CHAPTER 1

INTRODUCTION

1.1 GENERAL

Although people have lived in the region since time immemorial, the United Arab Emirates (UAE) is a new country. Its existence as a federation of emirates dates back to 1971. The people of the region were mostly nomadic with small fishing and pearl diving villages at the coast and small settlements, at oases inland, provided the only forms of permanent residence. The discovery of oil and its exploitation changed this (United Arab Emirates Yearbook, 2001).

Today the UAE is a developed country with all the trappings and infrastructure of a modern country. With development comes the need to know the weather for aviation, oilrig operation, fishing and other day-to-day activities. Historically, it has had little time to accumulate a scientific heritage. Meteorologically, this is evident by the dearth of detailed forecasting knowledge and material for forecasters in the UAE. What little information is available is fragmented and often anecdotal. This lack of published information became apparent when the author (de Villiers 2003) did background research on wind towers in the UAE. Knowledge of the area had to be gleaned from books which discuss the climate and weather in generalised form by authors such as Taha, Harb, Nagib, and Tantawy (1981) and Martyn (1992).

Taha, et al (1981), although describing the climate of the countries in the Arabian Peninsula, do not even mention the UAE although the country was formed in 1971. They broadly mention the prevailing northerly to north-westerly winds in summer due to the monsoon trough over north-western India to the Arabian Gulf and winds from “different directions” in non-summer months. Apart from drawing attention to the hot desert climate in the Arabian Peninsula they also mention the importance of passing troughs in the upper westerlies in winter and spring as an important source of rain as well as thundershowers. This is discussed in more detail by Membery (1997) when such a system passed over the Middle East during December 1995. It brought persistent and heavy rain to the UAE and the Musandam Peninsula, as well as heavy snow on the Zagros Mountains in Iran. Membery (1985) also draws attention to the occasional influence of tropical depressions when, in a case study, he cites such a system that moved from the Arabian Sea across Oman and the UAE to the Rub Al Khali (Empty Quarter) of eastern Saudi Arabia.

Martyn (1992) discussing the “Levant and the Arabian Peninsula” also uses a broad brush to cover the weather in the region. He also makes mention of passing depressions in winter months as being a source of precipitation. But he is more specific in mentioning the persistent summer wind over the Gulf Sea known locally as the Shamal (meaning northerly) and its cooler more north-easterly winter Nashi wind. Once again, there is no specific mention of the UAE. More recently there has been published work by Membery (1983) about the Shamal wind at the Gulf State of Bahrain and by Rao, et al (2001 and 2003) in nearby Qatar. Further to the north Safar (1985) published a booklet on dust and dust storms in Kuwait.

More UAE specific studies by Zhu and Atkinson (2004), Eager et al (2005) and Eager and Raman (2005) draw attention to the high annual consistency of the sea and land breeze across the UAE coast. Of a more maritime nature, Jackson (1987) discusses the occurrence of waterspouts known to occur within sight of the UAE coast and Davey (1987) documents the destruction caused to the Jebel Ali Sailing Club by a tornado waterspout and Western (1997) gives a synopsis of forecasting for offshore sport fishing. As is to be expected in such an arid area considerable weather modification research, supported by a lengthy cloud physics study has been carried out to investigate the feasibility of hygroscopic seeding to enhance the precipitation in the hyper-arid zone of the Arabian Peninsula. This is joint venture between the UAE, Sultanate of Oman and the National Center for Atmospheric Research in Boulder, Colorado, USA (Breed et al 2005, Breed et al 2002, Jensen et al 2005 and Bruintjes and Yates 2003). Consideration has also been given to the effect of sodium chloride aerosols due to the proximity of the Gulf Sea (Salazar et al 2003) and ground water recharge (Yates et al 2005). Most recently, Al-Brashdi (2007), after a 9 day study of convective activity over the Western Hajar Mountains in the Sultanate of Oman, proposed an improved technique for forecasting the occurrence of seedable clouds, the aim being to improve precipitation in the area. To do this he suggested the Oman Convection Index (OCI), an improved locally effective derivative of the K-index (KI).

In 1996 the United Arab Emirates Department of Meteorology published a statistical book on the "U.A.E. Climate." As the title suggests, this concentrates on climatic tables of temperature, wind speed, cloudiness, humidity and precipitation. It is pointed out that in the summer months the monsoon dominates the area. Rising air over the Assam area of India, results in a subsiding column over the Arabian Gulf. So, although there is a "shallow semi-permanent trough of low pressure" over the region, the subsidence sub-tropical anticyclone above it prevents cloud growth and therefore rainfall. As a result of this and the mostly light northerly winds off the Gulf Sea, the UAE is very hot and very humid during the summer months. Occasionally hot and dry winds blow from the south and disrupt the more persistent hot and humid Shamal from the north off the Gulf Sea. These are more likely during March and April and are "accompanied by sand storms." During the winter months the UAE comes under the influence of the Asian anticyclone with occasional cold and dry surges from the east. And, as mentioned above, occasional rain bearing troughs pass through.

All this is very interesting, but to the author's knowledge no researched and/or published aviation meteorological literature exists for Abu Dhabi International Airport (ADIA) and the UAE. Therefore, a greater understanding of the mechanisms of local significant weather processes in the UAE and a methodology for forecasting them, combined at one source, is important. An attempt is made to address this lack of knowledge in the various chapters that follow and deal specifically with weather phenomena such as fog, dust and dust storms, thunderstorms, land and sea breezes, the Shamal and the Nashi winds.

1.2 SCOPE OF THE STUDY

Meteorological aviation activity in the Emirates is primarily confined to providing a service for helicopter operations to the offshore oilrigs and onshore drilling sites, as well as the more critical take-off and landing information at the international airports for commercial airlines. General aviation activity is very limited. Internationally, the normal spectrum of information is provided to commercial airlines operating to and from the UAE. The World Area Forecast Service at Exeter in the United Kingdom provides most of the en-route information for international flights. This information is merely relayed to the airlines by the meteorological offices at the UAE international airports. Consequently, this study is confined to those meteorological phenomena peculiar to, and most important to, aviation in the region. Examples are fog, dust storms and dust, thunderstorms, rain bearing troughs, the Shamal (northerly wind) and (briefly) the Nashi wind, as well as land and sea breezes. In particular this study relates to ADIA, for which the observation data and numerical weather prediction (NWP) model data were obtained. By way of an introduction to weather in the region, the general atmospheric circulation and the seasonal sequence of the weather in the UAE is also presented. Although it gets very hot at ADIA, with summer maximum temperatures routinely reaching 45°C to 49°C (U.A.E. Climate, 1996), air temperature has not been included in this study. High temperatures decrease air density, increase aircraft take-off and landing speeds and considerably increase the runway length required (UKMO, 1994). However, at ADIA, and the UAE in general, this is not a problem, because the runways are suitably long and near to sea level.

1.3 METHODOLOGY

The lack of previous research dedicated to the UAE has meant that a method similar to that used by Taljaard (1985) in the ground breaking study of South African upper air cut-off lows has had to be adopted. This method relies on case studies and statistical analyses of limited data records when and where available. Taljaard (1994-1996) also relied on case studies in his 5 part series on South African weather phenomena, atmospheric circulation systems and synoptic climatology.

Observation data, both surface and upper air, at Abu Dhabi International Airport (ADIA) for the 20 years from 1983 to 2002 were analysed to identify significant weather phenomena and their associated weather systems as well as for statistical purposes. Included in this was the use, when and where possible, of radar and satellite imagery and when relevant, surface observation data at Al Ain were also used.

The most interesting and representative weather phenomena events from 2002 to 2004 were identified. Examples were then selected for analysis and presented in the form of case studies. Where the case studies were not fully representative they were supplemented with brief references to other events and statistical evidence.

Post-processed numerical weather prediction Eta model data, was also used to identify, analyse and present case studies as examples of situations that are likely to arise. Eta model versions used are the World Aviation Forecast System Aviation model (WAFS AVN) 1° horizontal resolution version, now called the Global Forecast Service (GFS) model, and the finer resolution 22 kilometres, 20 vertical levels version. Post-processing processes available were PCGRIDDS for the WAFS AVN/GFS 1˚ model and GRADS for the finer resolution model. These are powerful analysis systems facilitating analysis and research of the thermo-dynamical and circulation features of weather systems.

PCGRIDDS macros were developed by the author during 2002 to 2003 for operational use by the aviation forecasters in the ADIA Meteorological Office. These macros were also used in obtaining numerous charts that are used in this thesis. These can be made available on request.

After analyses and the presentation of case studies for each of the weather phenomena, a forecast methodology, or in aviation parlance a forecast checklist, is presented.

Note: Standard International (SI) metric units are used. However, the aviation industry still uses some non-metric units and will use them for a long time to come, as they still construct aircraft with altimeters in feet and air speed indicators in knots. It therefore makes sense to use these units, that is, feet (ft) for altitude instead of metres (m), or kilometres (km) and knots for the measurement of speed instead of metres per second (ms-1). The SI abbreviation for knot is kn, but in aviation and the International Civil Aviation Organization (ICAO) abbreviation is KT (ICAO 2004, WMO 1995 and UKMO 1994). Having said this, in order to conform as far as possible to SI practice, metres have been used instead of feet and where pertinent, measurements in feet have been provided in brackets. The measurement of wind speed is more complicated. All original operational observation and model data graphs and charts are produced in knots. To have changed these to metres per second would have been an impossible task. Therefore, in this thesis, knot(s), or KT, have been used. A rough conversion factor for knots to ms^{-1} is to divide by 2 and for feet to metres divide by 3. For the fastidious, conversion tables for these two units of measurement to metres (m), or metres per second (ms-1) have been provided in Appendix B.

