CHAPTER 4

FOG

4.1 INTRODUCTION

Fog is defined as occurring when water vapour in the atmosphere condenses into minute water droplets and the horizontal visibility falls below 1000 metres (UKMO 1991). Fog that reduces the visibility to the point where aircraft have to divert to another airport is not uncommon at ADIA. Over the period 1982 to 2003, the average annual frequency of fog at ADIA was 38 nights a year, the highest being 56 days in 2000 and the lowest, 23 days in 1992.

Until recently, the airport was equipped with a CAT IIIA Instrument Landing System (ADAC 2009a). This means that aircraft could land with a minimum runway visual range (RVR) of 200 m and 0 m decision height, or put another way 0 m cloud base or vertical visibility, provided the pilots are currently qualified and the aircraft is suitably equipped (table 4.1). However, from 2009 ADIA now has CAT IIIB capability, but, for technical reasons, is limited to 125m RVR (ADAC 2009a). RVR is the greatest distance that runway lights can be seen in the direction of landing, or take-off, along the runway as seen from the centreline at the point of touchdown at the average eye-level of the pilot (UKMO 1994). At ADIA RVR is electronically measured by equipment alongside the touchdown point at each end of the runway with another sensor at the centre point. This distance is usually further than the minimum non-directional distance that can be observed with the naked eye.

Table 4.1. Instrument landing system (ILS) criteria. Note, pilots must be suitably (and currently) qualified and the aircraft fitted with certified ILS equipment and autopilots operative.

ILS Category	CAT1	CAT2	CAT3A	CAT3B	CAT3C
Decision height in feet (metres)	200 (60)	100 (30)	0	0	0
Minimum runway visual range in metres	550	350	200	50	0
Or minimum visibility in metres	800				

Diverting flights to another airport due to below limit visibility results in considerable cost to airlines. The extra expense includes fuel used and hotel accommodation for the passengers. Flight and cabin crew can become duty time expired and by law may not fly again until they have been off duty for a specific period of time. Furthermore, passengers still have to get to their desired destination. When inclement weather is forecast by law civil aircraft must carry more fuel. This results in extra weight and therefore extra fuel consumption and lower profit for the flight. If cargo carried has to be decreased as a result, this will further decrease profit. Diverted and delayed flights also have a disruptive effect on the airport concerned. ADIA, the capital city's airport and Dubai International Airport, are important gateways to the United Arab Emirates. During 2008 there were over 93 163 aircraft movements at ADIA with 9 016 900 passengers and 353 820 tonnes of cargo processed (ADAC 2009b). Dubai airport in 2008, processed 37 441 440 passengers and 1 824 991 tonnes of cargo from more than 313 600 aircraft movements (Dubai International Airport, Department of Civil Aviation, 2009).

Many flights to ADIA originate from places up to ten hours flight time away. Added to this the flight dispatcher does the flight planning at least an hour before departure time. Fog is most common between 0300 to 0900 local time (2300 to 0500 UTC), so the best possible forecast, and fog warning, needs to be available by 1600 to 1800h. The latest available 24 hour terminal area forecast (TAF) would be the 1200 to 1200 UTC TAF, which is issued 6 hours before the valid time at 1000h or possibly the 1800 to 1800 UTC TAF issued by 1600h. This means that the latest available forecast could be 23 or more hours old by the time aircraft is due to land, or at best, at least 11 hours old for the later TAF. Aircraft such as the Airbus A340-500 have an endurance of up to 19 hours with Singapore Airlines making 18-hour non-stop flights between Singapore and New York (Airbus Industrie 2006). Since the 5th November 2008 the lead-time for forecasts issued at ADIA has been even longer, due to the introduction of 30 hour TAFs (ICAO 2007).

Better understanding of the conditions that cause, or accompany fog, or prevent it, will result in more accurate fog forecasts, less false alarms and earlier warning of the onset of fog. This will in turn result in improved flight planning by the airlines operating in and out of the airport, increased profit and improved preparedness on the part of the relevant airport authorities.

4.2 SCOPE OF THE STUDY

The weather conditions when fog occurred at ADIA during the 22 years from 1982 to 2003 are examined by means of a statistical analysis and case studies. This data set allowed the investigation of some local myths surrounding fog forecasting and at the end a proposed a methodology for forecasting fog at ADIA is presented.

A fog event, by meteorological definition, occurs when the horizontal visibility falls below 1000 metres (Roach 1994, UKMO 1991). Fogs observed in the close vicinity to the airport when the visibility remained ≥1000m have not been included in this study.

4.3 METHOD

The fog events were researched using surface observations at ADIA, as well as 1200 UTC and 0000 UTC atmospheric soundings at ADIA as well as Eta GFS NWP model data.

551 fog events at ADIA were used in the statistical analysis. 31 fog events during 2002 to 2003 were researched and includied 56 atmospheric soundings on most afternoons prior to the fog event and the early morning in question. During the two years of 2002 and 2003, 20 events, when fog was not expected and did not occur were also analysed for comparative purposes.

4.4 FOG PRODUCING PROCESSES

4.4.1 FOG TYPES

Most fog forms when the air in contact with the earth's surface cools and becomes saturated with respect to water. The two main types of fog being due to:

i Ground heat loss due to outgoing radiation (radiation fog).

ii Warmer air streaming over a colder surface (advection fog).

Other fog types are:

i Adiabatic cooling to saturation due to the expansion of air moving upslope under stable conditions, resulting in adiabatic cooling and saturation (upslope fog).

ii Frontal fog. This occurs when precipitation from warmer air falls into cold and stable air below and saturates the layer

iii A form of advection fog also occurs when cold, dry and stable air flows over a considerably warmer water surface (steaming fog).

iv The mixing of two slightly unsaturated air parcels at different temperatures, resulting in saturation (UKMO 1997, Roach 1994).

Most of the UAE is below 1500 feet, apart from at Al Hajar Mountains in the east, so upslope fog is not an important form of fog production. Due to its tropical position frontal fog is also, at most, a rare occurrence. The same applies to steaming fog.

In spite of the dominant fog forming mechanism, fog is rarely produced by a single process, but rather by any combination of the above, although one of them may be dominant (Petterssen 1956). Due to dry desert conditions next to the warm Gulf Sea, fog formation in the UAE is usually a combination of advection and radiation processes. Warm and moist Gulf Sea air is advected by the afternoon sea breeze and radiation cooling from the desert surface does the rest.

Radiation fog is most likely to occur when surface winds become calm, or light (below 7 knots at 10 m), with a clear sky (or limited to thin high cloud) and dry air above a moist boundary layer of about 350 feet (about 100 metres) and a weak pressure gradient. Anticyclones often cause weak pressure gradients suppressing the surface wind with stable atmospheric conditions due to subsidence and clear sky that promotes surface outgoing long wave radiation and cools the lower layers of air. A light wind enables the correct amount of turbulent mixing to take place, spreading the saturated layer through several metres, preventing all condensation to take place in the form of dew (UKMO 1994, UKMO 1997, Ricks 1981, Taylor 1917). Fog events are rarely associated with a cyclonic circulation.

Nocturnal radiation fog, over land with relatively windless air, is further encouraged to develop when the air has been previously moistened by rain or wet ground (Petterssen 1956, Xinmei, Lyons and Pitts, 1990).

The advection of warmer air over a colder surface, followed by nocturnal radiation cooling is a frequent combination resulting in the formation of fog (Petterssen, 1956). The formation of advection fog over land "is particularly likely in winter after a cold spell when a supply of milder air arrives from the sea" (UKMO 1997).

4.4.2 RADIATION FOG FORMATION PROCESS

After sunset incoming short wave solar radiation ceases but terrestrial outgoing long wave radiation to space in the atmospheric radiation window (wavelength 10 micron) continues with the result that the ground surface cools rapidly. This in turn cools the air in contact with the ground and creates a shallow surface inversion. When the air in contact with the ground is cooled to below its dew point temperature (saturation point), the excess water vapour in the air condenses on the ground and is observed as dew. The condensation process releases latent heat into this near surface layer and slows down surface cooling (figure 4.1a). If the light wind continues to bring new moist air over the surface and just enough turbulent mixing results to dissipate the latent heat, dew will continue to form. This continual dew deposition, removing water vapour from the air, will prevent fog from forming. The dew point temperature will continue to fall and the air will have to be further cooled before fog forms (UKMO 1997, Brown and Roach 1976, Roach, Brown, Caughey, Garland and Radings 1976).

If the wind drops and water vapour advection ceases, so that the air dries out at the surface due to latent heat release and dew formation ceases, but there remains just enough turbulent mixing, radiation cooling can be carried upward and the air immediately above the ground becomes supersaturated (figure 4.1b). Then a deeper layer of air is cooled to below its dew point temperature, or fog point. Water droplets form in the air and fog begins to form about 20 cm above the ground. It has been noted that initial fog formation occurs when the wind at 2 metres above the ground temporarily drops to 1 knot or less (Galvin 2004, Findlater 1985, UKMO 1997). It is obvious that there is a delicate balance between dew, or fog formation exists.

At first the ambient temperature inversion base remains close to the ground and the density of the fog decreases with height with the colder air at the surface. However, further radiation cooling lifts the temperature inversion and, as the fog thickens, a point is reached where the fog is deep enough to obscure the sky (at about 20 to 50 metres) and prevent infrared radiation cooling at the surface. Instead, this takes place at the top of the fog layer (figure 4.1c). Consequently, the top of the fog layer becomes colder and denser than at the surface. Convection overturning occurs. Turbulent mixing caused by sinking cold thermals and rising warm thermals quickly creates a well-mixed fog with uniform liquid water content (UKMO 1997, Stull 2000, Cotton and Anthes 1989, Korb and Zdunkowski 1970).

Radiation cooling at the top of the fog layer causes further condensation and the fog deepens (Roach 1995). This process lifts the inversion away from the ground with a saturated adiabatic temperature lapse rate below (figure 4.1d). Marked wind shear occurs at the fog ceiling, which is usually about 25 metres above the base of the temperature inversion (UKMO 1997), or 50 metres according to Stull (2000).

Radiation heating from the sun is the main cause of the fog dispersion with clearing from the outer edges inward. Ground heating also warms the lower part of the fog. The relative humidity decreases and droplets begin to evaporate. Heating and turbulent mixing of warmer and drier air at the top of the fog causes the fog to dissolve, as does lowering of the inversion. An increased wind above the fog will entrain dry air into the fog top and the fog will thin. Advection of cloud over the top of the fog is another reason for dispersion. This stops, or reduces, radiation cooling from the top of the fog and droplet settling causes the fog to become thinner. Dry air advection obviously reduces moisture in the air and causes the fog to clear (UKMO 1997).

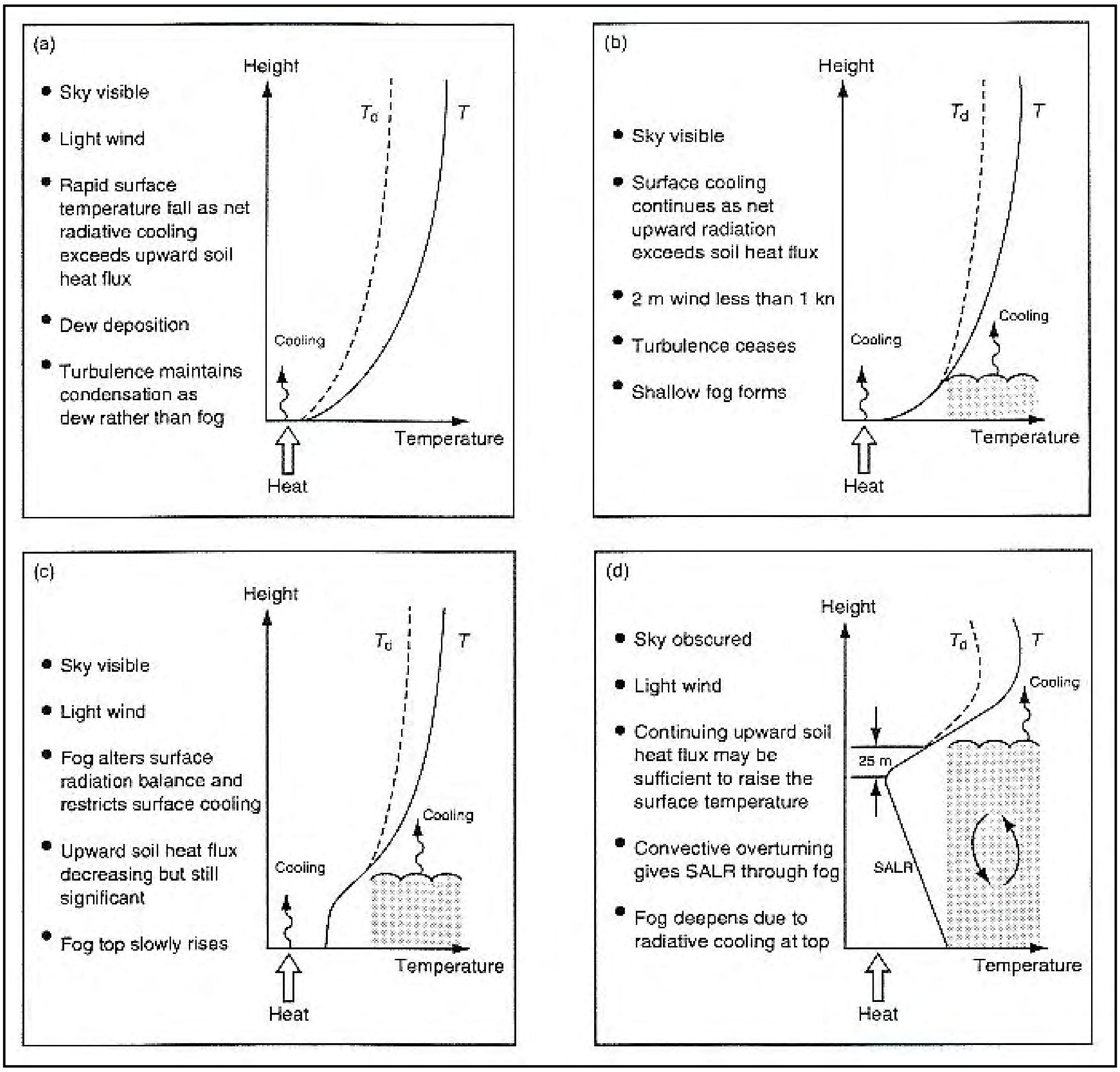


Figure 4.1. The sequence for fog formation taken from the UKMO Source book to the Forecaster's Reference Book (1997).

4.5 STATISTICS

Local rules of thumb for forecasting fog at ADIA abound. These include the relative humidity must be greater than 80% at 1800 UTC for fog to form later in the night; fog always occurs two nights in a row; fog does not form when certain wind directions occur and fog does not occur during full moon. Another is that very hazy conditions during the afternoon are often a precursor to fog later in the night, especially if low stratus cloud comes off the sea and passes inland of the airport. These factors confirm the abundance of hygroscopic particles, which promote condensation near the saturation level (Pruppacher and Klett 2003). Some rules of thumb can be shown to be statistically valid, others logically valid (as above) and others difficult to prove.

With respect to greater than 80% surface relative humidity at 1800 UTC being an indicator of fog, an analysis of all fog events during the 3 years from 2000 to 2002 was made. Results

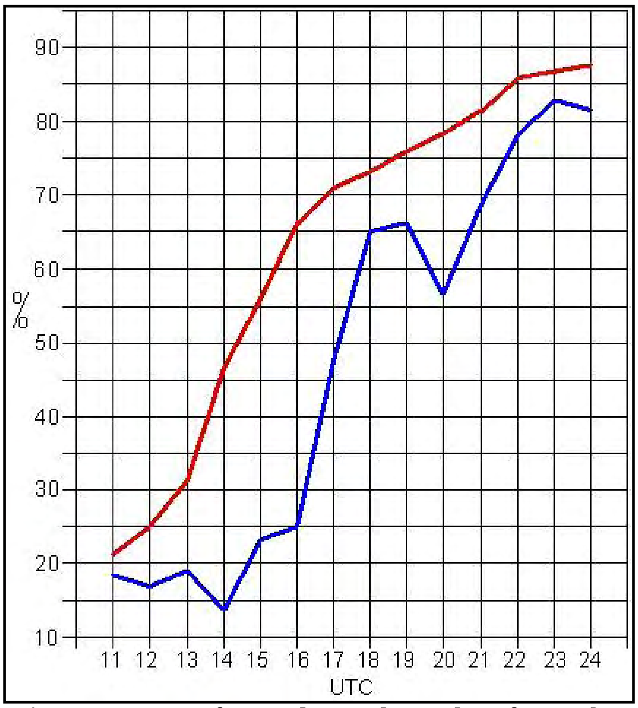


Figure 4.2. Surface relative humidity fog risk. The risk of fog later in the night is ≥90% if the relative humidity at a given time equals, or exceeds, the red line value. The blue line indicates the minimum value when fog has formed later in the night.

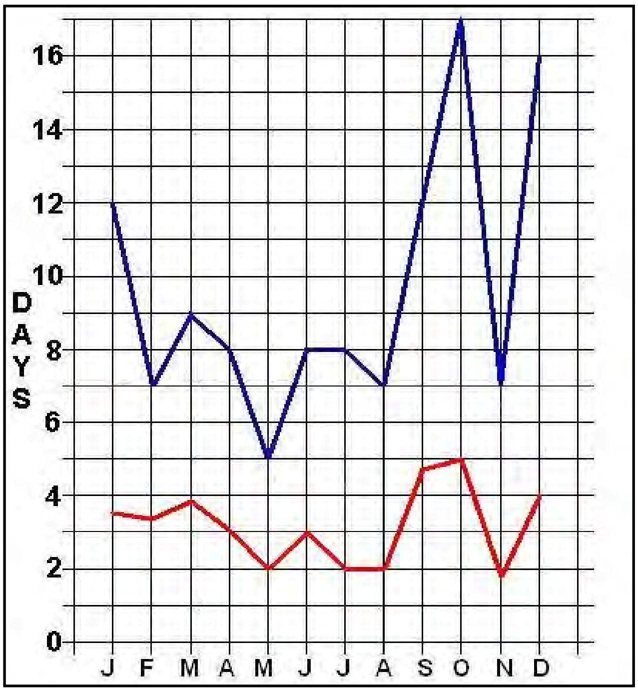


Figure 4.3. The extreme highest days with fog per month (blue line) and mean number of days with mean fog days per month (red line).

indicate that 90% of fog events occurred when the relative humidity was greater than 73% at this time (figure 4.2). Investigation of nights when fog did not occur showed that the relative humidity often exceeded 80% at this time as well. This was specially so during the hot and humid summer nights. Figure 4.2 shows the 90% and higher probability for other times in the night and late afternoon. The minimum relative humidity at a specific hour during a fog night is also shown. The conclusion is that this method can only be used as a short lead-time Nowcast tool.

During the ten-year period from 1993 to 2002 it was found that there was an 18% chance that fog will occur on two consecutive days, 6% that it will occur three days in a row, 2% and 1% for four and five days in succession, respectively. That is, persistence forecasting is practically useless.

The highest frequency of fog occurs in the autumn months of September and October and far exceeds the number of fog days at the end of winter and spring (figure 4.3). Ideally a minimum of 30 years data is needed to determine the climate of a place, but the airport has only been at its present location since 1982. Therefore, the figures may not be entirely climatologically representative. The monthly fog frequency distribution, both extreme and mean values, could possibly have a sinusoidal wave pattern, but they have been distorted by the anomalous October, November and December values, such as 17 days in October 1991, 16 days in December 1998 and 12 days in January 1985.

With longer nights in winter, fog occurs during more hours of the night and more frequently than in summer. During the winter months of January and February 1993 to 2002 (10 years) fog generally occurred between 1800 to 0700 UTC, but most frequently between 2200 to 0500 UTC

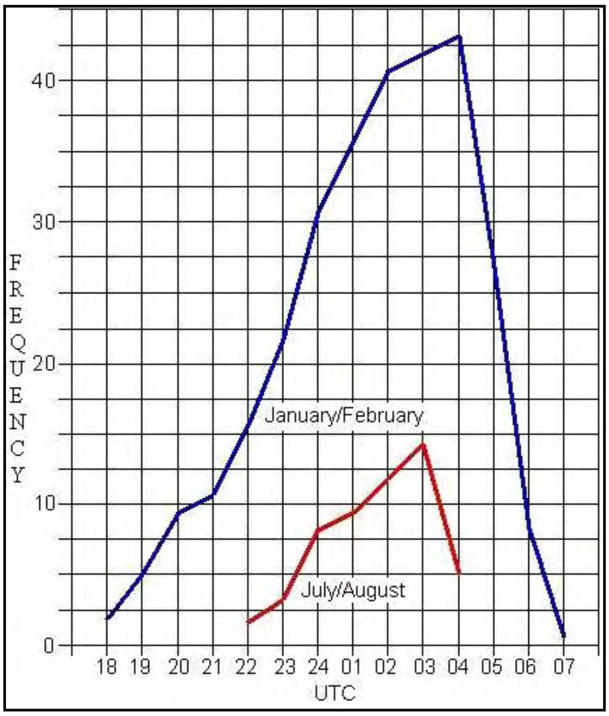


Figure 4.4. The hourly frequency of fog (visibility <1000) metres in winter (upper blue line) and summer (lower red line) for the period 1993-2002. The frequency is higher in winter, begins earlier in the evening and ends later in the morning than in summer.

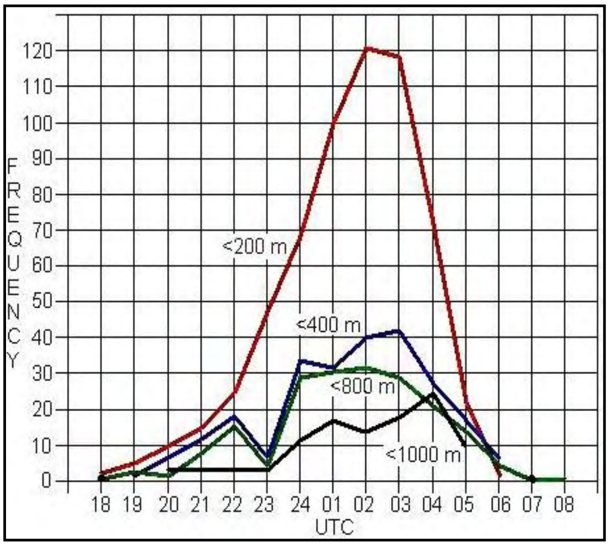


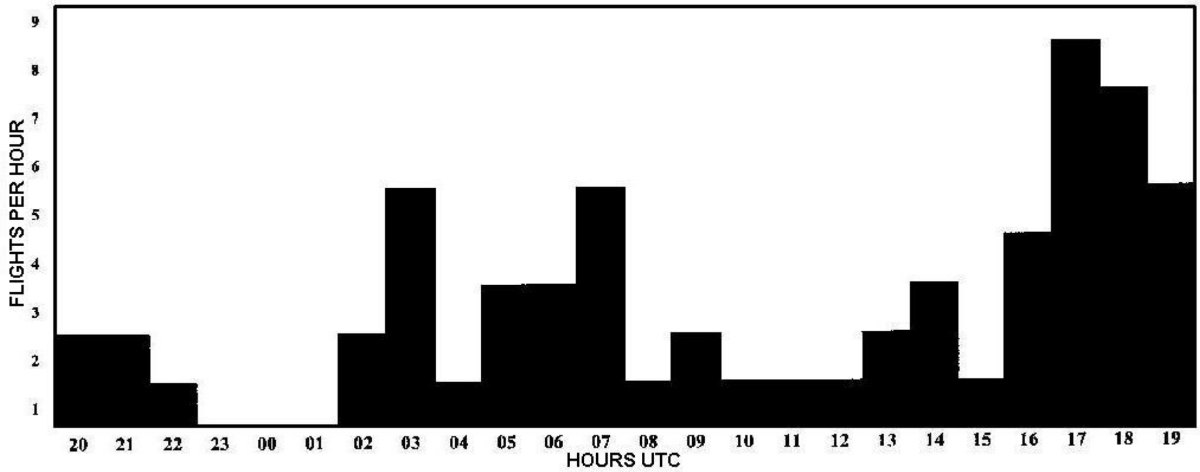
Figure 4.5. The hourly frequency of fog below different visibility levels for the period 1993-2002. 0200 – 0300 UTC) are most often the times of the worst visibility.

