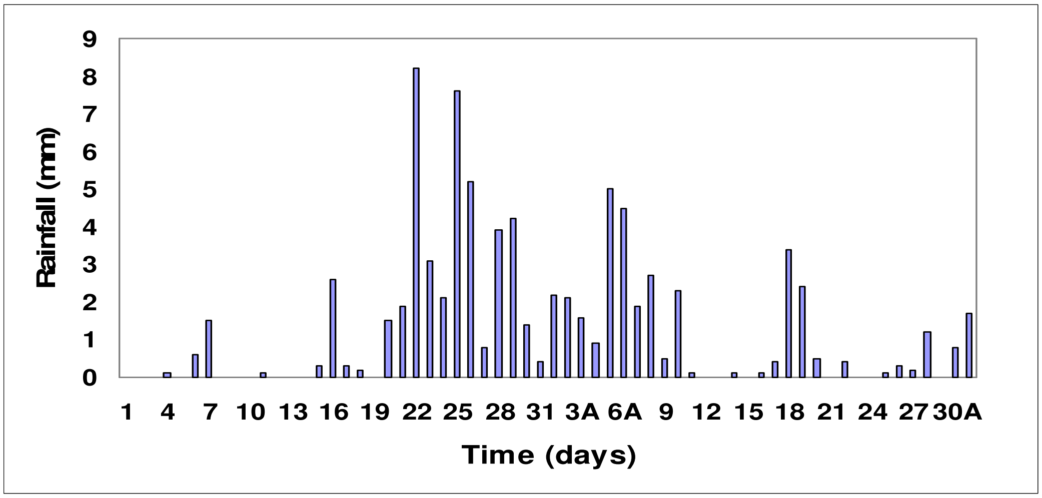


Figure 5. 18 Average daily rainfall in southern part of the Oman (1 July-31 August 1995).

The figure 5.19 shows a core wind that has been formed at 75º E in the latitude (17º N-20º N) around 06 March 1995. This wind moved towards northwest and reached southern region at 60º E around 13 March. It changed the direction and blow towards north and reached the south region of Oman when this core of wind reached the area close the longitude 55º E around 15 March causing rainfall amount less than 1 mm/day. This wind continued to move northward in the subsequent days and causing rainfall ranging between 1-10 mm/day.

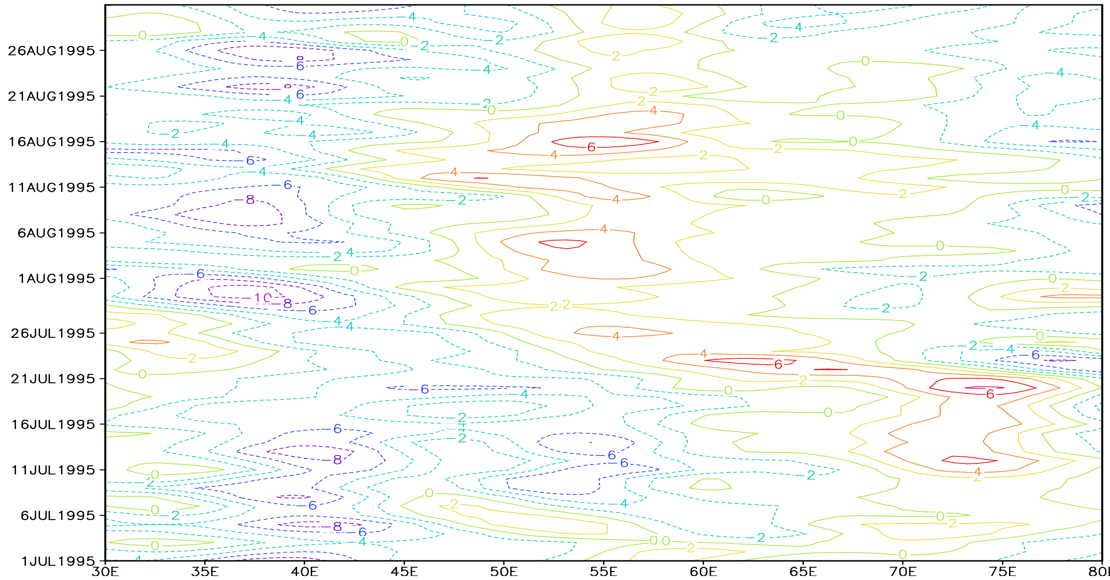


Figure 5. 19 Longitudinal cross section of zonal wind at 700 hPa over the latitude area (17º N-20º N)

The southwest flow over the Arabian sea is quite well reproduced as described in the Figure 5.19. The wind during July and August flow with speed of 6 m/s at 700 hPa level from the Somalia jet through Arabian sea towards south region of Oman. The same wind carries moisture from the Indian ocean to the Arabian sea causing rainfall in the southern Oman ranging between 5 and 10 mm/day.