1.4 OBJECTIVES OF THE RESEACH

The objectives of the research detailed in this thesis are:

The primary objective is the identification of significant weather phenomena and their associated regional weather systems that affect aviation in the UAE and ADIA in particular. Describe the forcing mechanisms responsible for their development and derive forecasting rules and principles applicable to these systems.

This has been achieved by the presentation of statistical analyses, case studies, a summary of the weather conditions to be expected and finally a forecast checklist to work through before issuing a forecast with respect to the relevant weather phenomena is suggested.

A secondary objective is to provide background information of the general seasonal climate sequence in the UAE.

This has been achieved by means of a literature study of the dominating weather systems and the presentation of surface and upper air mean circulation charts.

1.5 ORGANISATION OF THE DOCUMENT

General information about the UAE, such as historical and political background, geographical position, topography and airports is provided in chapter 2.

Chapter 3 outlines the major weather producing circulatory systems over the region through the use of mean circulation charts, January circulation, April, July and October, wind divergence at sea level, 850 hPa, 700 hPa, 500 hPa, 300 hPa and 200 hPa. Brief mention is also made of the effect of 200 hPa wind divergence, water vapour flux and sea temperature on the weather. A summary is provided.

After discussing fog dynamics, chapter 4 investigates the weather conditions under which fog occurs at ADIA. Fog statistics, such as when, why and how often it occurs, have been gathered. Meteorological phenomena that were observed during the 551 fog events at AIDIA, for the 22 years from 1982 to 2003, were collected and comprise the statistical data base. The selected 31 fog events, during 2002 to 2003, were researched, in detail. Data from these events include the analysis of 56 atmospheric soundings taken on the afternoons prior to, as well as on the morning of, the fog. During the two years of 2002 and 2003, 20 events, when fog was not predicted and in fact did not occur were also analysed for comparative purposes. The research also investigated the validity of several fog forecasting rules (of thumb) in general use prior to this research. The research results are summarised and a fog forecast methodology (or checklist) is presented.

The synoptic scale weather conditions that occur during the Shamal wind, at ADIA, are described in chapter 5. UAE Shamal statistics for the years 1992 to 2003 have been gathered. Due to the number of helicopter operations from the airport to the offshore oil rigs, the effect of the Shamal on the sea state in the Gulf Sea is explored. An example event is presented and discussed. A summary is presented and a forecast methodology is proposed.

Chapter 6 deals with dust storms. Dust storm dynamics are discussed, followed by a statistical analysis of their occurrence at ADIA from 1994 to 2003, including all events when the visibility was reduced to 5000 metres, or less. The dust storm case studies presented includes one event caused by the so called Nashi wind. Chapter 6 concludes with a summary and a forecast methodology.

In chapter 7 the dynamics, frequency of occurrence and general characteristics of UAE land and sea breezes are discussed. Their effect further into the desert, reaching Al Ain, the Abu Dhabi Emirates second international airport, is described. Case studies, including a brief discussion on inland anabatic and katabatic wind effects, are briefly investigated. The chapter concludes with the customary summary and a forecast methodology.

Winter rain bearing trough systems with imbedded thunderstorms as well as summer thunderstorms are detailed in chapter 8. This chapter briefly examines the rare tropical depressions that reach the UAE and present a summary and forecast methodology.

Chapter 9 deals with the conclusions and identifies topics for further research.

Appendix A provides definitions of the meteorological terms that frequently occur in the text.

Conversions factors: Knots to metres per second, feet to metres as well as the meaning of the term microbar are provided in appendix B.

Finally, appendix C explains the two fog point calculation methods mentioned in chapter 4. (UKMO Source Book to the Forecaster's Reference Book (1997))

CHAPTER 2

THE UNITED ARAB EMIRATES

2.1 GENERAL

The United Arab Emirates (UAE), often simply referred to as the Emirates, is a federation of seven Emirates, formed in 1971 when the British withdrew from the region. The seven Emirates are; Abu Dhabi, Ajman, Dubai, Fujairah, Ras al-Khaimah, Sharjah, and Um al-Qaiwain. Collectively they form and area of about 77,700 square kilometres (UAE Climate, 1996). Obviously it is not a big country, but very wealthy due to oil deposits offshore and on land in Abu Dhabi. Abu Dhabi is the largest and most wealthy Emirate, while Ajman and Um Al Qaiwain are the smallest (Abu Dhabi Explorer, 2001, Callan and Robison, 2000). The capital, Abu Dhabi (the city) is situated on one of the larger islands and is reached by crossing one of two bridges from the mainland. What is often confusing to visitors is the fact that the capital city, or town, of each emirate has the same name as the emirate.

2.2 POSITION

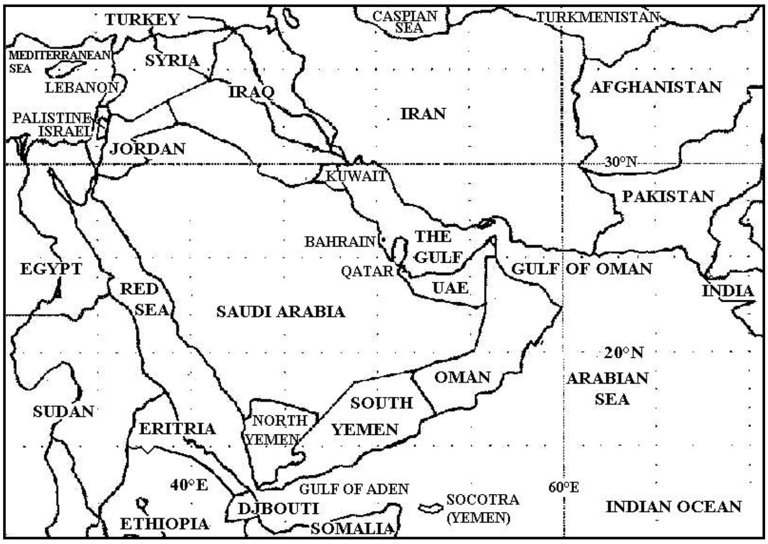

Figure 2.1. Political map of the Middle East.

The Emirates lie in the arid tropical zone extending across North Africa and into the Middle East. It is situated south-east of the Arabian Gulf (or simply The Gulf, or the Gulf Sea) on the Arabian Peninsula (figure 2.1) between 23°N to 25°N and 52°E to 57°E and extends to the east coast at the Gulf of Oman where the Fujairah Emirate is situated (figure 2.2). It is incorrect to refer to the Persian Gulf. If you are in the region it is wisest to refer to The Gulf, or the Gulf Sea. The Tropic of Cancer passes through the desert in the southern part of the country. To the south-east is the Sultanate of Oman, while to the south and west is Saudi Arabia. Qatar in the west, on its own peninsula is close enough to be a neighbour. The extreme north-eastern part of the land, at the Strait of Hormuz, is known as the Musandam Peninsula, which belongs to the Sultanate of Oman (United Arab Emirates Yearbook, 2001). There is also another enclave of the Sultanate of Oman in the Fujairah Emirate and an enclave of the Sharjah Emirate and Dubai as well.

2.3 TOPOGRAPHY

Over 90% of the UAE consists of sandy desert lowland with an elevation below 300 metres above mean sea level (MSL). From the low lying coastal plain, with large dry salt pans and isolated hills up to 40 metres above MSL, the land rises gently inland and quickly changes to sand dunes which are up 250 metres above sea level in the south. This southern portion of the UAE forms the beginning of what is known as the Rub al Khali (Empty Quarter) and extends into adjacent Saudi Arabia. Along the coast, the inshore area of the Gulf is very shallow, with literally hundreds of islands and coral reefs (Abu Dhabi Explorer, 2001, UAE Climate 1996).

In the extreme east, oriented from north to south is a mountain range that rises up to 1500 metres MSL. These are the Hajar (Rocky) Mountains (also known as the Western Hajar Mountains), but are known as the Musandam Mountains in the north. They extend to the south-east into the Sultanate of Oman, where they are known as the Eastern Hajar Mountains. The mountains are higher in Oman, the highest peak being Jabal al Sham (Mountain of the Sun) at 3075 metres (figure 2.2). Extending into the mountains and criss-crossing them are networks of wadis, which are valleys, usually very steep and narrow and which are prone to flash flooding when there is rain on the mountains (Abu Dhabi Explorer 2001, United Arab Emirates Yearbook 2001).

Figure 2.2. Map of the United Arab Emirates. The Hajar Mountains extend from the Musandam Peninsula at the Strait of Hormuz, south and south-eastward into Oman. The Empty Quarter is the area to the south and south-west of the U.A.E.

2.4 AIRPORTS

Considering the small size of the UAE, it has a high proportion of International Airports, but due to the small size of the UAE, nearly all flights to and from the airports are cross-border international flights.

The airports are listed below. The year in brackets is the date from which climate records are available at the modern airports. The metre readings are the altitudes of the airport's reference level above mean sea level.

Abu Dhabi International Airport (1982)	24° 26'N	54° 39'E	27 metres
Al Ain International Airport (1994)	24° 15'N	55° 36'E	265 metres
Dubai International Airport (1974)	25° 15'N	55° 20'E	8 metres
Fujairah International Airport	25° 06'N	56° 20'E	28 metres
Ras Al Khaimah International Airport (1977)	25° 37'N	55° 56'E	31 metres
Sharjah International Airport (1977)	25° 20'N	55° 31'E	33 metres

The first international airport at Abu Dhabi was on the island at Al Bateen, but had to give way to development on the island and it is now situated slightly inland of the coast, but about 32 kilometres from the city centre (figure 2.3). Climate records at the old Abu Dhabi Al Bateen airport date back to 1971 (figure 2.3), but were not used in the research.