(figure 4.4). In summer (July and August) fog occurred between 2200 and 0400 UTC, but most frequently between 0000 and 0300 UTC. These two summer months and two winter months were selected because they are the two hottest and two coldest months respectively.

As soon as a fog event begins the horizontal visibility rapidly deteriorates, often to below the CAT3A ILS 200 m minimum (figure 4.5). This occurred on 54% of the 1166 fog hours in the ten year period 1993 to 2002, or 58% out of a total of 104 fog hours if one considers the visually observed CAT1 800 metres limit. The visibility reduction is particularly apparent between the hours of 2200 to 0500 UTC (figure 4.5). Taken into consideration with the graphs in figure 4.4, fog is a bigger aviation problem in winter than in summer. Airline flight schedule planners take the tendency for fog to occur from about 2200 UTC to 0500 UTC into consideration. Figure 4.6 shows that there is a distinct absence of, or drop in, passenger flight activity between these times. Those that operate later in the period are usually freighters. Unfortunately, some scheduled passenger flights arrive from Europe about 0200 to 0300 UTC. Fortunately, take-off, in poor conditions is less of a problem.

Local lore, with respect to wind change, is that fog forms when the north-westerly wind during the day veers through easterly to south-easterly overnight, becoming light, or calm in the process. Legend also has it that fog is likely to occur after the Shamal has been blowing for a few days and then drops. A Shamal is defined as a north-westerly, or northerly, wind with the hourly mean wind speed at, or greater than, 17 knots for at least three hours in a day (Rao *et al.* 2001).

On the other hand, if the wind backed from north-westerly to a light south-westerly, or a southerly desert track and perhaps south-easterly later, fog does not occur. A study of overnight hourly-observed wind changes during fog events from 2000 to 2003 revealed that the local lore is generally valid. Fog occurred 87% of the time when the wind veered through easterly, with the wind backing through westerly during the



winter schedule.

remaining 13%. The propensity for the wind to veer rather than back is to be expected given the fact that the Coriolis force deflects the wind to the right in the Northern Hemisphere (Bradbury 1989, UKMO 1994). Note, there were no fog events when the wind persisted off the desert from a southerly direction throughout the night.

The wind generally becomes lighter at night, especially during fog events. Inspection of hourly wind observations on 20 nights when fog was expected and did not occur revealed that most often the surface wind blew consistently at about 3 to 6 knots and sometimes higher, irrespective whether it veered or backed. On one occasion when fog did occur, the wind veered from north-westerly to easterly and persisted blowing at 5 knots.

Fog did not occur when the wind persisted from the north-west to north-east. This is most likely during a Shamal when there is an increased pressure gradient between a surface low pressure cell or trough to the north-east, or east of the UAE and a ridge of high pressure situated over northern Saudi Arabia (Membury 1983). Under these conditions the wind is more likely to back to south-westerly over the Emirates at night due to the contribution of the land breeze. On rare occasions fog did occur when the wind backed through westerly (13%). This could happen when the Shamal drops and fog formation is likely. This happened when Abu Dhabi had been subjected to days of persistent moderate to fresh summer north-westerly Shamal wind, followed by 4 nights of fog from the 18 July 2002.

4.6 STUDY OF FOG EVENTS

4.6.1 INTRODUCTION

The conditions, under which fog forms and how its formation conforms to conditions established by research, is demonstrated in the following case study when fog occurred on four consecutive days. Other interesting and important aspects will be demonstrated by presenting more brief examples. The conditions when fog does not occur will also be discussed and examples presented.

4.6.2 FOUR CONSECUTIVE FOG DAYS IN SUMMER: 19TH TO 22ND JULY 2002

This summer fog event details, fog of varying intensity that occurred on 4 consecutive mornings from the 19th to the 22nd July 2002. The fog occurred after days of persistent north-westerly Shamal conditions that induced very humid air to flow southward onto the land from the Gulf, where surface sea temperatures were in the vicinity of 32°C.

4.6.2.1 NWP model data

Eta NWP model data analysis of the 0000 UTC (0400 local time) surface pressure fields indicated that, during the 4 day period, a col with a weak pressure gradient of about 1 hPa, persisted over the UAE. This col formed between a low pressure cell over the Gulf Sea and a semi-stationary low pressure cell over Saudi Arabia to the south of the UAE (figure 4.7a, b, c, d). The surface pressure over the Gulf slowly deepened from 999 hPa to 996 hPa, while inland it changed from about 1000 hPa to 997 hPa. At the 850 hPa and 700 hPa levels the circulation was persistently anti-cyclonic from the north to north-west with the centre of the anticyclone to the west of the UAE (not shown).

4.6.2.2 Surface observations

On all of the nights that fog occurred the onset of the 10 to 15 knots north-westerly sea breeze was between midday and 2 pm during the previous afternoon (0800 UTC to 1000 UTC). This gave ample time for the advection of surface moisture over the coast and adjacent interior (figures 4.8 to 4.11).

Every night fog formed after the wind at 10 metres became light variable, or light east-south-easterly, at 1 to 2 knots. Allowing for the effect of surface friction, it is feasible that the wind temporarily became calm at 2 metres above ground level prior to fog formation. An exception was the night of the 20th to the 21st when the wind blew consistently from the east-south-east to south-east at 3 to 5 knots, briefly dropping to 2 knots at 2300 UTC, over an hour after fog had already formed.

The fog naturally enough began to clear when the temperature began to rise after sunrise and the southerly to south-westerly land breeze picked up and had totally dissipated by 9 am (0500 UTC). Note the air temperature began to rise about two hours after the climate mean time of 0200 UTC indicated on the charts (figures 4.8 to 4.12). Sunrise at this time of the year is about 0145 UTC.

Local lore is that very hazy conditions the previous evening are often a forewarning of fog later in the night and especially so if low Stratus cloud comes off the sea and passes inland of the airport. The logic behind this is that hazy conditions confirm the abundance of hygroscopic particles favourable for condensation. On the first night, during the evening of the 18th (figures 4.8 and 4.9), hazy weather began about six hours before fog formed and the surge of shallow surface moist air was indeed sufficient to generate low Stratus cloud in the late evening between 10 pm and 1 am (1800 to 2100 UTC). On the other evenings the weather became hazy two to four hours before fog formed, except the 20th, which was hazy most of the preceding afternoon as well. These results appear to confirm the local lore, but by the time these factors are confirmed it is too late to be of much use in the preparation of landing forecasts, except in the very short term

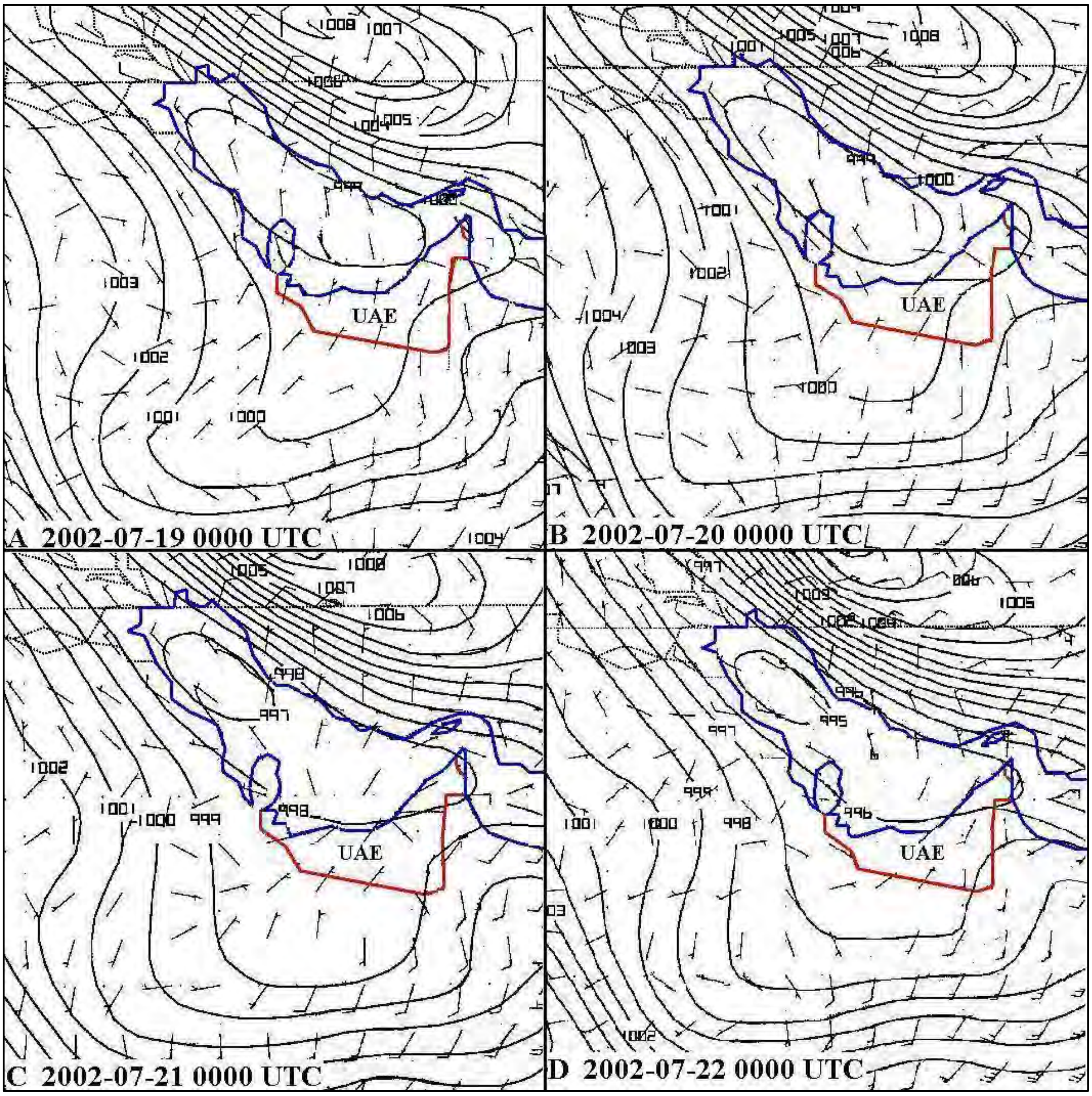


Figure 4.7. Eta GFS T+0 surface pressure and 10 metre wind analysis at 0000 UTC from the 19th to 22nd July 2002. Note a persistent low pressure cell over the Gulf Sea and the typical summer low pressure south of the UAE over the Empty Quarter.

Although fog was in and around the airport from 0000 UTC to about 0430 UTC on the 20th, it was only fully developed at the airport for about an hour around sunrise when the minimum temperature occurred (figure 4.10). This is probably due to the random nature of radiation fog, because the wind was certainly light enough at 3 knots from the east and the air over 95% moist from the surface up to 963 hPa (figure 4.11).

All of the hourly surface relative humidity observations on all four days exceeded the optimum values specified in figure 4.2 and in section 3 and the fog formed when the Stevenson screen relative humidity reached about 95%.

It is also worth noting that fog formed when the air temperature fell to below the maximum dew-

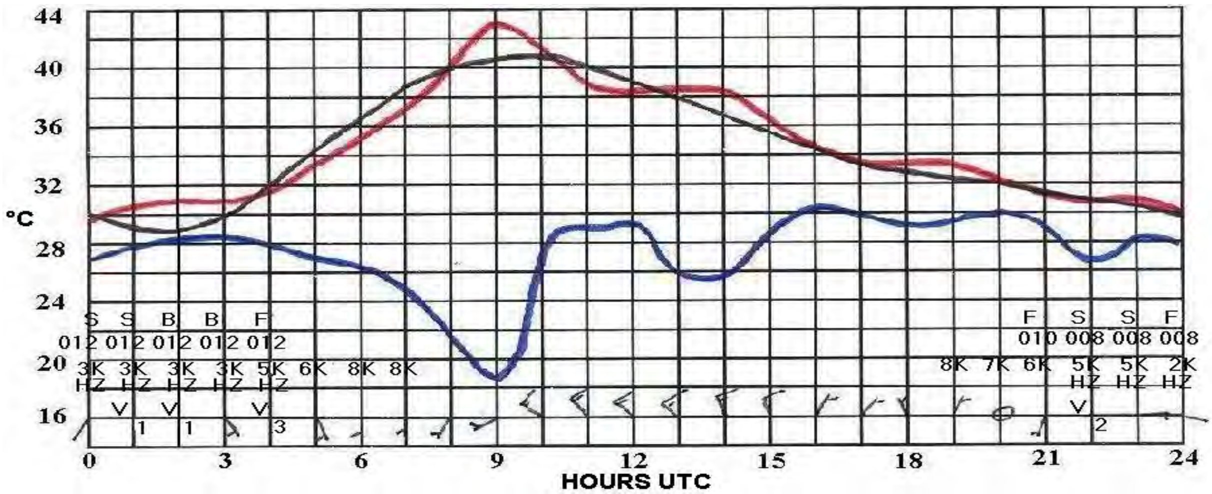


Figure 4.8. Surface observations on 2002-07-18. Air temperature (°C), red line; dew point temperature, blue. The black line is the long term mean derived from hourly observations from 1983 to 2002. Wind in knots. Few (F) scattered (S) and broken (B) cloud at 240 m 370 m (800 - 1200 ft) AGL. Visibility in metres and km. FG = fog, BCFG = broken (patches) fog. VCFG = fog in vicinity, BR = mist, and HZ = haze.

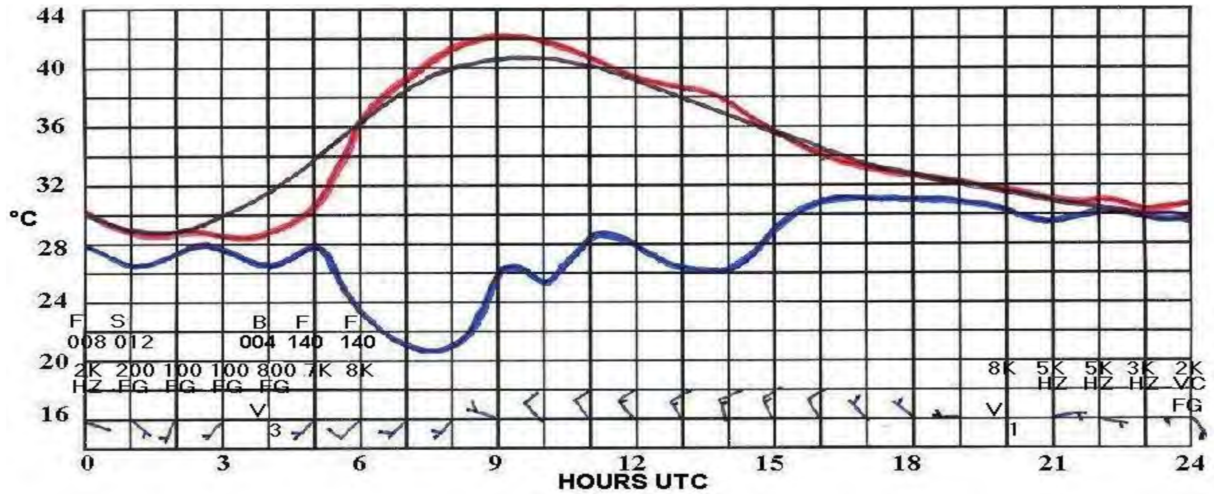


Figure 4.9. As in figure 4.8, but for 2002-07-19. The cloud is at 130 – 430 m (400 - 1400 ft) AGL

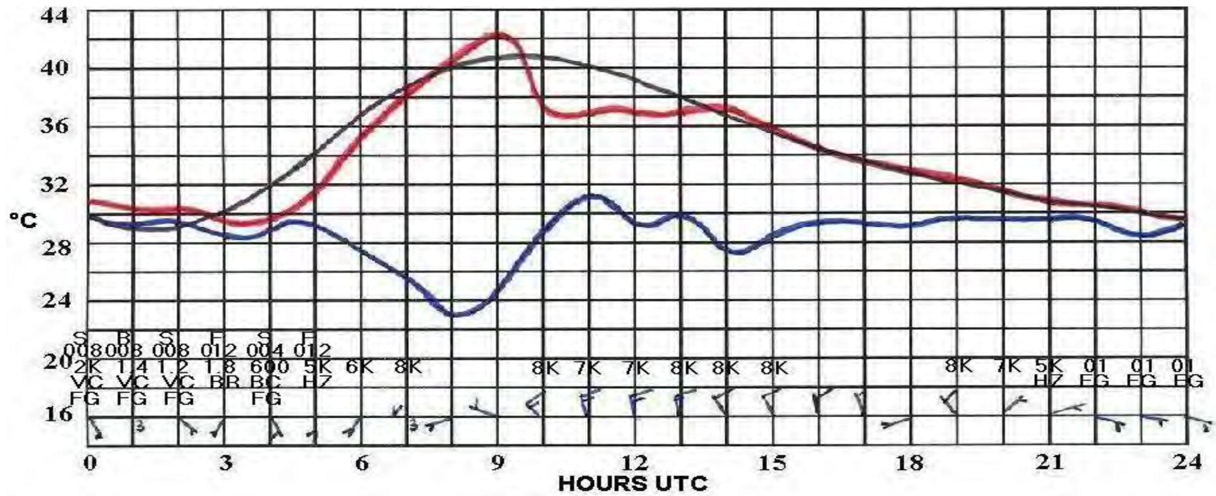


Figure 4.10. As in figure 4.8, but for 2002-07-20. The cloud is at 120 – 430 m (400 - 1400 ft) AGL.

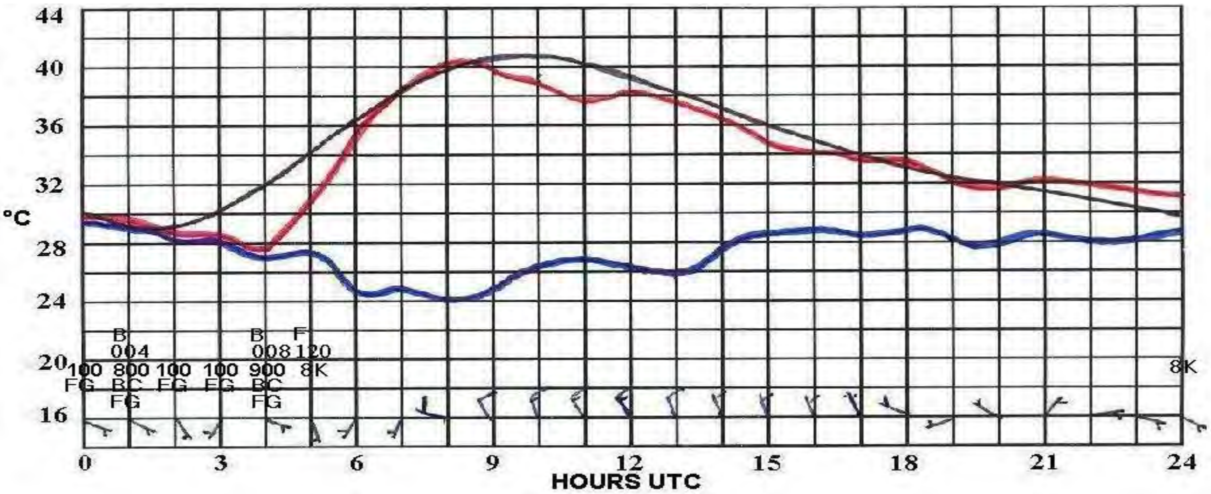


Figure 4.11. As in figure 4.8, but for 2002-07-21. The cloud is at 120 – 370 m (400 - 1200 ft) AGL.

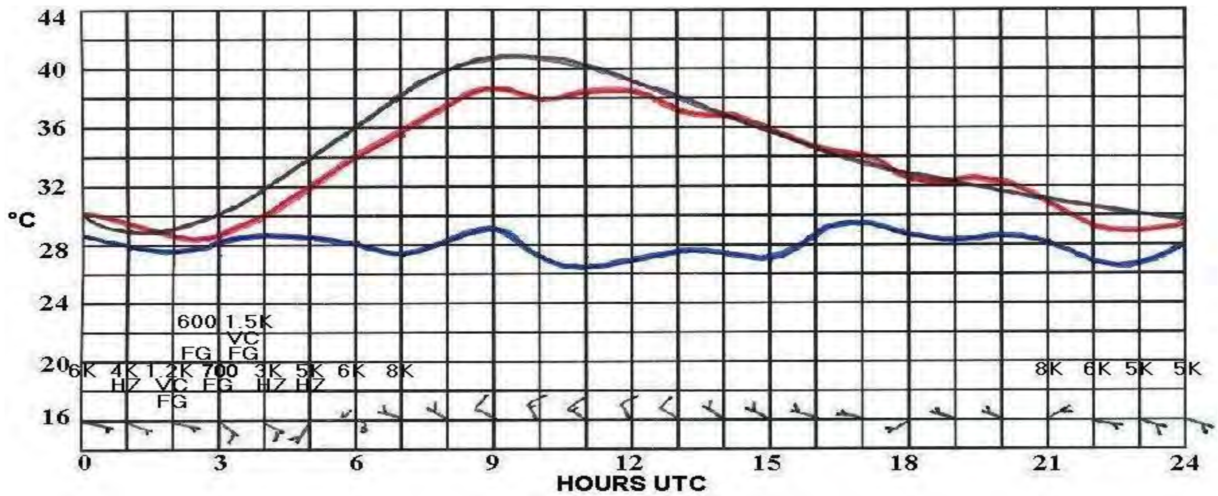


Figure 4.12. As in figure 4.8, but for 2002-07-22.

point temperature that prevailed the previous evening. For example, on the night of the 18th/19th, fog occurred at the airport from 0000 UTC when the air temperature fell to 30°C, which was the maximum dew-point temperature between 1600 UTC to 2000 UTC the previous day. Similar characteristics can be seen on the following nights (figures 4.8 to 4.12).

4.6.2.3 Atmospheric soundings

All of the soundings at 1200 UTC, prior to the fog later in the night, had near surface temperature inversions, indicating the invasion of cooler sea breeze air into an otherwise dry adiabatic temperature lapse rate (figures 4.13 to 4.17). Note; for convenience the soundings have been grouped 5 pages further on at the end of the discussion. Attention is also drawn to the fact that the Eta model vertical resolution is rather course and therefore inhibits the model's ability to reflect boundary layer inversions. As seen in table 4.2, the bases of the temperature inversions varied from 972 hPa to 960 hPa (213 metres to 316 metres AGL).

The afternoon soundings had relative humidity values >50% in the layer below the low-level temperature inversion, with markedly dry air above the inversion. The exception was on the afternoon of the 19th, when the humidity was marginally lower at 44% to 48% (figure 4.14).

North-westerly to west-north-westerly winds of 10 to 15 knots occurred below the temperature inversion, the wind becoming light easterly to north-easterly below the inversion by the time of the 0000 UTC sounding. Wind shear was noted at the inversion level on the mornings of the 19th and the 20th (figures 4.13 and 4.14), but it was absent on the other mornings.

The morning soundings had profiles very similar to the model in figure 4.1c with marked surface radiation cooling induced temperature inversions. The exception being the sounding on the morning of the 20th (figure 4.14), which had a close to saturated adiabatic lapse rate below the temperature inversion that is reminiscent of the profile in 4.1d.

The base of the temperature inversions at 0000 UTC varied from 974 to 958 hPa (201 metres to 323 metres AGL). Bearing in mind that research has shown that the fog top is 25 metres to 50 metres above the base of the inversion (UKMO1997 and Stull, 2000), the fog top probably varied between 251 gpm to 373 gpm (251 metres to 373 metres). Table 4.2 below shows the inversion bases in detail. Is it coincidence that the days with the shortest lived fog at ADIA were also the days with the highest inversion, namely, the mornings of the 20th and 22nd (figures 4.14 and 4.16)?

Table 4.2. Temperature inversion base height from the afternoon of the 18th to the morning of the 23rd.

	0000 UTC				**1200 UTC**			
		MSL	**AGL**			**MSL**	**AGL**	
	HPa	**M**	**m**	**Ft**	**HPa**	**m**	**M**	**Ft**
18					972	240	213	699
19	974	228	201	659	965	317	290	951
20	963	331	304	1000	961	343	316	1037
21	965	300	273	896	960	344	317	1040
22	958	350	323	1060	965	288	261	856
23	992	36	9	30				

During 2002 and 2003 the average base of the near surface temperature inversion on fog mornings was 19 hPa lower than the surface pressure at 987 hPa (171 metres AGL). Atmospheric pressure at the highest inversion base was at 958 hPa (400 metres AGL).