Water vapour is adverted from Indian ocean across south region of Oman. This coincide with low OLR values (180 W/m^2) in the area of longitude (60ºE-65ºE) around 6 July causing light rainfall amount (less than 2 mm/day). These clouds propagate further from the Indian ocean towards the east between 16 and 23 March. Further, these clouds move with the wind towards the northwest until they reach the southern region of the Oman around 13 July as shown in the figure 5.20. The movement of clouds/convection bands from east towards coast of the south region at level of 700 hPa could be seen in the figure, which has same wind pattern and flow direction. The rain system subsequently move from 65^0 E to 40^0 E in the month of July. Hence summer in south has an easterly advection of moisture from the Indian ocean associated with the summer monsoon

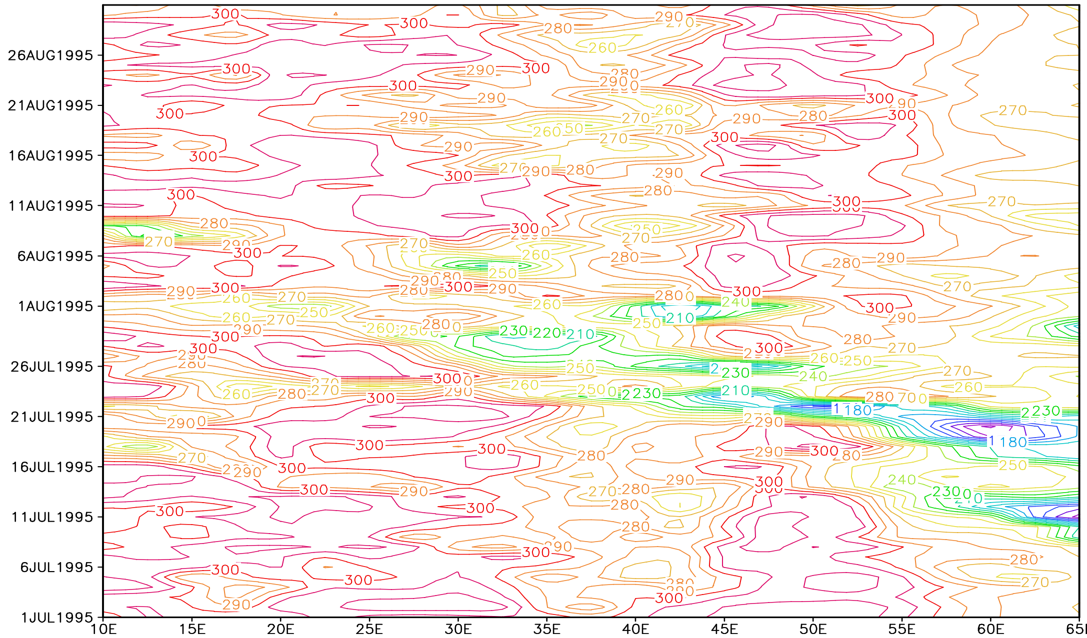


Figure 5. 20 Interpolated outgoing longwave radiation over southern part of the Oman (17ºN-20ºN)

5.4.6 Vertically Integrated Moisture Transport during summer

The VIMT analysis was carried out for the summer period of the Oman to identify the major moisture source of rainfall for the country. In general, Oman is one of the regions where the subsidence is dominant. This subsidence is caused by the down limb of the east-west indian circulation. Therefore it is difficult to identify the regions of moisture convergence and to find out the role of vertically integrated moisture flux most of the times. The VIMT for non-rainy and rainy periods during the summer monsoon season was calculated and shown in the figure 5.21.