Most of the present airports are virtually on the Gulf coast. Fujairah airport is on the narrow Gulf of Oman coast while Al Ain, which about 150 kilometres inland from Abu Dhabi differs from them all in that it has a continental desert climate. Al Ain is also close to and west of the Hajar Mountains, while Fujairah airport is on the eastern side of these mountains.

Airports have existed in the UAE from the late 1920's and early 1930's when they were constructed for use by British Imperial Airways flights from the United Kingdom to India and later on to Australia (Kay 1995). The oldest probably being Sharjah airport that was originally situated where the city centre is today. The earliest record of a landing strip at Abu

Figure 2.3. Location of Abu Dhabi International Airport. The airport is bottom, right of the picture, showing the two 4,100 metres (13,452 feet), runways oriented 310°/130° (ADAC 2009a). The island city of Abu Dhabi is to the left of the picture and the open sea toward the left and upper left off the picture. The old international airport (Al Bateen) is visible bottom/centre of the picture on the north-east corner of the Abu Dhabi Island (Photograph courtesy of Google–Imagery 2009 TerraMatics).

Dhabi dates back to 1935 when, after protracted negotiations, Sheikh Shaikhbut bin Sultan agreed to allow the British Royal Air Force (RAF) to build an emergency landing strip. It had to be 4 miles (6.4 kilometres) from the town and RAF personnel were not allowed in the town. The British paid an initial lump sum of 5000 Rupees and thereafter 400 Rupees per month rental (Tuson 1990). The airports are still not only important stopover points to the east and west, but also to other points of the compass.

To conclude, a comparative idea of the traffic through Abu Dhabi airport, both in terms of passenger and cargo, with other airports in the U.A.E. and others in the Middle East, is given in the list below, the statistics being for the 12 months up to September 2004 versus 2003 (Aviation Business, January 2005). ADIA is the second busiest in the U.A.E. and a close fifth to Kuwait in the Middle East.

	Passengers	Change (%)	Cargo (tonnes)	Change (%)
Abu Dhabi	5 032 390	+23.4	157 567	+13.7
Dubai	21 121 009	+21.6	1 123 467	+22.0
Fujairah	57 665	-42.6	28 703	-19.4
Ras Al Khaimah	150 468	- 8.8	8 198	+ 4.4
Sharjah	1 581 081	+34.0	472 776	+ 2.5
Amman (Jordan)	2 963 788	+26.8	98 097	+24.6
Bahrain	4 975 187	+17.9	276 243	+23.9
Beirut (Lebanon)	3 301 140	+19.7	66 100	- 1.1
Jeddah (Saudi Arabia)	12 304 650	+ 8.9	219 405	+ 7.5
Kuwait	5 051 076	+20.6	161 632	+14.9
Muscat (Oman)	3 503 970	+28.3	64 050	+36.1
Riyadh (Saudi Arabia)	10 185 554	+ 7.7	188 681	+11.9

CHAPTER 3

GENERAL ATMOSPHERIC CIRCULATION IN THE ARABIAN PENINSULA

3.1 INTRODUCTION

The Arabian Peninsula is approximately between 35°E to 60°E and 12°N to 30°N. It is bounded by the Gulf Sea and the Gulf of Oman in the east, the Arabian Sea in the south, the Red Sea in the west and to the north by Jordan, Iraq and Kuwait. It consists of the countries of the Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates and Yemen.

Topographically, the Arabian Peninsula is an inhospitable and vast sandy plateau with no permanent rivers, or streams. It is bordered by mountains in the west along the Red Sea and in the south and east along the Arabian Sea

This chapter outlines the major weather producing circulatory systems over the region.

3.2 DOMINATING WEATHER SYSTEMS

The dominating pressure systems are the winter cold Siberian anticyclone over central Asia, the summer monsoon Asiatic and India low (Glen 1954) and secondary depressions that migrate eastward from the Mediterranean (Kendrew 1961).

In winter, polar continental air masses form over central Asia. Characteristically the air mass has very low temperatures in a shallow surface layer with a marked inversion at about 1500 metres (5000 feet). When this stable air is advected over a warm moist surface, such as the Gulf, heating from below destroys the inversion and moisture absorption results in widespread cloudiness (Taha, Harb, Nagib and Tantawy 1981). Satellite imagery shows that frontal cloud patterns frequently extend from middle latitudes to the southern-most edge of the Arabian Peninsula, particularly in non-summer months. Their rainfall potential decreases from north to south and west to east (Taha, et al 1981). Maritime polar air follows transitory Atlantic low pressure systems across Europe and by the time the lows reach the Emirates they are considerably modified, but are still moister than the polar continental air mentioned above.

In summer the area is a meeting place of converging air masses forming a type of inter-tropical front. To the north the air mass, of moderate temperature and moisture content circulates in the sub-tropical anticyclone, while to the south very hot and dry air circulates in the monsoon trough. Maritime tropical air that loses its moisture over northern India infrequently arrives over the region as a very hot and dry air mass. Furthermore, the nearby water surfaces of the Gulf Sea, the Gulf of Oman and the Arabian Sea act as sources of moisture and heat (Taha, et al 1981).

In the pre-monsoon spring period of May and June and the post-monsoon autumn period of October and November, the Arabian Sea is invaded by tropical disturbances, some of which may intensify into tropical storms, but development into a full blown tropical cyclone is a rare event.

The majority of tropical cyclones occur in the post-monsoon period, but their influence is limited to the southern part of the Arabian Peninsula. The most frequent disturbances are easterly troughs, or easterly waves, moving from east to west (Taha, et al 1981) with the zone of convergence and convective activity on the eastern, or leading edge, of the trough axis.

During late spring to early autumn very dry and hot continental tropical air from the Sahara reaches the region (Taha, et al 1981).

3.3 MEAN CIRCULATION CHARTS

The charts used in the following sections on the seasonal flow, were obtained from the South African Weather Service (SAWS) publication "Charts of the mean circulation over the monsoon region of the world" (Triegaardt and Landman 1992). The mean charts were based on the 12h00 UTC initialised analyses of the European Centre for Medium Range Weather Forecasts (ECMWF) for the 8 years from 1980 to 1987.

In using these charts it must be borne in mind that there are limitations to their accuracy. Due to operational constraints and a cut-off time for inclusion of incoming observations, it is estimated that about 30% of a total observations are usually not available. Two other limitations are due to the fact that modifications are made to prediction models and data assimilation systems. While these changes improve the quality of the analyses and prognosis of the model, it does mean that the analyses produced are not homogeneous. For example, more recent modifications of the ECMWF model, after 1985, produce better enhancement of the Hadley circulation. The advantage is that this sort of analysis can generate information at a finer scale than a conventional observing system and it can generate data in data void area (Triegaardt and Landman 1992).

Note, due to the difficulty of pressure reduction to sea level over the continents isobars are confined to the oceans and for clarity the UAE appears as a black silhouette in the figures.

3.4 JANUARY CIRCULATION

The sea level and 850 hPa charts show that the circulation over the Asian continent is dominated by an anticyclone with a ridge, or separate cell, of the Asian anticyclone over Arabia (figures 3.1 and 3.2, respectively).

Latitudinal movement of this anticyclonic cell over Arabia and the passage of mid-latitude disturbances result in alternating southerly to south-easterly winds and Shamal winds. Rao, et al (2001) define the Shamal as a seasonal northerly to north-westerly wind with higher than normal strength (greater than 17 knots) blowing for three, or more, hours in a day. In winter they occur in the flow of colder air from the north in the wake of passing mid-latitude lows and the ensuing strong pressure rise ahead of the following anticyclone.

The southern part of the anticyclone is associated with an easterly flow over the Arabian Sea and northern Indian Ocean that forms the easterly trades, or the winter north-east monsoon, which brings rain to East Africa in the vicinity of the equator. The north-easterly flow over the Arabian Sea crosses the equator into the Indian Ocean, where it becomes westerly and converges with southern hemisphere air in the low pressure belt at the Inter-tropical Convergence Zone, or near-

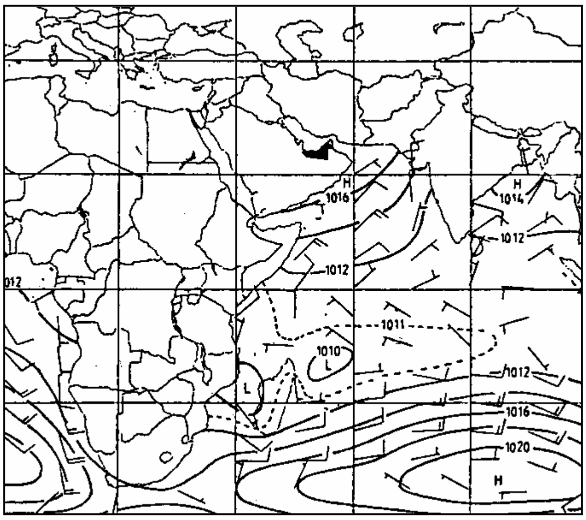

Figure 3.1. January mean sea level pressure (hPa) circulation. Mean wind velocity in knots (each full barb = ten knots = $5 ms^{-1}$).