On the 19th, considering that the morning sounding was done about 1½ hours before fog formed it already showed a typical fog profile (4.13). The inversion base was at 213 metres AGL and 201 metres at 0000 UTC. Earlier in the evening and at the time of the 0000 UTC sounding, broken to scattered Stratus cloud was estimated at 430 metres and later at 240 metres AGL. In view of the inversion base, it is doubtful if this observed cloud base was correct. The presence of this cloud drifting in from the sea, prior to fog formation, also suggests that advection played a role in the fog formation at 0030 UTC. It is also worth noting that the 10m wind became easterly to east-south-easterly at 2 knots to 1 knot from 2200 UTC to 0000 UTC. Allowing for ground friction, the wind was most likely dead calm at the surface at these times.

According to Erikson (2001) radiation fog forms with a temperature inversion below 100 metres and the visibility rarely falls below 135 metres. By his definition the fog that occurred on these four days, was predominantly advection fog, because the height of the lowest temperature inversion was above 100 metres and the visibility fell below 135 metres. Except on the 20th and 22nd, days when, although the inversions were at their highest, the visibility was greater than 135 metres at 600 and 700 metres, respectively (table 4.3 and figures 4.13 to 4.17).

Table 4.3. Sounding data up to the temperature inversion level on the fog days 19th to 23rd July 2002. Atmospheric variables are: Pressure, gpm height, temperature, dew point, relative humidity and wind velocity.

PRES hPa	HGHT gpm	TEMP °C	DWPT °C	RELH %	DIRC deg	SPED knot
00Z 19 Jul 2002						
996.0	27	31.0	28.8	88	90	0
995.0	36	29.8	28.2	91	86	0
982.0	155	29.8	28.2	91	29	6
974.0	228	30.0	28.6	92	354	9
972.0	247	31.5	21.3	55	345	10
970.0	266	33.0	14.0	32	341	10
00Z 20 Jul 2002						
996.0	27	30.6	29.9	96	90	3
963.0	331	28.6	28.1	97	21	6
956.0	396	32.8	5.8	19	6	7
950.0	453	36.2	2.2	12	353	7
00Z 21 Jul 2002						
995.0	27	29.8	28.5	93	100	2
969.0	263	29.4	28.7	96	53	4
966.0	291	29.6	24.9	76	47	5
965.0	300	29.4	21.4	62	45	5
963.0	319	30.4	13.4	35	42	5
956.0	384	35.0	12.0	25	29	6
00Z 22 Jul 2002						
993.0	27	30.4	28.2	88	110	3
961.0	322	29.6	27.6	89	94	3
958.0	350	29.6	25.2	77	92	3
944.0	483	37.4	8.4	17	85	3
00Z 23 Jul 2002						
993.0	27	28.8	26.6	88	110	6
992.0	36	28.2	25.8	87	107	6
988.0	72	30.0	28.9	94	97	6
973.0	211	36.4	3.4	13	58	6
968.0	258	37.0	3.0	12	45	6
944.0	487	37.4	0.4	10	340	7

Erikson (2001) also makes a distinction between marine and advection fog, but admits that marine fog is really “another type of advection fog.” From this point of view it can be argued that the fog on the mornings of the 19th, 20th and 21st (figures 4.13 to 4.15) was marine advection fog, because the winds below the temperature inversion were from the north-east to north-north-east.

That is, parallel, or onshore, to the coast. In similar vein, the fog on the 22nd (figure 4.16) must have been land advection fog, because the wind was light east-south-easterly to easterly (table 4.3). In any event, the author believes that there was moist air advection from the Gulf during the afternoon and evening and nocturnal radiation cooling did the rest. The author has also noted that fog tends to form inland of the airport and drift, or expand coastward on the light morning south-easterly wind.

Although fog did not occur on the morning of the 23rd, the soundings at 1200 UTC on the 22nd and 0000 UTC on the 23rd have been included (figure 4.17). The reason is that the temperature and dew-point profile was very similar to those of the preceding four afternoons. It was over 50% moist with 10 to 15 knots north-westerly winds below a temperature inversion at 965 hPa (288 gpm MSL). What changed seems to be that the surface wind remained consistently stronger throughout the night. Although the surface wind veered to east-south-easterly in the evening, it generally blew at 5 to 9 knots from the east-south-east and only momentarily dropped to 2 knots at 2100 UTC. Radiation cooling of the air was, therefore, limited to a very shallow near surface inversion at 992 hPa (9 gpm AGL, or 30 feet) (table 4.3). The wind maintained turbulent mixing and the visibility fell no lower than 5000 metres in haze.

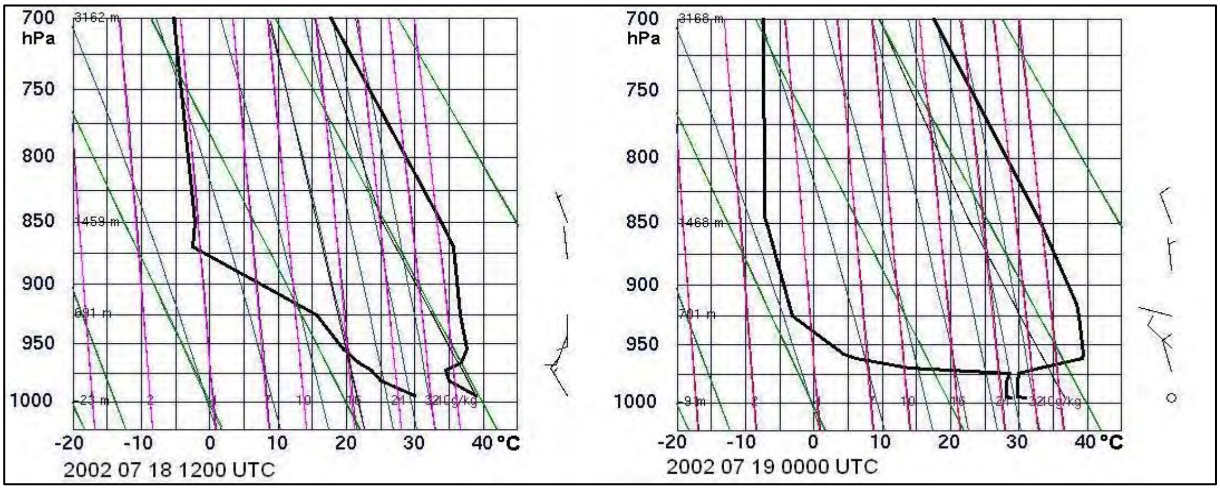


Figure 4.13.Atmospheric soundings at ADIA on 2002-07-18 1200 UTC and 2002-07-19 0000 UTC. The dry adiabatic lapse rate lines re in green and the mixing ratio lines in pink. (Courtesy

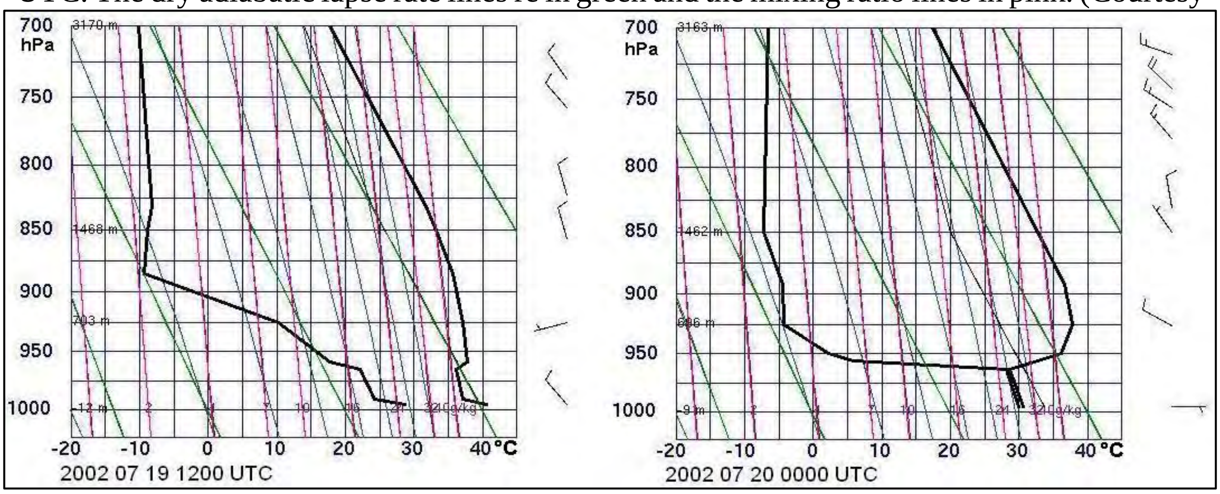


Figure 4.14. As in figure 4.13, but for 2002-07-19 1200 UTC and 2002-07-20 0000 UTC. (Courtesy of the University of Wyoming).

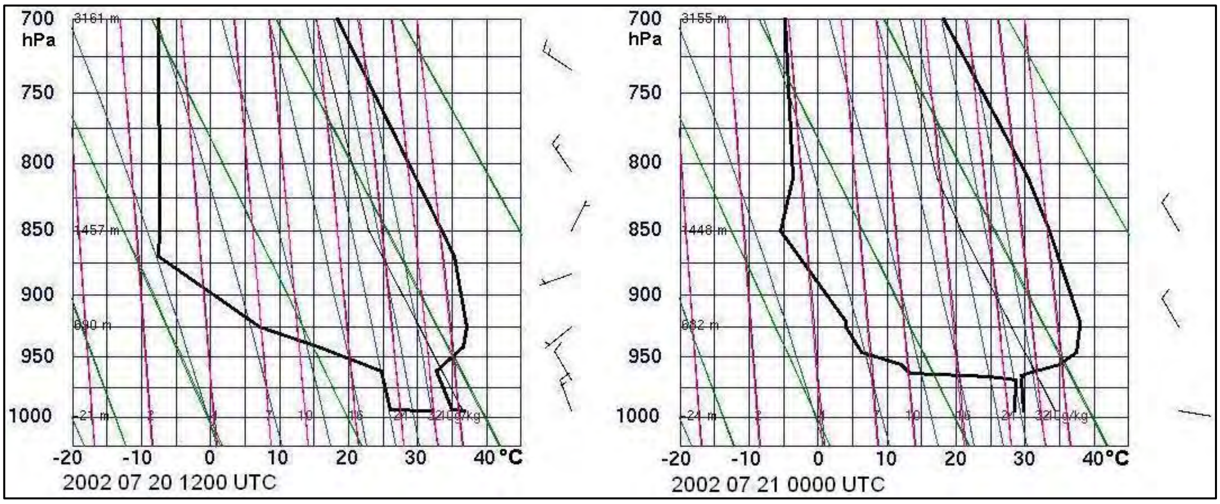


Figure 4.15. As in figure 4.13, but for 2002-07-20 1200 UTC and 2002-07-21 0000 UTC. (Courtesy of the University of Wyoming).

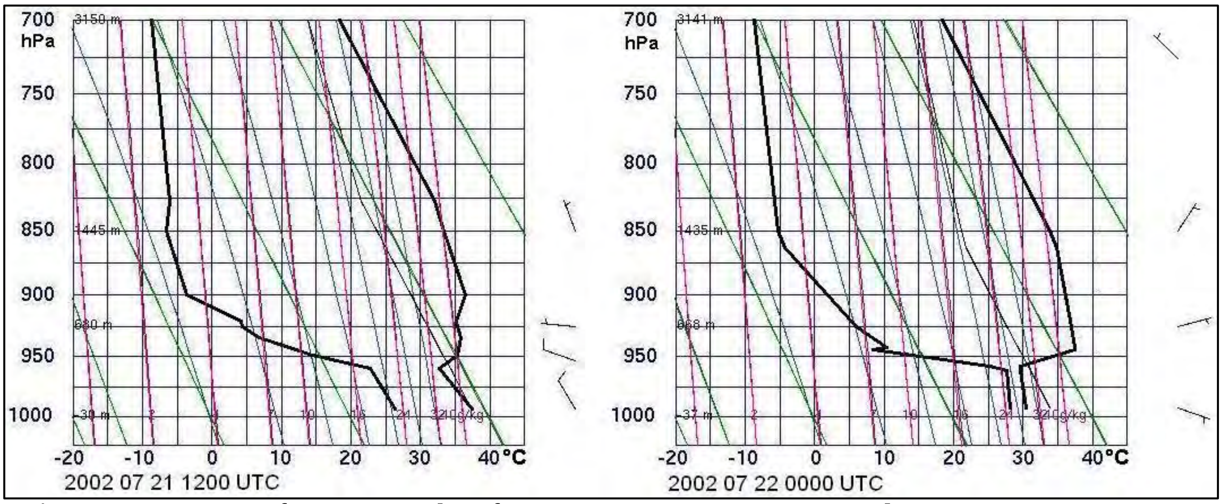


Figure 4.16. As in figure 4.13, but for 2002-07-21 1200 UTC and 2002-07-22 0000 UTC. (Courtesy of the University of Wyoming).

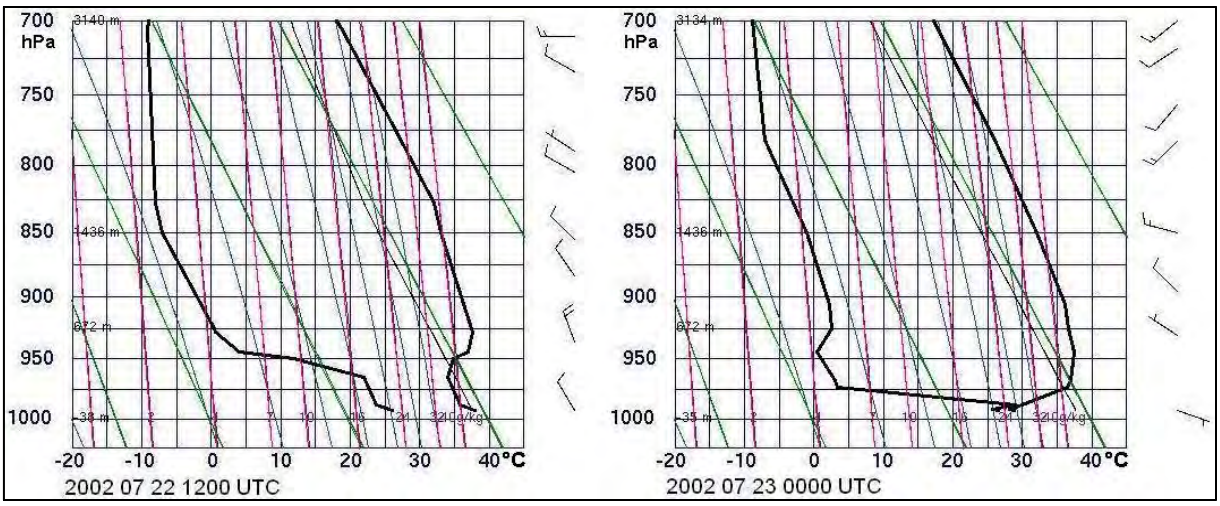


Figure 4.17. As in figure 4.13, but for 2002-07-22 1200 UTC and 2002-07-23 0000 UTC. (Courtesy of the University of Wyoming).

A feature of these soundings (figures 4.13 to 4.17), as well as other soundings detailed in this chapter is the extreme dryness of the air above a temperature inversion. This indicates the presence of a continental anticyclone, strong subsidence (superior air). During summer intense surface heating causes widespread thermal convection and a shallow warm cyclone (or heat low) develops below the subsiding air (Garbell 1947).

4.6.2.4 Summary

The fog formed in a weak pressure gradient after Shamal wind conditions.

A weak surface pressure gradient persisted over the UAE during the four days with the moderate afternoon sea breezes, which brought moist air from the Gulf Sea, and the surface wind veering to become a light south-easterly wind during the night. Although the weather conditions appeared favourable for fog formation on the 5th morning, this did not happen probably due to the wind at the surface, and the first 1000 feet, blowing consistently at 5 to 9 knots.

From the ground up to the temperature inversion the wind tended to back to north-north-easterly, but on the 23rd, when there was no fog, it remained east-south-easterly and stronger.

Evidence of moist air could be seen in the hazy conditions that developed in the evening prior to the fog forming. It was also apparent in the above 50% humidity below the near surface temperature inversions recorded by the afternoon atmospheric soundings.

Fog formed when the surface air temperature cooled to, and below, the maximum surface dew-point temperature that occurred in the late afternoon, or early evening.

The fog formed below temperature inversion bases that varied from about 200 metres (650 ft) AGL to just over 300 metres (1000 ft) AGL. A limited survey of fog events during 2002 and 2003 revealed that the inversion is on average 170 metres (560 ft) AGL. Wind shear was not always present at the temperature inversion. The marked dryness of the air above a temperature inversion is indicative of strong subsidence and superior air.

There is evidence that the fog formed as a result of a combination of radiation and advection processes.

The fog cleared about 2 hours after sunrise when the ground warmed due to insolation and the effect of insolation on the fog cloud top.

4.6.3 THREE CONSECUTIVE FOG DAYS IN WINTER: 9TH TO 11TH JANUARY 2003

Fog of varying intensity, occurred on three consecutive mornings from the 9th to the 11th January 2003.

The fog occurred after three days of north-westerly Shamal winds. These were fresh to strong at first due to the pressure gradient between an anticyclone of about 1025 hPa over Saudi Arabia and a low pressure cell over southern Iran. However, by the time the fog days occurred, the winds had moderated considerably as the weakened anticyclone moved over the area. The fog happened when the anticyclone was overhead and, characteristically of an anticyclonic circulation, the winds became light at the surface and aloft in the boundary layer up to 900 metres (±3000 ft).

4.6.3.1 NWP model data

Model data was not available for all the days on which fog occurred. However, there is enough to demonstrate the dilemma faced as a result of conflicting information when forecasting fog.

During the night of the 8th/9th the ETA NWP model indicated sufficient 500 hPa to 350 hPa moisture that is indicative of extensive middle and high layer cloud. It was thought that with this cloud, radiation cooling would have been inhibited and fog would not form. However, all that transpired was very patchy and thin Cirrus cloud, which therefore did not have the expected effect.

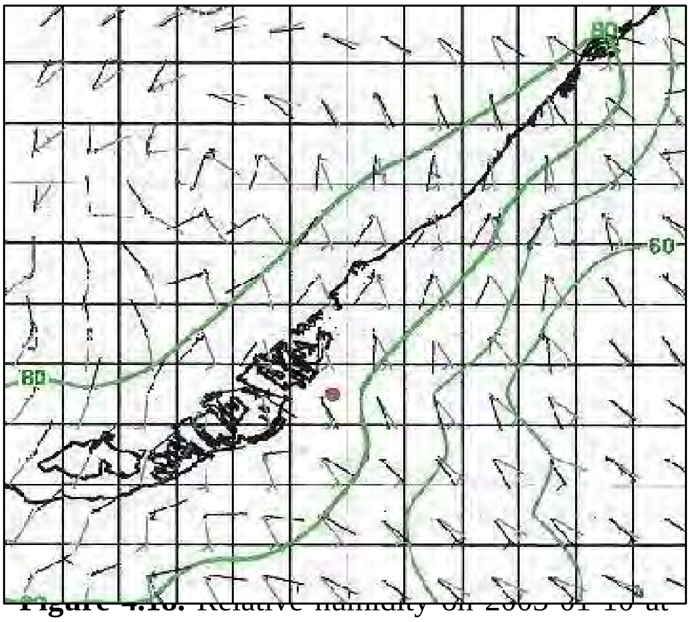


Figure 4.18. Relative humidity on 2003-01-10 at 0300 UTC (T+15). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

The T+12 and T+15 humidity fields at 0000 UTC and 0300 UTC on the 10th gave conflicting evidence. Only about 80% humidity was indicated along the coast and adjacent interior, but the winds at the surface and at 950 hPa were light with little directional shear (figure 4.18).

The prognostic atmospheric profiles at the same times confirmed the very light low level winds, but showed a temperature inversion at about 950 hPa with a lifted condensation level close to 900 metres (figure 4.19). The latter is not really significant except that it means that the surface temperature and dew point temperature cannot be close to saturation and therefore there should not be a lot of surface moisture. But one has to bear in mind that the coarseness of the model resolution, available at this point, is too large for reliable profiles.

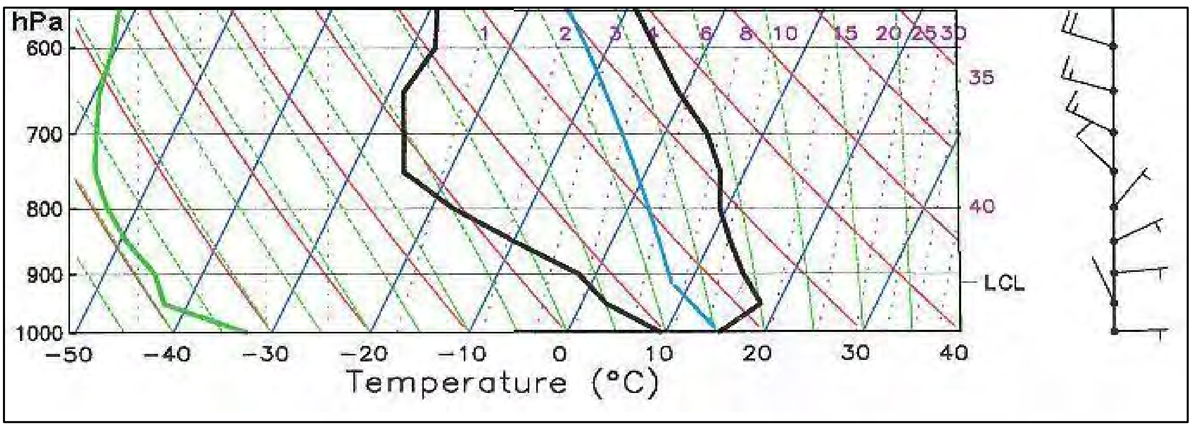


Figure 4.19. Eta WAFS prognostic profile at ADIA on 2003-01-10 at 0300 UTC (T+21).

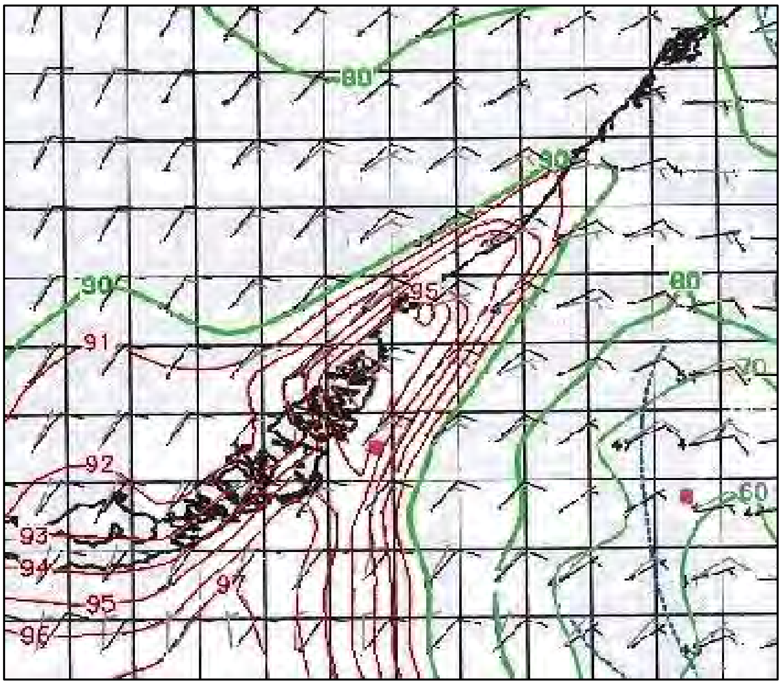


Figure 4.20. Relative humidity on 2003-01-11 at 0300 UTC (T+39). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

The surface humidity and wind prognostic fields at 0000 UTC (T+36) and 0300 UTC (T+39, figure 4.20) for the following day the 11th, showed much higher humidity values than those of the 10th with light north-easterly surface winds, but stronger at 950 hPa. In other words there was again conflicting evidence, especially when experience with the model is that the humidity is always higher with a longer lead time. According to local belief, a north-easterly surface wind is also not a favourable wind direction for fog.

