CHAPTER 8

RAIN BEARING TROUGHS, THUNDERSTORMS AND TROPICAL DEPRESSIONS

8.1 INTRODUCTION

The UAE lies in an arid tropical zone that extends across North Africa and rainfall is in short supply, the main supply of water being from desalination plants and underground water. The mean rainfall for the UAE as a whole is around 0.1 mm in May and July in summer, but 0.3 mm in June rising to 11 to 14 mm in the winter months of December and January (UAE Climate 1996).

In winter the passage of upper air troughs from the west are the main producers of cloudy weather and rain in the area. Extensive middle layer cloud with embedded thunderstorm line squalls develop in the south-westerly flow ahead of the trough (Taha, et al 1981). Due to the high cloud base and low mixing ratio conditions below, not much rain reaches the surface, although heavy and persistent rain can occur (Membery 1997) there are more likely to be strong wind gusts with temporary sand storms may (Tantawy 1961). Apart from the aviation hazard caused by thunderstorms, more often than not, these systems drastically reduce visibility by a combination of wind blown sand, or dust and rain.

During summer, when the thermal equator and associated low pressure belt is further north, thunderstorms develop on the Hajar Mountains when an easterly wave, or trough, migrates from east to west from the Arabian Sea over the Gulf of Oman and then over the Emirates. Al-Brashdi (2007) also draws attention to the Arabian Peninsula “heat low” as an important producer of low level moisture from the Gulf of Oman and subsequent convection. The thunderstorms then drift westward from the mountains to the Gulf coast. On the rare occasion a dissipating tropical cyclone may reach ADIA. (Taha, et al 1981).

Needless to say, the occasional thunderstorm that produces about 15 mm of rain is a noteworthy event and reports of heavy rain appear in the press. The Gulf News (2003-04-18), when reporting a late winter trough thunderstorm, told of “heavy lashing downpours” in the UAE that “inundated low-lying residential and commercial areas across the country” and the “municipality pumped water from streets.” The rain recorded at Fujairah was 28 mm, ADIA 13 mm, Sharjah 12.2 mm, Ras Al Khaimah 9 mm and Dubai 4.4 mm.

What is more usual in these storms and does more damage, are strong and gusty winds. During the above event very strong winds uprooted trees, broke electricity cables, blew down billboards, demolished shacks, damaged buildings and caused trouble to vessels at sea. In Dubai two floating restaurants that were “caught up in giant waves” needed assistance. But the most amusing quote is from a farm resident who said "I was trying to cover the ply woods (sic) when one of them suddenly flew away. I quickly backed and saw them fly one by one. I also found myself little above the ground while walking towards my room" (Gulf News, 2003-04-18). A particular danger is that the runoff from a sudden thundershower in the mountains quickly fills the dry wadi beds and can catch the locals and wadi bashing 4x4

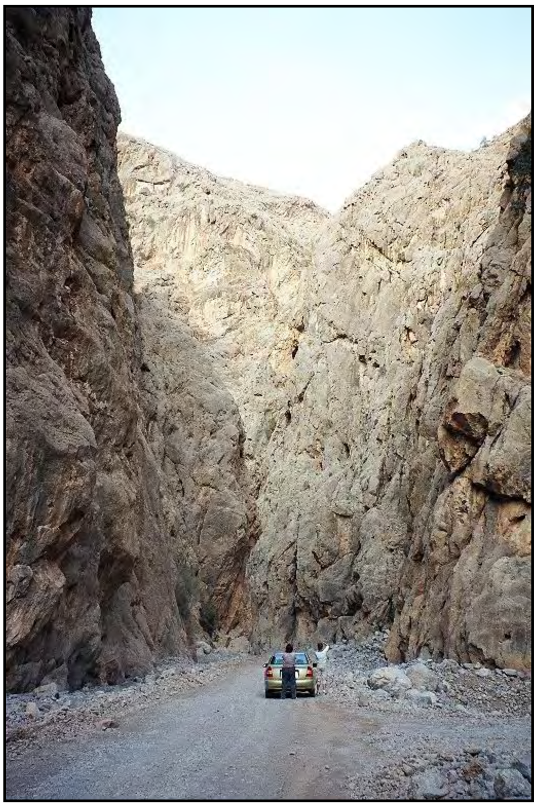

Figure 8.1. A wadi in the Hajar Mountains. The dry riverbed on the left and the road both become one and go into a narrow cleft in the rocks ahead of and slightly to the left of the motor car.

drivers unawares (figure 8.1). Wadi bashing is the popular off-road pastime of exploring wadis in luxurious 4x4's and camping in them.

Apart from investigating winter rain bearing trough systems with winter thunderstorms and summer thunderstorms, this chapter also briefly examines rare tropical depressions that occur and proposes a forecast methodology.

8.2 STATISTICS

The winter trough systems have a distinct effect on the rainfall at ADIA with most of the rain falling in the later part of the winter (figure 8.2). While the dominant effect of the middle and upper troposphere anticyclone is clearly evident in the extremely dry summer (Martyn 1992, UAE Climate 1996). The average annual rainfall at ADIA is 84 mm with the highest monthly on record, 202.3 mm, falling in February 1988, 119.9 mm of this fell in less than 24 hours on the 19th during a thunderstorm. Thunderstorms account for most of the rain in tropical deserts (Critchfield 1974) and the U.A.E is no exception.

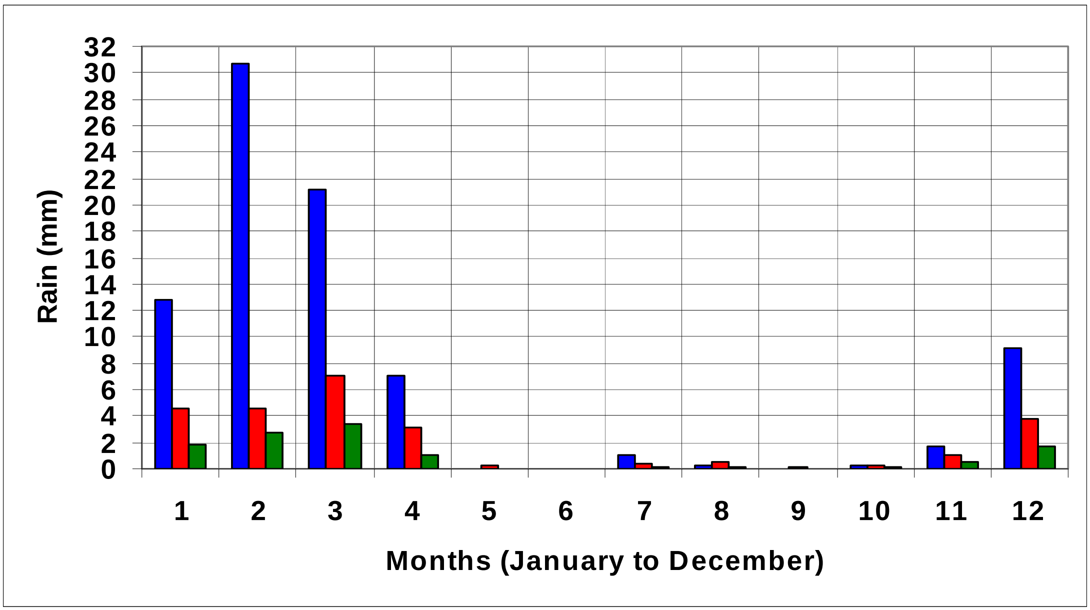

Figure 8.2. Rainfall statistics at ADIA from 1982 to 2001. The blue column depicts the mean rainfall, the red column depicts rain days (including traces) and green column days with >0.2 mm of rain.

The effect of the winter trough systems is also evident in the cloudiness at ADIA. The mean daily cloudiness (if one may be so bold to call it that) from ADIA climate data during 1982 to 2001 is between 2 to 3 oktas (eighths) in the winter months from December to March, with 1.2 oktas at the beginning in November and 1.8 oktas at the end in April. While the summer months of May to October average 0.5 to 0.8 oktas, except for July and August which increase to 1.3 and 1.1 oktas, respectively. The increase in cloud during these two months corresponds with a slight increase in rainfall (figure 8.2) and summer thunder activity (figure 8.3) drifting westward from the Hajar Mountains.

It was also noted that cloudy periods associated with the passage of trough systems at ADIA, usually lasted less than 24 hours, but may last longer. Occasionally cloudiness persisted, as happened in January 2004 when the weather was predominantly cloudy, mainly due to middle layer cloud, from the 14th to the 18th and with a few drops of rain. Thesiger (1990) writing about his epic journey by camel across the Empty Quarter in 1948, from the Oman coast through Saudi Arabia to ADIA, mentions that when west of the Sabkhat Matti, they had cloudy weather for ten days with distant thunder and lightning. It then rained "almost continuously for three days and intermittently for the next four, often with thunderstorms, especially at night."

The seasonal and geographical variation in thunder activity (and paucity) mentioned in the introduction (8.1) is illustrated by the mean thunderstorm days at ADIA on the coast and Al Ain, which is about 150 km inland (in the desert) in the eastern lee of the Hajar Mountains (figure 8.3). ADIA has a winter maximum associated with the passage of winter troughs (blue columns), which have been known to reach a maximum of 8 days in February (red columns), while Al Ain has a winter peak as well as a summer peak due to the passage of summer tropical easterly waves and orograhically induced summer thunderstorms drifting westward off the mountains (green columns). ADIA is too far downstream in the lee to feel the effect of these convection storms.

Hail has not been observed at ADIA, but it does occur, albeit rarely. On the 14th April 2003, during the passage of an upper air trough with embedded thunderstorms, a report was received of a helicopter being damaged by hail while returning from an offshore oilrig. A severe thunderstorm also produced grape size hail at Dubai on the 15th November 2004. Referring again to Thesiger (1990), after crossing the Sabkhat Matti in 1948 and heading toward the Liwa Oasis he saw where, in many hollows between the sand dunes, the rain had formed a crust on the sand and it had been pitted by hailstones.

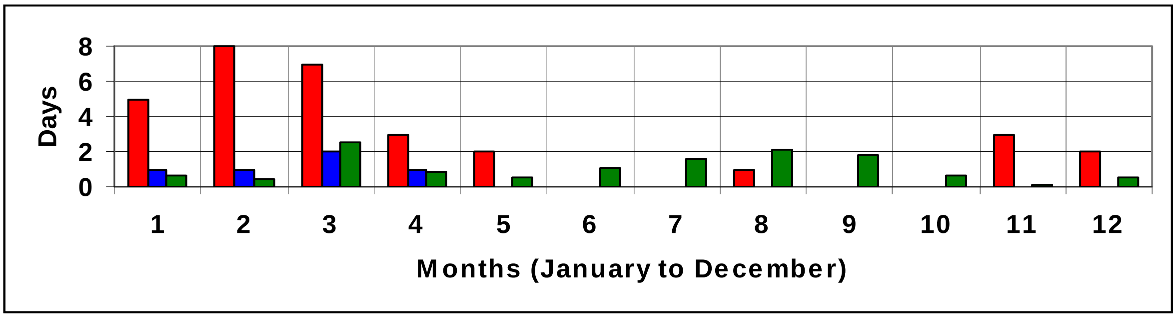

Figure 8.3. Thunderstorm days at ADIA (1982 to 2003) and Al Ain (1994 to 2001). The red columns show the highest thunderstorm days at ADIA and the blue the mean. The green columns are the mean thunderstorm days at Al Ain.

8.3 WINTER TROUGH SYSTEM: 27TH JANUARY 2004

8.3.1 INTRODUCTION

Rain fell when the tail of a baroclinic trough system passed over the Emirates. Most of the rain fell over the northern part toward the Strait of Hormuz where Ras Al Kaimah received 14.5 mm, Sharjah 11.4 mm and Dubai 11 mm. Further south, ADIA had 8.6 mm and Al Ain 4.8 mm. Fujairah, on the east coast and in the lee of the Hajar Mountains, received 1.8 mm. The rain bearing cloud band is shown in figure 8.4.

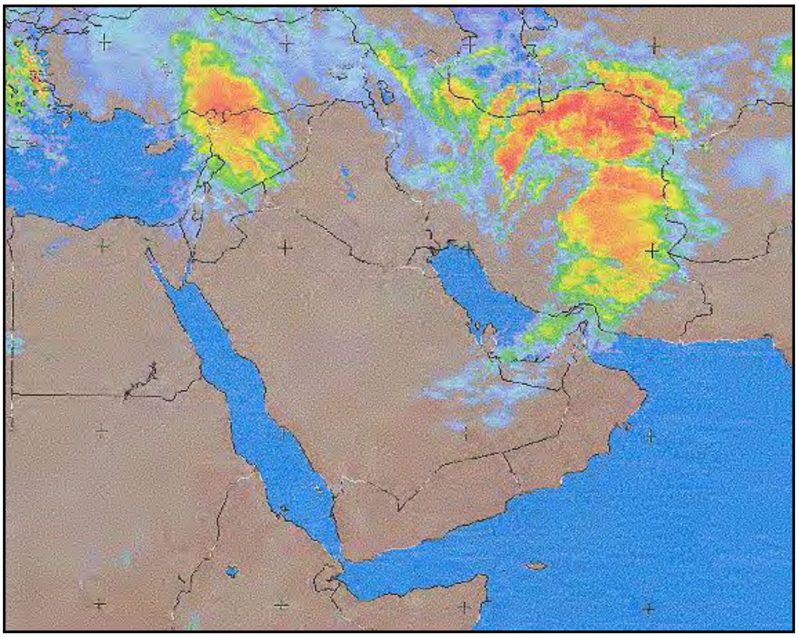

Figure 8.4. Eumetsat infrared image 2004-01-27 0300 UTC.