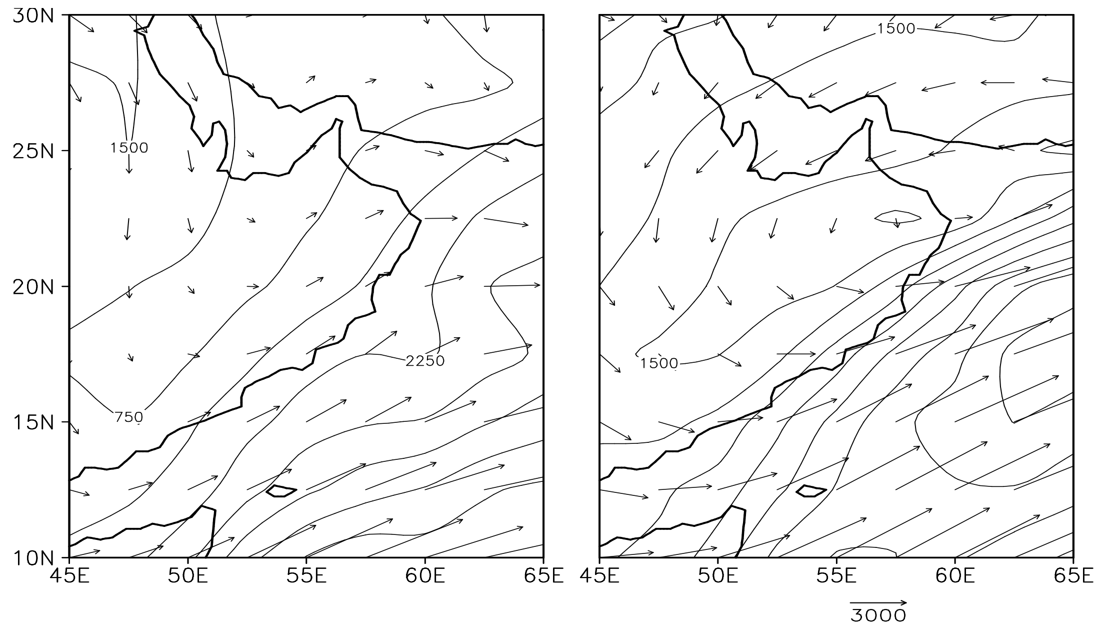


Figure 5.21: Vertically integrated moisture transport (kg/kg m/s) during a non rainy period and a rainy period during summer monsoon period. Each of one having a composite of five days

The left panel of the figure shows the VIMT during non rainy period and right panel of the figure shows for the rainy periods. The non-rainy periods and the rainy period are considered from 1 to 5 July 1995 and 21st to 25th July 1995 respectively. These days were identified on the basis of time series of the daily rainfall over the southern part of Oman as shown in the Figure 5.20. The pattern of the VIMT during non-rainy and rainy episodes was different in both the values and the transport direction. The values of VIMT during non rainy days in the southern part of Oman are less than 1500 kg/kg m/s whereas it is slightly more than 1500 kg/kg m/s in the coastal areas adjacent to the Arabian sea., Divergent of moisture flux can be seen in most of the Oman region except the coastal belt of the Arabian sea which may be due to the presence of the subsiding limb of the east-west Indian circulation.

The values of the moisture flux during the rainy period are much higher than that of the non- rainy periods all over the Oman region. The value of the moisture flux in coastal areas adjacent to the Arabian Sea was more than that of the other parts. The coastal areas in the southern part were zones of moisture convergence which is aligned parallel to the coastal belt. One limb of the moisture flux seem to originate from the northern part of the Arabian sea, turning anticlockwise to merge with the cross equatorial flow associated with the Somali jet. Hence the region of conveyed is near off-shore coast of Arabian peninsular. Thus may be northern source of moisture flux seems to be as the Arabian Sea from the transport direction of moisture flux and this component is relatively weak while comparing with the cross equatorial flow component from the equatorial Indian ocean. It could be concluded from these figures that the main moisture source during the summer season in the south/coastal areas of Oman is the Arabian sea and equatorial Indian ocean.

5.5 Tele-connection of ENSO with Oman Rainfall.

El-Nino is a warm current of water, which is initially referred to as a weak warm current appearing annually around Christmas time along the coast of Ecuador and Peru. The El-Nino repeats every 3 to 7 years and it lasts for many months, having significant atmospheric consequences around the world. Ten of such major El-Nino events have been recorded during the last forty years as illustrated in the Table 5.1. The worst of which began in 1997, but the El-Nino in 1982-1983 was the strongest. More over, rainfall shows an abnormal increase during El Nino years across the southern USA and Peru causing destructive flood and drought in the West Pacific; sometime it is associated with devastating bush fires in Australia.

Table 5.1: Years in which El Nino has occurred.

1902-1903	1905-1906	1911-1912	1914-1915	1918-1919	1923-1924
1925-1926	1930-1931	1932-1933	1939-1940	1941-1942	1951-1952
1953-1954	1957-1958	1965-1966	1969-1970	1972-1973	1976-1977
1982-1983	1986-1987	1991-1992	1994-1995	1997-1998	

La-Nina is a drop in average sea surface temperature to more than 0.4^o C below normal lasting at least six months across specified part of the eastern Pacific (5^o N-5^o S, 120^o-170^o W). This change in ocean temperature could cause change in the weather around the world (drought or floods). La-Nina typically occurs every 3 to5 years as shown in the Table 5.2.