The conflicting information is clearly visible in the time cross section for Abu Dhabi which shows ideal light south-easterly surface winds around 0000 UTC on the 10th and moderate humidity, but less favourable stronger north-easterly winds with higher humidity around 0000 UTC on the 11th (figure 4.21).

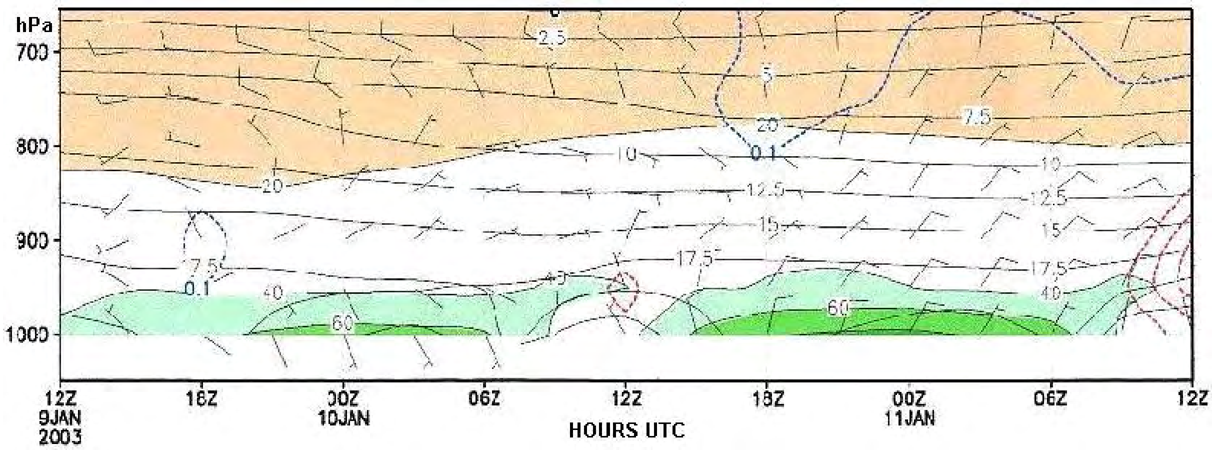


Figure 4.21. Time cross-section at ADIA from 2003-01-09 1200 UTC (T+0) to 2003-01-11 1200 UTC (T+48). The sequence reflects the higher humidity on the morning of the 11th around 0000 UTC, with less favourable 1000 hPa winds.

4.6.3.2 Surface observations

As in the previous study, a north-westerly sea breeze preceded the fog events, but the sea breezes were about 5 to 10 knots lighter (figures 4.22 to 4.25). Onset of the sea breeze wind was about 1 pm (0900 UTC), but it was as late as 5 pm (1300 UTC) on the 9th (figure 4.23). Veering of the wind to the east and its becoming light usually began about 1800 UTC, but was stronger and from the east at 4 to 6 knots until 2200 UTC on the 10th (figure 4.24).

Fog formed once the wind at 10 metres had become almost calm, but once again the exception was on the morning of the 10th (figure 4.24) when it formed with an easterly wind of 5 knots.

All of the hourly surface relative humidity observations on all days exceeded the optimum values specified in figure 4.2 in section 3 and the fog formed when the Stevenson screen relative humidity reached about 95%. The fog also formed earlier in the night than in the previous summer situation.

An intriguing and unexplained contrast with the summer study above was that fog formed three to six hours after the ambient temperature fell below the maximum dew-point temperature earlier in afternoon and evening. For example, on the night of the 10th/11th, the maximum dew-point temperature the previous evening was about 17°C, but the fog did not develop until 2200 UTC when the air temperature had fallen to about 14°C (figure 4.24). On the night of 8th/9th the air temperature was 6°C cooler before fog formed (figures 4.22 and 4.23).

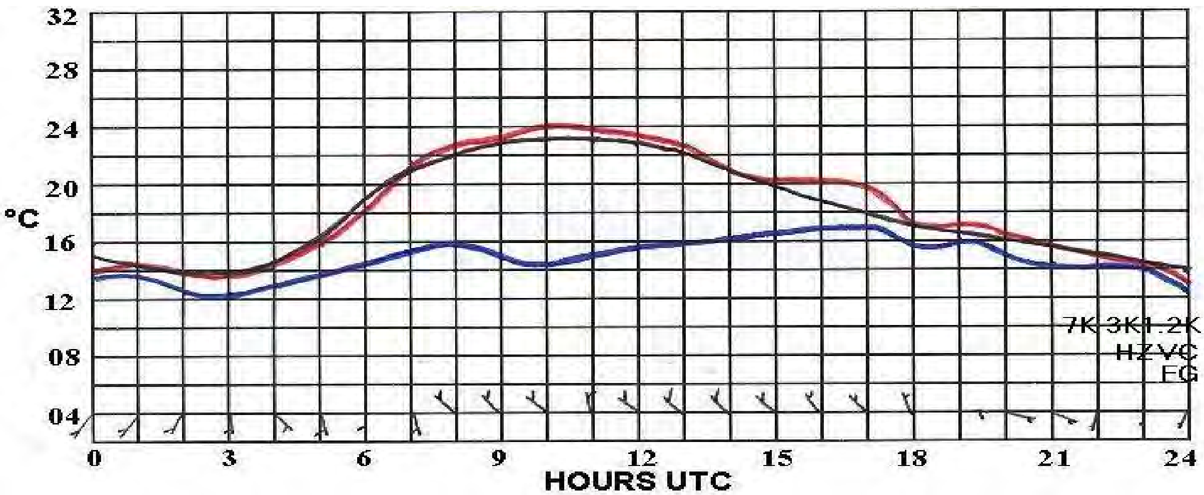


Figure 4.22. As in figure 4.8, but for 2003-01-08.

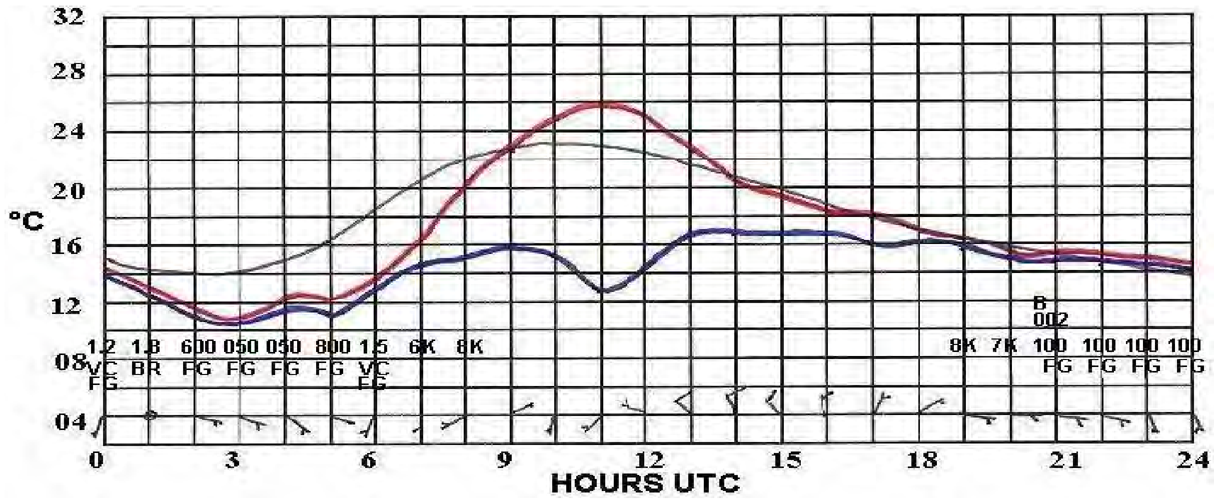


Figure 4.23. As in figure 4.8, but for 2003-01-09. The cloud is at 60 metres (200 ft) AGL

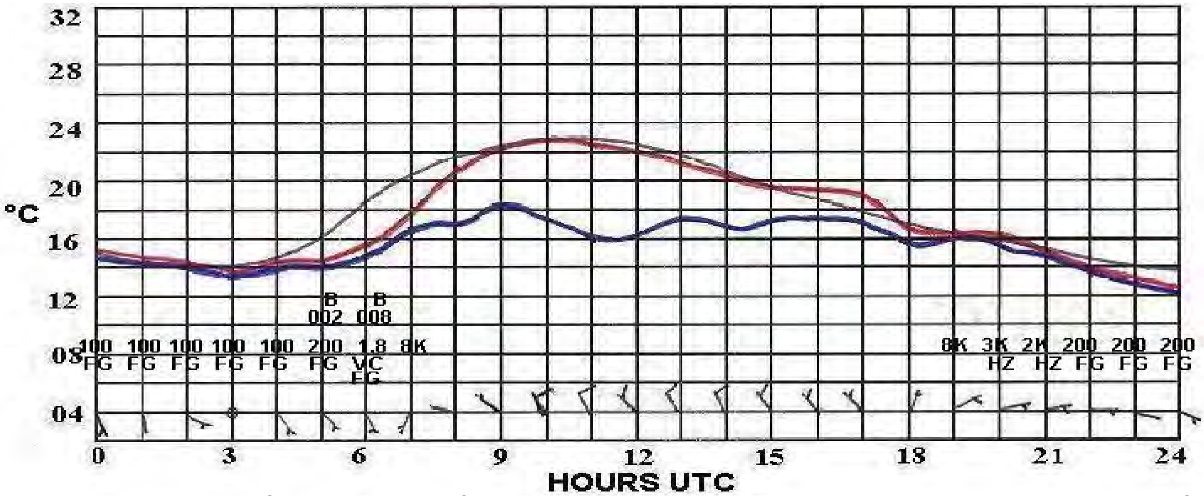


Figure 4.24. As in figure 4.8, but for 2003-01-10. The cloud is at 60 – 240 m (200 - 800 ft) AGL.

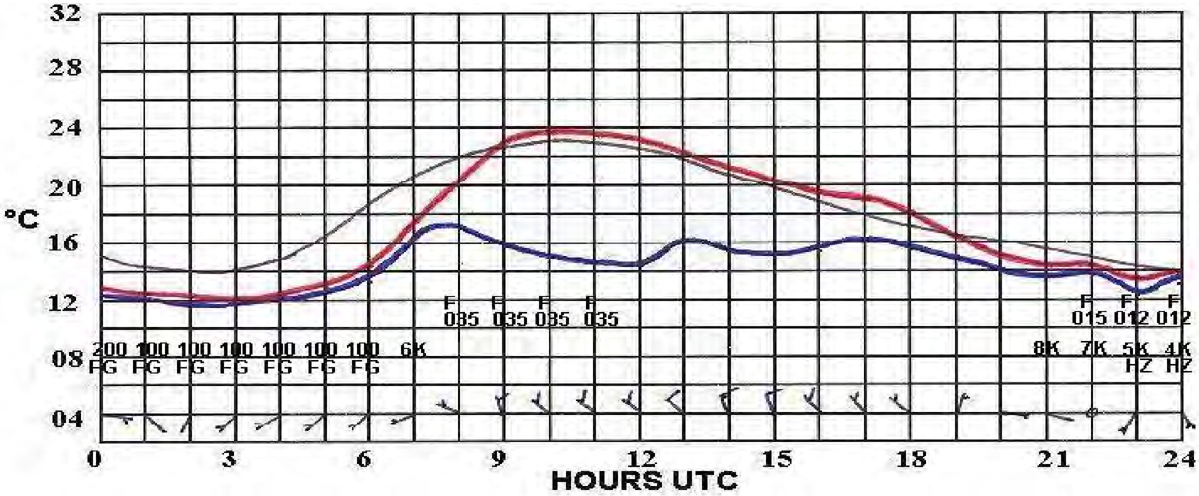


Figure 4.25. As in figure 4.8, but for 2003-01-11. The cloud is at 370 – 1066 m (1200 - 3500 ft) AGL.

4.6.3.3 Atmospheric soundings

What is clearly evident in this study is that the atmospheric sounding profiles (figures 4.26 to 4.28) differ from those in the previous study (figures 4.13 to 4.17). Due to the lower winter land temperatures, the wedge of cooler maritime air, brought by the sea breeze, is less pronounced on the afternoon soundings. Meanwhile, the morning ascents had shallow surface inversions, or difficult to discern near surface inversions surmounted by an isothermal layer as opposed to a marked temperature inversion that was evident in the previous summer event.

The sounding at 1200 UTC, on the afternoon of the 8th (figure 4.26), did have had a near surface temperature inversion, but, at 907 hPa (966 gpm MSL, or 961 metres AGL) this is usually considered to be far too high for later fog development, with the dry adiabatic lapse rate and near constant humidity mixing ratio below the inversion being indicative of turbulent mixing of the air and more likely to produce Stratocumulus cloud beneath the inversion.

Pre-fog afternoon soundings were moist near the surface. Near to 60% relative humidity existed up to 966 metres MSL on the 8th (figure 4.26) and up to 167 metres on the 10th (figure 4.28), with near 50% relative humidity up to 608 metres on the 9th (figure 4.27) and marked drying of the air was present in a roughly isothermal layer above the moist air.

The afternoon ascents of the 8th and 10th (figures 4.26 and 4.28) were accompanied by north-north-westerly winds of 5 to 10 knots in the moist surface layer, veering to north-easterly higher up on the 8th (figure 4.26). The sounding on the afternoon of the 9th (figure 4.27) differed in that the low level winds were still light south-south-westerly. Inspection of the surface observations on the day show that at the time of the sounding the wind was still in the process of changing from a light southerly land breeze to a north-westerly sea breeze. The late persistence of the drier land breeze accounts for lower near surface relative humidity on this sounding as opposed to the other two days.

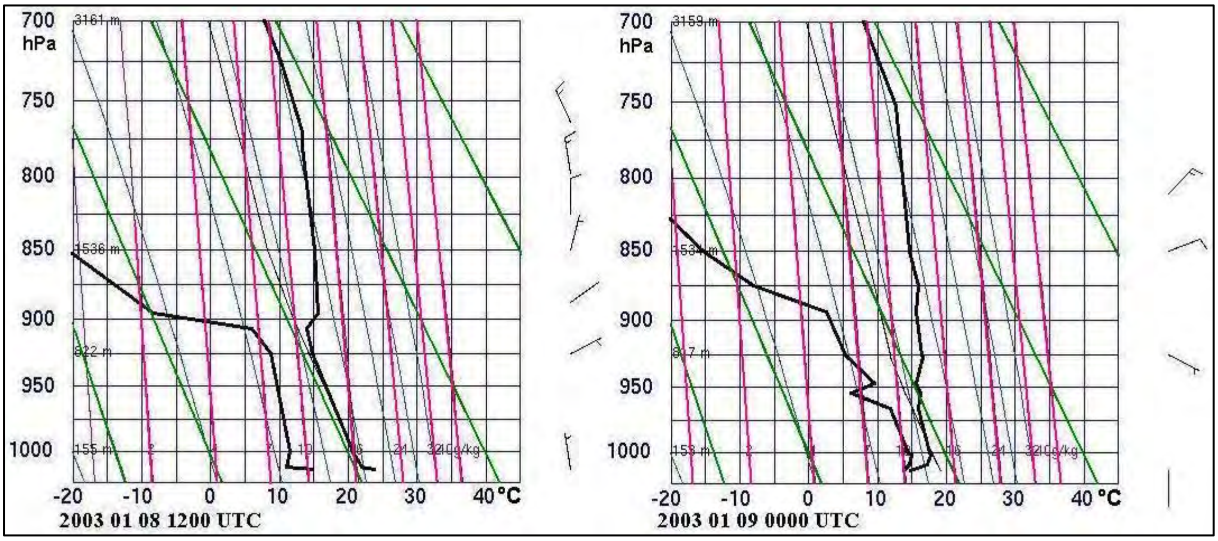


Figure 4.26. As in figure 4.13, but for 2003-01-08 1200 UTC and 2003-01-09 0000 UTC. (Courtesy of the University of Wyoming).

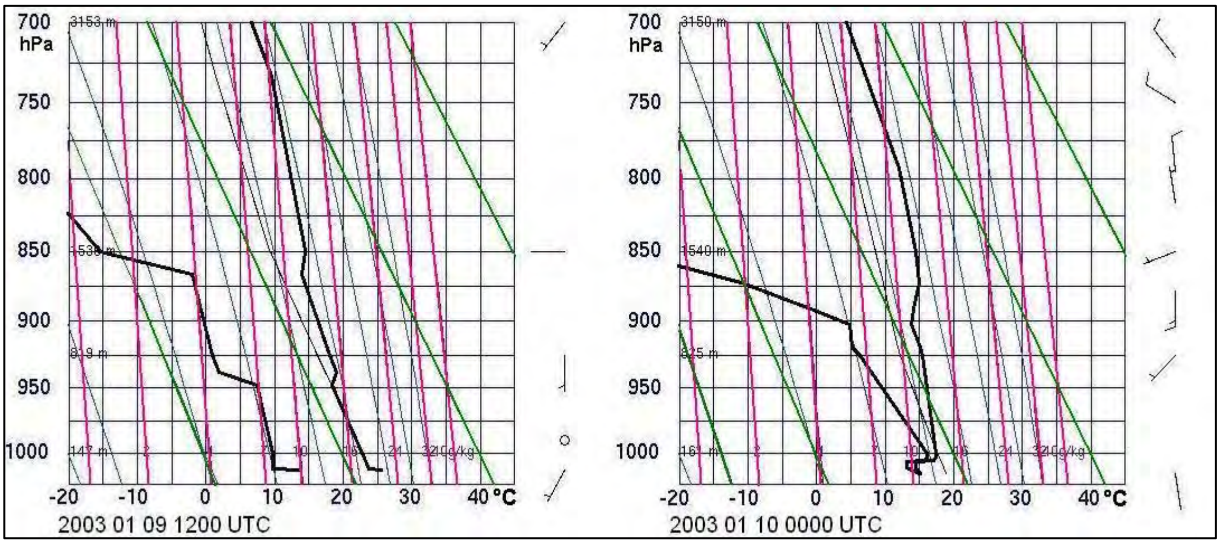


Figure 4.27. As in figure 4.13, but for 2003-01-09 1200 UTC and 2003-01-10 0000 UTC. (Courtesy of the University of Wyoming).

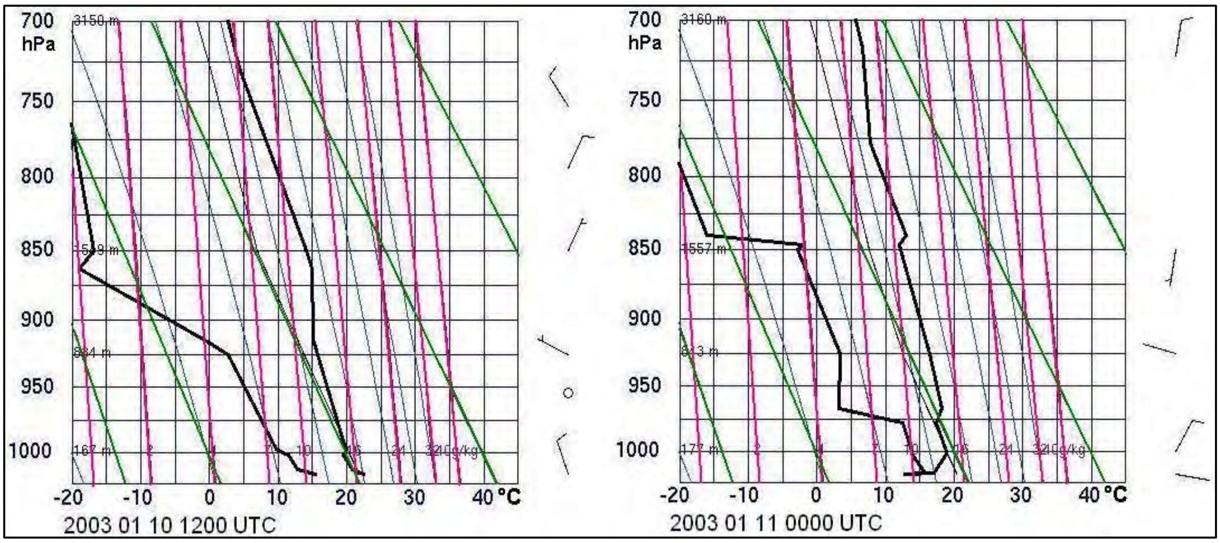


Figure 4.28. As in figure 4.13, but for 2003-01-10 1200 UTC and 2003-01-11 0000 UTC. (Courtesy of the University of Wyoming).

In contrast to the pronounced and usually elevated summer morning inversions, the base of the temperature inversion at 0000 UTC on the 9th and 11th lay at the surface, while on the 10th it was slightly elevated to 102 metres MSL (75 metres AGL). The low level winds were light south-easterly to easterly, with little in the way of wind shear, apart from the morning of the 11th when the wind changed to north-easterly 9 knots at the top of the inversion (table 4.4).

Table 4.4. Sounding data at ADIA for 09th to 11th January 2003. Pressure, gpm height, temperature, dew-point, relative humidity and wind velocity sounding data up to temperature inversion level on fog days.

PRES hPa	HGHT gpm	TEMP °C	DWPT °C	RELH %	DIRC deg	SPED knot
00Z 09 Jan 2003						
1015.0	27	14.8	13.8	94	180	1
1010.0	69	17.2	14.7	85	120	2
1002.0	136	17.8	14.9	83	24	3
00Z 10 Jan 2003						
1016.0	27	15.2	14.9	98	170	2
1012.0	60	14.4	13.1	92	144	3
1007.0	102	14.4	13.1	92	111	5
1006.0	110	17.0	15.7	92	105	6
1003.0	136	17.4	16.1	92	85	7
00Z 11 Jan 2003						
1018.0	27	13.2	12.9	98	100	1
1017.0	35	17.0	15.7	92	96	1
1002.0	160	18.8	13.8	73	38	9

4.6.3.4 Fog indices

The two previous case studies were used to investigate the use of fog indices to forecast fog. The three indices selected for trials were those given in the Source Book to the Forecaster's Reference Book (UKMO 1997), namely, the Saunders and the Craddock and Pritchard methods of fog-point calculation and the fog point in relation to the 850 hPa wet-bulb potential temperature (WBPT).

The Saunders method uses the condensation level calculated from the temperature and dew point temperature at the time of the midday sounding. The humidity mixing ratio where the condensation level cuts the dew point line is then traced back to the surface. The temperature at this level is the expected fog temperature. Certain provisos, such as excluding a surface superadiabatic temperature lapse rate and increased dew point lapse rate aloft are applied (appendix C). Invariably dry air present aloft at ADIA always rendered a far too low fog temperature. The Craddock and Pritchard method is an empirical formula that utilises the 1200 UTC screen temperature and dew point temperature along with wind and cloud tables to calculate a fog temperature in relation to the minimum temperature expected the following morning, values of 1°C or more above being an indication of fog (appendix C). It usually rendered values 2°C to 4°C below the expected minimum temperature, or about the same, thereby indicating no fog, or a risk of fog, respectively. The 850 hPa WBPT generally produced values below the fog temperature. The Saunders and 850 WBPT being closer to the mark in the winter event when there is a greater depth of higher humidity (appendix C, table 1)

Two locally suggested methods to calculate a WBPT fog point were tested. The first uses the surface 1200 UTC WBPT (excluding a surface superadiabatic temperature lapse rate), while the second uses the earlier 0000 UTC surface temperature and the 1200 UTC surface dew point temperature to calculate a forecast surface WBPT, or fog temperature for the following night. The two methods, tested on numerous fog days in addition to those shown in table 1, appendix C, yielded mixed results. The methods were just as likely to indicate values favourable for fog, or unfavourable values, the results being more reliable during persistent fog, that is, no air mass change, but unreliable at the onset and clearing phases.

The opinion of the author is that the indices are more suited to the wetter and more temperate climate of England where they were developed, than much drier UAE. The surface WBPT method using a 0000 UTC maximum temperature and 1200 UTC dew point gave favourable results often enough to be promising, but it must be more fully investigated and it is believed that numerous exception stipulations will have to be applied and their further use at ADIA is not advised.