The significance of this event is that it demonstrates the usually fleeting effect of the systems over the UAE after crossing the Saudi Arabian desert. The cloudy weather lasted for only 9 hours at ADIA and the rain lasted for less than 3 hours. However, a few days earlier the system caused strong wind and dust storms followed by rain at Cairo and Beirut where flights were diverted. Strong winds also caused the Suez Canal to be closed for 12 hours on the 23rd (Gulf News, Saturday 24th January 2004).

8.3.2 GFS NWP MODEL

8.3.2.1 Synoptic situation

A dust event on the morning of the 26th, when visibility fell to 2500 metres in a 15 knot southerly wind, was followed, on the 27th, by a moderate to fresh north-westerly Shamal that blew at 8 to 17 knots at the ADIA following the passing of the surface trough. Figure 8.5 shows GFS model prognosis of the situation on the morning of the 26th and at 0000 UTC on the 27th immediately prior to the wind becoming north-westerly. Note the precipitation indicated over southern Iran in the right hand figure, but none over the UAE. The winds also brought a marked change in the surface air temperature. These were up to 30°C on the 26th in the southerly wind, but barely exceeded 21°C on the 27th when the northerly wind brought colder air, with the cloud aloft blocking the sun.

8.3.2.2 Upper air

At 0000 UTC on the 27th the southern tip of the upper air trough was still west of the UAE with the advance cloud band beginning to pass over the UAE. The cloudy weather, of greater than 4 oktas of middle layer cloud, lasted from 0300 UTC to 1200 UTC with the fell rain from 0530 UTC to 0830 UTC, apart from a brief light shower earlier ADIA at 0300 UTC.

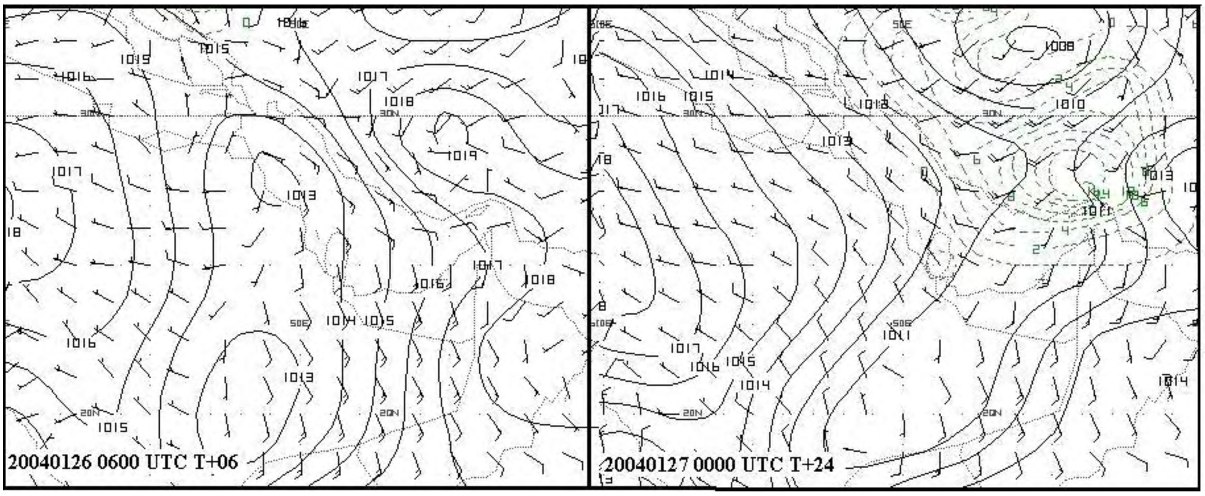

Figure 8.5. Eta NWP surface prognosis 2004-01-26/27. This shows the southerly wind at 0600 UTC on the 26th with an approaching low pressure cell and at 0000 UTC on the 27th immediately prior to the arrival of the surface ridge and north-westerly winds. The dashed green lines indicate precipitation.

Figure 8.6 at 0000 UTC on the 27th, depicts the T+24 GFS NWP model geopotential heights, wind and relative humidity at 700 and 500 hPa, respectively. Eighteen hours later at 1800 UTC the model indicated that moisture would have passed over ADIA and moved to the east. This prognosis turned out to be very good. Indeed, the relative humidity at the 700 hPa and 500 hPa levels was a better indicator of where precipitation would occur than the precipitation field in figure 8.5 at 0000 UTC. The latter showed the rain boundary to be too far to the north, although it was a good indicator where most of the rain and heavier rain fell.

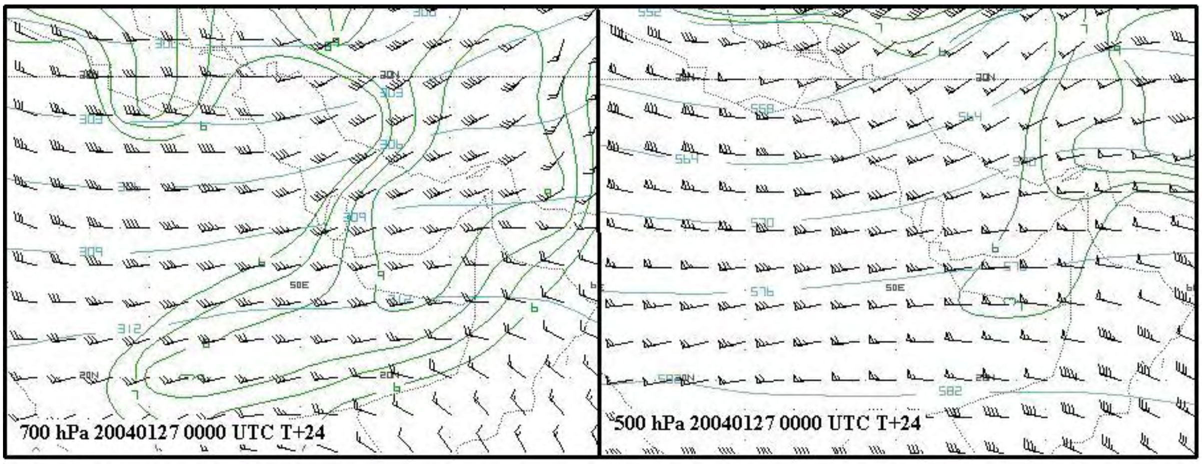

Figure 8.6. Eta GFS model geopotential heights, wind and relative humidity at 700 and 500 hPa, respectively on 2004-01-27 at 0000 UTC.

The vertical velocity and divergence fields also gave a clear indication of the time when most of the weather was to be expected. The zone of maximum upward motion is shown over ADIA at about 0600 UTC (figure 8.7). This corresponds with the predicted maximum divergence aloft at about 300 hPa below a 125 knot jet stream at 250 hPa (figure 8.8). This is nearly in the middle of the period when rain fell from 0530 UTC to 0830 UTC, as well as the cloudy period that lasted from 0300 UTC to 1200 UTC. Apart from the earlier short light rain shower at 0300 UTC, the rain coincided with the time of maximum vertical velocity in the middle troposphere and maximum upper air divergence. This divergence and vertical motion pattern is typical of a mid-latitude baroclinic trough (Membury 1997, Kurz 1994 and Petterssen 1956).

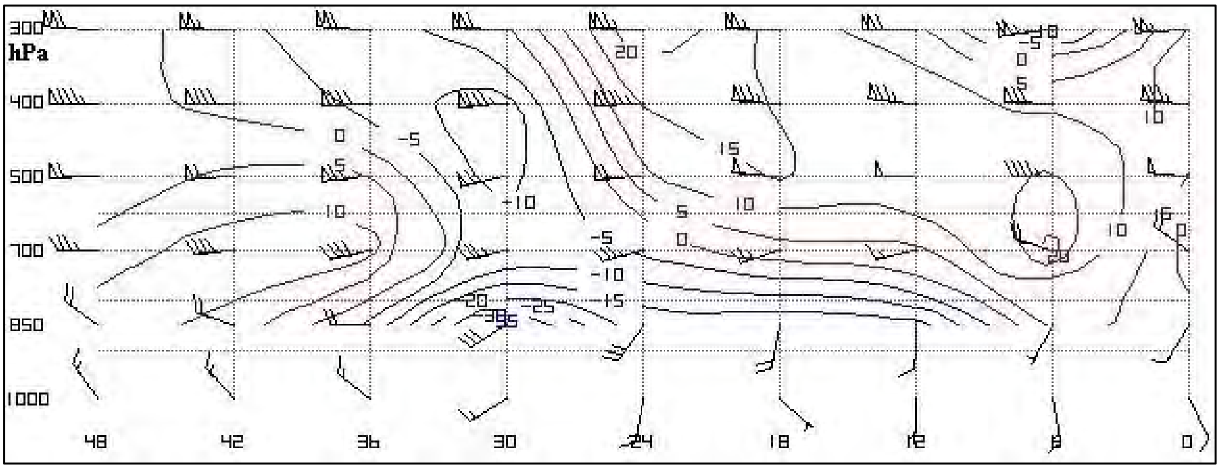

Figure 8.7. Eta vertical velocity (microbars/second) field from 2004-01-26 0000 UTC (T+0) to 2004-01-27 2400 UTC (T+48). The zone of maximum upward (negative) motion (blue) is over ADIA at about 0600 UTC (T+30) on the 27th. Pressure levels (hPa) on the left.

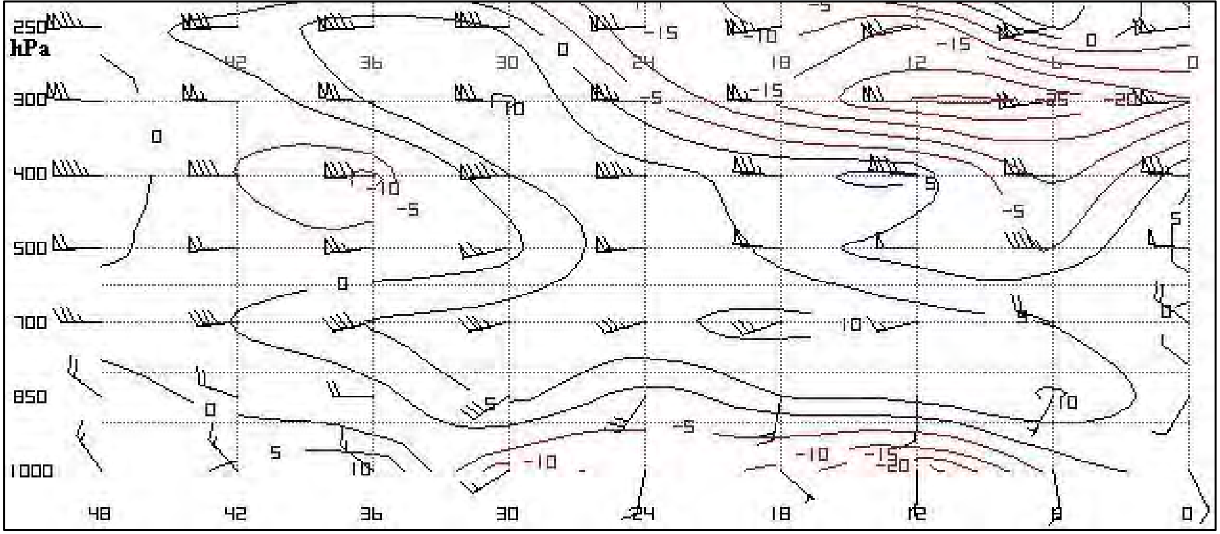

Figure 8.8. Eta wind divergence (blue lines) and convergence (red lines) field from 2004-01-26 0000 UTC (T+0) to 2004-01-27 2400 UTC (T+48). The zone of maximum divergence is shown over ADIA at 300 hPa at about 0600 UTC (T+30) on the 27th.

8.3.3 ATMOSPHERIC SOUNDINGS

That the rain fell from middle layer cloud can be seen in the sequence of atmospheric soundings at ADIA (figure 8.9). These clearly show the increase in moisture in the layer up to

900 hPa where the ambient temperature lapse rate is equal to DARL (unstable) (figure 8.9 and b). Higher conditions remained conditionally unstable with the ambient temperature lapse rate between the DALR and the SALR up to between 6 and 700 hPa. The higher dew-point (relative humidity) in this layer probably indicate the layer cloud was probably down to about 750 hPa with the tops up to nearly 600 hPa. During the passage of most intense part of the cloud band, the cloud layer probably occurred up to 340 hPa.