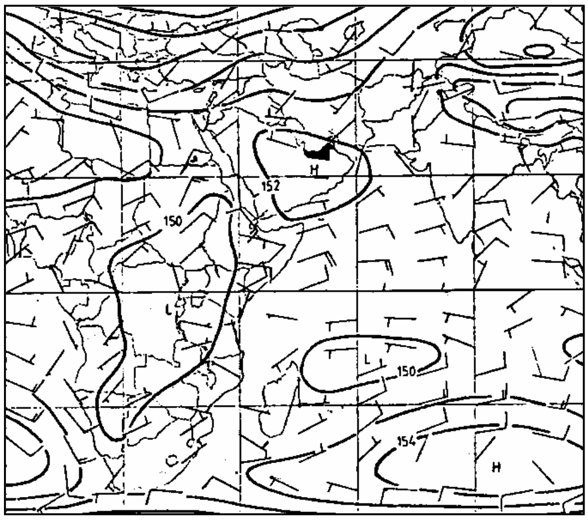

Figure 3.2. January mean 850 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = $5 ms^{-1}$).

equatorial trough (figures 3.1 and 3.2).

At 700 and 500 hPa (figures 3.3 and 3.4) there is a change to a westerly flow and strengthening of the wind with height. A significant feature of the wind at 300 and 200 hPa (figures 3.5 and 3.6) is the sub-tropical westerly jet stream that reaches maximum strength at 200 hPa. It dominates the middle and lower latitudes in winter and is known for its steadiness of wind direction and geographical location. At times its steadiness and location is affected by the passing of westerly troughs from west to east when 5° to 10° meridian oscillations of the jet stream occur (Taha, et al 1981).

Notice the trans-equatorial flow of air over Africa and the Indian Ocean from the southern hemisphere to the northern hemisphere at 200 hPa (figure 3.6). This is the reverse flow of air seen at the surface and at 850 hPa in figures 3.1 and 3.2 and forms part of the Hadley circulation (Triegaardt and Landman 1992).

The tropospheric wind divergence at the sub-tropical jet stream in association with upper air troughs, along with the lower wind convergence associated with passing low pressure cells, are important winter weather producers. These marked synoptic systems are the main producers of cloudy weather and rain in the area. Precipitation is highest in the north and decreases from west to east, except where the topographic effect of the high mountains in the south-west again increases rainfall. The polar jet stream, in association with the passage of mid latitude depressions, frequently invades the area and amalgamates with the sub-tropical jet stream. Extensive middle layer clouds with embedded isolated thunderstorms often precede the trough (Taha, et al 1981). However, the often prevailing dry conditions and consequent high cloud base mean that not much rain reaches the surface, although strong wind gusts and sandstorms do occur (Tantawy 1961).

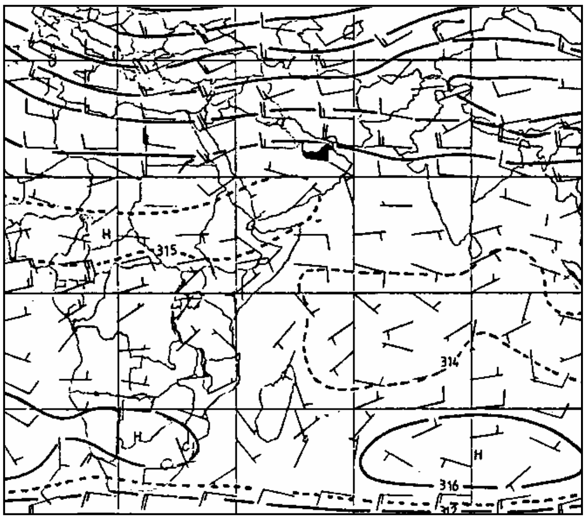

Figure 3.3. January mean 700 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

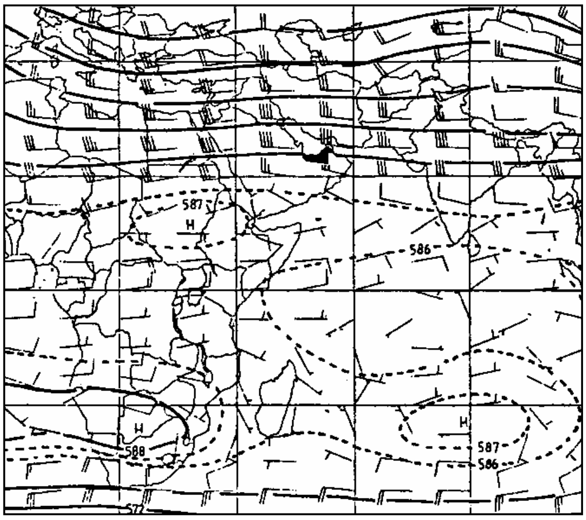

Figure 3.4. January mean 500 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

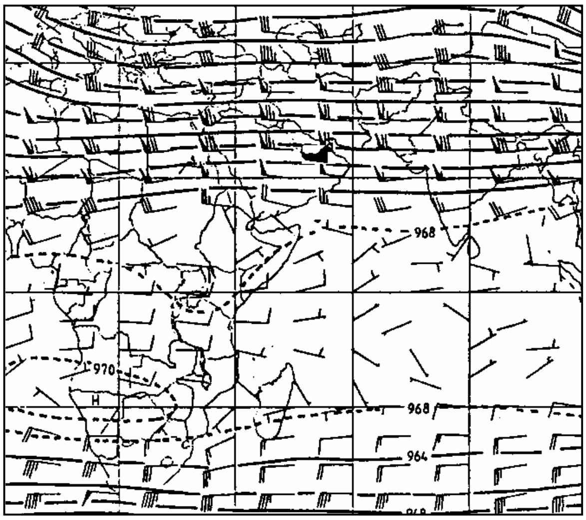

Figure 3.5. January mean 300 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

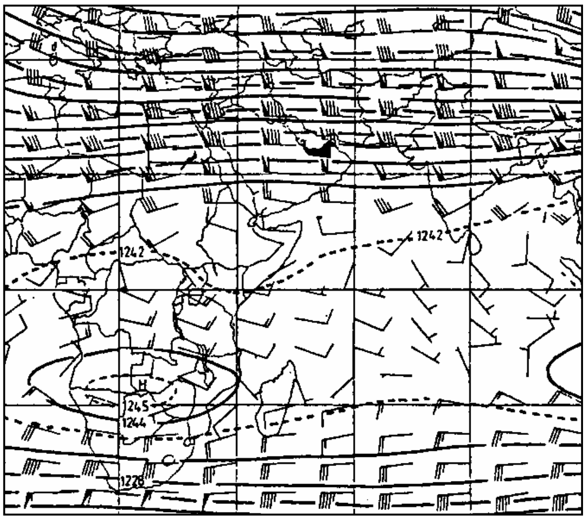

Figure 3.6. January mean 200 hPa circulation. Mean wind velocity in knot (each full barb = ten knots = 5ms^{-1}).

3.5 APRIL CIRCULATION

In this transition period from winter to summer circulation, the surface (figure 3.7) and 850 hPa (figure 3.8) anticyclone of January, over Arabia and the Arabian Sea, is already less intense. Mean sea level pressures show a fall from 1016 hPa and higher to about 1010 hPa in April. The north-east monsoon over the northern Indian Ocean becomes weaker and the flow more confused. The same applies to the westerly flow at 850 hPa to the north where low pressure cells migrate from the Mediterranean to the west.

At 700 hPa (figure 3.9), 500 hPa (figure 3.10) and 300 hPa (figure 3.11) the westerly wind, over predominately the northern part of Arabia, also weakens and shows a slight shift to the north. A similar process is evident at 200 hPa (figure 3.12), while the trans-equatorial flow from the southern hemisphere is very weak, or non-existent. Although the westerly flow moves further

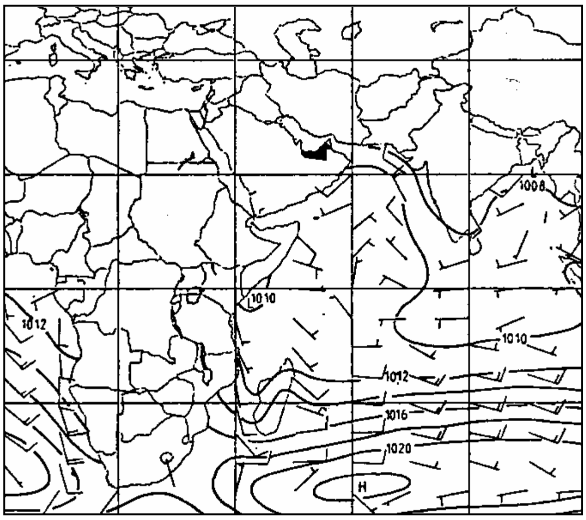

Figure 3.7. April mean sea level pressure (hPa) circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