Table 5.2 The years of La-Nina.

Strong La Niña Years	1909-10, 1916-17, 1933-34, 1942-43, 1949-50, 1955-56, 1970-71, 1973-74, 1975-76, 1988-89
Moderate La Niña Years	1897-98, 1898-99, 1903-04, 1906-07, 1908-09, 1910-11, 1917-18, 1920-21, 1924-25, 1938-39, 1943-44, 1944-45, 1950-51, 1954-55, 1964-65, 1967-68, 1971-72, 1974-75, 1983-84, 1984-85, 1985-86, 1995-96

According to the data available (1977-2007) from all parts of Oman, it could be observed that rainfall in the country was recorded more than usual in the years 1976-1977, 1982-1983, 1991-1992, 1993-1994, 1997-1998 when El-Nino event was taken place. However El-Nino effect was entirely different in the 2002-2003 than previous El-Nino years when Oman suffered drought. Oman has gone through dry years (i.e. 84-85, 88-89) when the rainfall was less than normal as seen in the Figure 5.22 during La-Nina effect. However it would be difficult to conclude relationship of rainfall in the Oman with ENSO tele-connection. Therefore, EOF analysis of zonal wind anomaly at 850 hPa over the Middle East region was carried out to identify the major mode of variabilities and association of the different types of variabilities with the global tele-connection

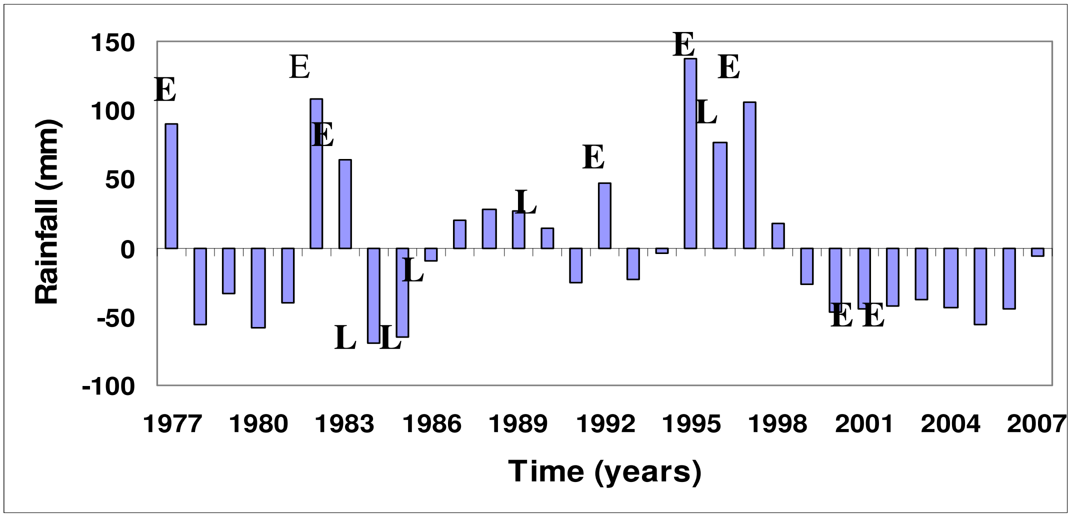


Figure 5. 22 The Departure from the mean of rainfall over Oman for period 1977-2007 and indicates El-Nino (E) and La-Nina (N).

5.5.1 EOF Analysis of zonal wind anomaly over the Middle East

Empirical Orthogonal Function (EOF) technique aims in finding a new set of variables that capture most of the observed variance from the data through a linear combination of the original variables. EOFs have been introduced in atmospheric science since early 1950's (Obukhov, 1947, 1960, Fukuoka, 1951, Lorenz, 1956). The EOF terminology was used first time by Lorenz (1956) who applied it in a forecasting project at the Massachusetts Institute of Technology. The EOFs have since then become a popular analysis tools in climate research. EOF techniques are deeply rooted in statistics, and go back to Hotelling (1933) who introduced principal component analysis (PCA), another name for EOFs. Further, a review of PCA/EOFs was undertaken by Kutzbach (1967). This technique has been used in the present study to link the major mode of variability over the Middle East regions to the climatic variabilities to the rest of the world such as El Nino/La Nina.