4.6.3.5 Summary

The model data gave conflicting clues as to whether fog would form or not. First of all, middle and high layer moisture suggested cloud development at these levels, which did not materialise. Then on another night favourable light south-easterly to southerly winds were indicated with less than favourable surface humidity. Finally, on another night a light surface wind was indicated with high humidity, but it was from the north-east, a direction not locally considered conducive to formation. The stronger north-easterly wind at 950 hPa also did not help.

Figure 4.29. A photograph of winter fog at Abu Dhabi at 8 am on the 7th March 2004. The fog drifted, or expanded, to the island city from the interior via the airport.

As in the previous study, the fog is likely to form after the north-westerly Shamal wind has been blowing for a few days and then drops.

Also in common with the previous study, the fog formation on the three nights occurred with a weak surface pressure gradient and light surface wind, but with more moist surface conditions.

The event also differed from the previous study in that the fog was associated with an anticyclone, as opposed to a col area. The north-westerly wind was a precursor to an anticyclone, with a weak pressure gradient, arriving over the area where the stable and subsiding conditions, as well as clear sky aloft, fostered radiation cooling and fog formation immediately inland of the coast. Fog development was aided by the availability of hygroscopic particles in the form of sea salt in suspension, which the light morning south-easterly land breeze then carries back to the coast (figure 4.29).

The fog began earlier in the night than the previous summer event, probably due to the longer winter night and cooler temperatures. The air temperature also fell to well below the maximum dew point temperature earlier in the evening before fog formed.

The atmospheric soundings differed in that, due to the cooler winter land temperatures, the wedge of sea breeze air was less pronounced on the afternoon soundings. Meanwhile, the morning ascents had shallow surface inversions, or difficult to discern near surface inversions. These were surmounted by an isothermal layer as opposed to a marked temperature inversion seen in summer.

Pre-fog afternoon soundings relative humidity was 50% to 60% moist near the surface, with markedly dry air above. This is in common with the previous event, as were the light low level south-easterly to easterly winds.

4.7 STUDY OF NON-FOG PRODUCING EVENTS

4.7.1 INTRODUCTION

There are a few basic synoptic patterns that prevent fog formation. Essentially they involve a surface low pressure cell and its position in relation to the UAE. These are a low pressure cell to the west of the UAE (including north-west and south-west), or to the east (including south-east and north-east) of the UAE. Having said this there is another typical winter circulation that also does not result in fog and this involves an anticyclone over southern Iran, of which a brief example will be given.

The key to all of them is a wind strong and/or dry enough to maintain turbulent mixing of the boundary layer air and prevent condensation in the air near the ground.

These situations are often not as obvious as one would like and can lead to mental agonising by the forecaster whether the wind is going to drop sufficiently for fog to form and then a nail biting night wondering whether the correct decision has been made.

4.7.2 SURFACE LOW PRESSURE CELL TO THE WEST: 13TH JUNE 2003

Irrespective of the position of the low pressure cell to the west, the cyclonic circulation brings dry air from the desert to the UAE from the south, or south-west.

4.7.2.1 NWP model data

A surface low developed over the western UAE and, according to NWP model data, it was expected to remain centred more or less in this position until the 14th, before moving to the eastern UAE on the 15th. This is not uncommon in the summer months. Intense surface heating, results in an almost permanent heat low over the Arabian Peninsula with fluctuations in the position of the centre of the low dependent upon surrounding synoptic scale changes.

Figure 4.30 shows the Eta NWP analyses and T+24 prognostic positions of the low pressure cell west of Abu Dhabi on the 12th and 13th, with a 1000 hPa high over Oman. In spite of the fact that there is normally a late afternoon north-westerly sea breeze, the cyclonic circulation is producing a southerly flow over the eastern UAE, particularly in the vicinity of Abu Dhabi. That is, dry air from the desert.

In addition to the indicated light southerly wind, the surface relative humidity prognostic field with low level winds at 0000 UTC on the 13th confirmed that dry air would be carried to the coast from the desert (figure 4.31).

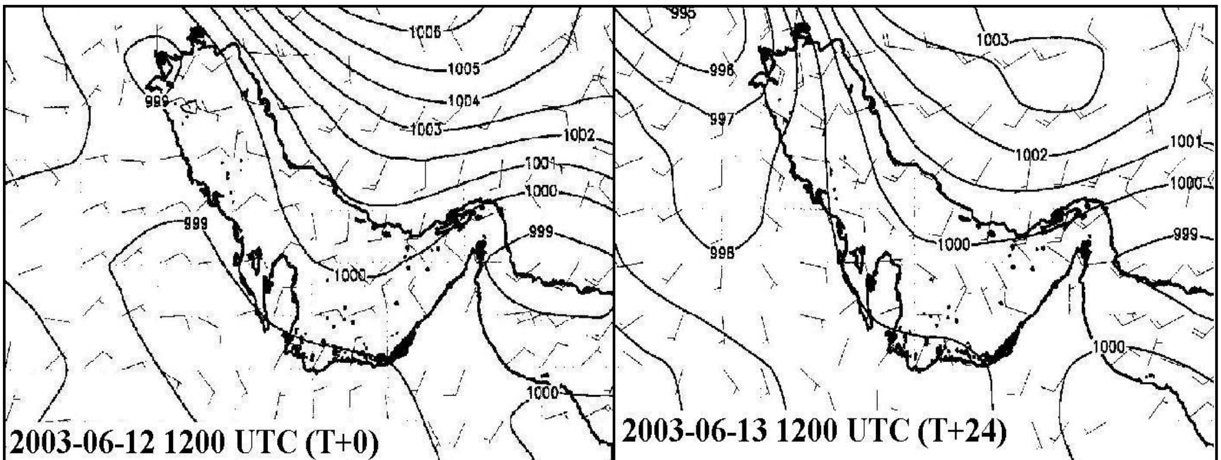


Figure 4.30. Eta GFS fields of surface pressure (hPa) and wind (knots) on 2003-06-12 1200 UTC (T+0) and 2003-06-13 1200 UTC (T+24).

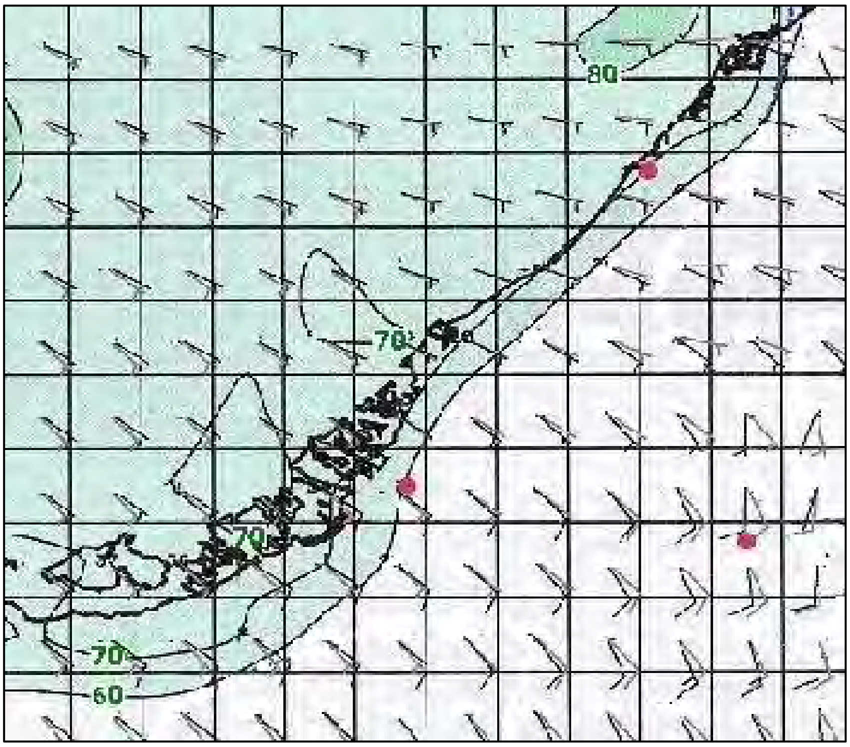


Figure 4.31. Eta relative humidity on 2003-06-13 at 0000 UTC (T+24). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

The surface time cross sections at Abu Dhabi and Al Ain also indicated very dry surface conditions with delayed onset of the north-westerly sea breeze to after 1200 UTC. But, more important, they also show early onset of the morning southerly land breeze on the 13th (figure 4.32). The fact that this is more than a common land breeze is evident by the depth and strength of the southerly wind from about 0000 UTC to 0800 UTC at Abu Dhabi and Al Ain. Notice the lighter (and dry) southerly wind the previous morning of the 12th. Furthermore, on both days the model indicated a stronger wind at Abu Dhabi than further inland at Al Ain. This invariably results in worse visibility at Abu Dhabi than at Al Ain, but no fog.

4.7.2.2 Surface observations

Under these circumstances the southerly circulation east of the low pressure cell strengthens the morning land breeze and delays the start of the sea breeze until later during the afternoon. On the 12th the low was still developing and the land breeze was light. Never the less it was strong enough to raise the maximum temperature to about 4°C above the normal and delay the sea breeze until 1100 UTC, or 1500 local time (figure 4.33). Overnight the wind became light and variable enough to probably be of some concern to the forecaster, but the surface moisture remained reassuringly low enough to allay any last minute fears of fog forming.

On the 13th, a stronger pressure gradient produced an earlier and stronger southerly land breeze with higher temperatures throughout the day after the wind started and a later start of the sea breeze at 1200 UTC (1600 local time)(figure 4.34). Even so, there was enough surface moisture brought from the Gulf Sea by the sea breeze to cause much moister conditions overnight and result in early morning haze and mist patches. In this instance the pressure gradient effect was such that the sea breeze barely reached Al Ain and when it did it was a temporary affair in the early evening.

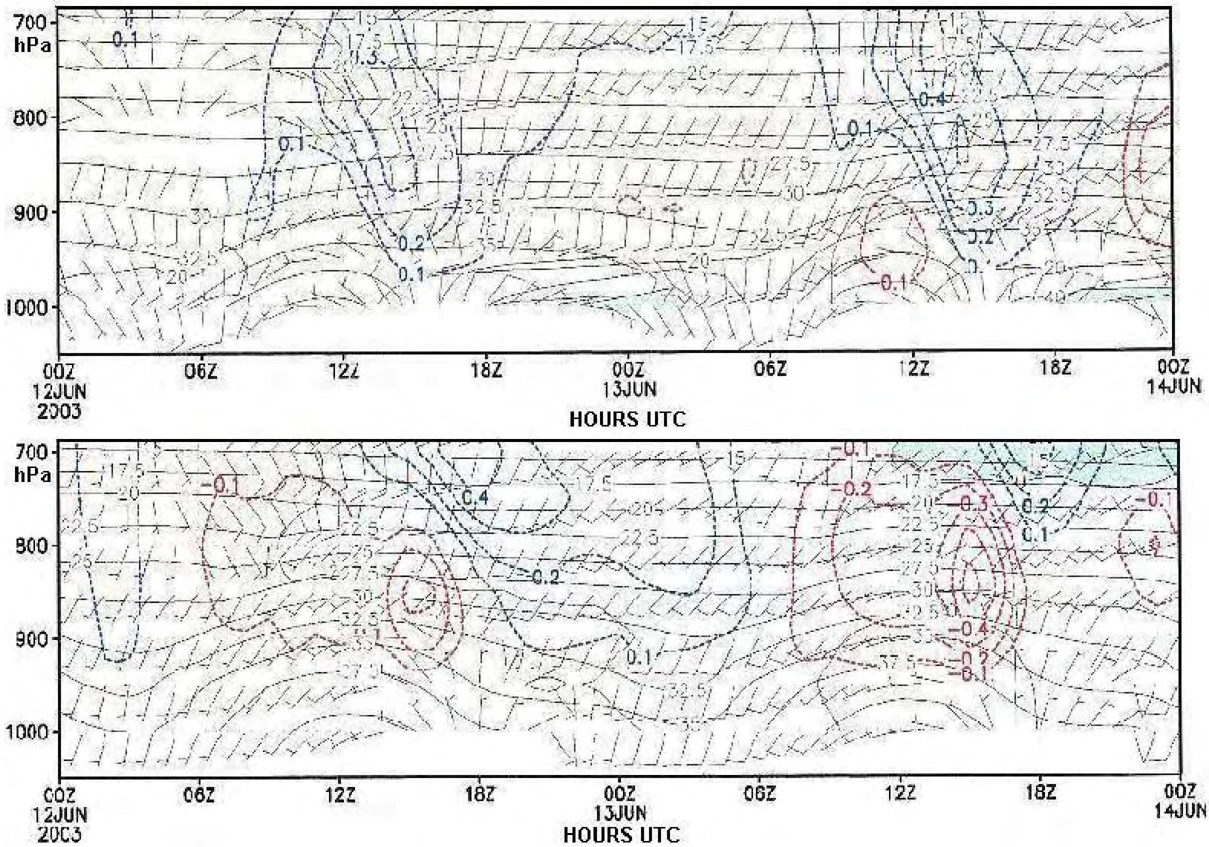


Figure 4.32. Time cross-sections at ADIA (top) and Al Ain (bottom) from 2003-06-12 0000 UTC (T+0) to 2003-06-14 0000 UTC (T+48). Note the very dry conditions, compared with figure 4.21. They also indicate early onset of the land breeze on the morning of the 13th.

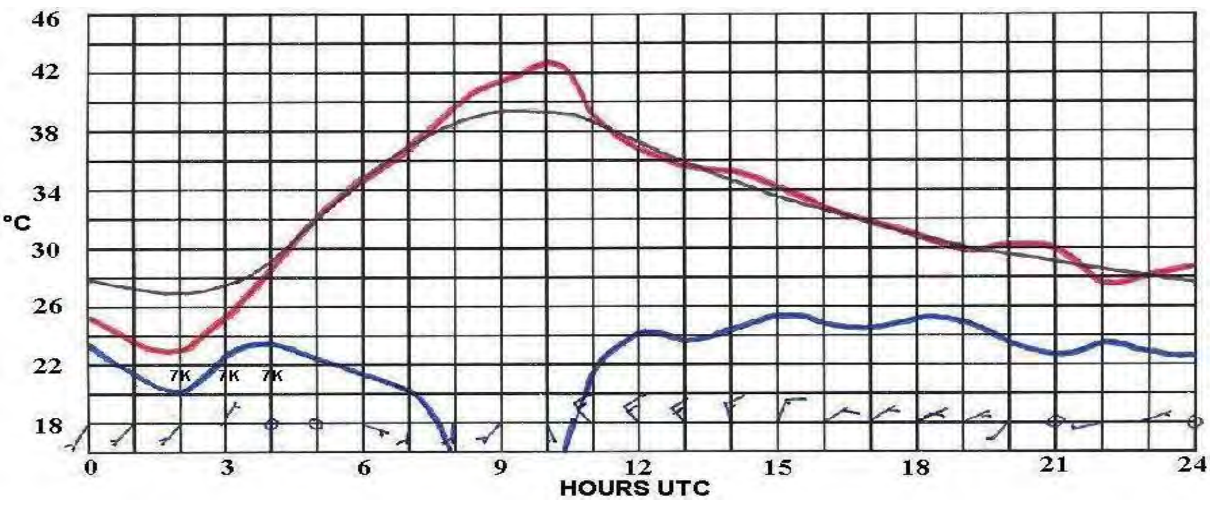


Figure 4.33. As in figure 4.8, but for 2003-06-12.

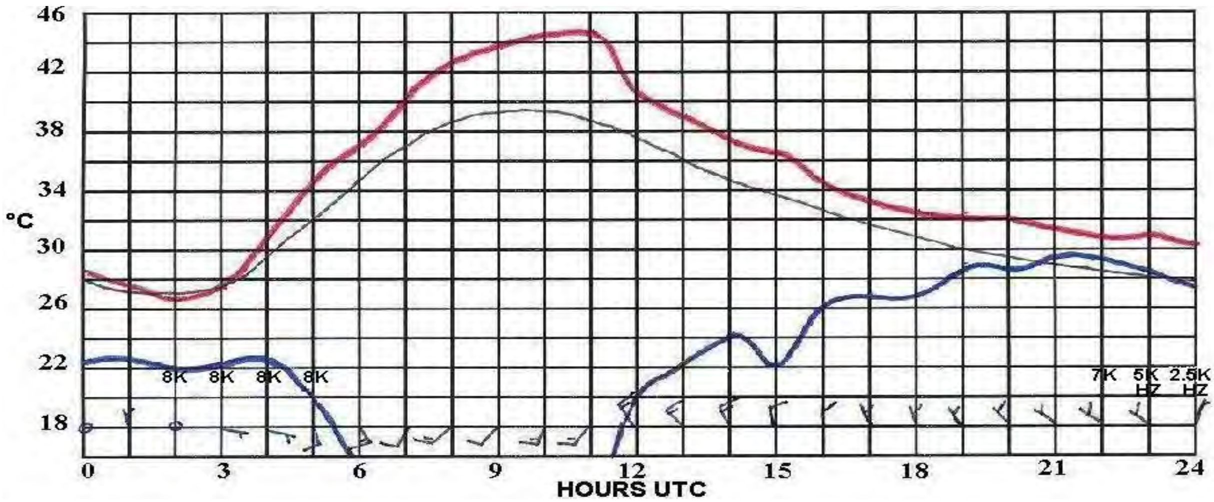


Figure 4.34. As in figure 4.8, but for 2003-06-13.

4.7.2.3 Atmospheric soundings

Unfortunately, no sounding data for the afternoon of the 12th is available, apart from wind velocity, which was north-westerly at 8 to 12 knots before backing to southerly higher up at 911 hPa.

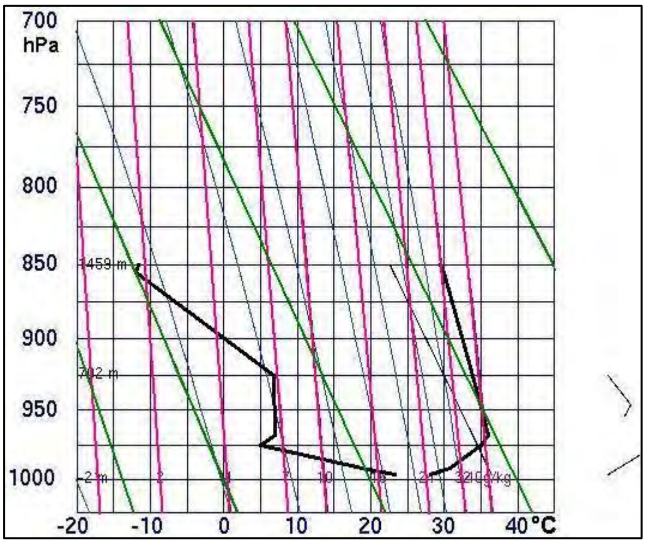


Figure 4.35. As in figure 4.13, but for 2003-06-13 0000 UTC. (Courtesy of the University of Wyoming).

On the morning of the 13th at 0000 UTC (0400 local time) the low level winds were light east-north-easterly to easterly at 3 to 6 knots up to 960 hPa with a 12 knot south-easterly wind at 925 hPa. Comparison with the surface observations reveals that the upper air sounding was made well before the southerly winds began, hence the low level east-north-easterly wind, which was probably still in the process of veering from the north-westerly of the previous afternoon and the very shallow surface moisture layer below a surface inversion (induced by nocturnal ground radiation cooling), with dry conditions above 992 hPa (±47 metres AGL) (figure 4.35).

4.7.2.4 Summary

A surface low pressure cell to the west of the UAE, or over the western part of the UAE, produced a dry offshore southerly flow that strengthens the early morning land breeze and prevents fog formation.

The synoptic circulation delays the onset of the sea breeze until late in the afternoon and can prevent it from extending too far inland. This limits the amount of moisture carried inland. Along with the very dry air already in circulation there is not enough moisture for nocturnal radiation cooling to cause fog to form. Although, there can be enough present for early morning haze.

The stronger and earlier beginning of the land breeze also causes turbulent mixing of the surface air with drier air aloft, thereby prematurely curtailing the radiation cooling effect and prevents fog formation.

4.7.3 SURFACE ANTICYCLONE OVER SOUTHERN IRAN: 9TH NOVEMBER 2003

The surface fields, from model runs on the 6th, clearly indicated the development of the anticyclone over southern Iran from the afternoon of the 8th to the afternoon of the 9th and a strengthening southerly wind (figure 4.36).

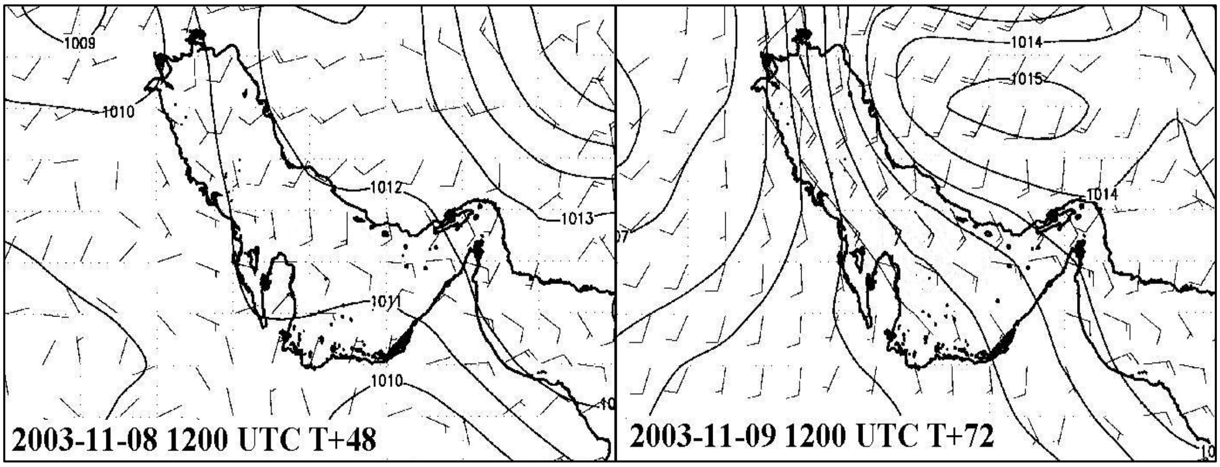


Figure 4.36. Eta GFS fields of surface pressure (hPa) and wind (knots) on 2003-11-08 at 1200 UTC (T+48) and 2003-11-09 at 1200 UTC (T+72)

The time cross section at Abu Dhabi (figure 4.37) reflects the change in the wind from a northerly to north-westerly flow into the low to the south on the 8th (figure 4.36), to a much deeper southerly flow early on the 9th.

What is interesting is the increase in moisture aloft and even, to some extent, near the surface. This is unusual in a wind from the south off the desert. What transpired was that the southerly circulation to the east of the high pressure cell over Iran brought moist air from the Arabian Sea and over Oman to the UAE.

The moisture was sufficient to produce high Stratocumulus cloud during the day under a temperature inversion at about 2400 metres AGL (figures 4.38), but not moist enough beneath the inversion, nor the wind light enough, to produce early morning fog.