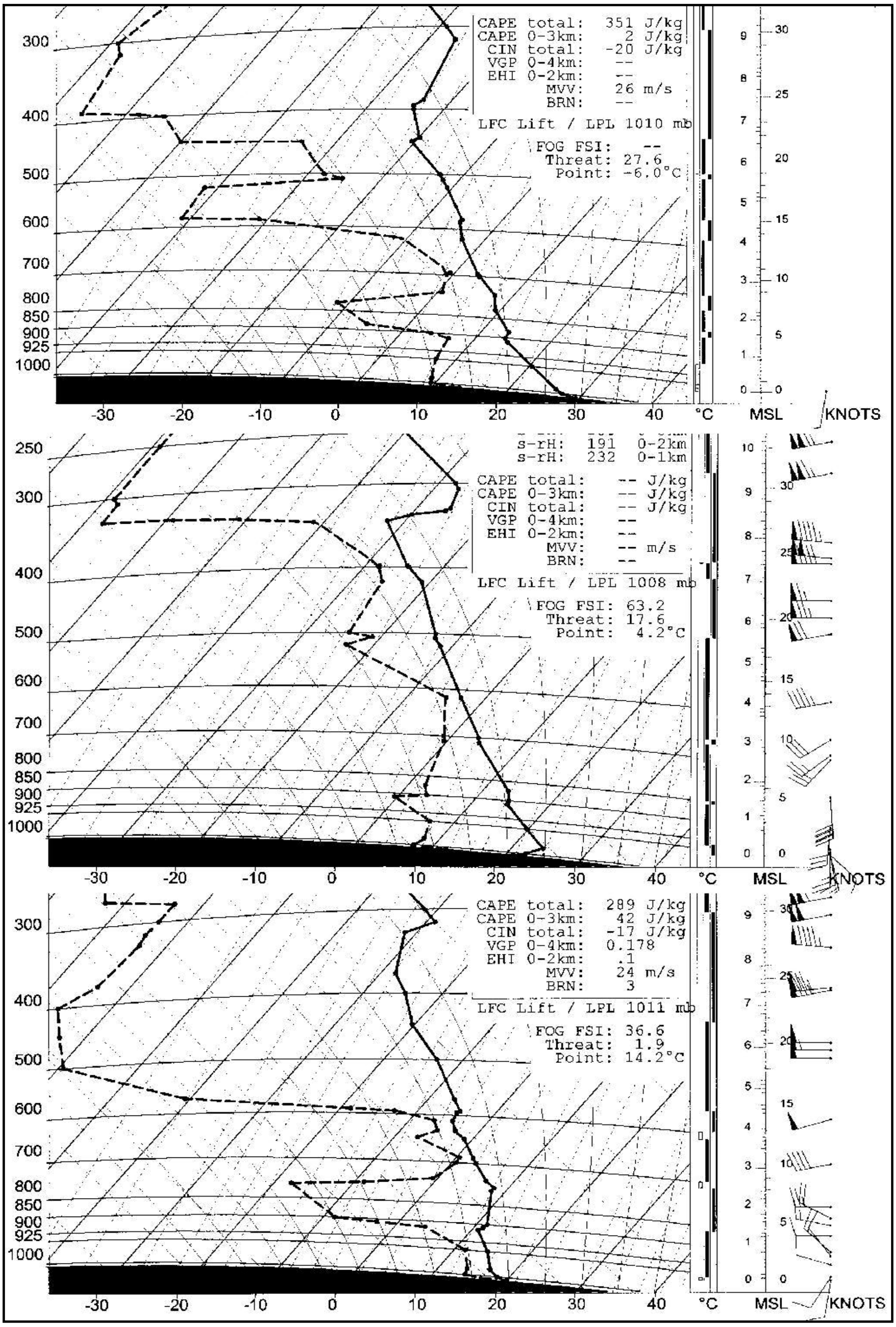

Figure 8.9. The sequence of atmospheric soundings at ADIA from 1200 UTC 2004-01-26 through 0000 UTC to 1200 UTC on the 27th.

8.3.4 RADAR IMAGES

The two images from the weather radar at Al Ain, which show most of the echoes over the northern UAE and the Oman Musandam area and the radar reflectivity data indicate that generally light rain occurred, except for some higher rainfall in the north (figure 8.10).

The fact that most of the radar reflectivity was low at 26 dBZ, with a few cells near to 40 dBZ also suggests that the rain fell mainly from layer cloud and any embedded thunderstorms were light and very isolated (as indicated in the guide in table 8.1). At ADIA portions of thunderstorm clouds and their tops were vaguely observed through layer cloud from time to time to the distant north over the Gulf Sea, but no thunder was heard, nor lightning seen.

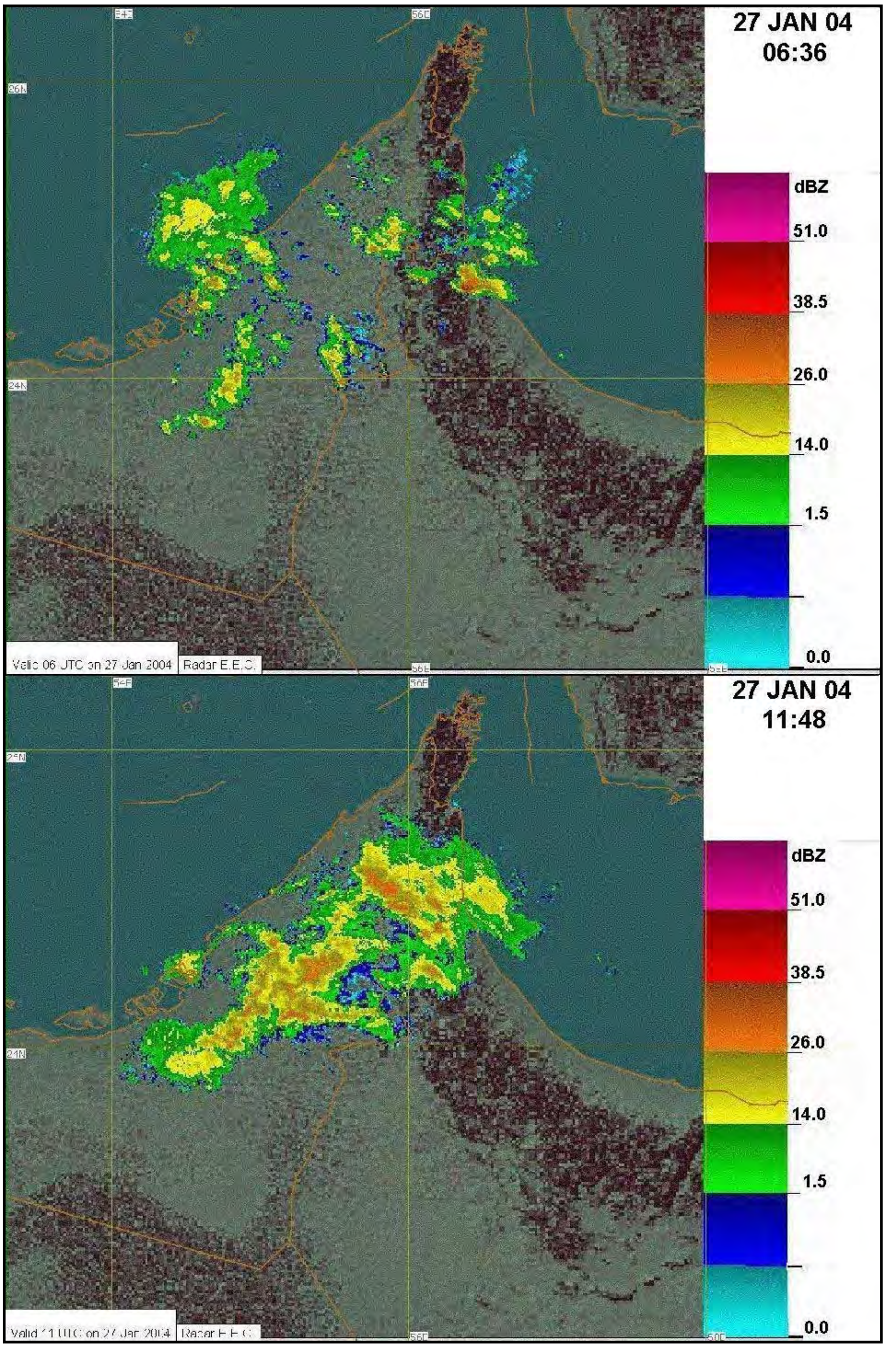

Figure 8.10. Al Ain weather radar PPI reflectivity dBZ images on 2004-01-27. Local times shown (UTC + 4 hours).

Table 8.1. Radar reflectivity dBZ and rainfall rate comparison as used by the National Center of Meteorology and Seismology (2008). The comparative values are a rough guide only.

dBZ	Comments
10	Cloud or rising sand
20	Cloud
25	Chance of light rain
30	Light to moderate rain
40	Moderate to heavy rain
45	Heavy rain
60	Heavy rain. Chance of hail
70	Heavy rain with hail

8.3.5 SUMMARY

The rain occurred when the southern tip of an intense trough system passed quickly over the region. The cloudy weather lasted less than 9 hours at ADIA and the light rain fell in less than 3 hours. The previous day a southerly wind, preceding the trough, raised dust and reduced the visibility to 2500 metres.

Post-processing products of the GFS model data gave the forecaster a good indication of when and where the rain would occur. These were the 700 hPa and 500 hPa relative humidity fields and the time cross-sections of vertical velocity and divergence.

Weather radar data at Al Ain indicated that the light rain fell mainly from layer cloud and the embedded thunderstorms were light and very isolated. This was supported by atmospheric soundings that indicated an increase in middle layer cloud and conditional instability up to the morning of the rain with drier and more stable conditions by the afternoon.

8.4 ABU DHABI WINTER THUNDERSTORM: 18TH MARCH 2002

8.4.1 INTRODUCTION

A particularly severe thunderstorm with strong winds occurred late in the afternoon of the 18th March 2002 at ADIA, in the United Arab Emirates. In the city centre the wind blew over trees and construction boards. There was also a report of large vehicles almost blown off the road. Nearly an hour later, at the airport, strong wind gusts preceding the thunderstorm produced a wall of sand that reduced the visibility to 1000 metres, which was followed by strong sustained wind and rain.

Throughout the previous night a moderate south-easterly wind blew off the desert. By 0330 UTC (07:30 am) the wind was blowing at 20 to 25 knots at ADIA and wind blown sand reduced the visibility to 800 metres. Late in the afternoon, at 1300 UTC, the wind moderated and the visibility improved to 3 kilometres.

A line of developing thunderstorms was detected by weather radar over the south-western part of the UAE about two hours prior to reaching ADIA. The storms produced radar echoes up to 50 dBZ. As a result airport warnings for heavy rain and 30 to 40 knots wind gusts were issued by the weather office more than an hour in advance.

At 1330 UTC the thunderstorm struck the airport and the wind suddenly switched to south-westerly in excess of 30 knots with gusts up to 43 knots. The visibility deteriorated to 1 kilometre in raised sand. At this time the anemometer at the threshold to runway 13 recorded a wind of 234° at 33 knots gusting to 43 knots and at the threshold to runway 31 the wind was 216° 25 knots gusting 34 knots.

Behind the gust front a swirling motion could be seen in the base of the thunderstorm cloud and shortly after this the downburst rain began. In total 9.5 mm of rain fell in 40 minutes. This is a significant amount of rain in this part of the world.

This case study, demonstrates the value of using numerical weather prediction (NWP) model information. As well as the use of some of the more common parameters, or indicators, associated with thunderstorm prediction, to identify and anticipate thunderstorm activity over the United Arab Emirates. Due to the low frequency of thunderstorms, the list of parameters and procedures is by no means comprehensive and deductions made are applicable to this case study only. Furthermore, it does not present any hard and fast rules to be adopted to forecast thunderstorms. Some common thunderstorm indicators were not available for analysis for technical reasons, perhaps the most important being the convective available potential energy (CAPE). Other more complex thermo-dynamical indicators, which produced the same results, for brevity, have not been included.

The NWP model used in this study was the United States of America National Weather Service (NWS) 1° horizontal resolution Global Forecast Service (GFS) model initialised at 0000 UTC on the 18th. Confidence in the model prognoses was raised because the model initialisation, 12 hours earlier at 1200 UTC on the 17th, presented very much the same prognosis with respect to the approaching trough. This model gave more than adequate warning of the impending weather.

8.4.2 SYNOPTIC SITUATION

The severe weather was caused by a marked baroclinic trough system. At the time of the onset of the sand storm, about 10 hours prior to the thunderstorm, a low pressure was to the immediate west and an anticyclone to east of the UAE. The upper air trough extension of the surface low leaned back well to the west and at 500 hPa it was positioned about 10° west of the ADIA. This is a situation conducive to significant upward motion over and ahead of the surface low and with surface cold air advection behind the surface low and below the trough it promotes development of the system (Holton, 1992).

8.4.3 GFS NWP MODEL

8.4.3.1 Surface

Initially, at T+0 (0000 UTC, 0400 UAE local time) the model indicated a west to east surface pressure gradient of 4 hPa across the UAE (±5° latitude) and a southerly wind of 10 to 15 knots at 10 metres. At T+06 (0600 UTC), the prognosis was for a pressure gradient increase to 5 hPa and a southerly wind of 15 to 20 knots (figure 8.11). This is consistent with the observed situation mentioned in the previous section, although the predicted wind speed was was about 5 knots too low. Twelve hours later, at T+12 (1200 UTC), the model indicated a decrease back to a 4 hPa gradient and decrease in wind speed to 10 to 15 knots.