It has been revealed in the study that rainfall has a random variability in interannual time scale in most part of the Oman and variabilities can not be attributed to any specific climatic variabilities. Kepping this in view, EOF analysis of zonal wind anomaly during summer months for 51 years 1948-1998 was undertaken to find out the major mode of variabilities. There are three EOFs presents (EOF1, EOF2 and EOF3) the study which represent 60% of the total variability. The Figure 5.23 represents the three EOFs and their corresponding PCs. The first EOF corresponds to 30% of the total annual variability and the second mode of EOF (EOF2) shows 19% of the total variability and the third mod (EOF3) represents 13 % of the total variability of summer monsoon season in interannual time scale. The time evolution of the corresponding EOFs are also given in the right panels of the figure.

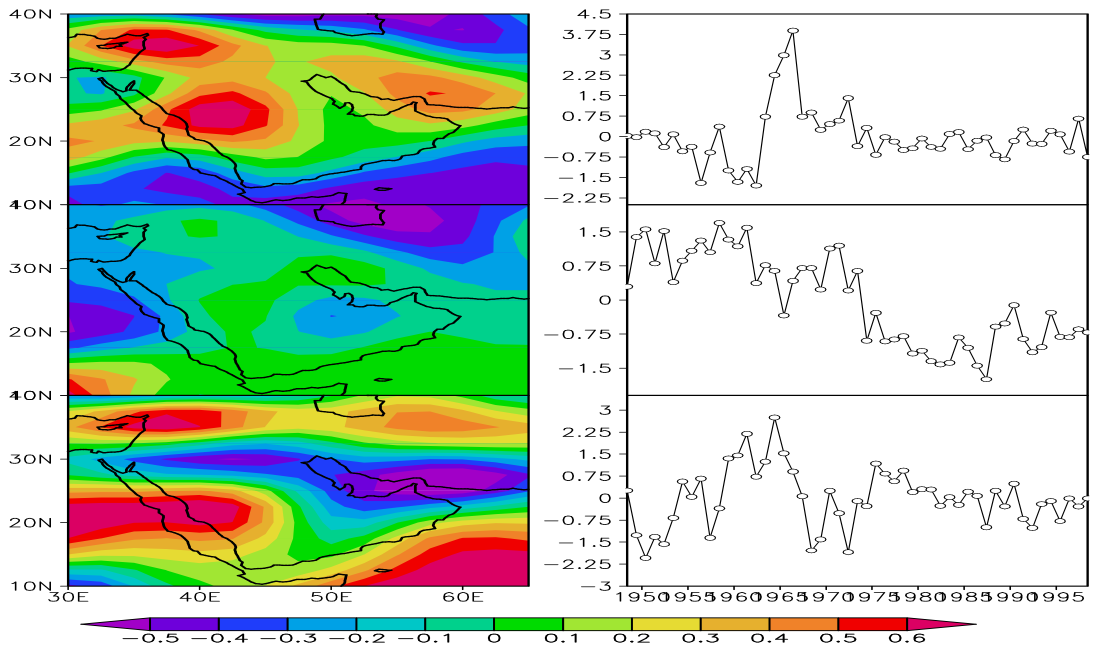


Figure 5.23: Three modes of EOF and their PCs. In the spatial plot the first one is for EOF1 and middle one is for EOF2 and the bottom one is for EOF3. Similarly first, second and third are for PC1, PC2 and PC3 respectively

It could be clearly noticed from the figure that the first mode of EOF shows high variance in the central part of the Middle East. The variance over the Oman region of the first mode is negligible. It has been noticed that the amplitude of the variability is considerably high over the Oman region in the second mode (EOF2 and could be concluded that this mode is largely influences the Oman climatology. The third EOF has also high variability in the northern part of Oman. Now it could be observed that the EOF1 is largely playing its role in the central part of the Middle East and it has no influential role in regulating the Oman climatology. However, the second and third

EOFs contribute about 32% of the total variance of the interannual variability during summer monsoon period over Oman region. However it is difficult to conclude that this variability has any connection with any other kind of known variability such as El Nina/La Nina.

The Fast Furrier Transformation (FFT) analysis has been employed first to understand the periodicity of the variability for the corresponding PCs of the EOFs. The Figure 5.24 shows the FFTs of PC1, PC2 and PC3. The dotted line in the figure indicates the 95% confidence level. It has been observed from the FFT analysis that PC1 shows some mode of variability but it is below 95% confidence level. The FFT of PC2 shows a peak at about 5-6 years with a confidence level of more than 95%. Another peak was observed at about 10 year periodicity but this one has a confidence level of less than 95%. FFT analysis of PC3 shows a high peak at about 6 years similar to that was observed in the FFT of PC2. The second peak in the FFT of PC3 is observed at about 16 years (less than 95% confidence level). Therefore, from the PC2 and PC3, a significant periodicity at about 5-6 years has been observed.