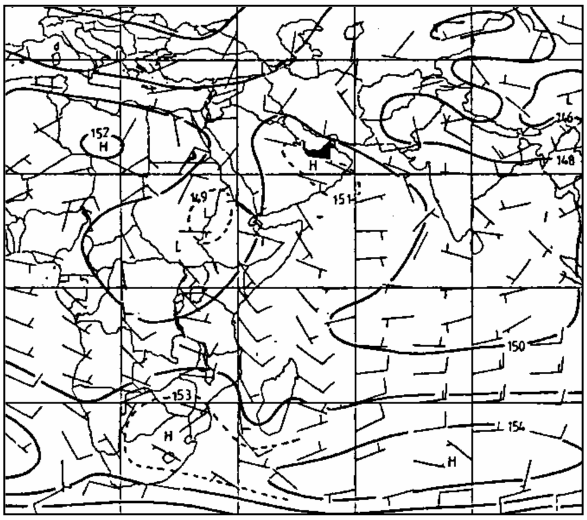

Figure 3.8. April mean 850 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

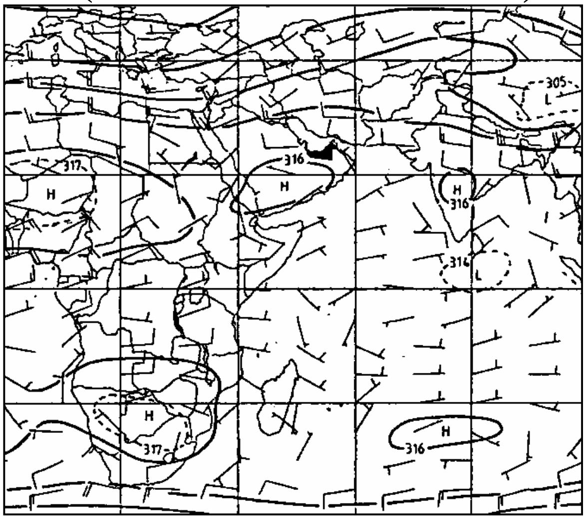

Figure 3.9. April mean 700 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

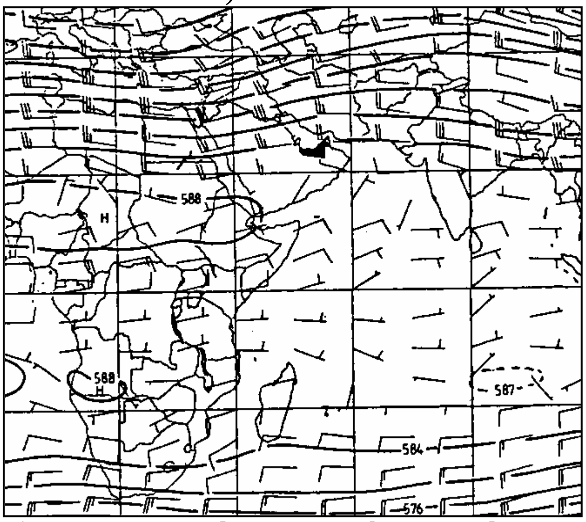

Figure 3.10 April mean 500 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

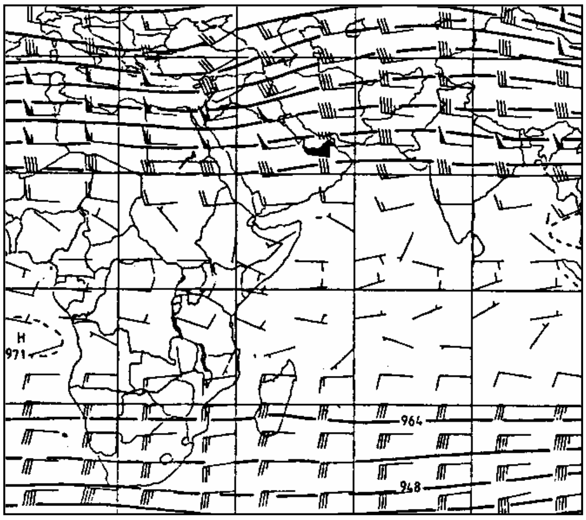

Figure 3.11. April mean 300 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

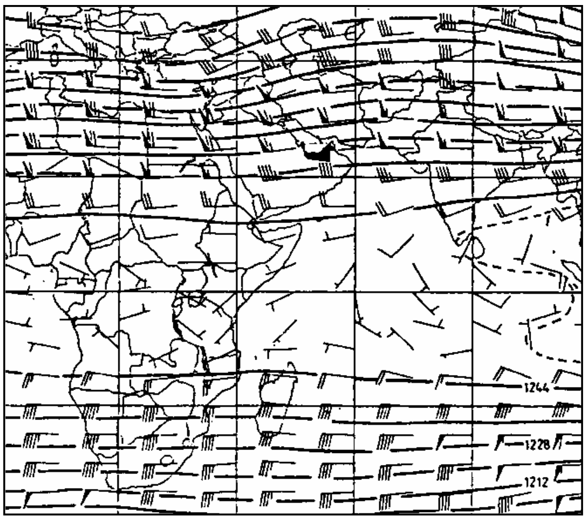

Figure 3.12. April mean 200 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

northward, upper air troughs in the westerly flow and topographic ascent over mountains remain conducive to spring rainfall.

Rao et al (2001) regard April as not being part of the winter season by virtue of the fact that mid-latitude frontal systems no longer occur over the Gulf Sea. However, Taha, et al (1981) state that winter to summer circulation change takes place in two, or three, weeks in May to June. Whatever the conclusion reached about this time of the year, an important factor is the change in low level atmospheric static stability. Rapid heating of the land increases the ambient temperature lapse rate in the lower layers and this decreases the stability (increased instability). At the same time the density of the air decreases, as does the air pressure and this has the effect of deepening desert depressions. The large day time temperature difference between the land and the still cool water surfaces results in increased local wind circulations such as land and sea breezes (Taha, et al 1981).

A characteristic of spring is the frequent passage of desert depressions that originate over north-west Africa and move eastward parallel to the coast to the northern part of the Arabian Peninsula. They are of sub-synoptic scale and usually disappear above the 700 hPa level. Ahead of these depressions southerly winds cause intense heat waves and sand storms. The sand storms can extend upward to a height of 3 kilometres (nearly 10 000 feet), while post-low moist advection from the Gulf Sea can provide enough moisture for infrequent thunderstorms (Taha, et al 1981).

3.6 JULY CIRCULATION

Comparison of the July surface circulation (figure 3.13) and at 850 hPa (figure 3.14) with the corresponding charts in January (figures 3.1 and 3.2) reveals significant differences. Over Arabia, the Arabian Sea and across to northern India, an area of low pressure has replaced the anticyclone of winter. Pressures are as low as 998 hPa occur in the vicinity of the Gulf of Oman. To the east, the low pressure area centred over the Asian continent, with a trough extension toward Arabia, is due to the summer continental heat low (Hastenrath 1985).

The near-equatorial trough is now situated much further north of its January position and there is a strong flow of air from the South Indian Ocean sub-tropical high pressure cell across the equator to the Asia low (Webster, 1983). This results in the strong south-west monsoon over the northern Indian Ocean and Arabian Sea and southern Arabia (figures 3.13 and 3.14). Over the rest of Arabia, the position of the summer low results in a consistent northerly to north-westerly wind over most of Arabia, particularly in the north. Locally this is often referred to as the forty day Shamal. The consistency of this summer wind is emphasised by Rao, et al (2001) who state that the 3 summer months of May to July account for 51% of the annual Shamal days, while only 21% the occurrences are in the 5 winter months of November to March.

At 700 hPa, 500 hPa and 300 hPa (figures 3.15, 3.16 and 3.17, respectively) the westerly wind has moved well to the north of Arabia and is considerably weaker than in January. Furthermore, although a cyclonic circulation extends up to about 700 hPa, from 500 hPa upward to 200 hPa (figures 3.16 to 3.18) a strong and well developed anticyclonic circulation replaces the westerly flow over most of northern Africa, Arabia and eastward to northern India. This anticyclonic belt results in middle troposphere subsidence and warming over northern Arabia in particular. Note the easterly flow, south of the anticyclone at 500 hPa and 300 hPa (figures 3.16 and 3.17, respectively) that drives thunderstorms from the eastern highlands of the Emirates, westward to

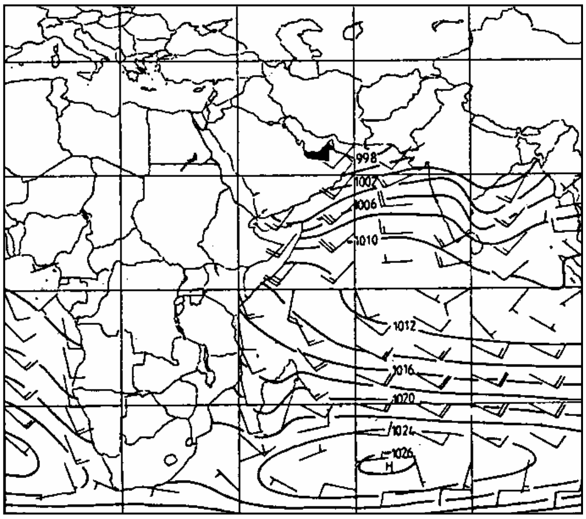

Figure 3.13. July mean sea level pressure (hPa) circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