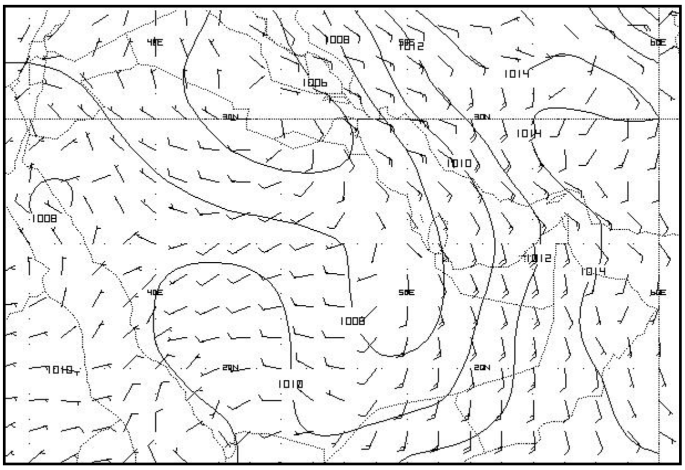

Figure 8.11. Prognosis of surface pressure and 10 metre wind 2002-03-18 at 0600 UTC (T+6). Note the 15 to 20 knots southerly wind over the UAE.

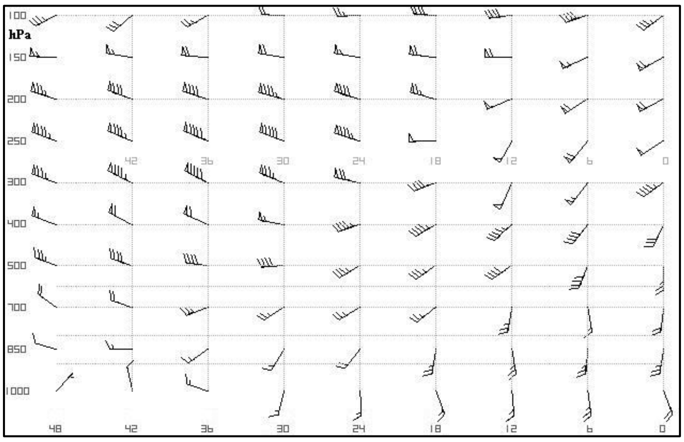

Figure 8.12 Prognostic wind vertical time cross section in knots at ADIA 2002-03-18. Note the 25 to 15 knots southerly wind at 1000 hPa at 0600 and 1200 UTC (T+6 and T+12), respectively, below from the right .

The lower level southerly winds were notable for their consistency of speed and direction, both with respect to those observed by atmospheric sounding and those indicated by the GFS model. The time cross section at ADIA shows the low level wind pattern (figure 8.12). Note, the 1000 hPa wind at 0600 UTC and 1200 UTC was the same as that observed at 10 metres (Figure 8.11)

Although the low level winds were from the south, off the desert and dry, the 1000 hPa dew-point temperature and boundary layer moisture flux fields at 1200 UTC (T+12), figures 8.13 and 8.14 respectively, indicated a marked increase in low level moisture. In this instance the 1000 hPa level was about 120 metres above mean sea level (MSL) at ADIA, compared with surface observations taken at about 27 metres above MSL. Dew-point temperatures over the UAE were expected to reach 16°C (figure 8.14). While earlier and later boundary moisture layer flux fields show that it was transported from the northward from the Arabian Sea, across southern Oman and then over the UAE.

These are in themselves, strictly speaking, not severe weather indicators, but viewed together with the 850 hPa wet-bulb potential

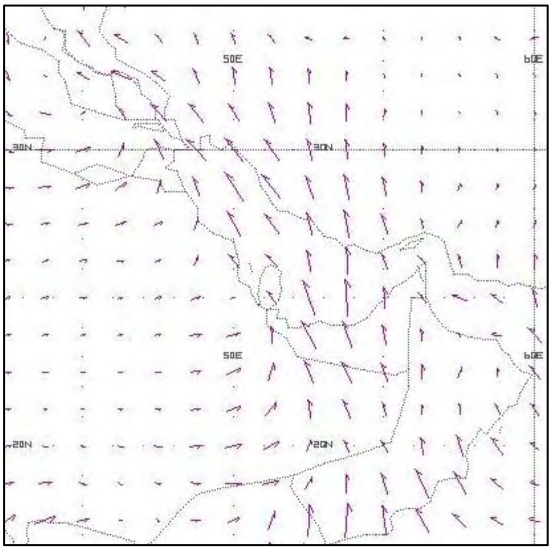

Figure 8.13. Boundary layer moisture flux at 1200 UTC (T+12).

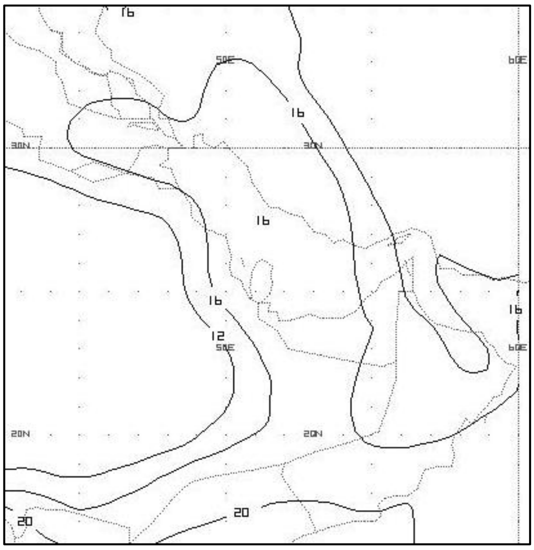

Figure 8.14. Surface dew-point temperature at 1200 UTC (T+12).

temperature (WBPT), they do indicate that enough surface moisture is available to support convective development (Membery 1997). Ample moisture combined with 700 hPa upward motion is a clear sign where deep convection is probable. Thunderstorm development will often be aligned along lines or zones of moisture convergence. Subsequent direction of movement of the storms can frequently be determined from the movement of these zones of moisture convergence. Ridges, or plumes, of higher WBPT often also determine the source region for severe storm development and they frequently develop upstream of the WBPT ridge axis. In this case study higher energy, indicated by increased 850 hPa WBPT, got it right. But, sadly, the predicted low level moisture convergence and 700 hPa upward motion failed to pinpoint the convective development. Only weak convergence was indicated west and east of where the line of thunderstorms developed and the maximum 700 hPa upward motion was predicted over southern Iran (fields not shown).

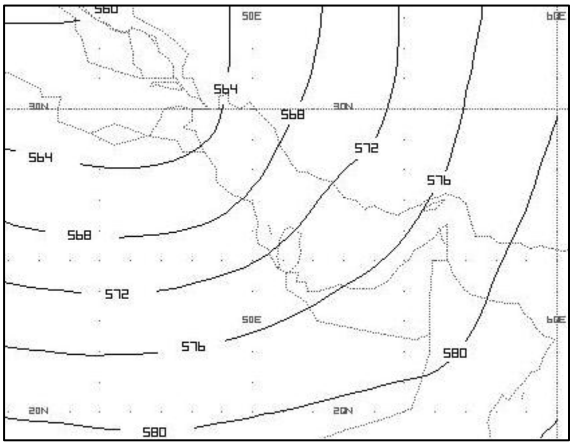

Figure 8.15. 500 hPa circulation at 1200 UTC (T+12) showing the trough west of the UAE.

8.4.3.2 Upper air

The upper air prognostic circulation at T+12 (1200 UTC) at 500 hPa confirmed the marked vertical slope of the system by placing the trough about 10° west of the UAE (figure 8.15). During the following 24 hours, moved to east of the UAE.

The time section graph for vertical velocity, between T+0 and T+12, showed an increase in middle atmosphere upward motion which lowered and became stronger ahead of the approaching trough (figure 8.16). This coincided with an increase in upper air relative humidity and it is indicative of adiabatic cooling (figure 8.17).

Maximum upward motion that continued until 1800 UTC (figure 8.16) was also coincident with areas of maximum low level convergence (negative divergence) and higher level wind divergence indicated by the model prognoses at 1200 UTC and 1800 UTC (T+12 to T+18) (figure 8.18). Convective development occurred in the south-westerly airflow ahead of the advancing trough and the prognostic maps along with the observed convective development provide a good example of Dines compensation as described by Membury (1997), Kurz (1994) and Holton (1992).

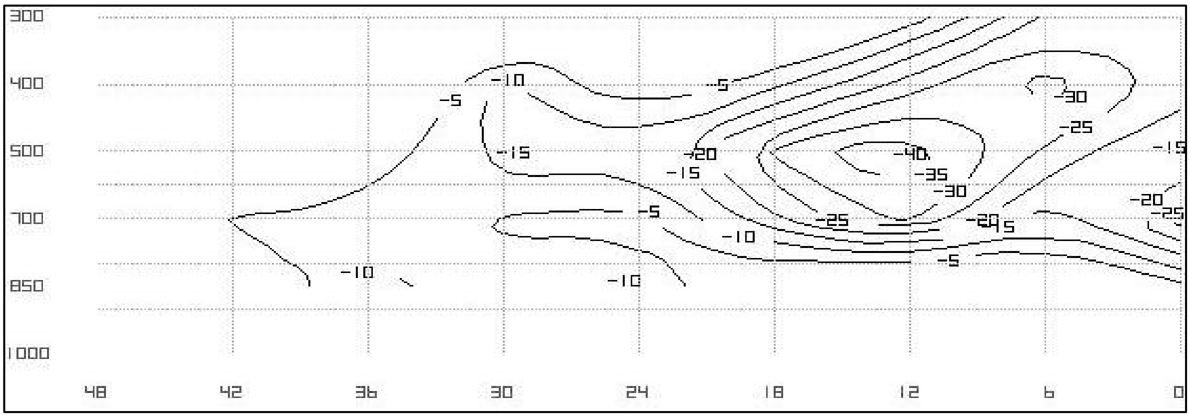

Figure 8.16. Vertical velocity (ω) time cross section at ADIA. Upward, motion (ω<0) increased ahead of the advancing trough, reaching a maximum at the time when the thunderstorm line squall passed ADIA.

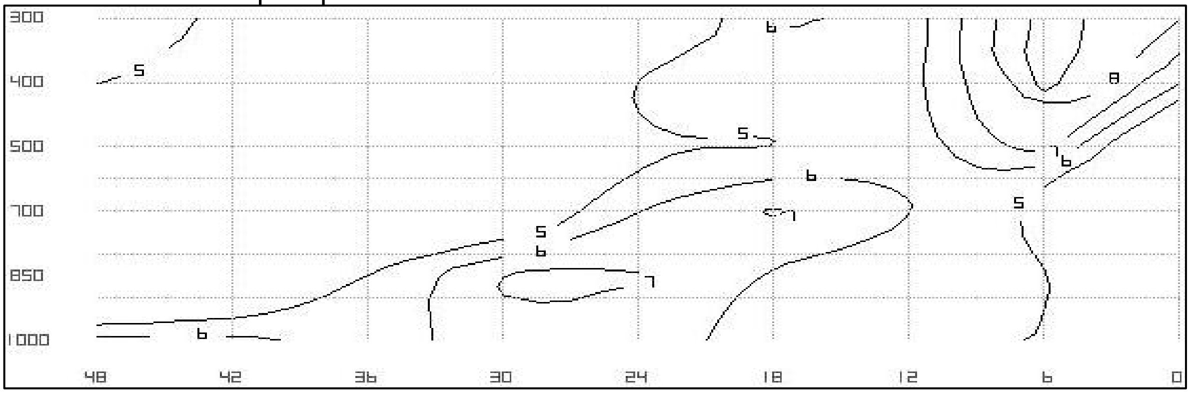

Figure 8.17. Relative humidity time cross section at ADIA. The Eta NWP model indicated increased layer moisture around the time of the thunderstorms.

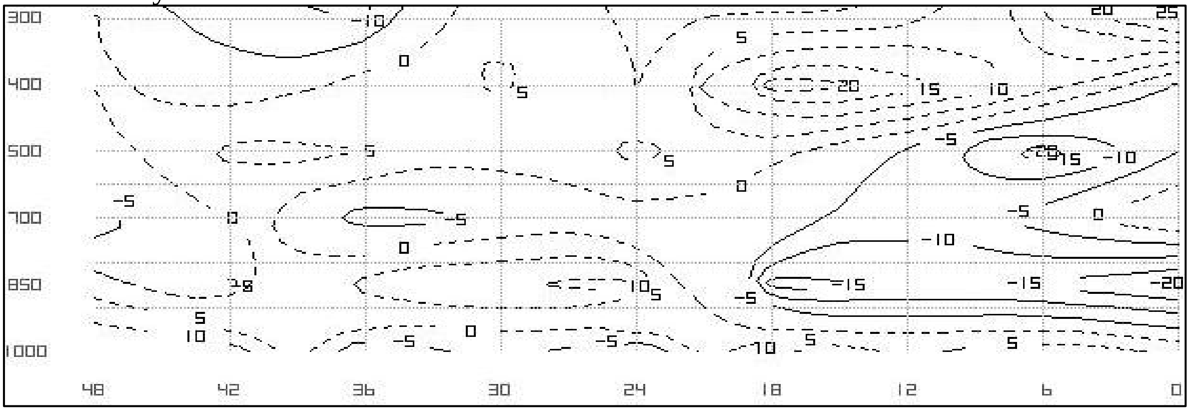

Figure 8.18. Wind divergence time cross section at ADIA, indicating low level convergence (-) and upper level divergence (+). Considering mid-level upward velocity in figure 8.16, this is consistent with the vertical motion field ahead of an upper air trough.