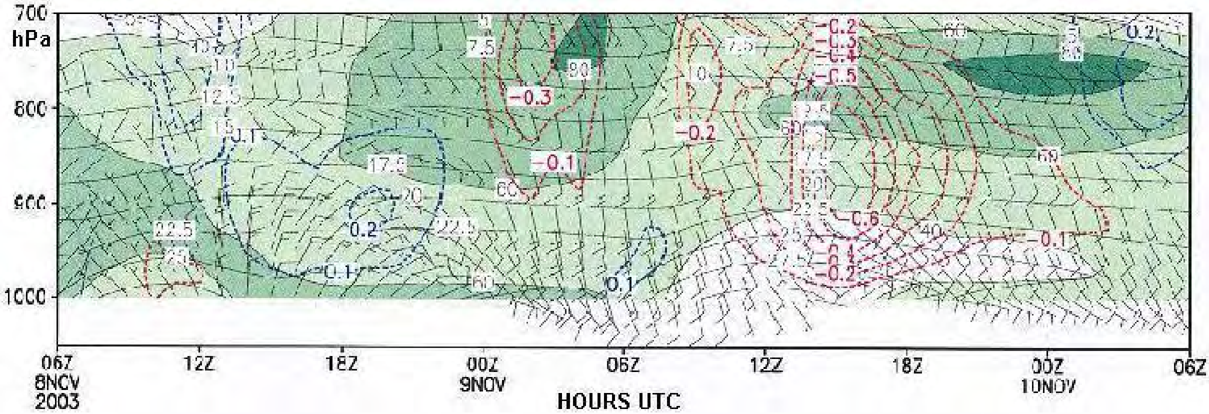


Figure 4.37. Time cross-section at ADIA showing the change from a northerly flow to a deep southerly flow from 2003-11-08 0600 UTC (T+0) to 2003-11-10 0600 UTC (T+48)

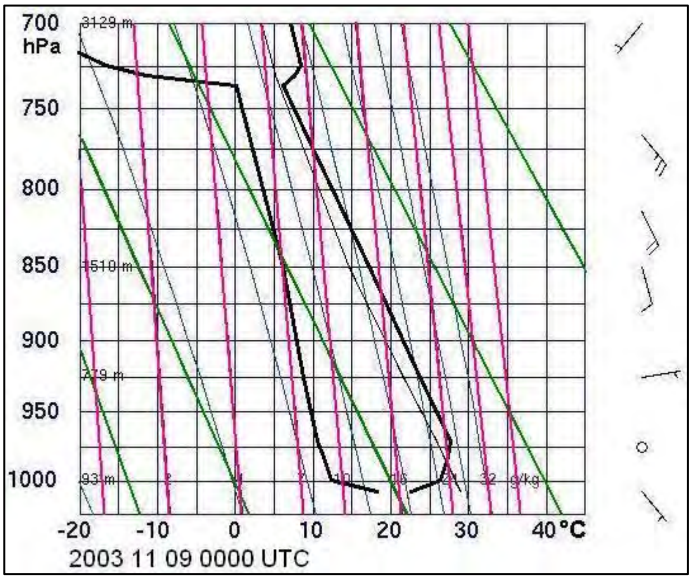


Figure 4.38. As in figure 4.13, but for 2003-11-09 0000 UTC. (Courtesy of the University of Wyoming).

4.7.4 SURFACE LOW PRESSURE CELL TO THE EAST: 31ST AUGUST 2003

4.7.4.1 NWP model data

The surface low was situated to the south–south-east of the UAE on both days and deepened by 1 hPa during the 24 hour period from 1200 UTC on the 30th to the same time the following day. However, the pressure gradient over the Gulf and the UAE weakened (figure 4.39).

Fog did not occur, even though very moist conditions were indicated by the surface relative humidity fields around Abu Dhabi at 0000 UTC and 0300 UTC on the 31st (figure 4.40) in a clearly evident cyclonic circulation with maximum moist air advection in the onshore northerly

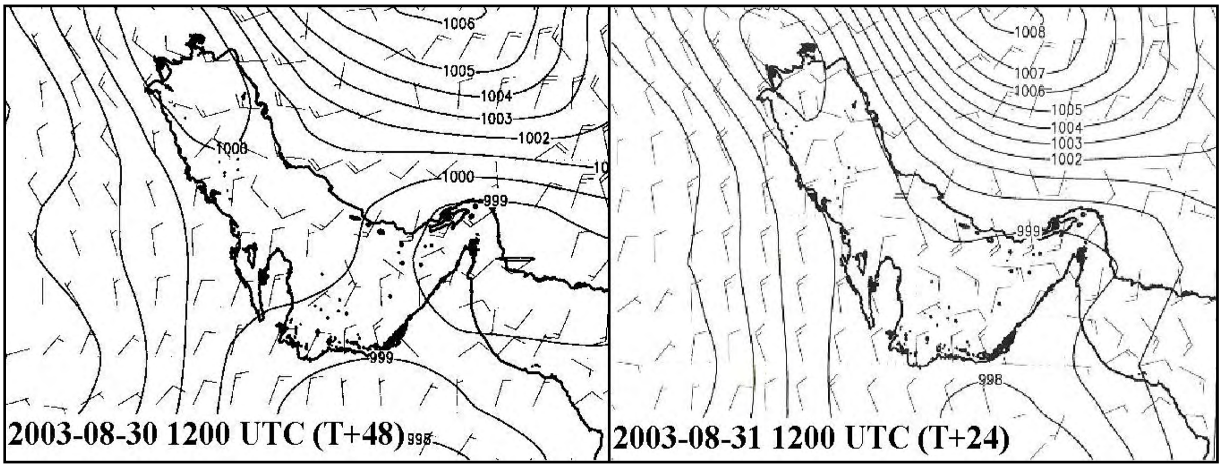


Figure 4.39. Eta GFS fields of surface pressure (hPa) and wind (knots) 2003-08-30 1200 UTC (T+48) and 2003-08-31 1200 UTC (T+24). Even 48 hours ahead the model gave a clear indication of a low pressure cell to the east, which, it transpired, weakened the following day.

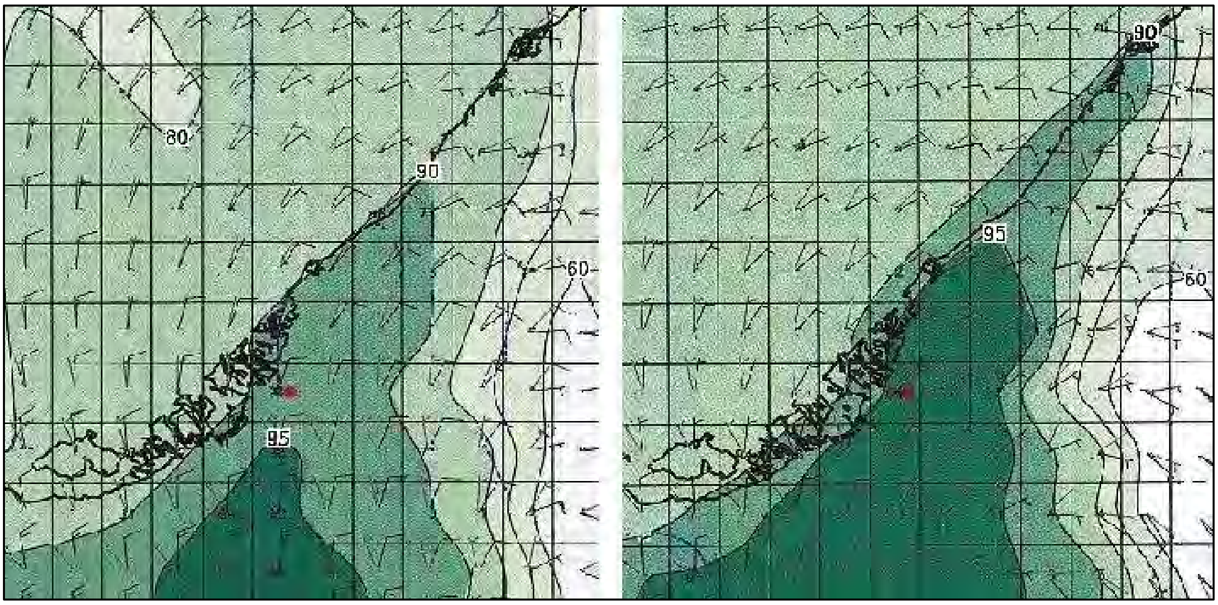


Figure 4.40. Eta relative humidity on 2003-08-31 at 0000 UTC (T+24) and 0300 UTC (T+27). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

flow in the vicinity of Abu Dhabi.

The 950 hPa northerly wind, at about 10 knots in the vicinity of Abu Dhabi, is also a fair reflection of the wind that occurred at this level, although the light northerly surface wind indicated by the model was really out of the north-east.

The time cross section for Abu Dhabi (figure 4.41) shows that the model predicted a northerly flow throughout the night, even when very light to calm wind conditions were expected between 0200 UTC to 0500 UTC. Given that these are instantaneous values and not representative of the hour, the author’s experience is that the model can be misleading about the wind direction when the speed is low. The prognoses must be treated with caution and the reality is that the wind tends to become light south-easterly to southerly.

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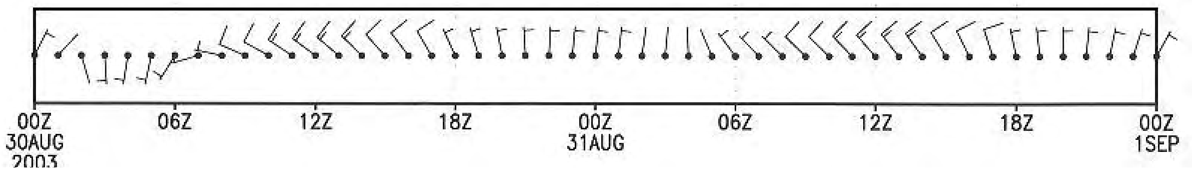

Figure 4.41. Eta GRADS surface wind time section at ADIA showing the predicted light winds on the morning of the 31st.

The prognostic atmospheric profiles at 0000 UTC and 0300 UTC (figure 4.42) indicated the near surface wind would still be north-easterly and too strong at about 10 knots at 0000 UTC and only veer to the north-east and become light toward 0300 UTC. This is usually too late to allow fog formation. However, the soundings are not a reliable indicator due to the fact that the first wind presented above the surface is about 950 hPa. Furthermore, at about 950 hPa (±460 metres/1500 ft AGL) the temperature inversion would be rather high for the formation of fog.

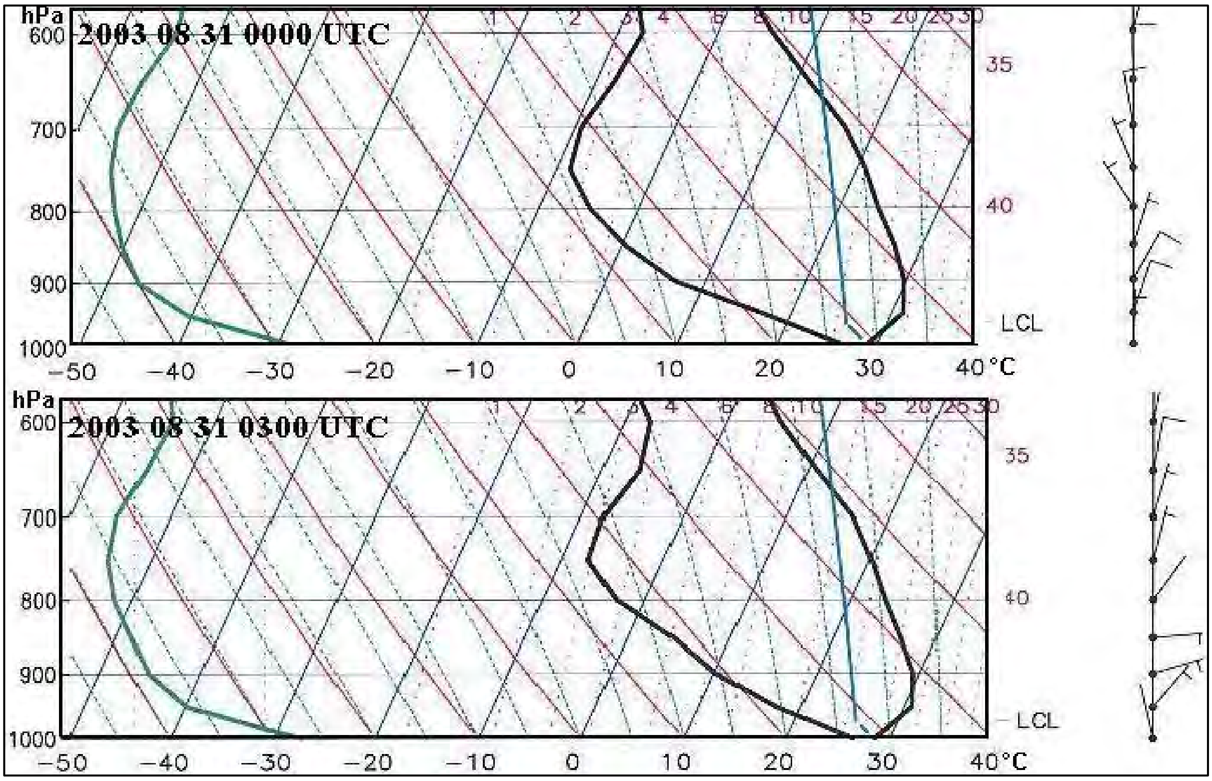

Figure 4.42. Eta GRADS prognostic atmospheric profiles at ADIA at times that are most critical for fog on 2003-08-31 at 0000 UTC (T+24) (top) and at 0300 UTC (T+27) (bottom).

4.7.4.2 Surface observations

As opposed to the previous example, the cyclonic circulation about the low results in an onshore north-easterly to north-westerly flow off the Gulf Sea. It also produces an earlier beginning of the sea breeze, which tends to be more from the north-north-west (figures 4.43 and 4.44).

In the evening, the wind veers to north-east and, if the pressure gradient is strong enough, the land breeze does not appear at all, as was the case later on the 31st (figure 4.44). Under a weaker pressure gradient conditions the wind turns to easterly during the night and it is sunrise before it turns to a south-easterly land breeze. During the later part of the 30th (figure 4.43) the wind did indeed become easterly and it was about an hour before sunrise on the 31st at 0100 UTC before it turned to south-easterly (figures 4.44).

Obviously, the overnight land breeze, being in opposition to the synoptic circulation, is much lighter than when the low pressure cell is to the west, as in the previous case study. On the night of the 30th/31st the opposing pressure gradient was weak enough to allow a 5 to 8 knots southerly surface wind during the early hours of the 31st (figure 4.44).

The earlier sea breeze also brings cooler weather. In this instance the daytime temperatures were slightly lower than normal (figures 4.43 and 4.44).

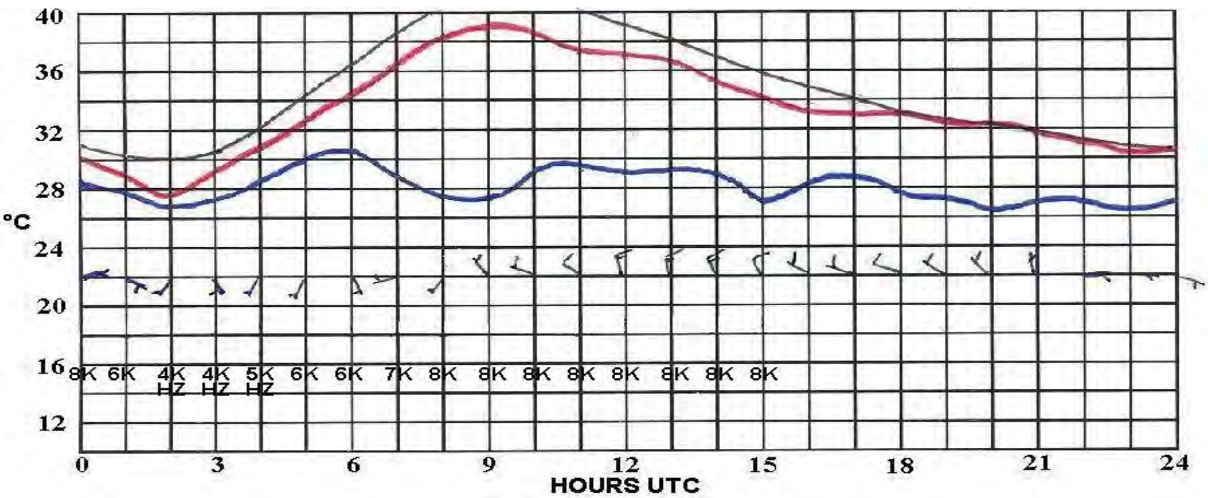

Figure 4.43. As in figure 4.8, but for 2003-08-30.

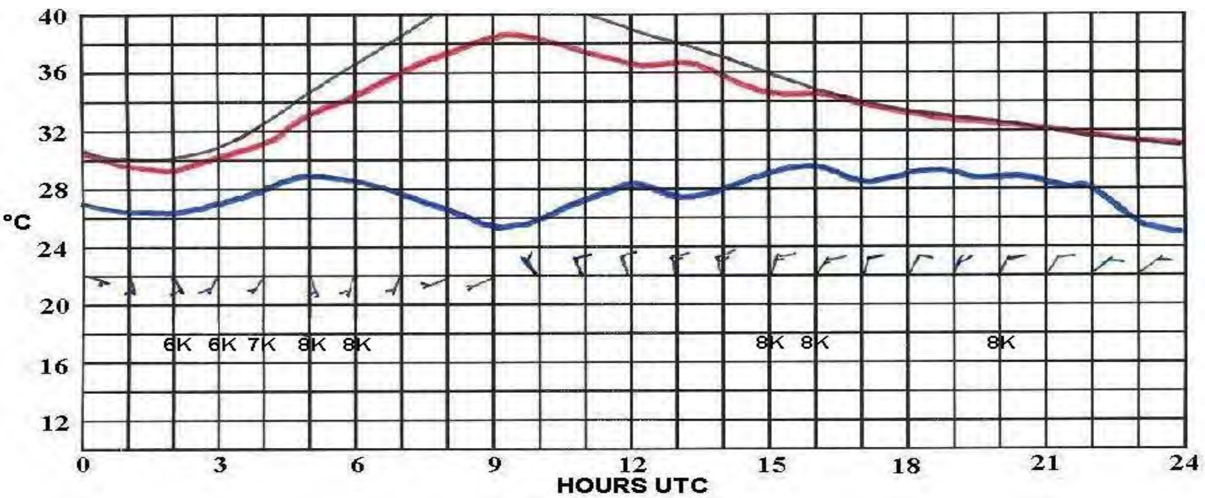

Figure 4.44. As in figure 4.8, but for 2003-08-31.

4.7.4.3 Atmospheric soundings

The sounding profile on the afternoon of the 30th shows the familiar wedge of cooler sea breeze air (figure 4.45, left). The wind near the surface was northerly at about 10 knots, but above this, up to the rather high temperature inversion base at 920 hPa, the wind was light variable. The relative humidity beneath the inversion was between 52% and 63%.

The following morning, a near surface temperature inversion had formed at 980 hPa with an offshore wind below it at 090° 5 knots to 070° 6 knots at the inversion top. The main inversion remained at nearly the same level as the previous afternoon (914 hPa) with a steady northerly wind off the sea at 8 knots (figure 4.45, right).

The wind above the near surface inversion to the main inversion was strong enough to maintain turbulent mixing. Evidence of this can be seen on the morning sounding in the form of the dry adiabatic air temperature lapse rate and the close to constant humidity mixing ratio dew point temperature trace.

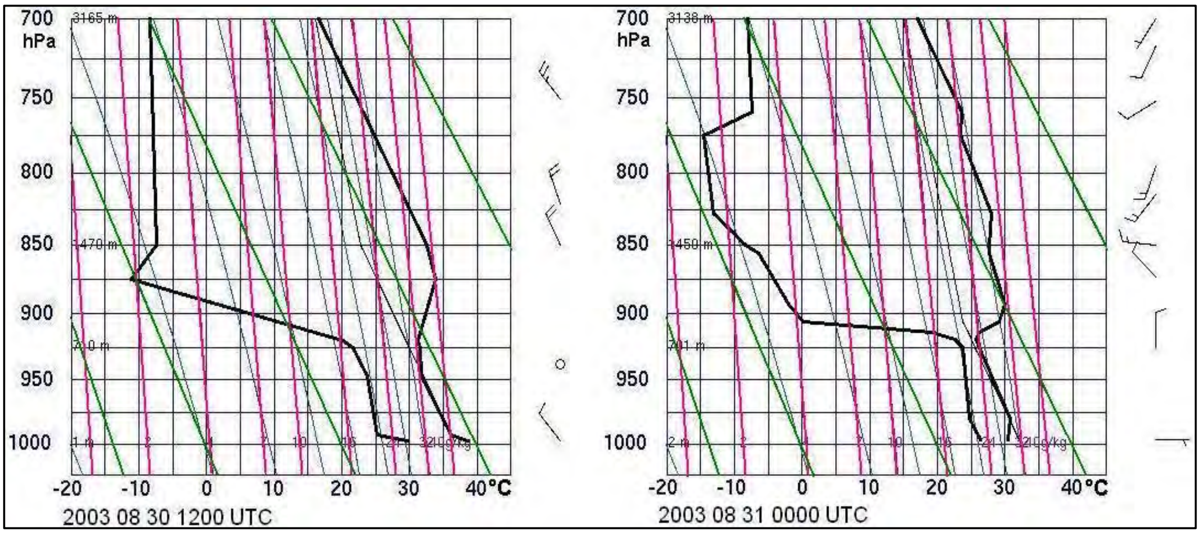

Figure 4.45. As in figure 4.13, but for 2003-08-30 1200 UTC and 2003-08-31 0000 UTC. (Courtesy of the University of Wyoming).

4.7.4.4 Summary

A source of concern for the forecaster would have been that up until 1800 UTC on the evening of the 30th, the relative humidity was well above the values one can expect with fog formation later in the night as indicated in figure 4.2 in section 3. However, the surface temperature, which had been cooler than the normal, began to cool less rapidly at this time and the air remained about 75% to 80% moist. This is normal under these conditions. Air off the sea, being less influenced by nocturnal surface radiation cooling maintains warmer conditions than when it arrives from the cooler desert. The later swing in wind direction to the south-east, due to the synoptic circulation, and increased radiation cooling over the land, was too late to enable the air to cool to below the dew-point temperature, or fog point.

The steady 6 to 8 knots north-easterly to northerly from the surface up to the main inversion, was also strong enough to maintain turbulent mixing, thereby preventing fog formation.

When the wind remains from the north-west to north-easterly throughout the night, due to a surface low pressure cell to the south, or south-east, fog does not occur.

4.7.5 SURFACE LOW PRESSURE CELL TO THE NORTH-EAST: 23RD OCTOBER 2003

This event demonstrates that fog does not occur when there is a low pressure cell to the north-east of the UAE in the Gulf. This situation is also normally associated with Shamal wind conditions, because there is invariably an anticyclone to the west over Saudi Arabia and if there is sufficient pressure gradient between the two systems, the Shamal can become strong.

4.7.5.1 NWP model data

The prognosis of the 0000 UTC run of AVN model on the 22nd October 2002 was that, by 1200 UTC, a moderate to fresh (15 to 20 knots) north-westerly Shamal would develop. This would be due to a 3 hPa pressure gradient in the Gulf between an anticyclone to the west over Saudi Arabia and a low pressure centre located in the vicinity of southern Iran and the Straits of Hormuz (figure 4.46, left). The situation would persist on the 23rd, but with a weakened pressure gradient and a moderated wind (figure 4.46, right).

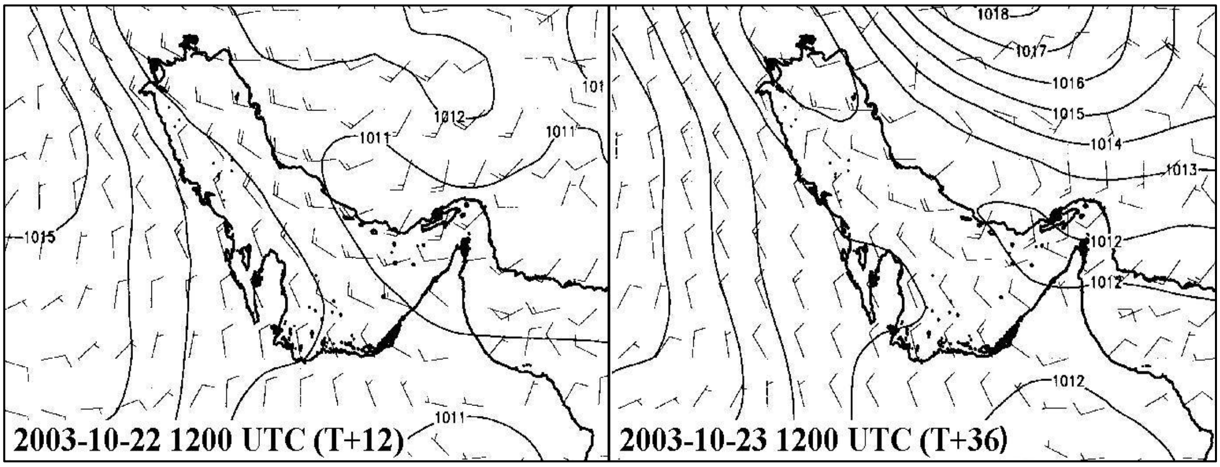

Figure 4.46. Eta GFS fields of surface pressure (hPa) and wind (knots) on 2003-10-22 at 1200 UTC (T+12) and 2003-10-23 at 1200 UTC (T+36).