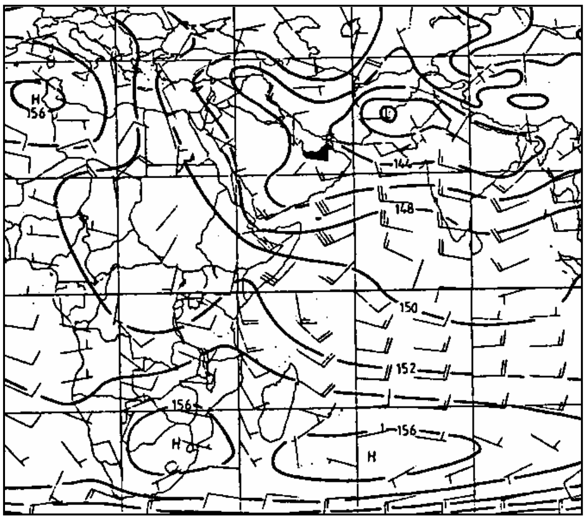

Figure 3.14. July mean 850 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

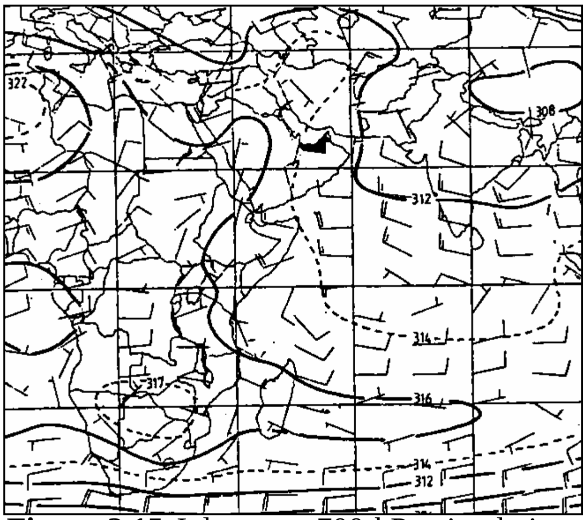

Figure 3.15 July mean 700 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

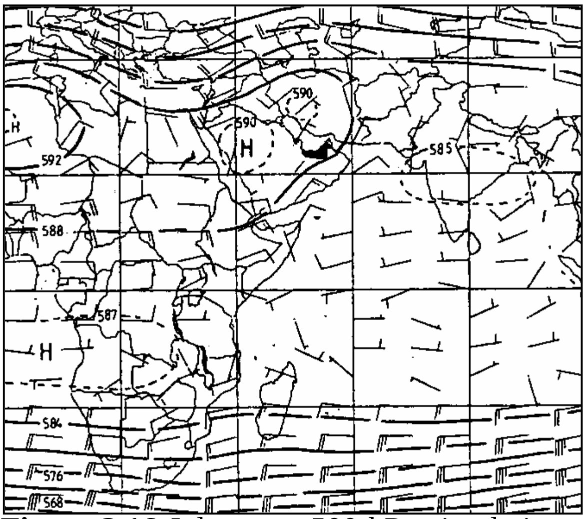

Figure 3.16 July mean 500 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

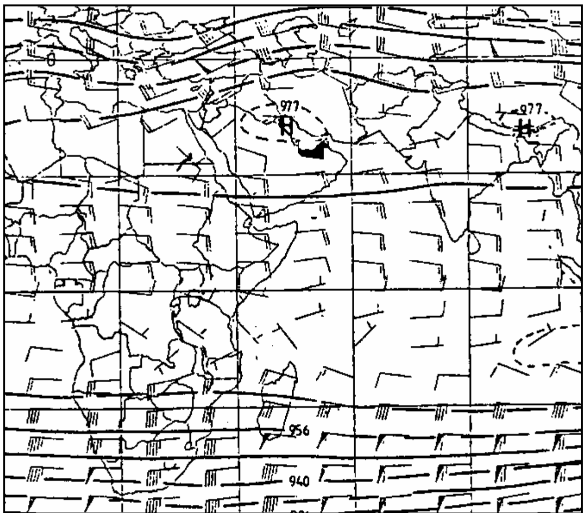

Figure 3.17 July mean 300 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

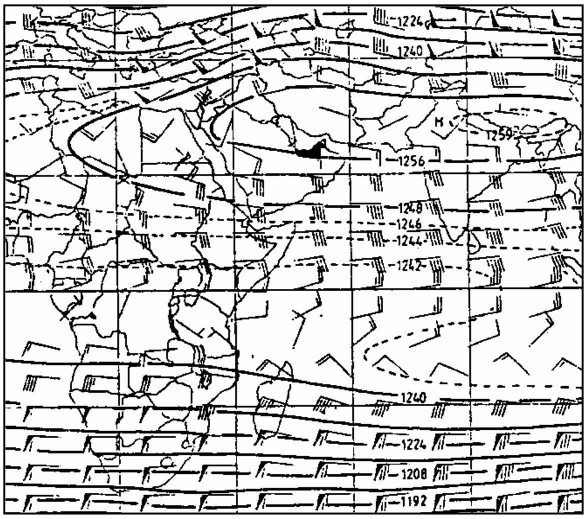

Figure 3.18 July mean 200 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

the Emirates coast in summer.

The anticyclonic circulation at 200 hPa (figure 3.18), centred over Tibet, is most prominent with a strong tropical easterly jet on the equator side of the anticyclone, which lasts from late June to early September (Hastenrath 1985). Another feature is the trans-equatorial flow from the northern hemisphere to the southern hemisphere. This is the converse of what happens in January and is a reversal of the Hadley circulation.

In summery, during January there is a surface north-east monsoon flow to the southern hemisphere with a compensating south to north air flow and westerly jet stream at 200 hPa. In July this is reversed to a surface south-west monsoon flow to the northern hemisphere with a compensating north to south flow and tropical easterly jet at 200 hPa.

3.7 OCTOBER CIRCULATION

By October continental radiation cooling causes a considerable rise in the surface pressure, which extends to the Arabian Sea and eastward to China (figure 3.19). This pressure rise is also evident in the 850 hPa geopotential heights over Arabia and Asia (figure 3.20) and it should be noted that the 850 hPa geopotential heights over Arabia are back to January values.

At 700 hPa and 500 hPa (figures 3.21 and 3.22, respectively), while the anticyclone is still prominent over Arabia, there is a distinct increase in the westerly flow to the north of Arabia when compared with the same levels in July (figures 3.15 and 3.16).

Comparing the 300 hPa and 200 hPa levels (figures 3.23 and 3.24, respectively) with those of July (figures 3.17 and 3.18) it will be noted that the westerly circulation has increased and extended southward as far as northern Arabia and the anticyclonic circulation has all but vanished.

In the same way that change in spring from a winter to summer circulation takes place over a few weeks (Rao el all 2001), the transition from summer to winter weather patterns also takes place in a short period of time, usually between October and November (Taha, et al 1981). Rapid cooling of the land in autumn causes much more stable air in the lower layer of the atmosphere and the frequency and intensity of sandstorms decreases considerably. However, the upper layer tends to become more unstable when cold air invades from the north behind westerly troughs. Occasionally the advancing trough is intense enough to cause thunderstorms and on occasion the trough may be deformed into an upper cut-off low through a process described as anticyclonic disruption (Taha, et al 1981).

3.8 WIND DIVERGENCE AT 200 HPA

Figures 3.25 to 3.28 show the mean January, April, July and October divergence fields at 200 hPa for the period 1980 to 1987. The divergence was calculated from the mean u and v components of the initialised ECMWF wind fields at the 200 hPa level (Triegaardt and Landman, 1992). A definition of divergence can be found in appendix A.

There is marked convergence (negative divergence) in January at 200 hPa (figure 3.25) between

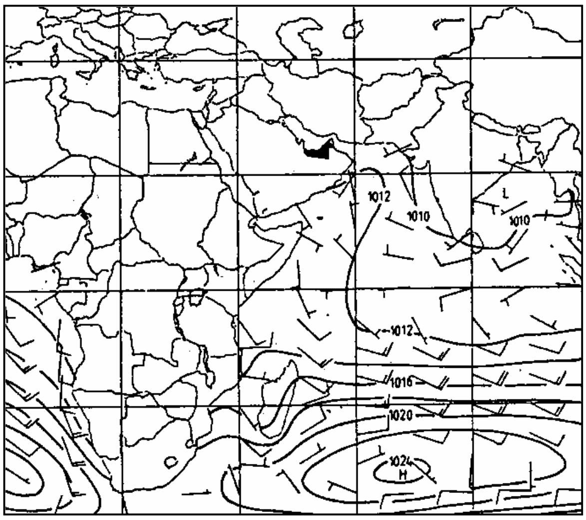

Figure 3.19. October mean sea level (hPa) circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

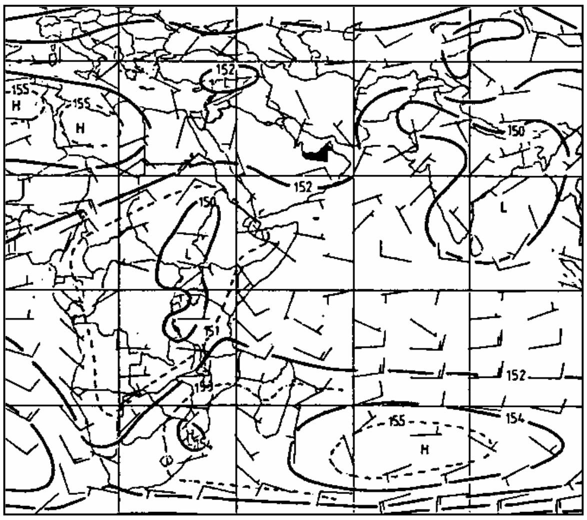

Figure 3.20. October mean 850 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

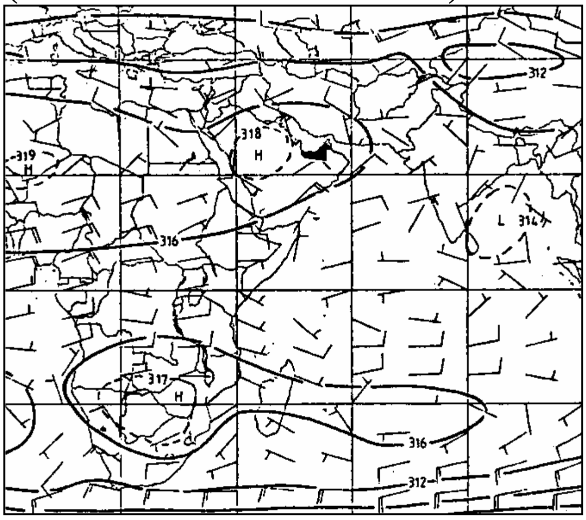

Figure 3.21. October mean 700 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