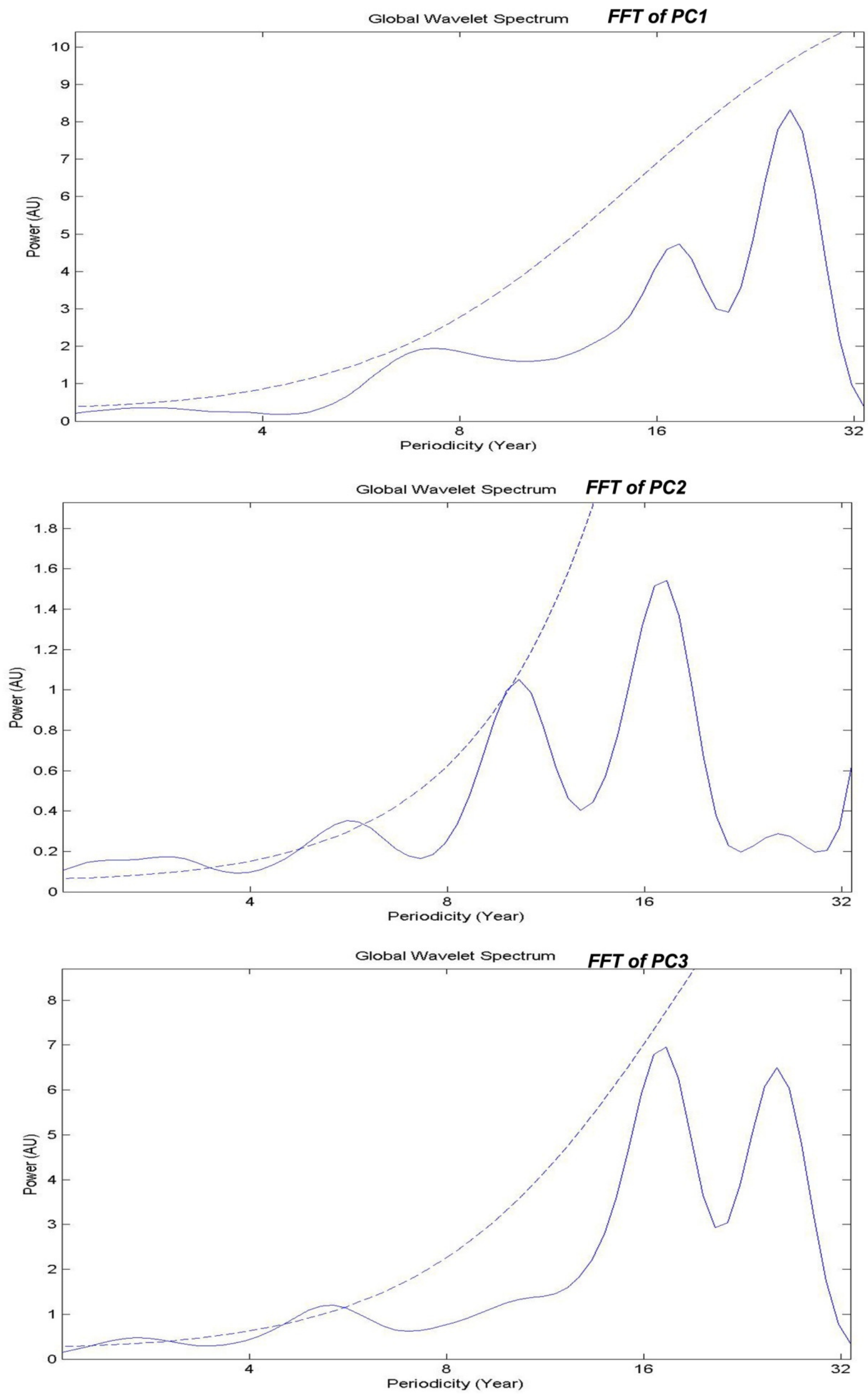


Figure 5.24: FFT analysis of PC1, PC2 and PC3. The dotted line indicates the 95% confidence level

A spatial correlation of zonal wind anomaly was made to identify the global linkage of these variabilities at 850 hPa during summer period of 51 years. It has been observed from EOF1 that the high amount of variability contributes in the central part of the Middle East region. Therefore a box average zonal wind anomaly was made at 850 hPa over the area 37.5º E-40º E & 20º N-27.5º N and correlated it with each grid point between 60ºS to 60ºN for the entire latitude (upper panel of the Figure 5.25). The spatial correlation pattern of zonal wind anomaly of different parts of the Middle East is given in the Figure 5.25. The spatial correlation does not influence much with other region in the global scale. High correlation value (more than 0.7) was noticed just east of the Mediterranean Sea and an area of negative correlation was observed just above the area of positive correlation.