Areas below strong upper troposphere divergence are very favourable regions for severe thunderstorm development, in that they serve to draw air upwards and intensify a thunderstorm up draught (Eagleman 1983).

Figure 8.19 shows that a zone of 500 hPa maximum relative vorticity advection, was over the UAE in the south-westerly circulation ahead of an upper air trough at 1200 UTC (T+12) . Holton (1992) showed that when this happens rapid downwind movement of the trough (toward the UAE) will take place.

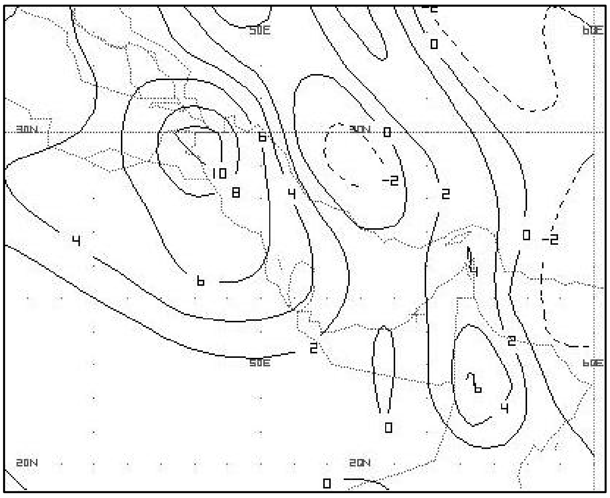

Figure 8.19. 500 hPa vorticity advection at 1200 UTC (T+12) showing a local maximum over eastern UAE and northern Oman.

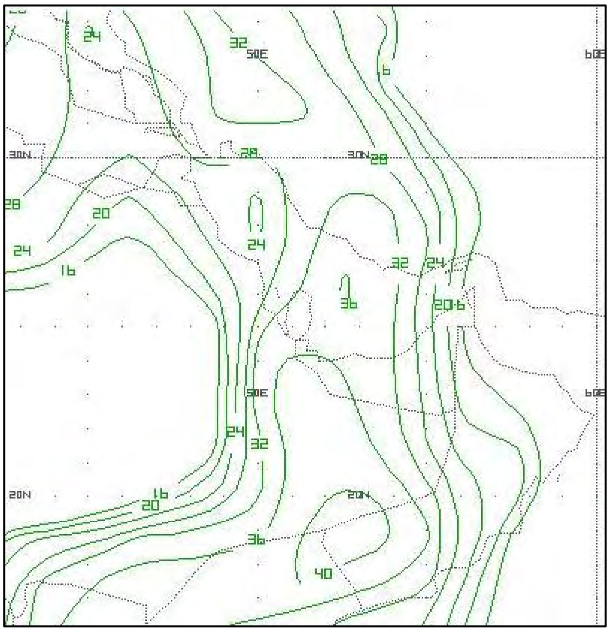

Figure 8.20. A band of increased K Index values positioned over the Gulf and the UAE at 1200. UTC (T+12)

8.4.3.3 Instability Indices

Instability indices,, computed for this day over the UAE, also indicated of the potential for the development and passage of thunderstorms. There was an increase in K Index values of up to 32 to 36 over most of the UAE by 1200 UTC, followed by a decline later as the thunderstorms moved eastward. K index values of 30 to 40 being indicative of moderate thunderstorm potential and heavy rain, while values greater than 40 indicate the high potential of heavy rain (figure 8.20).

The K Index (Appendix A) considers temperature differences between the 850 hPa and 500 hPa levels, as well as 850 hPa dew-point temperatures and 700 hPa dew-point temperature depressions. That is, index values increase with increased moisture. Note dry air at 700 hPa can result in a misleading low value. However, with a lifting mechanism and enough moisture below this level, strong thunderstorms can still occur.

Spatially, maximum Total Totals Index values (Appendix A) lagged slightly behind those of the K index. Values in excess of 30 for the 850 hPa to 500 hPa layer were indicated over the UAE with the highest values of 52 over Qatar and the extreme western part of the UAE (figure 8.21). Index values of 50 and above are indicative of scattered to numerous thunderstorms, while 46 to 49 indicates scattered development.

The index has a bias toward steep lapse rates and determines the 850 hPa to 500 hPa dew-point temperature (moisture) and ambient temperature lapse rates.

A similar spatial discrepancy to the Total Totals Index was noted with respect to the Showalter Index (Appendix A and figure 8.22), with a maximum value of –6 at 1200 UTC, which is just below the strong, or severe, cut-off mark at –7 (Sanders, 1983). This index calculates the lifted condensation level dry adiabatically from the 850 hPa level and then compares the parcel temperature with the environment at 500 hPa to determine instability.

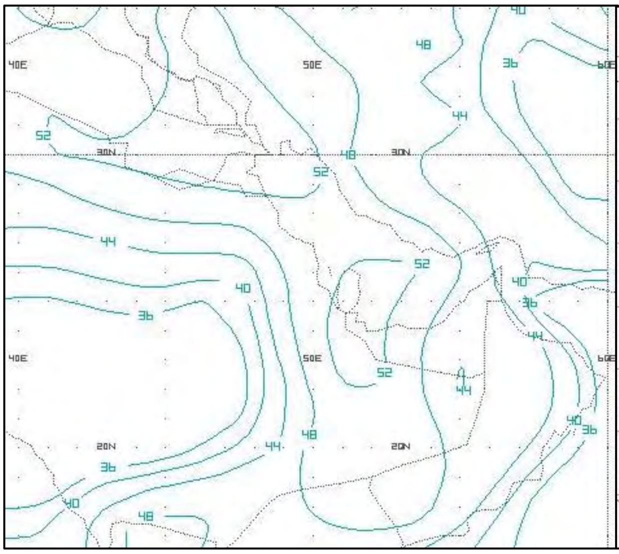

Figure 8.21. Raised Total Totals Index values over western UAE at 1200 UTC (T+12).

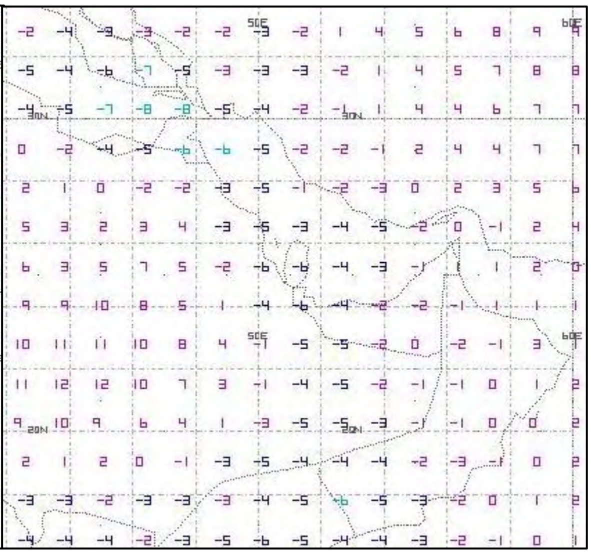

Figure 8.22. Showalter Index at 1200 UTC (T+12). Maximum negative values are over Qatar and the extreme western part of the UAE**.**

Over the UAE 850 to 500 hPa Lifted Index (LI) values (not shown, Appendix A) of up to –4 were indicated. Conditions are considered moderately unstable between –3 to –5, with more negative LI values indicating strong conditional instability. This index is very similar to the Showalter Index, but differs in that the lower start level can be varied. In this instance the 850 hPa base level is used.

Note, these are all empirical indices, which are adjusted for different parts of the world. Consequently significant values and intensity thresholds will vary from region to region.

8.4.3.4 Relative vorticity and dry line

Cyclonic relative vorticity plumes (positive in the northern hemisphere, negative in the southern hemisphere), particularly along an upper air trough axis, as well as in the lee of the axis, are often present with a plume of drier, colder air. This is often referred to as a dry slot that can be seen on water vapour imagery (Lemon 2001). This cold, dry slot can be entrained into deep convection, where the resultant evaporative cooled downdraughts cause strong wind and gusts at the surface (Sanders 1983). Certainly in this instance, strong winds and gusts were experienced at the airport and in the city.

The dashed lines in figure 8.23 show that a plume of cyclonic relative vorticity was indicated, but it was to the west of the UAE at about the time of thunder activity. Better positioned is the elevated dry line at 4267 metres (14000 ft), indicated by the thick red lines over the

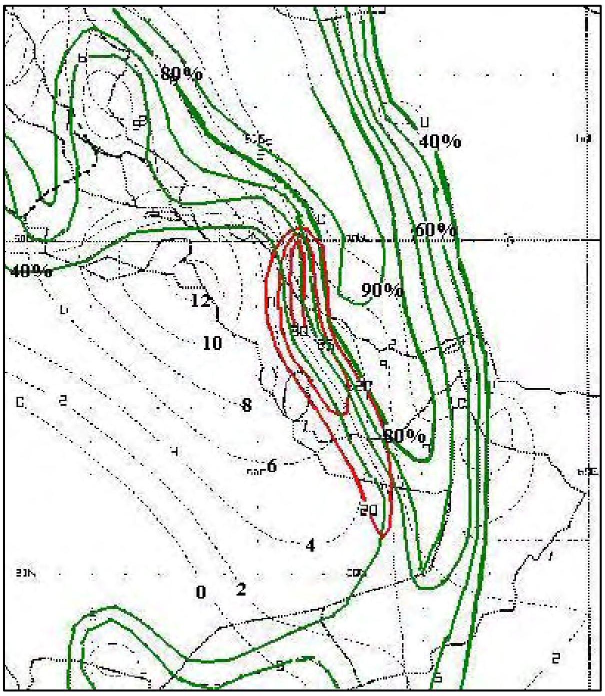

Figure 8.23. Cyclonic vorticity (dashed line), elevated dry line (red) and 600 hPa relative humidity (green) at 1200 UTC (T+12).

western UAE and the central Gulf, as well as the 600 hPa relative humidity shear from 80% to 40% over the western part of the UAE (green lines).

8.4.3.5 Lapse rate

The steeper the lapse rate the greater the atmospheric instability. McCaul (1987) showed that instability in the 850 hPa to 700 hPa layer is a good indicator of the potential for dry microbursts. The closer the ambient temperature lapse rate gets to the dry adiabatic lapse rate (9.8°C/km, 3°C/1000 feet,), the greater the risk of microbursts. When the ambient temperature lapse rate becomes less than 5.5°C/km (±1.7°C/1000 feet) the layer is considered stable.

In this instance the lapse rate was 0.6°C/km (figure 8.24a), indicating conditional instability and almost stable conditions. The stability criteria proved to be correct and valuable because rain accompanied the thunder and there was no evidence of a microburst, dry or otherwise. A strong gusty wind spread ahead of the thunderstorm as a gust front. Wallace and Hobbs (1977) point out that the downdraught is usually strongest and deepest just behind the gust front. Apart from one report of a 40 knot wind on approach to the runway at ADIA, the lack of any aircraft wind shear reports seems to confirm that there was no microburst. However, given the lack of surface observational data the presence of a microburst cannot be ruled out completely.

Mid-level instability, in the 700 hPa to 500 hPa layer, has an effect on hail growth. Moderate instability in this layer favours large hail growth, while strong instability favours stronger upward velocity and the greater risk of dry air entrainment. At about the time of the thunderstorm, the model indicated about 6.4°C/km for the 700 hPa to 500 hPa layer over the UAE and slightly higher to the east (figure 8.24b). In the absence of observed hail, it would seem that the instability present favoured dry air entrainment, rather than hail growth. This in turn supports the evidence presented in the section on relative vorticity and dry line and the strong gusty winds that occurred.