The surface wind and pressure fields at 0000 UTC on the 23rd (figure 4.47) placed the low in the Gulf near to the Iranian coast, with the surface wind in the Gulf Sea from the north-west in the west backing to south-westerly in the east. Light westerly to southerly winds were indicated immediately inland of the coast from Abu Dhabi to Dubai with a pressure gradient of 1 hPa, or less, over the UAE. Both the light wind and the weak pressure gradient being favourable for radiation fog development.

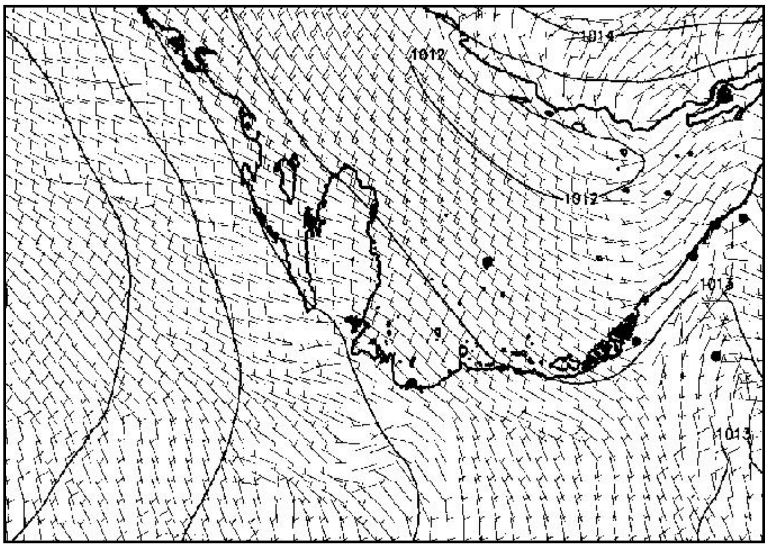

Figure 4.47. Eta GRADS surface pressure (hPa) and winds in knots) on 2003-10-23 at 0000 UTC (T+24).

In addition to light winds and a weak pressure gradient, the model indicated that a zone of surface relative humidity of 90% and higher would increase over the eastern part of the UAE and extend southward into the Empty Quarter at 0000 UTC and 0300 UTC on the 23rd (figure 4.48). The surface wind would be light north-westerly backing to southerly. At 950 hPa (±460 metres MSL) the wind was also indicated as becoming light north-westerly, but remaining about 10 knots over the sea to the west of Abu Dhabi.

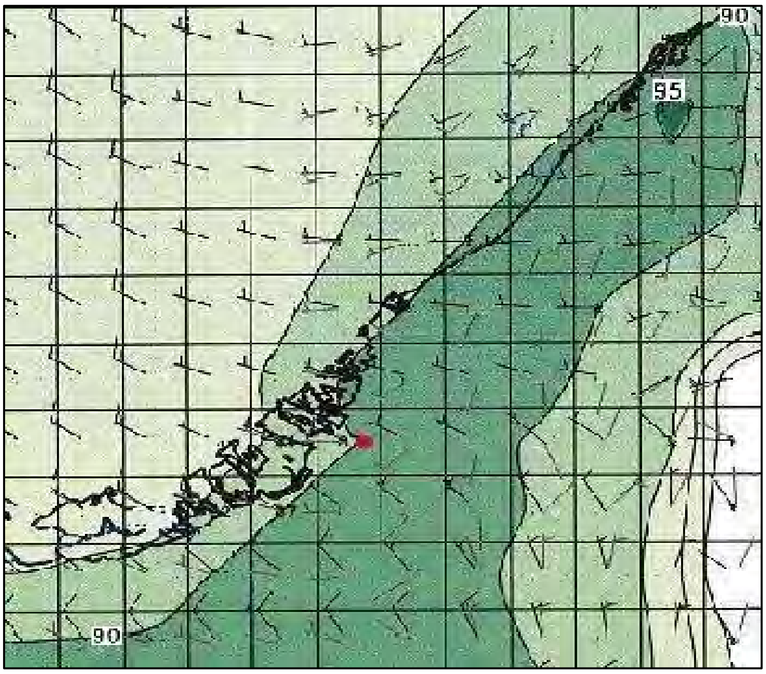

Figure 4.48. Eta relative humidity on 2003-10-23 at 0300 UTC (T+27). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

The prognostic atmospheric profiles at 0000 UTC (figure 4.49, top) and 0300 UTC (figure 4.49, bottom) indicated a temperature inversion at about 950 hPa (±460 metres MSL) with light north-westerly winds below it, becoming light south-westerly at the surface. At the inversion level a north-westerly wind of 10 knots was predicted. The temperature inversion usually forms in the afternoon when cooler maritime air, brought by the sea breeze, undercuts the normally dry air with a near dry adiabatic environmental lapse rate. The prognostic soundings looked very similar to the atmospheric sounding carried out the previous morning at 0000 UTC on the 22nd (figure 4.54) when fog very nearly formed at Abu Dhabi. Note, as opposed to earlier prognostic soundings these later soundings, from a newer and finer model grid, now had more levels between the surface and 900 hPa and, therefore, more detail.

The time section at Abu Dhabi (figure 4.50) indicated a marked north-westerly flow developing in an approximately 3000 feet boundary layer from the surface to 900 hPa from 0900 UTC on the 22nd. Increased moisture was indicated within this layer up to about 460 metres altitude (±1500 feet) from about 2100 UTC to 0900 UTC. Usually a very shallow surface layer is presented.

The later model run at 0600 UTC did not help matters. Apart form presenting very similar aspects as the previous run, it most disconcertingly indicated an even bigger area of higher relative humidity at 0300 UTC (figure 4.51) on the 23rd than the previous run (figures 4.48).

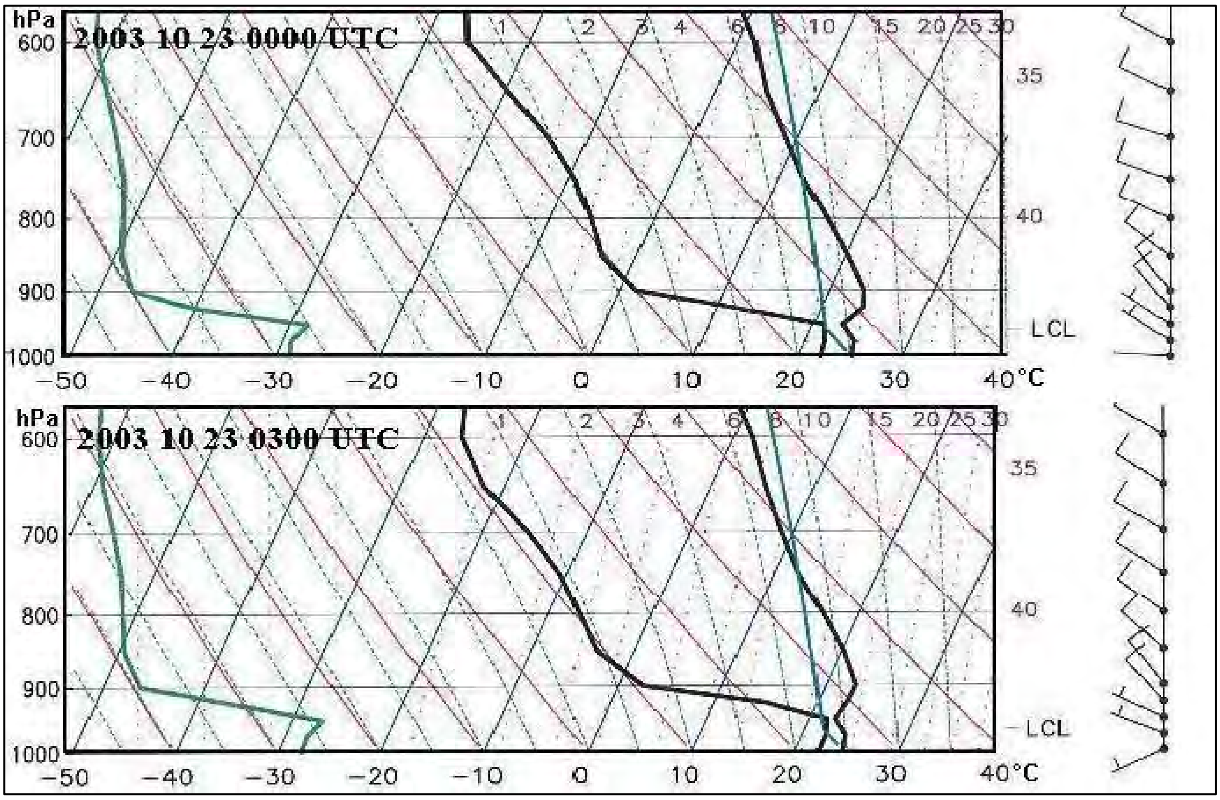

Figure 4.49. Eta GRADS prognostic atmospheric profiles at ADIA at times that are most critical for fog on 2003-10-23 at 0000 UTC (T+24) (top) and at 0300 UTC (T+27) (bottom).

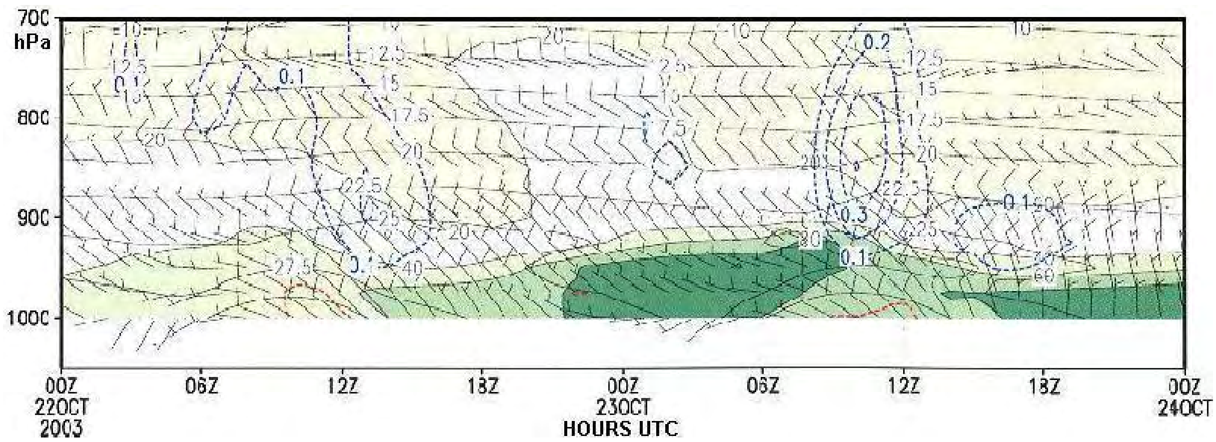

Figure 4.50. Eta time cross-section at ADIA showing the predicted north-westerly flow and increased surface moisture on 2003-10-22 at 0000 UTC (T+0) to 2003-10-24 at 0000 UTC (T+48).

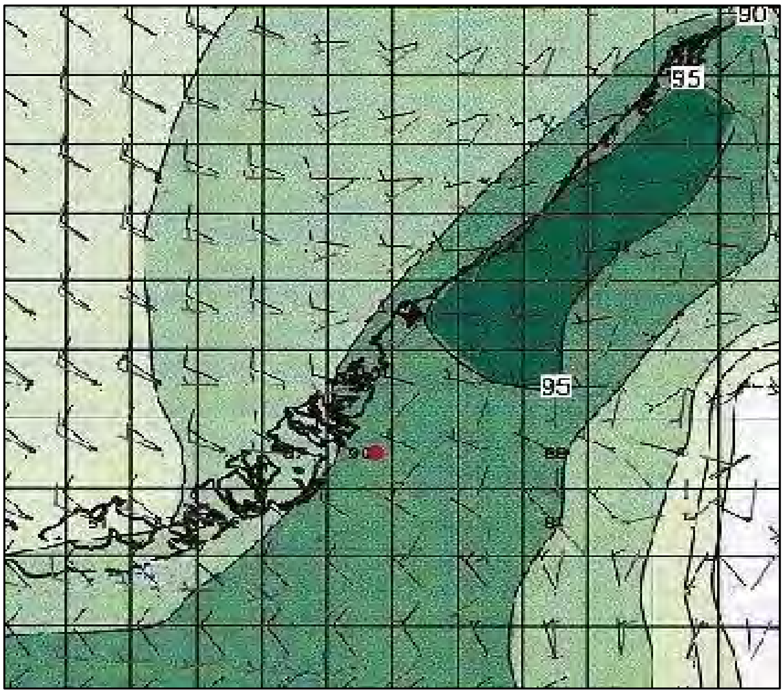

Figure 4.51. Eta relative humidity on 2003-10-23 at 0300 UTC (T+27). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

4.7.5.2 Surface observations

Very moist surface conditions prevailed on the morning of the 22nd with the observed surface relative humidity 92% to 96% at ADIA. The visibility came down to 1.4 kilometres due to fog in the vicinity and a cool light southerly wind blew (figure 4.52). The air remained moist during the day and one could be forgiven for believing that it would remain very moist the next morning and with light winds forecast, fog was highly likely.

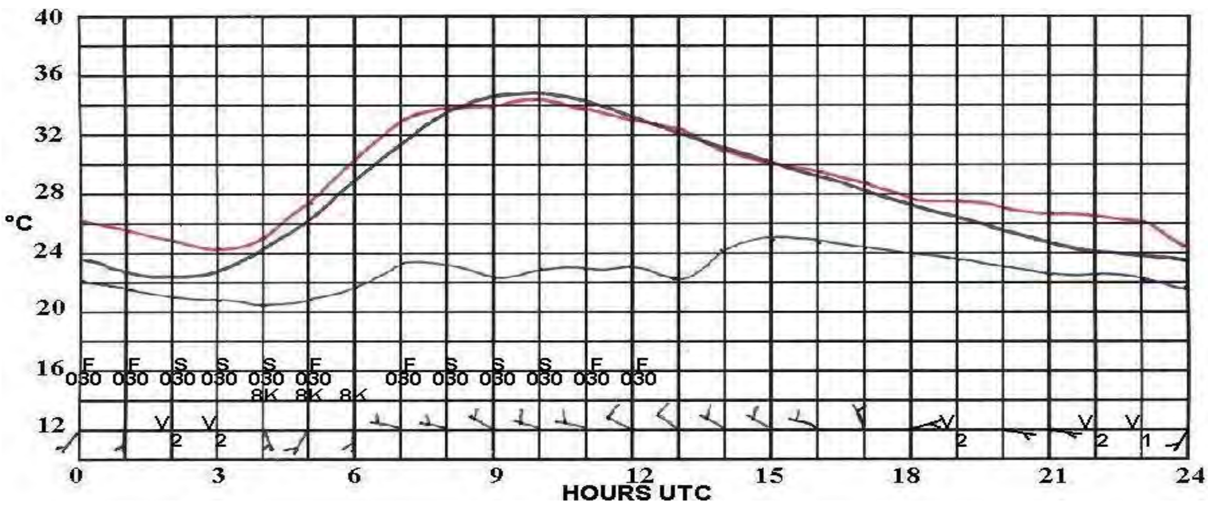

Figure 4.52. As in figure 4.8, but for 2003-10-22. The cloud is at 900 metres (3000 ft) AGL.

However, on the morning of the 23rd (figure 4.53), although the dew-point temperature was still about the same as the previous morning, the low level onshore westerly to south-westerly wind maintained warmer maritime air in circulation than the previous night and the relative humidity did not exceed 82% at ADIA. This was lower than the 90% and above indicated by the NWP model (figures 4.48 and 4.51). When the wind did become light variable it was too late in the night and the air was still too warm for sufficient radiation cooling and condensation.

There is also evidence of turbulent mixing as seen by the low cloud patches observed at about 900 metres and by the visibility that did not deteriorate to worse than 8000 metres (figure 4.53).

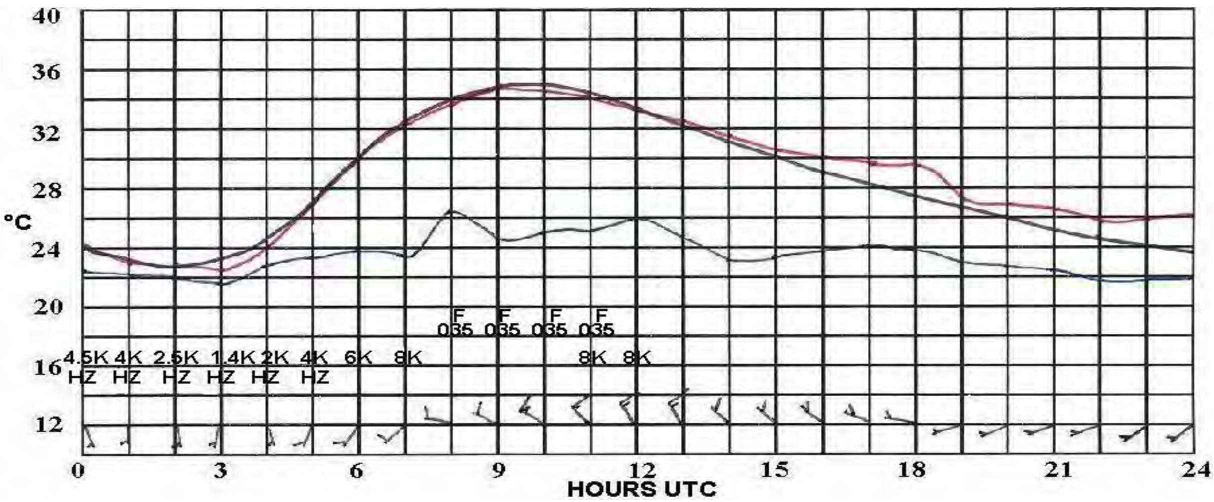

Figure 4.53. As in figure 4.8, but for 2003-10-23. The cloud is at 1067 m (3500 ft) AGL.

4.7.5.3 Atmospheric soundings

The sounding on the morning of the 22nd (figure 4.54, left), when fog very nearly formed, has a marked temperature inversion at 952 hPa (±516 metres AGL), with another near surface inversion below it. The lower inversion probably developed due to nocturnal radiation cooling of the ground and conduction to the air in contact with it. The wind below the higher inversion was southerly to south-south-westerly at 2 to 3 knots (table 4.5).

At 1200 UTC on the 22nd (figure 4.54, right) a surface superadiabatic lapse rate was evident with a weak temperature inversion at about 930 hPa (±728 metres AGL). The wind below the inversion being west-north-westerly at 8 to 11 knots (table 4.5). As the soundings are actually carried out at 1100 UTC and the sea breeze only began to blow about an hour to an hour and a half earlier, it is assumed that the full effect of the cooler maritime air brought by the sea breeze is still not evident on the environmental lapse rate. The wedge of cooler air above the ground could therefore be expected to increase and the surface superadiabatic lapse rate would disappear.

On the morning of the 23rd (figure 4.55) the inversion had lifted up to 894 hPa (±1069 metres AGL). This is more than double the altitude indicated by the model (figure 4.49). Near the surface, radiation cooling resulted in a shallow temperature inversion at 1000 hPa (±86 metres

AGL). Although the air is moist at the surface (80%) and immediately below the upper inversion (87%), the air in between has relative humidity of about 60% to 75% (table 4.5). It is worth noting that the wind between the two inversions was still off the sea, namely, a south-westerly to west-north-westerly wind at 6 to 10 knots (table 4.5).

As mentioned at the end of the previous section, the observations showed evidence of turbulent mixing of the air. The sounding supports this in that the temperature lapse rate has been reduced to the dry adiabatic lapse rate and the dew-point trace to a constant humidity mixing ratio lapse rate (figure 4.55) (Handbook of Aviation Meteorology, 1997).

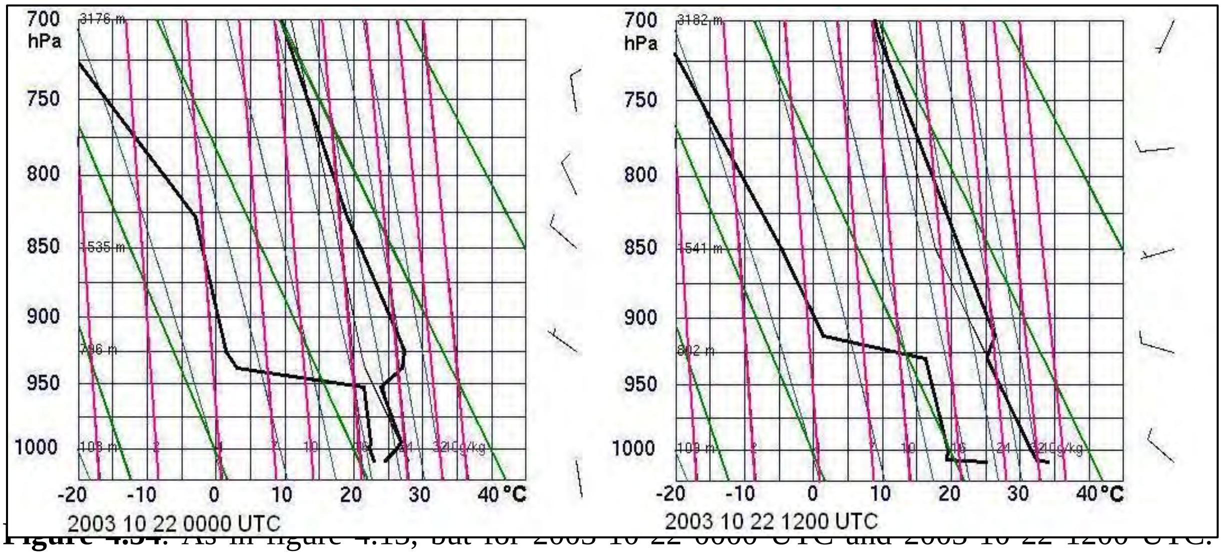

Figure 4.54. As in figure 4.13, but for 2003-10-22 0000 UTC and 2003-10-22 1200 UTC. (Courtesy of the University of Wyoming).

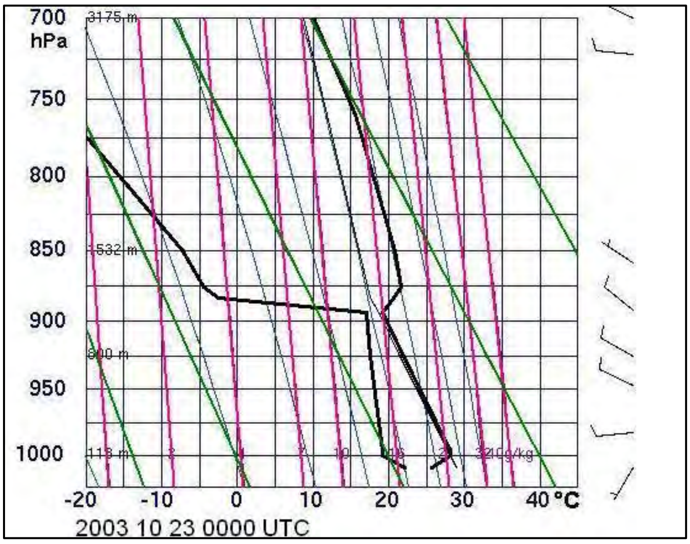

Figure 4.55. As in figure 4.13, but for 2003-10-23 0000 UTC. (Courtesy of the University of Wyoming).

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Table 4.5. Details of pressure, gpm height, air temperature, dew-point temperature, relative humidity and wind velocity up to temperature inversion level on the 22nd and 23rd October 2003.

PRES hPa	HGHT gpm	TEMP °C	DWPT °C	RELH %	DIRC deg	SPED knot
0000 UTC 22 October 2003						
1010.0	27	24.6	22.9	90	170	2
1000.0	108	26.2	22.3	79	195	2
995.0	152	26.8	22.4	77	202	2
952.0	543	24.0	21.5	86	264	3
938.0	673	27.0	3.0	21	285	3
1200 UTC 22 October 2003						
1010.0	27	34.0	25.0	59	310	11
1008.0	43	32.4	19.4	46	309	11
1000.0	109	31.6	19.6	49	305	10
930.0	755	25.2	16.2	57	286	8
913.0	917	26.4	1.4	20	280	7
0000 UTC 23 October 2003						
1010.0	27	25.8	22.1	80	210	3
997.0	140	28.2	19.2	58	240	7
947.0	593	23.9	18.1	70	295	9
894.0	1096	19.2	17.0	87	309	10
876.0	1272	21.6	-4.4	17	308	8

4.7.5.4 Summary

The model correctly presented the low level circulation in the region, but the surface relative humidity was misleading.