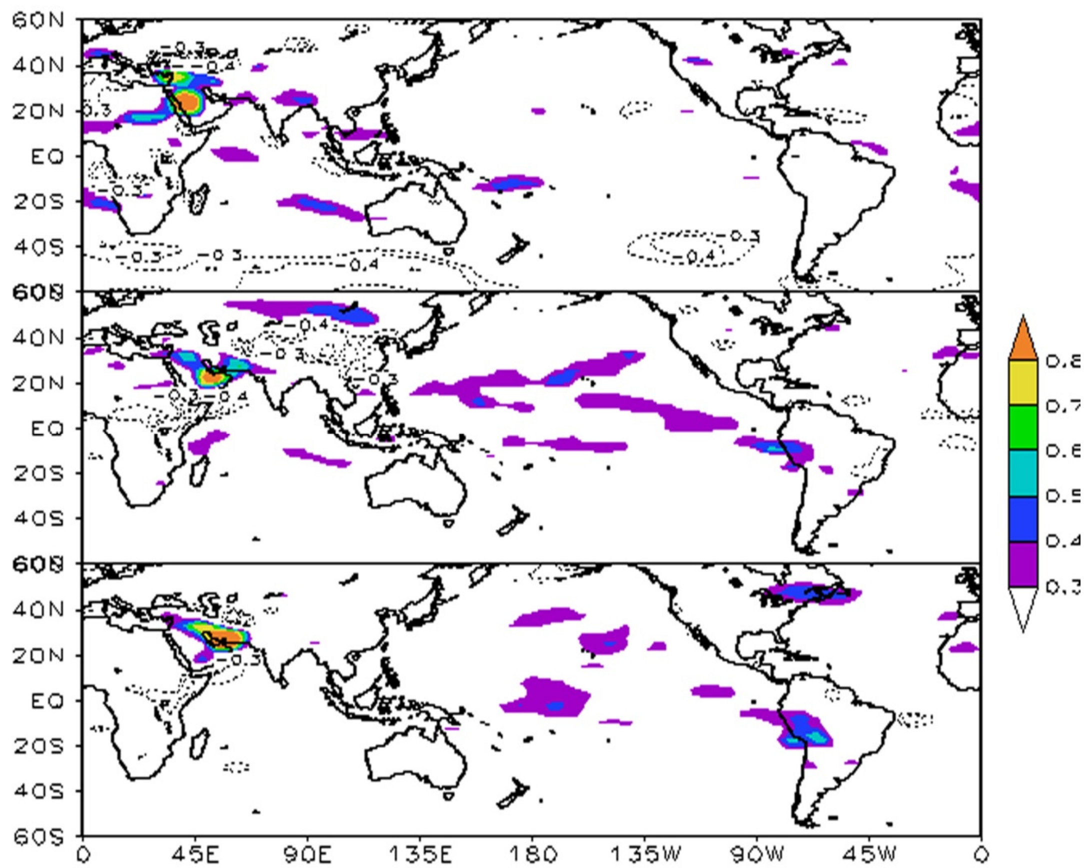


Figure 5.25: Correlation of zonal wind anomaly at 850 hPa with the same parameter over the each grid point in the entire altitude between 60º S to 60ºN.

The second and bottom panels of the Figure 5.25 shows the same as that of the upper panel but the box area has been changed. The box average in the case of second panel of the figure is over the area 47.5ºE-55ºE & 20ºN-25ºN and that for the bottom figure is 50ºE-62.5ºE & 22.5ºN-30ºN. It has been observed that Oman region (Central region in the case of EOF2 and Northern region in the case of EOF3) in the EOF2 and EOF3 shown high amount of variance in the zonal wind anomaly at 850 hPa level. It has been observed from the correlation analysis that high values of correlation coefficient (more that 0.4) in the region of east equatorial Pacific Ocean (Nino 4 region). This correlation value indicates a positive phase in the zonal wind anomaly over the Oman region. It has been discussed in previous section that the zonal wind at 850 hPa is a good agreement with the summer rainfall in the central part of Oman. Therefore, it could be concluded that the zonal wind anomaly over the east equatorial Pacific has a good correlation with the zonal wind anomaly itself over the Oman region and this wind has a good agreement with the rainfall over the same region and therefore the zonal wind anomaly over east equatorial Pacific Ocean has a positive correlation with the rainfall over the Oman region.