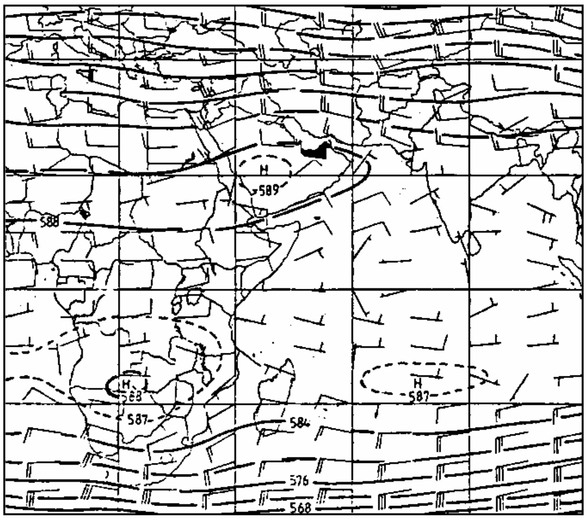

Figure 3.22. October mean 500 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

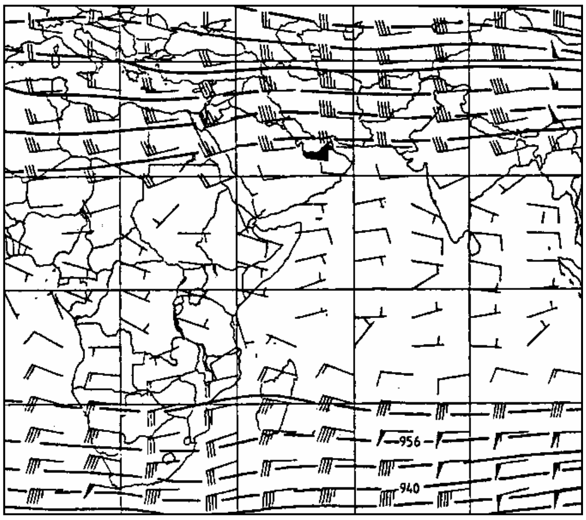

Figure 3.23. October mean 300 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

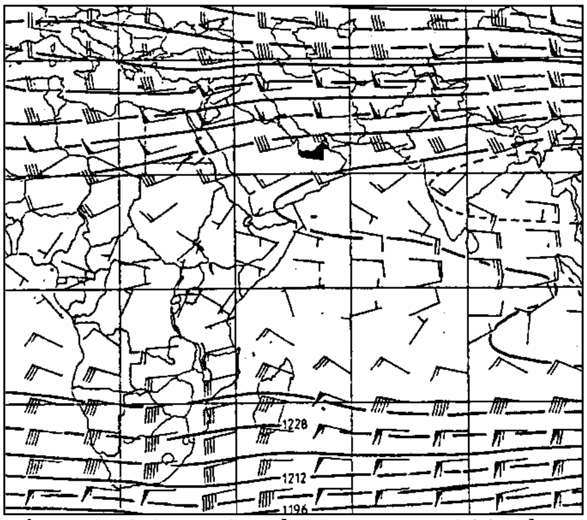

Figure 3.24. October mean 200 hPa circulation. Mean wind velocity in knots (each full barb = ten knots = 5ms^{-1}).

20° to 40° north, predominantly over the Asia continent. This implies subsidence below this level with divergence at the surface. Inspection of the surface and 850 hPa circulation in section 3.4 (figures 3.1 and 3.2) confirms the presence of high pressure at the surface and surface divergent trans-equatorial flow toward the near-equatorial surface trough in the southern hemisphere. This is indicated by the north-east monsoon over the Arabian Sea and northern Indian Ocean which becomes and easterly wind south of the equator. At 200 hPa (figure 3.6) there is a compensating northward flow.

In April the 200 hPa pattern is still very similar to January, but showing signs of weakening convergence over the Asian continent (figure 3.26). The divergence associated with the surface near-equatorial trough has also moved northward nearer to the equator.

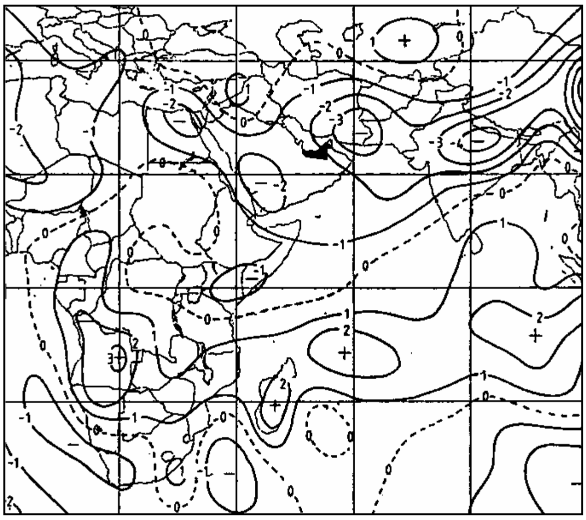

Figure 3.25. January mean 200 hPa divergence (x 10^{-6} sec^{-1}) from 1980 to 1987.

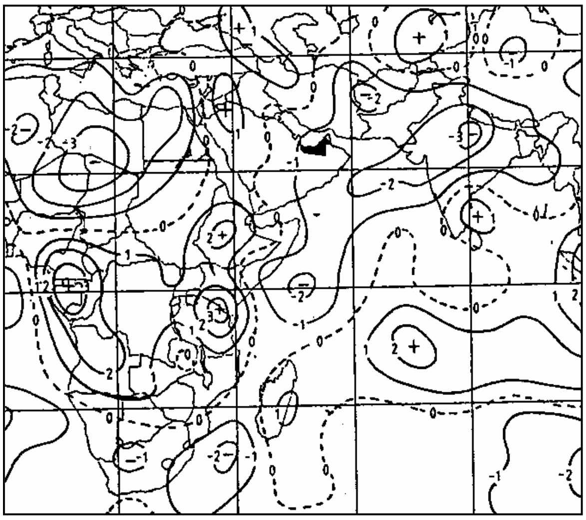

Figure 3.26. April mean 200 hPa divergence (x 10^{-6} sec^{-1}) from 1980 to 1987.

In July (figure 3.27) there is a complete reversal with positive divergence north of the equator to about 20°N, which corresponds with the steady 200 hPa easterly jet (figure 3.18). This compensates for the marked surface convergence in the belt of surface near-equatorial low pressure that now lies north of the equator (figures 3.13 and 3.14) and which is reinforced by summer surface radiation heating. By October there is already a return to marked winter convergence, similar to January, over the Asian continent and extending into Arabia (figure 3.28).

Triegaardt and Landman (1992) noted that marked positive divergence extends in an almost unbroken belt from Africa east across the Asian continent in July (figure 3.27). However, at about 40°E there is a break with neutral (and possibly negative divergence) while at about 70°E, immediately west of the India west coast, there is zone of enhanced positive divergence. The revised July 200 hPa analysis for 1985 to 1987 (not shown) indicated much stronger positive divergence in this zone. The strong divergence corresponds with a zone of heavy rainfall in excess of 500 mm in July along the Indian west coast where the surface and 850 hPa circulations in July (figures 3.13 and 3.14) show that this is an area of marked onshore flow from the south-west monsoon. This implies that the rainfall is the result of marked topographic forcing. The zone of enhanced 200 hPa divergence is therefore believed to be compensation for the marked surface convergence and strong upward vertical (positive) velocity (Triegaardt and Landman 1992). To take this one step further, it is postulated that the zone of neutral, or possibly

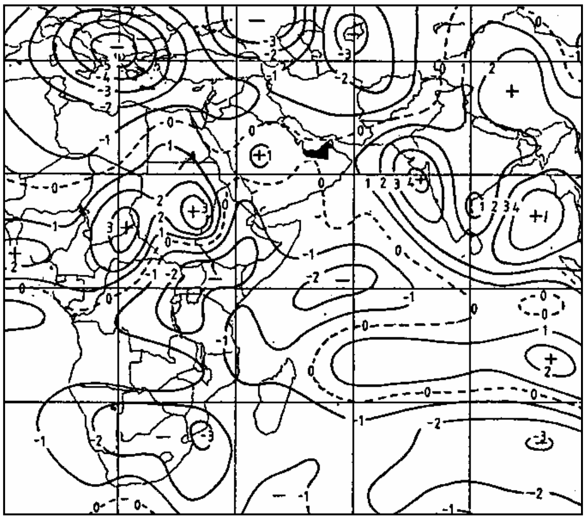

Figure 3.27. July mean 200 hPa divergence (x 10^{-6} sec^{-1}) from 1980 to 1987.

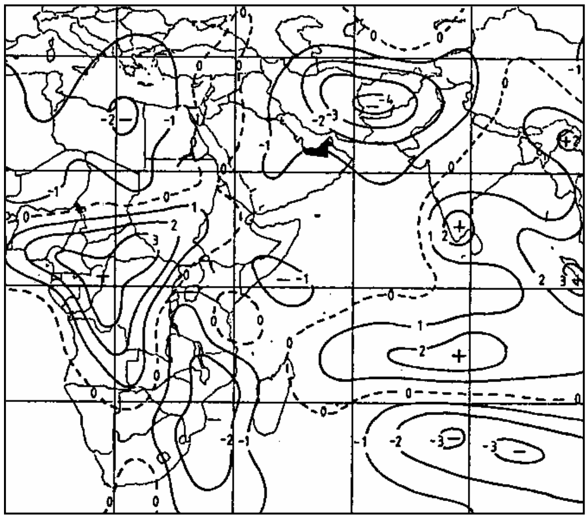

Figure 3.28. October mean 200 hPa divergence (x 10^{-6} sec^{-1}) from 1980 to 1987.

convergent air at about 40°E (figure 3.27) is a compensatory effect for the upward flow at 70°E and the subsiding air below this weak convergent zone at 40°E in turn contributes to the dry summer weather over Arabia.