8.4.3.6 Wind shear

In simple terms wind shear tends to destroy up and down draughts and it is not generally conducive to single cell air mass thunderstorm development (Agee 1982, Bennetts, McCullum and Grant 1986, Eagleman 1983). However, in strong up draught forcing, wind shear fosters up draught rotation and storm intensification. The wind shear necessary is generally accepted as having to be >40 to 50 knots within 4 to 6 km AGL (Weisman and Rotunno 2000). Supercell propagation to the left (right) is favoured when the shear vectors turn counter clockwise (clockwise) with height and the shear strengthens (Bunkers 2002, Doswell and Evans 2003). The red lines in figure 8.25 show that higher wind shear values of

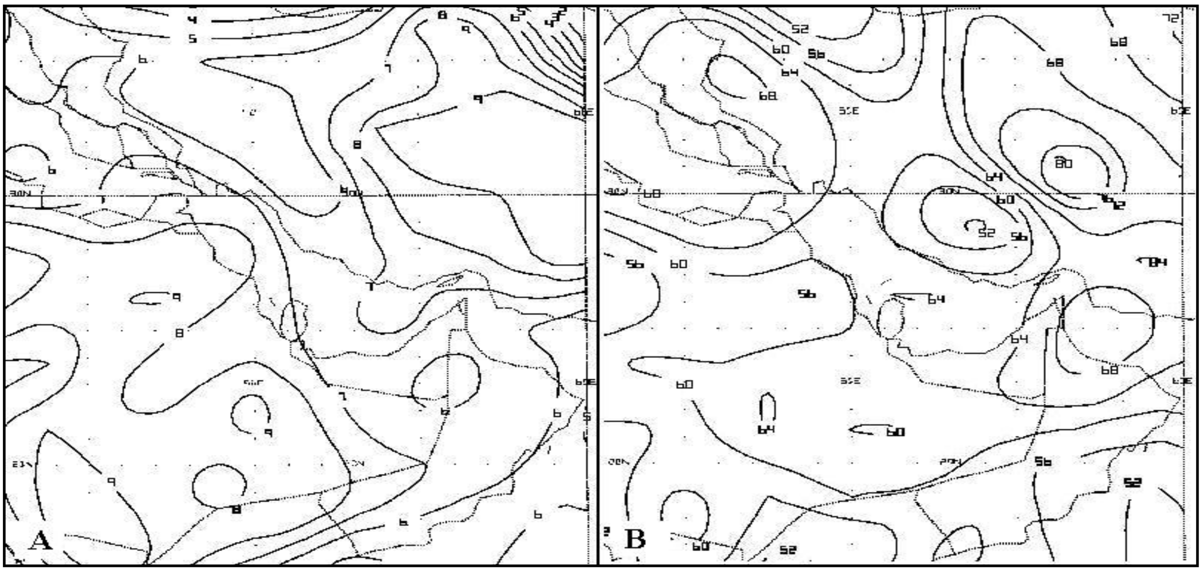

Figure 8.24a and b. Lapse rates (a) 850 hPa to 700 hPa at 1200 UTC (T+12) and (b) 700 hPa to 500 hPa at 1200 UTC (T+12).

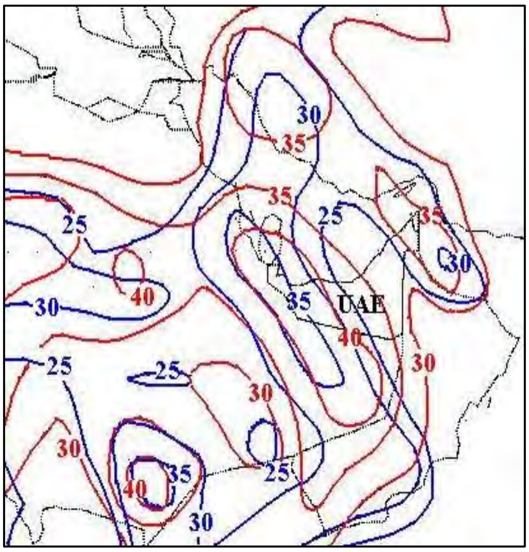

Figure 8.25. Wind shear from the surface to 500 hPa (red lines) and the surface to 600 hPa (blue lines) at 1200 UTC (T+12).

30 to 35 from the surface to 500 hPa were predicted over the UAE, with higher values, up to 40, in the west. Between the surface and 600 hPa (blue lines) values of 25 to 30 were predicted, with up to 35 to the west of the UAE. Marked veering and increased wind speed was also predicted (figure 8.12), although speed increase was only about 25 to 35 knots. Therefore, there was enough wind shear to foster vigorous development, but not enough for a supercell thunderstorm.

8.4.4 SUMMARY

The most important conclusion reached is that the GFS NWP model gave adequate advance warning of the development and passage of a significant baroclinic trough system over the UAE, with thunderstorms. The model also indicated the potential for the thunderstorms to be severe. Considering this desert region and infrequency of thunderstorms, the model prognoses and the derived parameters faired fairly well. The model also predicted the development of the preceding strong southerly winds that gave rise to a dust storm.

Meteorological parameters associated with a synoptic scale baroclinic system, such as vertical velocity, divergence and relative vorticity and humidity, also correctly indicated the development of convection in the south-westerly flow ahead of an advancing trough. Instability indices, notably the K Index, Lifted Index, Total Totals Index and Showalter Index, all served to warn that thunderstorm development was imminent and significant, although, the Total Totals Index and Showalter Index indicated convection spatially slightly to the west of the area where the maximum development occurred. The elevated dry line and

600 hPa moisture shear gave a clue to the potential for strong and gusty wind conditions as did the instability of the 700 hPa to 500 hPa lapse rate.

This convective system had all the ingredients to produce heavy rain described by Membury (1997). Namely, low level flow anticyclonic flow of moist air advected from the Arabian Sea with upward motion under a strong jet stream ahead of an eastward moving mid-tropospheric trough. Under more favourable conditions, that is, greater instability and higher humidity, this system could well have produced the copious rain mentioned in his study when a slow moving trough system produced 131 mm at Dubai and 283 mm fell at Khasab in December 1995.

8.5 SUMMER THUNDERSTORM: 7TH SEPTEMBER 2003

8.5.1 INTRODUCTION

In summer an area of surface low pressure exists over Arabia, the Arabian Sea and across to northern India, which is a trough extension of the summer heat low pressure area centred over the Asian continent (Rao, et al 2003). This generates the general south-west Monsoon flow (the Khareef) over southern Arabia toward the Indian continent, seen here in the surface analysis at 0600 UTC on the 14th August 2003 (figure 8.26), that is, nearly a month earlier than the case study about to be discussed.

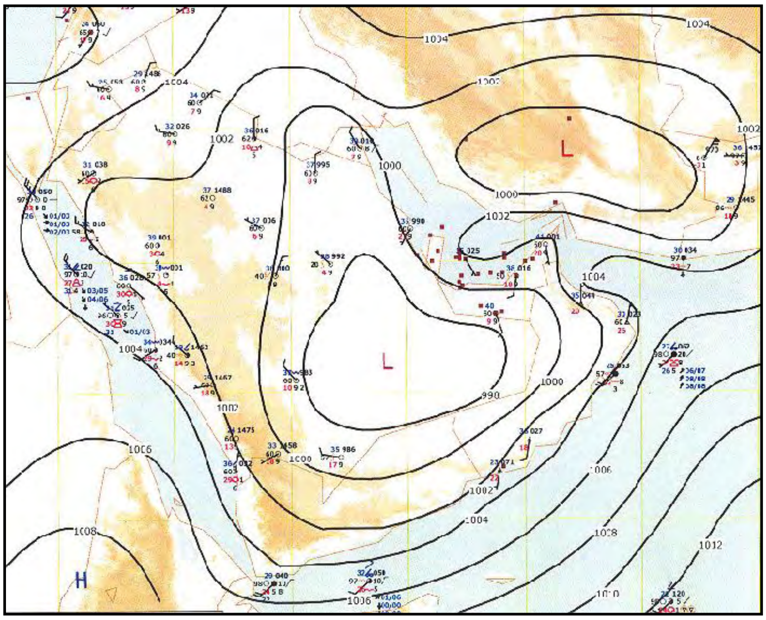

Figure 8.26. Surface analysis at 0600 UTC on the 14th August 2003.

Above 700 hPa a well developed anticyclonic circulation over northern Arabia replaces the winter westerly circulation over the region with a summer easterly to north-easterly flow, particularly at 500 hPa and 300 hPa (Hastenrath 1985). The anticyclone maintains strongly stable and subsiding conditions (UAE Climate 1992, Garbell 1947). Summer thunderstorms are triggered by the Hajar Mountains protruding into this easterly flow. The mountains being both an elevated diurnal radiation heat source and causing topographic uplifting as the air is forced to rise over the mountains (Bradbury 1989). The thunderstorms that develop are then steered to the Gulf coast by the 500 hPa easterly steering winds (UKMO 1997). This is particularly so when a low pressure cell, or easterly wave, migrates from east to west from the Arabian Sea over the Gulf of Oman and then over the Emirates.

The Hajar Mountains are subdivided into the north-south oriented Western Hajar Mountains in the north and the north-west to south-east oriented Eastern Hajar Mountains further to the south-east in Oman. The thunderstorms that form on the Western Hajar Mountains are the ones that influence the weather over the UAE.

8.5.2 GFS NWP MODEL

On the 7th the GFS NWP model indicated that thunderstorms were a distinct possibility. Low level moisture advection was indicated within an area of higher 850 hPa potential temperature and 700 hPa upward motion (figure 8.27a). All were concentrated over the mountains and northern Oman. Other parameters concentrated in the same area and favourable for development were the Total Totals index, the K index (figure 8.27b) and the Showalter index (figure 8.27c). Due to the parcel method used by the Showalter Index this product always indicates raised negative values over the warm Gulf Sea and these are ignored, unless they are supported by other criteria.

Lower winds over the UAE are usually south-westerly due to the thermal low over the Arabian Peninsula (figure 8.26). Ascending, the thermal low is replaced by an anticyclone and the wind backs to north-easterly becoming easterly above 700 hPa. In these conditions, thunderstorms that develop on the mountains slopes would tend to remain there, or drift to the west, or south-west, in these steering winds (Bennetts, McCallum and Grant 1986). The thunderstorms that develop in the north-easterly flow above 700 hPa tend to remain on the Oman part of the mountains, especially where the Hajar Mountain curve to the east and are almost perpendicularly oriented to the upper airflow. On the 7th, the predicted wind circulation at 700 hPa and 500 hPa (figures 8.27d and 8.27d) was 5-10 kn north-westerly and 10 kn northerly, respectively. Therefore, the thunderstorms were expected to either remain over the mountains, or drift southward away from the UAE to Oman.

Further factors promoting thunderstorm development on the mountains is found in the time vertical motion cross section at Al Ain (figure 8.28). Marked upward vertical velocity is indicated in a south-westerly flow toward the mountains at 1200 UTC on the 7th enhanced by topographic lift against the mountains. Note the veering of the wind to north-north-easterly at 500 hPa. The change in wind direction with height from the surface was very similar to the synoptic situation nearly a month earlier, on the 14th August 2003 (figure 8.26), when isolated thunderstorms also developed on the Hajar Mountains.

8.5.3 RADAR IMAGES

Thunderstorms developed on the western Hajar Mountains from 1000 UTC. The radar images from about 1420 UTC to 1630 UTC (figure 8.29) show the position of isolated cells, some of which had cores of around 40 dBZ. The images also show the most common location of the cells. That is, mainly on the Hajar Mountains in Oman, although they do develop further north into the Musandam Peninsula section of the mountains. Of note, in chapter 6, is the satellite image during the dust storm on the 12th December 2003 that shows the remnants of a thunderstorm on the northern tip of the peninsula (figure 6.33).

These thunderstorms tend to develop after 1000 UTC (14:00 local time) and have usually dissipated by 1500 UTC (19:00 local time). The cells tend, for the most part, to be very isolated and not very intense. Although radar echoes of up to 50 dBZ are not uncommon, it is speculated that dust contamination contributes to the stronger reflected radar signal, as the rainfall measurements often do not reveal heavy precipitation. Observations also indicate that the storms are usually sparse and generate more dust than rain at ADIA.

As is often the case, the storms shown in the radar images were semi-stationary in the vicinity of the mountains. If the steering winds at 700 hPa and 500 hPa are easterly, and the thunderstorms drift toward the Gulf coast, more often than not they collapse shortly after leaving the highlands and Altocumulus and Cirrus anvil remnants drift to the Gulf Sea coast. Evidence of this is the higher incidence of summer thunderstorms at Al Ain, near to the foothills of the mountains, than at ADIA on the coast (figure 8.2). Sometimes they drift to Ras Al Kaimah, Dubai and Sharjah on the west coast and even more rarely, to ADIA. They do not reach the western part of the UAE, that is, most of the Abu Dhabi Emirate.