It has also been observed from the FFT analysis that the periodicity is about 4-7 years and hence it could be concluded that the El Nino has a positive correlation with the rainfall over the Oman region. Therefore the Oman region gets significant amount of rainfall during El Nino years. It has also been observed in the time series of annual rainfall that Oman receives above normal rainfall in most of the El Nino years.

Chapter 6 Conclusion

Oman lies in the Middle East region with hyper arid-arid-semi-arid climate. The drought in the region is largely due to the inadequate rainfall and the amount of rainfall shows large variations from the mean value of rainfall. Studies of rainfall features over Oman region has not yet been carried out properly. Therefore the studies of climatic regimes and their regulating mechanisms over the region are very important to both the country and its population. The rainfall climatology and its regulating mechanisms were studied in the present study. The first part of the thesis consists of year to year variations and monthly climatology using the daily rainfall data from 12 different stations. These stations are almost uniformly distributed all over Oman and have a good temporal coverage of 31 years (1977-2007). In addition to the above, a statistical presentation was made for the trend of rainfall for the recent 30 years in different intensity ranges such as low, medium and high for all the stations. The second part of the thesis consists of the mechanisms that regulate the rainfall over the different parts of Oman during different seasons. The influence of ENSO was also studied on the rainfall in Oman employing the EOF and spectral analysis. The NCEP-NCAR wind fields were utilized to understand the mechanisms along with OLR data sets. These data sets are available on a daily basis with a spatial resolution of 2.5º latitude-longitude grid. The results are summarized in the subsequent paragraphs.

The study of the annual rainfall reveals that the year to year variation of rainfall for all the stations is not uniform. Similarly, the variability of rainfall from year to year is sufficiently high and standard of deviation is observed to be more than its annual mean rainfall for some of the stations. The maximum rainfall of 401.9 mm/year during the study period was observed in the station Saiq in the year 1997. The minimum rainfall of 0.4 mm/year was observed at station Marmmul in the year 2000. The station Saiq was observed to have a maximum annual rainfall of 900.9 mm, while the station

Marmmul receives the minimum annual rainfall among all the other stations. Khasab station has the largest number of wet years (7 years), while Marmmul station has 14 dry years. The years 1982, 1995, 1996, 1997 and 2007 were wet years and 1974, 1975, 1980, 1984, 1985, 2000 and 2001 were dry years for entire country.

It has been observed from the studies of monthly climatology of all the stations that the northern stations (Khasab, Shinas, Sohar and Buraimi) have almost similar trend. All the stations in the central part (Ibri, Seeb, Saiq, Sur and Masirah) and southern stations were also similar. The maximum rainfall in northern stations takes place during December to March period (winter monsoon). However maximum rainfall takes place in both winter monsoons (December-April) and during Indian Summer Monsoon (June-September) in the central region. The southern region receives the rainfall during Indian summer monsoon period and minor amount of rainfall in winter season. It has been observed from the trend analysis that the high intensity rainfall shows a peak increase at most of the stations, However, there are no variations in the low intensity rainfall.

From the case study, the rainfall in the northern part of Oman is mainly contributed by the weather systems from the Mediterranean region., It has been observed on the basis of the daily wind fields and OLR that the bands of strong wind with low values of OLR (indicating convection) start to generate around 35º E during the winter season. This system moves towards the east and reached the northern part of Oman and causes rainfall. The moisture source for the rainfall during this period comes from the Mediterranean sea which is confirmed from the vertically integrated moisture transport analysis. It has been observed in the central part of the Oman that two seasons are prominent (December-March, and June-August). The rainfall is mainly contributed by the Mediterranean systems and Indian monsoon systems from December to March and from June to August respectively. The wind with abundant of moisture from the

Arabian sea reaches the region during this season and causes rainfall over the central part. Two prominent rain seasons (June to August and March and April) have been observed in the case of the southern region similar to the central part of the country. The rainfall during June to August comes from the Indian southwest monsoon as observed in the central part.

The tele-connection of ENSO with Oman rainfall has been explored and found that zonal wind anomaly over the east equatorial Pacific has a good correlation with the zonal wind anomaly itself over Oman region. This wind at 850 hPa shows good agreement with the rainfall in Oman. Therefore the zonal wind anomaly over the east equatorial Pacific ocean has a positive correlation with the rainfall over Oman region. It has been observed from the EOF analysis that 32% of the total variance is controlled by the east equatorial Pacific ocean. It has been observed form the FFT analysis that the periodicity of this variability is about 4-7 years and therefore it could be concluded that the El Nino has a positive correlation with the rainfall over Oman region with above normal rainfall was observed in the country during El Nino years.

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