3.9 WATER VAPOUR FLUX

The mean horizontal water vapour flux (transport) for the 850 hPa to 300 hPa layer (Triegaardt and Landman 1992) in January (figure 3.29) indicates weak winter moisture transport from the east over the Arabian Sea and northern Indian Ocean. This is consistent with the drier continental north-east monsoon shown in figures 3.1 and 3.2. However, over northern Arabia and the United Arab Emirates, there is stronger moisture transport from the west. As stated in section 3.2, this is consistent with the winter rainfall brought by low pressure systems, and their associated upper air troughs, that originate in the Mediterranean and sometimes as far west as the Atlantic (Kendrew 1961).

Comparing the July mean horizontal water vapour flux (figure 3.30) with that of January (figure 3.29), it will be seen that there is a total reversal of the circulation over the Arabian Sea and across India to the Bay of Bengal. In July this moisture, in association with the strong westerly to south-west monsoon, is transported from the ocean off east coast of Africa and to some extent from the southern hemisphere.

Over northern Arabia and the United Arab Emirates, the water vapour flux is somewhat less and is now from a northerly direction (figure 3.30), as opposed to westerly in winter (figure 3.29). The northerly direction can be attributed to the air which circulates southward to the east of the monsoon trough over Asia and often arrives as a modified very hot and dry air mass. Other, weak, water vapour flows present can be attributed to moisture from the Gulf of Oman to the east and the Gulf Sea to the north. Thunderstorms that develop in this moist air along the eastern mountains are then propagated westward to the coast by the prevailing easterly winds in the mid and upper levels (figures 3.16 and 3.17).

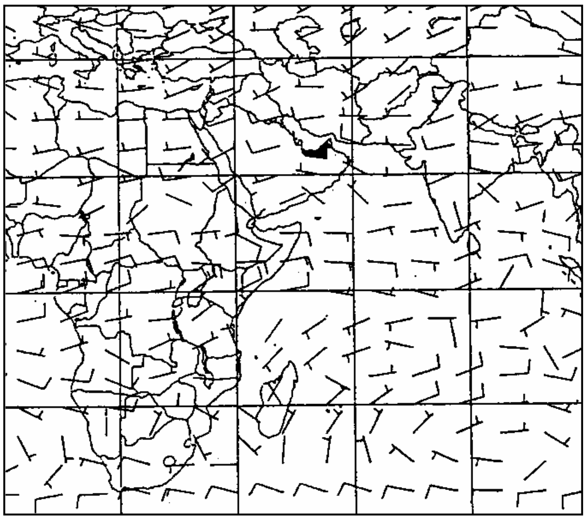

Figure 3.29. January mean horizontal water vapour flux vectors from 1980 to 1987. Each barb represents 10^2 gm cm^{-1} sec^{-1}.

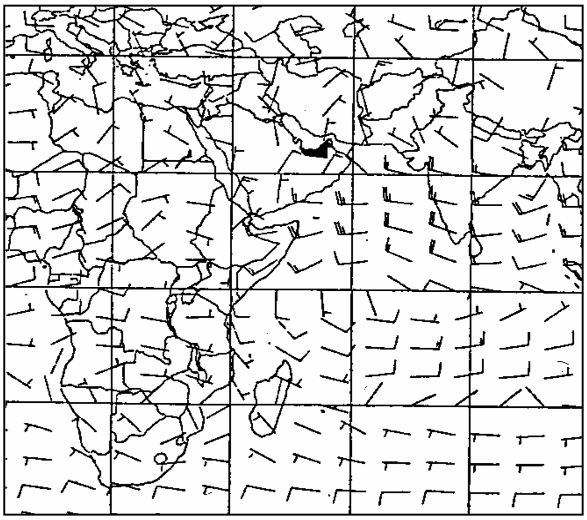

Figure 3.30. July mean horizontal water vapour flux vectors from 1980 to 1987. Each barb represents 10^2 gm cm^{-1} sec^{-1}.

3.10 SEA SURFACE TEMPERATURE

Annually the large heat capacity of the water in the Gulf Sea means that sea temperature changes tend to lag behind that of the land (Bradbury, 1989 and Griffiths, 1976). Consequently, the lowest sea temperatures tend to occur in February in winter and the highest temperatures in the summer month of August. That is, about a month later than the coldest and hottest times on land. In winter (February) the water around Arabia and in the Gulf Sea is about or slightly below 25°C (figure 3.31). In summer (August) it rises to about 27°C in the Gulf of Oman and above 30°C in the Gulf Sea (figure 3.32).

The differences in the diurnal heating and cooling over the land and sea (and resultant local pressure gradient differential) give rise to the well known mesoscale circulation known as the land and sea breeze (Riehl 1979). The seasonal temperature lag results in a stronger sea breeze effect at the beginning of summer when the land has already become considerably hotter and the sea surface is still closer to winter temperatures (Bradbury 1989).

Close proximity to the sea means that ADIA is prone to fog. High water vapour content sea air is brought over the land by the afternoon sea breeze. During the night the air is cooled to below its dew point temperature by the colder land surface, resulting in condensation in the form of dew, or fog (Hsu 1988).

The sea surface temperature reaches and exceeds 30°C in summer in the Gulf Sea. However, in the Arabian Sea, adjacent to the coast of Oman and toward the horn of Africa, it is about 5°C cooler (figure 3.31) with little change in winter (figure 3.30). The lack of warmer water in summer is due to up welling caused by the offshore component of the summer south-west monsoon wind, known locally as the Khareef. The upwelling of cooler water from below also brings plankton that attracts fish and gives rise to the fishing industry along the coast (Gill 1982). However, the stabilising cooling effect of the sea decreases the amount of rainfall along the southern coast (Taha, et al 1981).

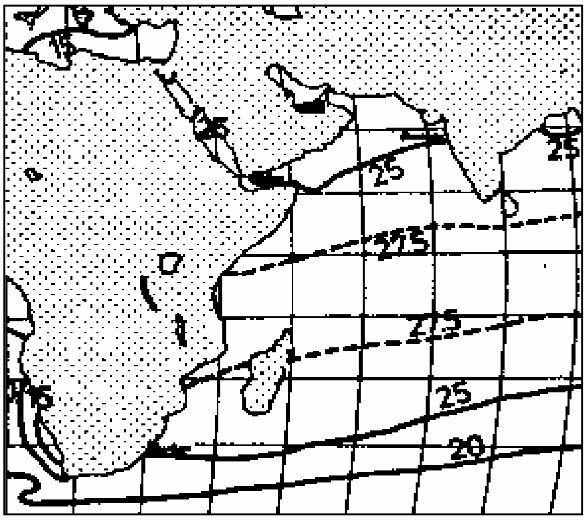

Figure 3.31. February mean sea surface temperature in ˚C (Rudloff 1981).

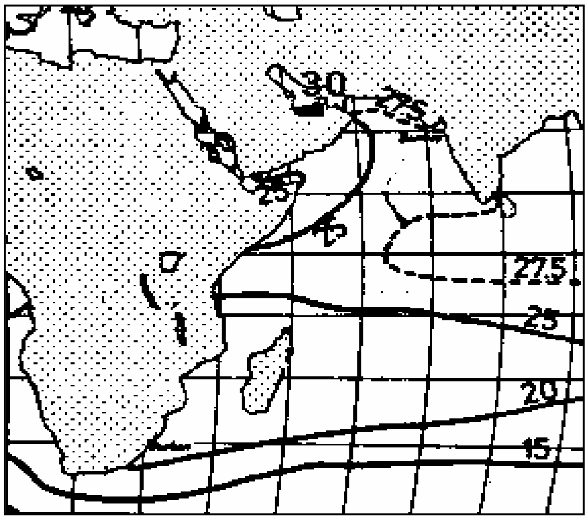

Figure 3.32. August mean sea surface temperature ˚C (Rudloff 1981).

3.11 SUMMARY

The atmospheric circulation and the weather experienced in the Arabian Peninsula, are strongly influenced by the summer and winter Monsoon over Asia and the annual reversal of trans-equatorial flow of air at the surface and the upper troposphere, as well as associated changes in divergence and convergence.

Primary effects are the surface transition from winter high pressure to summer low pressure, while in the upper troposphere, there is a change from a winter subtropical westerly jet stream to the summer tropical easterly jet. The circulation changes are reflected in a corresponding change in the water vapour flux.

Although Arabia is dominated by a high pressure cell in winter, the passage of mid-latitude low pressure cells, in association with upper air troughs, are important weather and rain producers. In conjunction with the passing lows, latitudinal movement of the surface anticyclonic cell over Arabia results in alternating southerly to south-easterly winds and northerly Shamal winds.

The summer circulation is dominated by the effect of the Asia low, the position of which results in a consistent northerly to north-westerly Shamal wind over most of Arabia, particularly in the north. Moist advection, into the low from the Arabian Gulf can provide enough moisture for frequent thunderstorms, which are driven to the UAE Gulf coast by the mid-level easterly circulation.

In spring rapid land surface heating causes increased instability, which accentuates shallow, near sub-synoptic depressions from north-west Africa. These shallow low pressure cells are preceded by southerly winds with intense heat waves and sandstorms.

Spring is also characterised by large day time temperature difference between the land and the still cool Gulf sea temperatures. This results in increased local wind circulations such as land and sea breezes and valley wind effects. The sea temperature is also influential in increased fog, particularly in autumn.