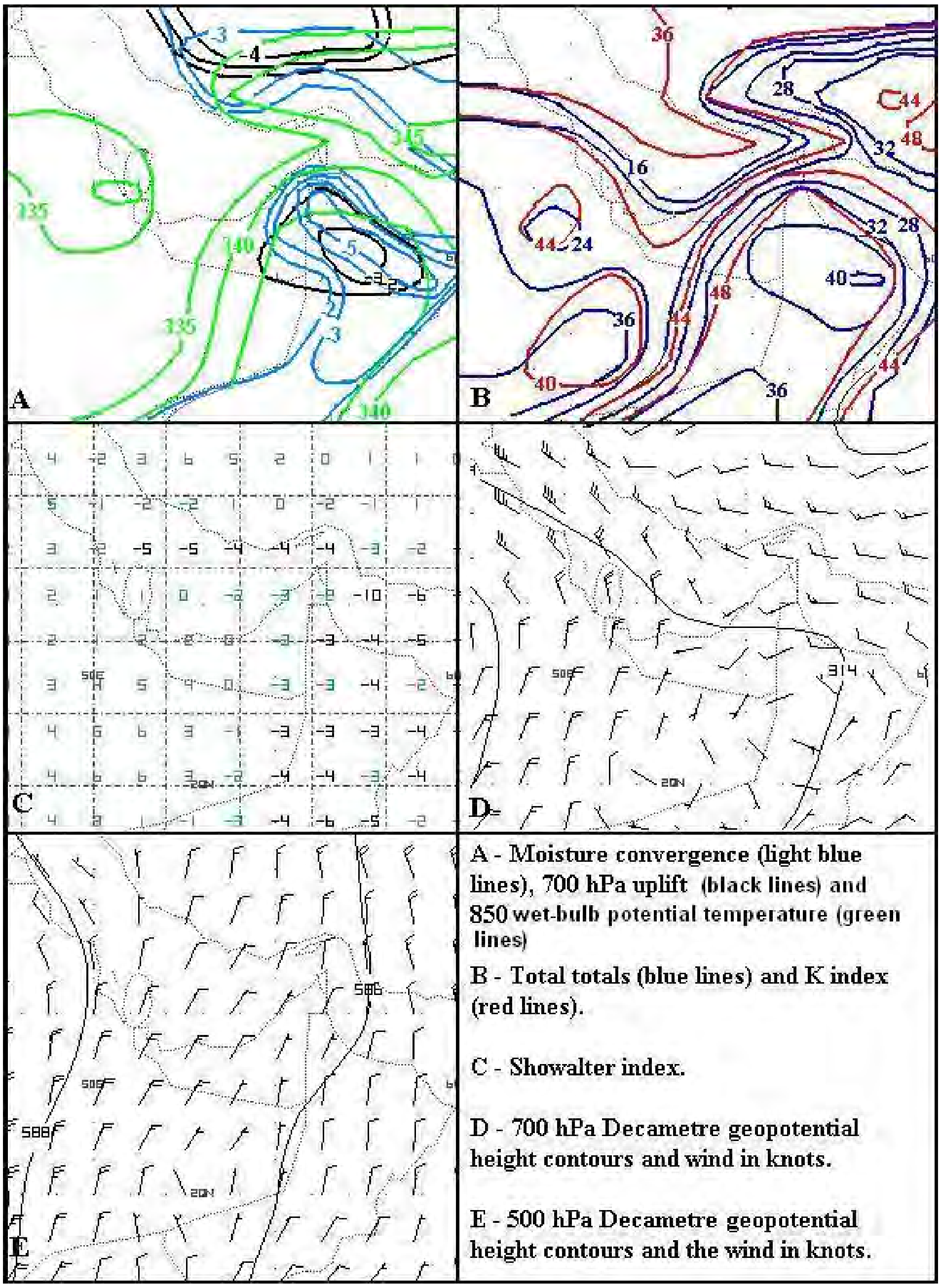

Figure 8.27. Eta NWP model T+12 fields at 1200 UTC on 2003-09-07.

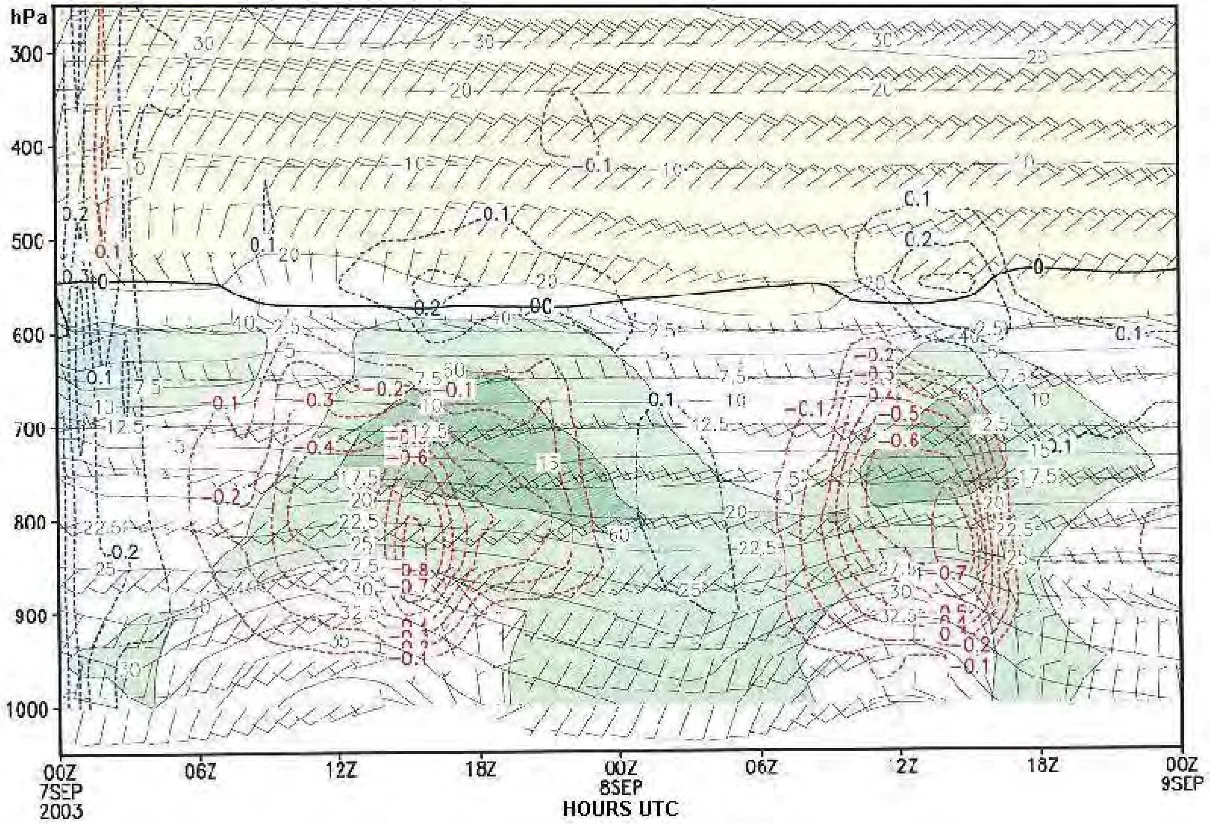

Figure 8.28. Eta NWP model time cross section at Al Ain. The 0000 UTC 2003-09-7 model run indicates marked upward velocity (negative red lines) after 1200 UTC with 60% to 80% relative humidity (dark green) above 800 hPa.

Two isolated cells developed on the higher ground east of and slightly away from the mountain range in the vicinity of Dhaid (figure 8.29). It is suspected that the afternoon sea breeze gust front from the Gulf Sea against higher ground added impetus to their development (Riehl 1978). The development of these cells prompted the forecaster at Dubai to amend the Terminal Area Forecast (TAF) for the airport. In this instance the observed base of the storms was around 1500 metres (5000 ft) AGL and tops were estimated to be about 13716 metres (45000 ft). If thunderstorms are steered by the wind at one third of its base this would be the wind at about 5800 metres (19000 ft), or approximately 500 hPa (UKMO 1997). At this level the forecast and observed winds were north-north-easterly and given the prognostic south-westerly winds lower down (figure 8.28), there was no chance of these storms drifting to the coast. Rather, any movement would be into the desert to the south-south-west. Indeed, figure 8.29 shows that the storms developed and died where they were.

The base height of these storms supported the findings of Al-Brashdi (2007). From a study of 04:00 atmospheric soundings at Seeb Airport, near Muscat in the Sultanate of Oman (figure 2.2), during July 2004, he found that the lifted condensation level (LCL) needs to be below 1800 m above MSL. He also found that the mean mixed layer mixing ratio (ratio of the mass of water vapour to the mass of dry air) must be above 12g/kg in a flow of low level moisture from the Gulf of Oman westward to the surface heat low over the Arabian Peninsula.

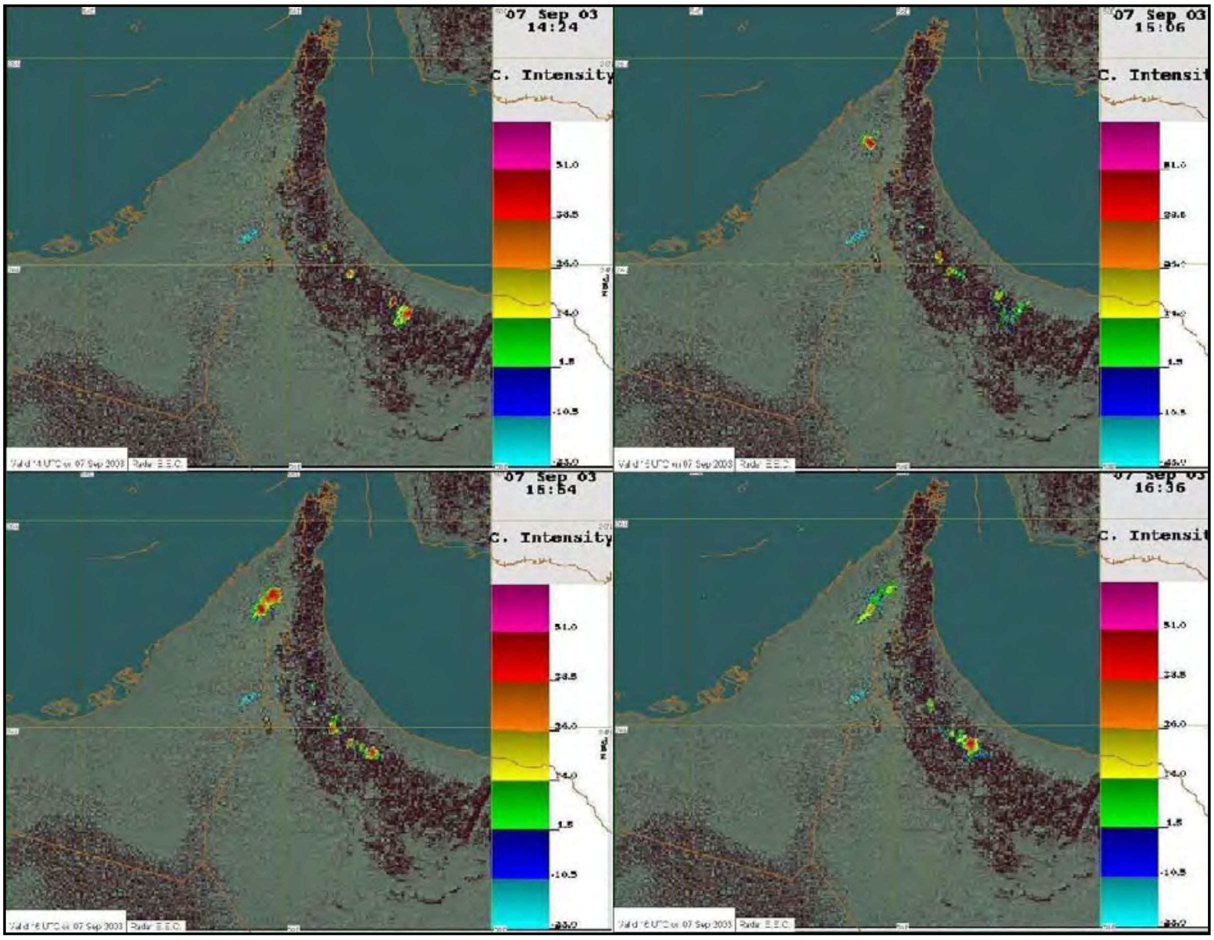

Figure 8.29. Al Ain weather radar PPI dBZ reflectivity images from about 1420 UTC to 1630 UTC, clockwise from the top left, on the 7th September 2003.

8.5.4 SUMMARY

Diurnal thermal heating and topographic forcing of humid air from the Gulf of Oman, in an easterly flow, cause summer thunderstorms to develop in the afternoon on the Hajar Mountains. The thunderstorms develop after 1000 UTC and have usually dissipated by 1500 UTC. They tend, for the most part, to be very isolated and not very intense, although radar echoes of up to 50 dBZ are not uncommon. Rainfall is sparse and the storms usually generate more dust than rain.

The thunderstorms also develop in a north-easterly steering flow above 700 hPa along the eastern edge of an upper air anticyclone situated to the north and west of the UAE. In the UAE these steering winds are around the 500 hPa level. The thunderstorms tend to predominate on the Oman part of the mountains where the mountains are more perpendicularly oriented to the airflow. By virtue of the north-easterly steering winds what little distance they drift, before collapsing, is to the south-west and do not have an effect on the UAE. However, sometimes they develop far enough to the north that they occasionally pass over Al Ain, or close to it.

Sometimes the storms develop far enough north on the mountains in the Musandam Peninsula in an easterly steering wind and the storms to drift to Ras Al Kaimah, Dubai and

Sharjah on the west coast and very rarely, to ADIA. They are more likely at Al Ain, which is nearly in the foothills of the mountains, than at ADIA on the coast. They do not reach the central and western parts of the UAE, that is, most of the Abu Dhabi Emirate.

The GFS NWP model, through fields such as moisture convergence, 850 hPa potential temperature, 700 hPa uplift, Total Totals index, the K index and the Showalter index, gives clear indication whether thunderstorms are likely, or not. Differential relative vorticity advection, which forces upward motion, was not found to be a good indicator as a pronounced upper trough system is not often present. Time cross-sections, such as at Al Ain, provide details of upward vertical velocity and the availability of moisture for thunderstorm development. The wind fields from this product as well as the 700 hPa and 500 hPa wind fields are essential to determine the movement of thunderstorms away from the source region. Particularly whether they will drift eastward to ADIA and Al Ain airport, or drift to the south to south-west into the desert. The weather radar at Al Ain is especially useful for identifying the position of cells and their track away from the mountains.

8.6 TROPICAL DEPRESSIONS

Over the Arabian Sea tropical cyclones, or cyclones as they are known in the region, average 2.3 per year, ⅔ of which occur in the post-monsoon period of October to November and ⅓ in the pre-monsoon period of May to June. Only about 33% of the tropical depressions, found over this part of the Indian Ocean, develop into tropical storms or cyclones (Taha, et al 1981, Koteswaram 1962, Bruintjies and Yates 2003). Tropical depressions are an even rarer event over the Gulf of Oman and the UAE (Martyn 1992), mostly because dry air entrainment from the desert leads to their rapid demise as soon as they move close to the Arabian Peninsula. It is worth noting that Membery (1985) documented a most unusual out of season cyclonic storm that, during August 1985, moved well north of the usual track from the Arabian Sea across northern Oman and the UAE to Rub Al Khali (The Empty Quarter) in eastern Saudi Arabia. The classification of deep tropical depressions and cyclones, by the India Meteorological Department, is listed in table 8.2.

Table 8.2. India Meteorological Department cyclone Classification.

10 minute sustained winds	**Category**
Knots (km/h)	
28-33 (52-61)	Deep Depression
34-47 (62-87 km/h)	Cyclonic Storm
48-63 (88-117 km/h)	Severe Cyclonic Storm
64-119 (118-167 km/h)	Very Severe Cyclonic Storm
≥ 120 (222)	Super Cyclonic Storm

During the period from the beginning of 2002 to mid-2007 only one, classified as a tropical depression (number 01-A) reached the UAE in a much depleted state, but, although it brought some wind damage (Gulf News, 12th May 2002), it did provide welcome rain and one tropical cyclone, 02-A (Gonu) passed close to Muscat.

The tropical depression (01-A) of 2002 had begun to move north-eastward from the Arabian Sea and crossed the coast on the 10th May in the vicinity of Salalah on the south coast of

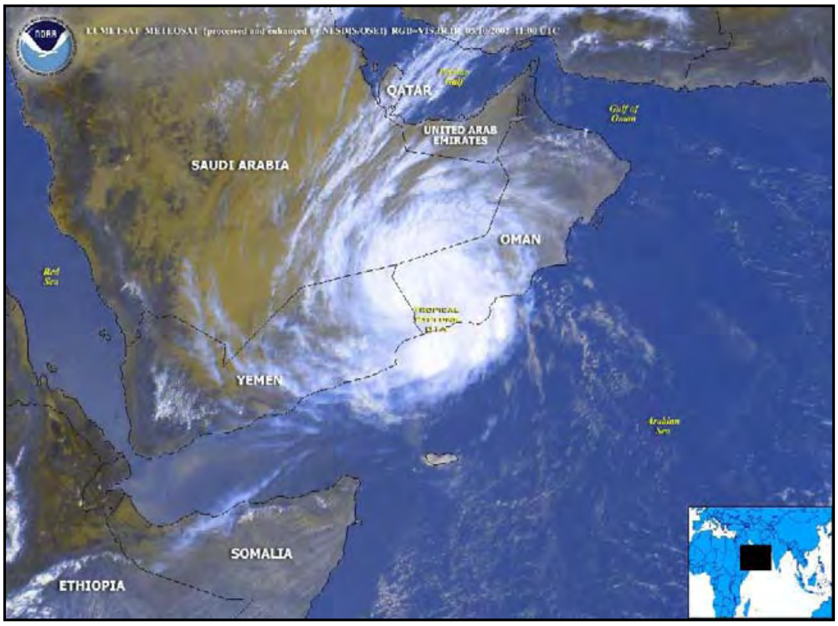

Figure 8.30. Tropical depression 01-A at 1100 UTC 2002-05-10. EUMETSAT METEOSAT image processed and enhanced by NOAA NEDSIS/OSEI. At 0600 UTC it was over southern Oman near 16.5N 56.6E, moving to the NW at 10 knots, with a sustained wind of 40 knots and 50 knot gusts.

Oman (figure 8.30). The wind reached 40 knots (about 78 kilometres per hour) in the Governorate of Dhofar where flash floods killed three people (Gulf News 13th May 2002) and Salalah received about 60 mm of rain. Salalah is on the coast in the south-west corner of Oman. It was immediately west of where the centre of the depression crossed the coast.

In the UAE, the system was preceded by a strong southerly wind that reached 29 knots and reduced the visibility to 600 metres at 1900 UTC on the 10th, followed by a thunderstorm at 2000 UTC. Cloudy weather, mainly in the form of middle layer cloud, with patches of low cloud at 1067 metres (3500 ft) AGL, lasted until 0800 UTC on the 12th. A thunderstorm at 1400 UTC on the 11th brought some rain that lasted until 1600 UTC with another isolated rain shower at 2200 UTC and 0300 UTC to 0500 UTC on the 12th. Cloud, consisting of Stratus patches during the rain, was never lower than 460 metres (1500 ft) AGL.

More recently, on the 6th of June 2007, the centre of tropical cyclone, 02-A (Gonu) passed close to Muscat in the Sultanate of Oman before moving away to the north. This event had very little effect on ADIA, but it is worth mentioning, because it was the first recorded tropical cyclone to enter the Gulf of Oman.

On the 27th May an area of widespread convection was identified on satellite imagery over the south-eastern Arabian Sea and by the 31st it had developed into an organized tropical disturbance with significant cyclonic circulation extending to mid-troposphere levels by the 1st June. It then moved west-north-westward along the south-western edge of a mid-level high pressure situated over north-western India. On the 2nd the Joint Typhoon Warning Center (JTWC 2007) classified it as a Tropical Cyclone 02A. At this time it was 685 km south-west of Mumbai, India and the India Meteorological Department (IMD, 2007) graded it a Cyclonic Storm named Gonu (which means a bag made from palm leaves in the Maldivian language). By the 3rd a typical and well defined eye developed in Gonu, which was clearly seen on satellite imagery and the IMD classified the storm as Very Severe Cyclonic Storm Gonu. It reached its maximum intensity late on the 4th and early 5th with an estimated central surface pressure of 920 hPa and a maximum one minute sustained wind of 135 knots (250 km/h) gusting to 165 knots (306 km/h). It was now classified as Super Cyclonic Storm Gonu by the IMD. However, later on the 5th it was downgraded to a very severe cyclone as it weakened due to the increased entrainment of dry desert air from the Arabian Peninsula, as well as moving over cooler water that decreased the latent heat available from the ocean (Gray 1968, 1979, Bowditch 2002). At this time the steering mid-level high pressure cell had moved to central India and a second high pressure cell was positioned over the Arabian Peninsula. This combined with a mid-latitude trough approaching to the north of the UAE, created a trough between the high pressure systems and this meant that the cyclone was now steered in a north-westerly direction. So that instead of following the original predicted track over Sur and then inland to the west of Muscat, it eventually passed seaward to the east of Sur and Muscat on the 6th (figure 8.31). By the time it passed about 96 kilometres to the east of Muscat on the 6th it had been downgraded to a severe cyclonic storm with the maximum sustained wind down to 70 knots (130 km/h) gusting to 85 knots (157 km/h) (figure 8.32). Early on the 7th, as it neared the coast of south-eastern Iran, increased land interaction and increasing vertical wind shear (Gray 1968, 1979) took its toll and the cyclone had weakened to 25 knots (46 km/h) maximum sustained wind gusting to 35 knots (65 km/h) and it was reclassified as a tropical depression (JTWC, 2007).

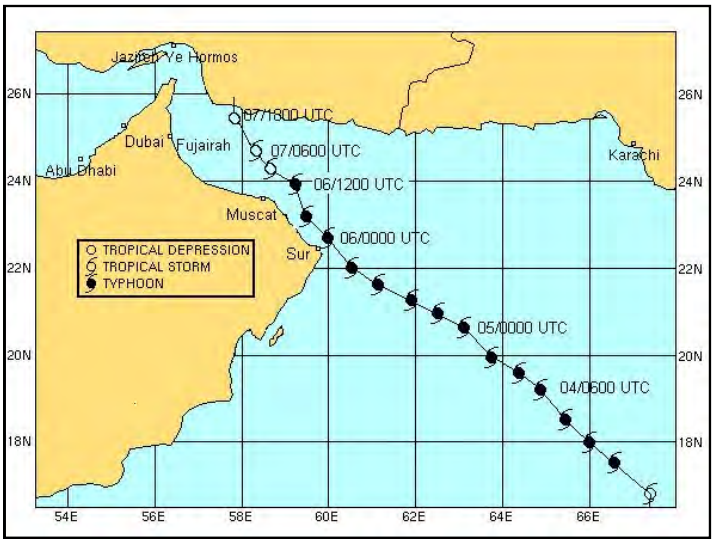

Figure 8.31. The track of Cyclone 02-A Gonu from data supplied by the Joint Typhoon Warning Centre.

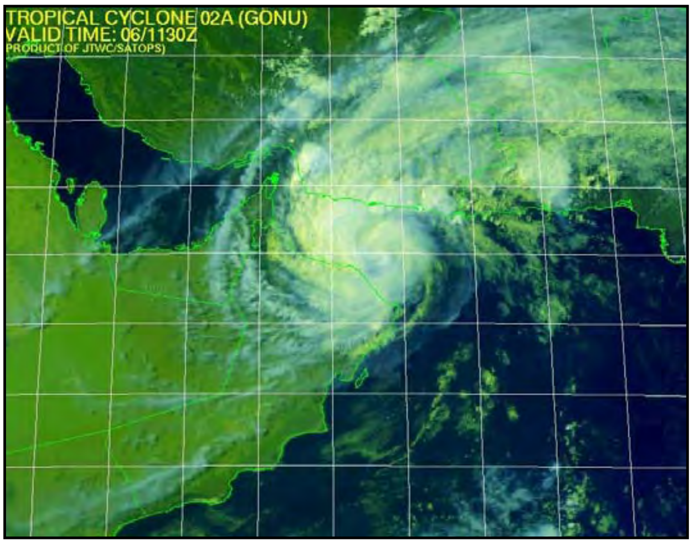

Figure 8.32. Cyclone 02-A Gonu in the Gulf of Oman and passing Muscat (Image courtesy of the Joint Typhoon Warning Centre).

At its peak the maximum significant wave height was estimated as 43 feet at 0000 UTC on the 5th, but by the time it passed along the Oman coast on the 6th it was estimated to be 28 feet decreasing to 26 ft (JTWC, 2007). Nevertheless, the still strong wind and heavy sea caused flooded coastal roads with power and telephone failure across the eastern part of Oman northward from Sur. At Muscat's Seeb airport the visibility was reduced to 300 to 500 metres in rain and thundershowers during the afternoon and evening of the 6th. The wind averaged between 25 to 30 knots with 45 to 50 knots gusts and a total of 70 millimetres of rain fell in the 18 hour period up to 1800 UTC on the 6th. 32 people were reported dead. The airport was closed for about 24 hours. Fortunately, little damage was done to the nation's oil fields and the oil exporting harbour was closed for only 4 days (Arabian Business 2007).

In the UAE along the Fujairah coast some light rain fell, but the storm surge forced water ashore and roads were closed, such as the coastal road between Kalba and Fujairah. ADIA to the west of the Hajar Mountains was far removed from the action and at its worst experienced a north-easterly to northerly wind that reached 20 knots and caused blowing sand to reduce the visibility to as low as 2000 metres between 1000 to 1200 UTC. At Al Ain the wind reached 19 knots from the north-east with the visibility reduced to 4000 metres in blowing sand.

8.7 FORECAST CHECKLIST

Use of the GFS NWP model post processing products give ample warning of impending rain bearing trough systems and tropical depressions and greatly facilitated the means to predict thunderstorms. Satellite, radar imagery and observational data are vital to pinpoint and track these storms after they appear.

Important general considerations:

- Rain bearing baroclinic upper air troughs occur in winter.
- Their associated weather usually last less than 24 hours, but may rarely persist up to 4 days.
- Rain, from Ac and As cloud, is usually light and isolated. Heavy rain does occur, albeit rarely, from isolated thunderstorms.
- Primary indicators are the 700 hPa and 500 hPa relative humidity and upward (negative) vertical velocity fields.
- Tropical depressions are extremely rare and move from the south-east over Oman and the eastern Empty Quarter.

Winter Thunderstorms:

- A baroclinic trough system advancing from the west.
- Low level moisture, advected from the south to south-east, reflected by increasing moisture at 850 hPa.
- Increasing middle atmosphere upward motion accompanied by increasing 700 hPa and 500 hPa relative humidity.
- Plumes of cyclonic relative vorticity along an upper air trough axis, near a clear slot indicated by the Meteosat Geostationary Satellite water vapour (0.62 micron) channel.
- The presence of an elevated dry line at about 600 hPa.
- Steep ambient temperature lapse rate in the 850-700 hPa layer (indicative of surface wind gusts and potential microburst).
- Raised instability indices, such as KI (>30), Total Totals (>44), Lifted (<-3) and Showalter (-3 to <-6).
- Steep ambient temperature lapse rate in the 700-500 hPa layer (potential hail development).
- Wind direction veering with height and speed shear (25-30 kn) with higher values indicative of possible Supercell development.

Summer Thunderstorms:

- A low level easterly wave moving westwards from the Gulf of Oman.
- Deepening Arabian Peninsula heat low.
- Lower level moisture moving from the Gulf Sea towards the Hajar mountains. (Mean mixed layer mixing ratio ≥12g/kg and LCL <1800m above MSL.)
- Upward motion below the 800 hPa level identified by time cross sections of predicted vertical motion.