The prognostic atmospheric soundings at ADIA gave a good indication of the environmental lapse rate that could be expected and the presence of a boundary layer temperature inversion, although the observed inversion was over double the altitude indicated by the model.

The winds and moisture layer below the inversion were accurately presented and gave a clear indication of low cloud development, but the forecaster would have been misled into forecasting a cloud base of about 300 metres AGL as opposed to the observed base of 900 metres AGL.

In spite of the weak surface pressure gradient, high relative humidity and light low level winds predicted by the NWP model, which duly occurred, fog did not form.

The low pressure cell to the north-east of the UAE, over the Gulf Sea, caused moderate to fresh north-westerly to westerly winds to blow during the day to the south of the low over the southern Gulf Sea and the UAE. The so-called Shamal winds.

During the Shamal conditions fog does not form. Turbulent mixing of the warm and moist air from the Gulf Sea tends to form thin Stratocumulus, or Stratus, cloud under the inversion with sea haze moderately reducing the visibility.

4.7.6 SURFACE LOW PRESSURE CELL TO THE NORTH-EAST: 6TH OCTOBER 2003

This episode is similar to the previous study in that it demonstrates that fog does not occur when there is a low pressure cell to the north-east in the Gulf. What sets is apart and makes it particularly interesting, is that it disproves the local traditional belief that if fog occurs on one morning, more likely than not, it will occur on the second morning. In this instance fog occurred on the morning of the 5th, but not on the 6th.

4.7.6.1 NWP model data

The fog on the morning of the 5th formed in a weak surface pressure gradient that existed over the UAE (figure 4.56, left). However, the Eta model indicated that the low pressure cell, to the east of the Straits of Hormuz would move westward into the Gulf and the pressure gradient in the Gulf would intensify by the following day (figure 4.56, right). By 0000 UTC on the 6th the pressure gradient in the Gulf would be about 3 hPa (figure 4.57).

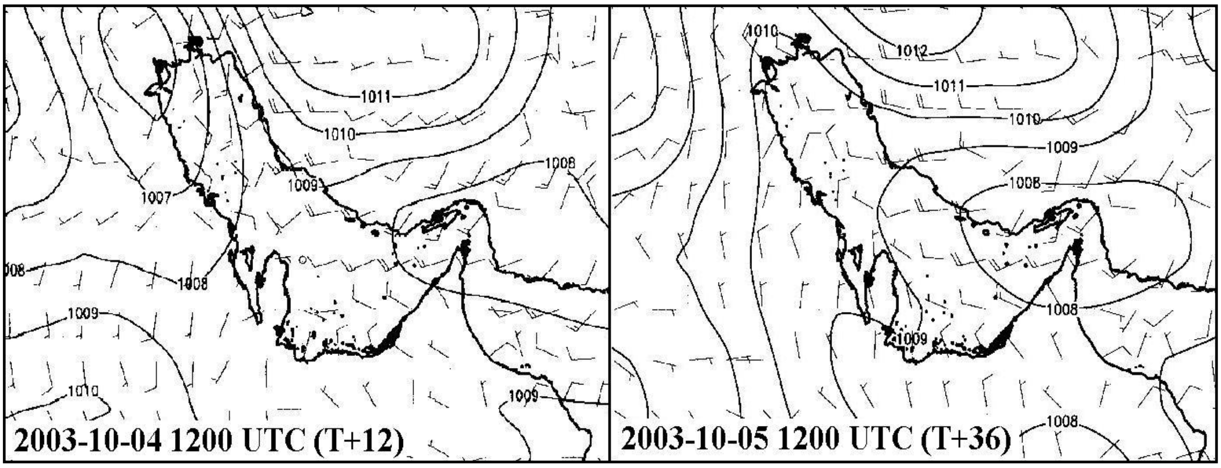


Figure 4.56. Eta GFS fields of surface pressure (hPa) and wind (knots) on 2003-10-04 at 1200 UTC (T+12) and 2003-10-05 at 1200 UTC (T+36).

Considering the surface relative humidity indicated by the model data, fog formation seems probable. More than 95% relative humidity was indicated for the region at 0300 UTC on the 6th in the prognostic field at T+33 for the region (figure 4.58). This is considerably moister than the model predicted for the previous morning when fog actually occurred. A light surface wind was indicted from the south-west, but stronger from the north-west at 950 hPa in the vicinity of ADIA. Both these winds are indicative of fog not occurring. However, a later model run reduced relative humidity at 0300 UTC. This prognosis was reassuring for a “no fog” forecast.

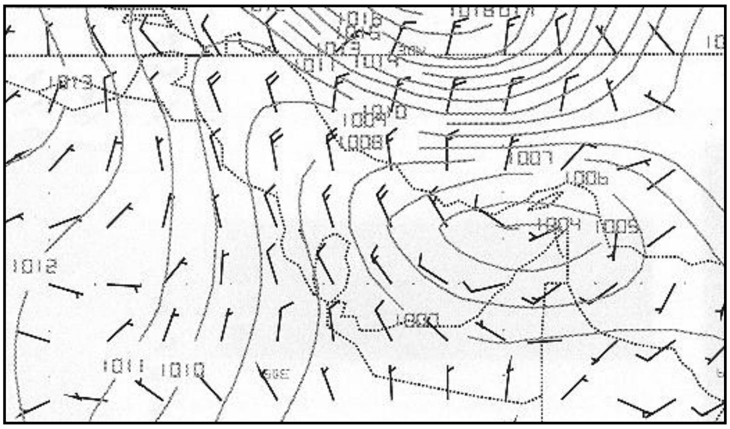


Figure 4.57. Eta WAFS fields of surface pressure (hPa) and wind (knots) on 2003-10-06 at 0000 UTC (T+24).

The surface wind time section for ADIA (figure 4.59) supported the conviction that there would be no fog in that it indicated a light south-westerly wind in the early hours of the 6th. This is the opposite of the very light south-easterly to light southerly winds of the previous morning when the fog occurred.

The resolution of Eta model prognostic atmospheric profile is usually not good enough to be trusted. However, it indicated that the 950 hPa wind at 0000 UTC (T+30) on the 6th, would be stronger from the north-west than the previous morning (figure 4.60). On the other hand more surface moisture was indicated with a more pronounced surface temperature inversion.

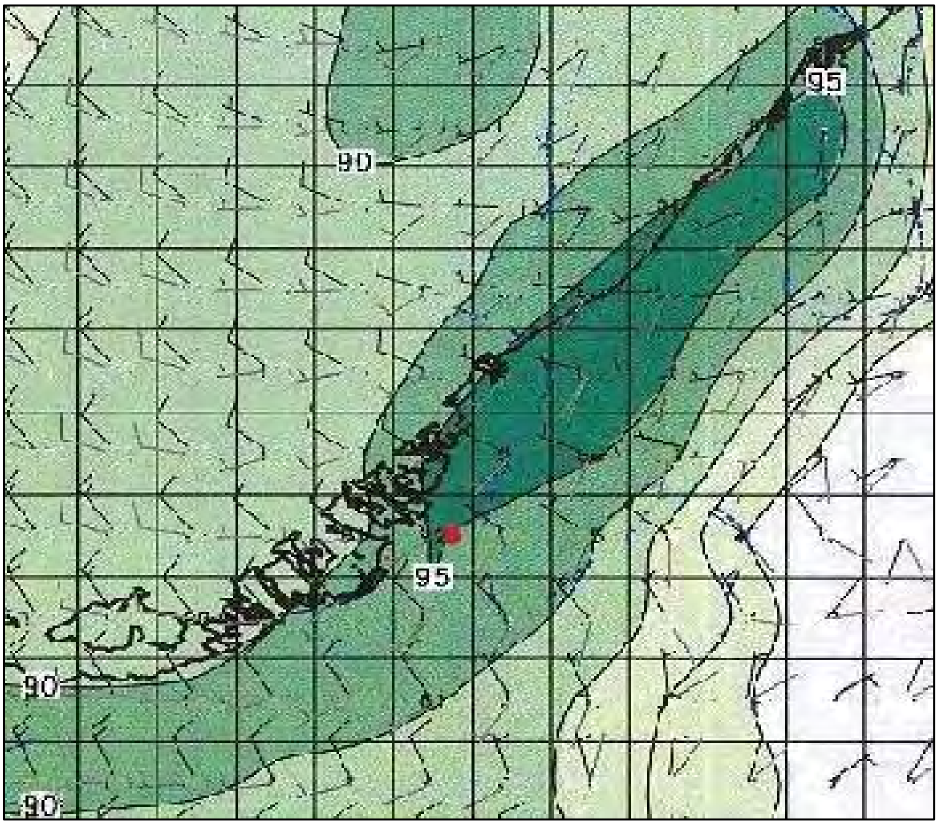


Figure 4.58. Eta relative humidity on 2003-10-06 at 0300 UTC (T+33). Winds (knots) at 10 metre (black) and 950 hPa (grey) with downward vertical velocity (blue lines).

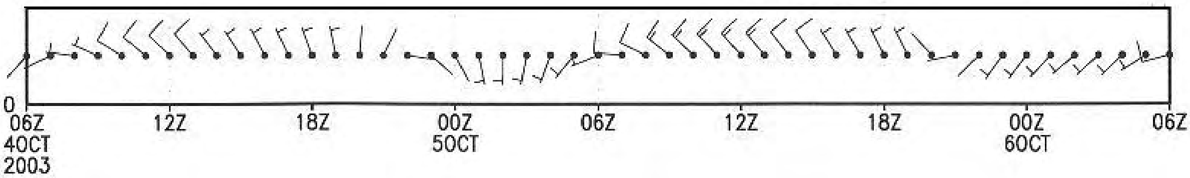


Figure 4.59. Eta GRADS surface wind time section at ADIA from 2003-10-04 to 2003-10-06. A light south-westerly wind is indicated for the morning of the 6th, as opposed to the slight south-easterly to southerly wind on the morning of the 5th.

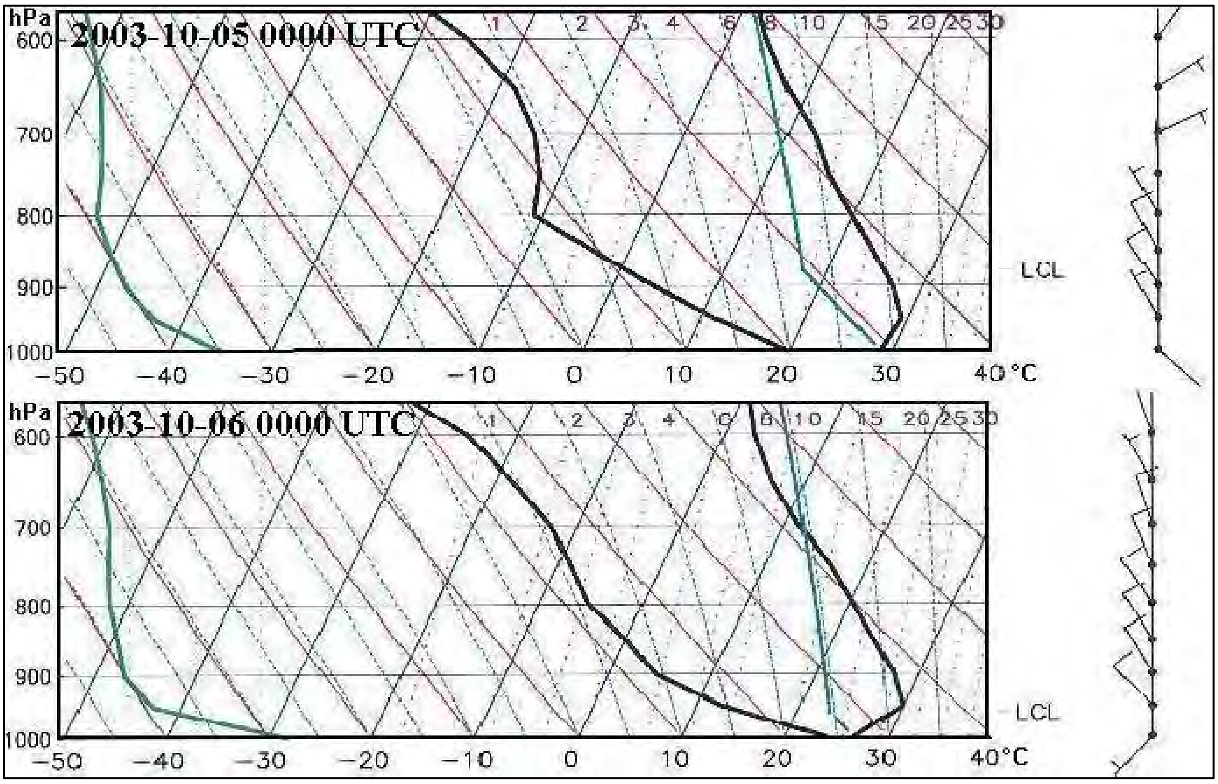


Figure 4.60. Eta GRADS prognostic atmospheric profiles at ADIA on 2003-10-05 at 0000 UTC (T+12) (top) and 2003-10-06 at 0000 UTC (T+30) (bottom).

4.7.6.2 Surface observations

The surface observation graphs at ADIA show the moist conditions on the 4th and 5th (figures 4.61 and 4.62). Fog formed on the morning of the 5th (figure 4.62) when the surface wind became light east-south-easterly and when ambient temperature fell below the dew-point temperature experienced earlier in the evening.

During the 5th, the increasing pressure gradient resulted in a stronger north-westerly sea breeze than the previous day and caused a persistent south-westerly wind during the night. The effect of this wind was that, although the ambient temperature fell to below the dew-point temperature experienced earlier in the afternoon and evening, it kept warmer maritime air in circulation and maintained turbulent mixing with drier air aloft. The result was no saturation of the air and no fog (figure 4.62).
The moderating effect of the maritime air overnight, becomes apparent when comparing the

much higher evening temperatures on the 6th (figure 4.63), after the north-westerly circulation about the low became properly established, with the cooler east-south-easterly wind off the desert on the evening of the 4th prior to the fog forming (figure 6.61).

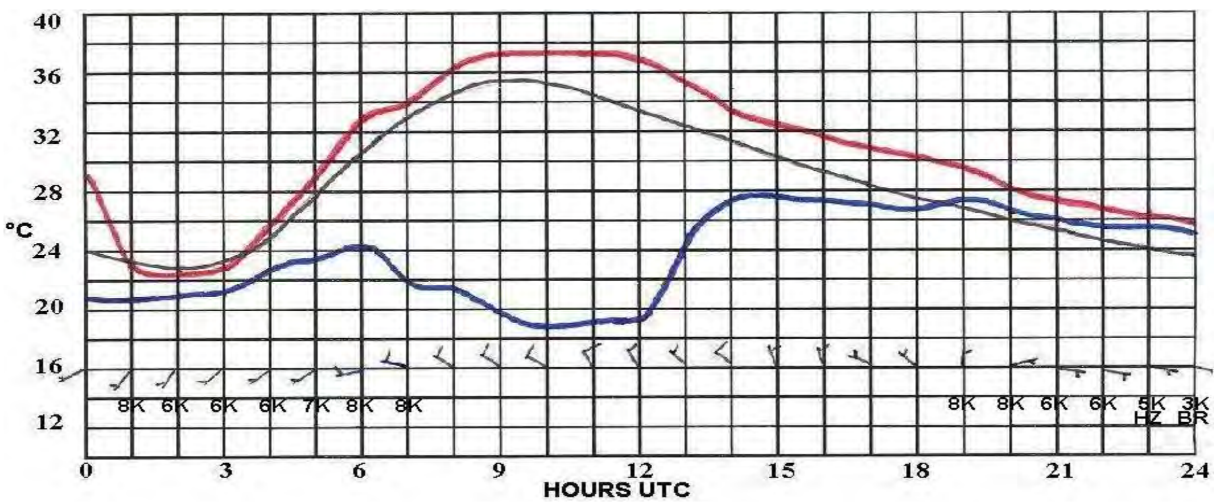


Figure 4.61. As in figure 4.8, but for 2003-10-04.

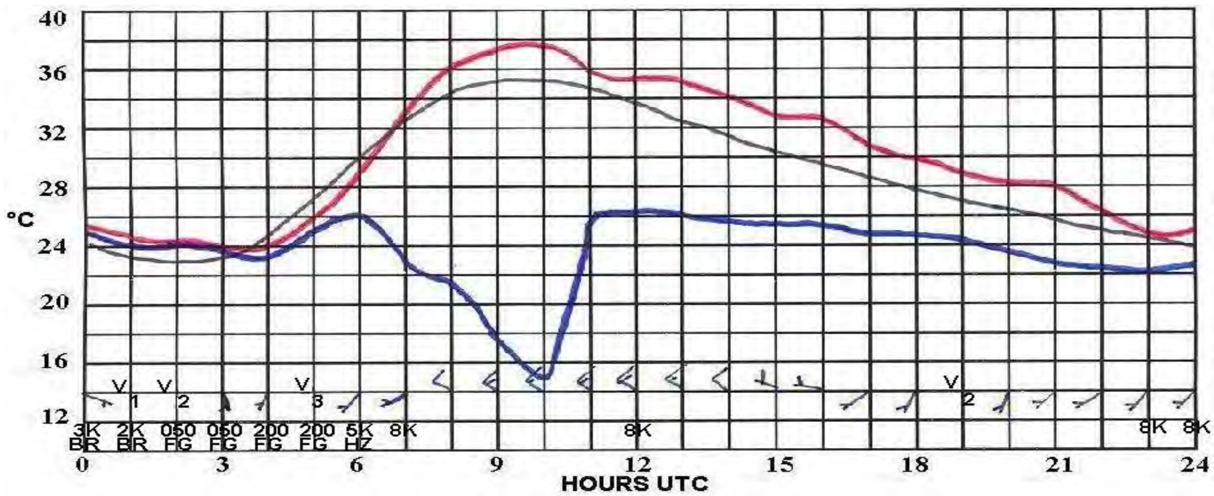
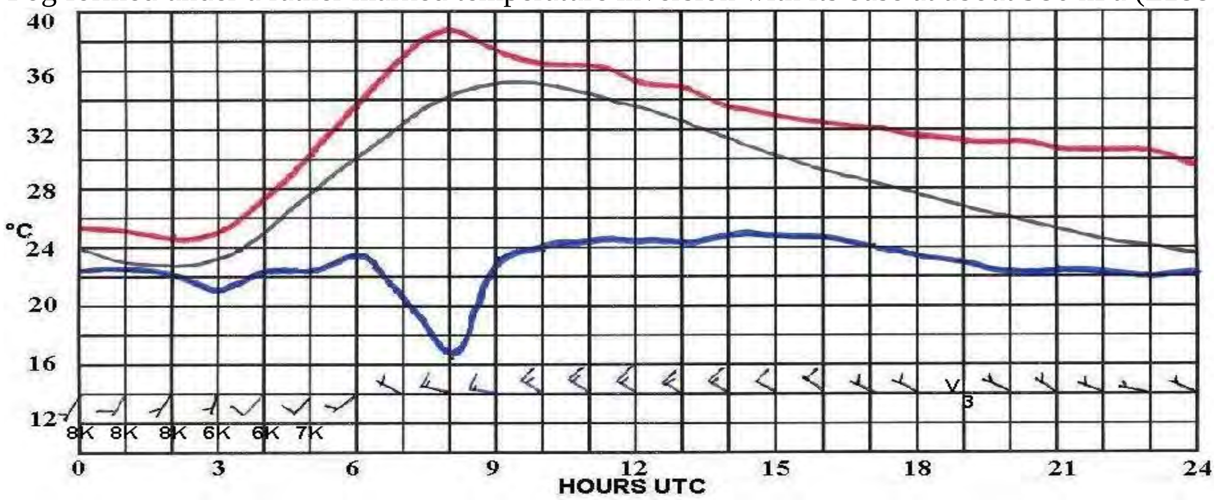


Figure 4.62. As in figure 4.8, but for 2003-10-05.

4.7.6.3 Atmospheric soundings

Fog formed under a rather marked temperature inversion with its base at about 986 hPa (±188



although the inversion was higher than normal at 937 hPa (±637 metres AGL). An inversion at this height being more likely to cause Stratocumulus clouds to collect under it.

On the morning of the 6th, a temperature inversion had formed at 995 hPa (±78 metres AGL) with the wind below it having backed from north-westerly to south-westerly at 5 to 7 knots (figure 4.65). That is, increased thermal stability at night causes the wind under the inversion to become uncoupled from the circulation around the low above the boundary layer and then backs from north-west to blow from the south-west toward the low pressure cell. Conversely, one can say the wind veers with height from the surface upward (Pal Arya 1988, Riehl 1954).

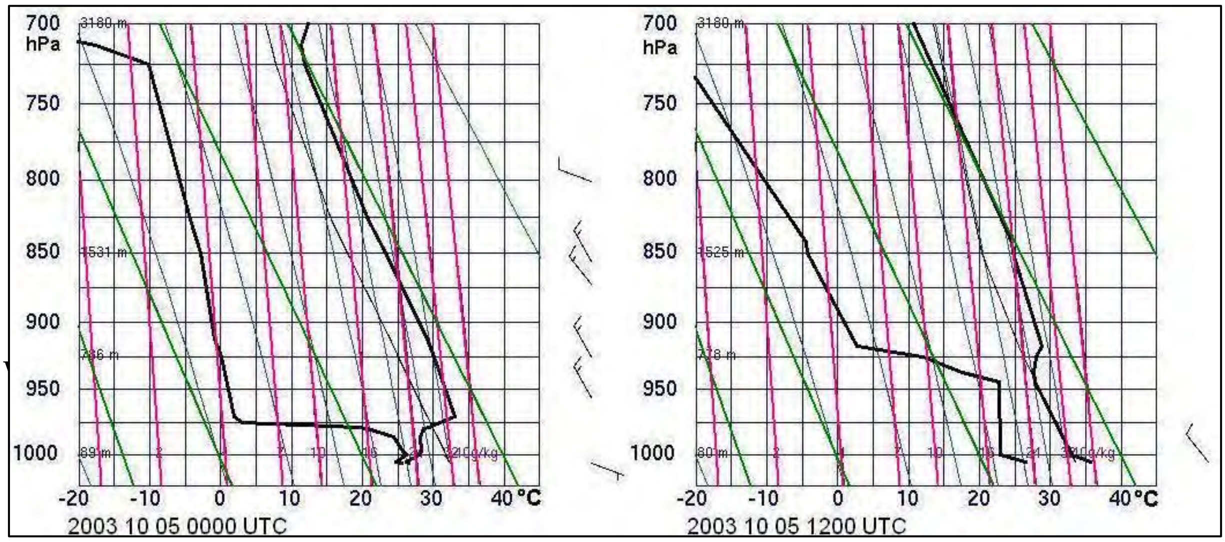
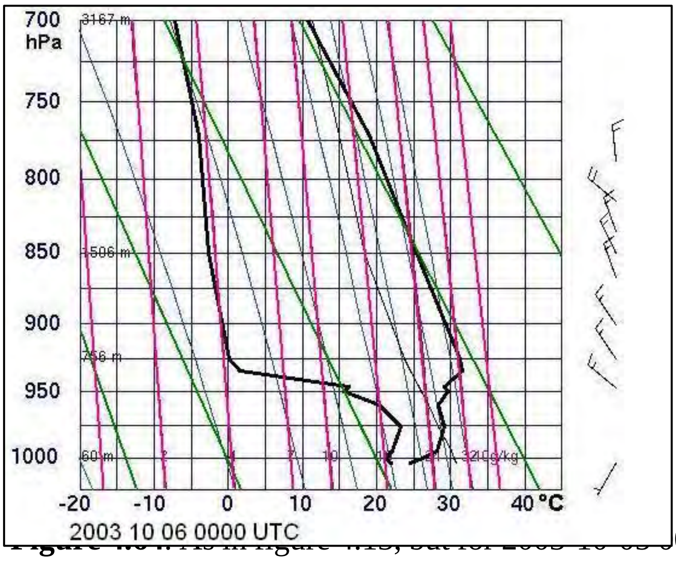


Figure 4.64: As in figure 4.13, but for 2003-10-05 0000 UTC and 1200 UTC. (Courtesy of the University of Wyoming).

Although moist below the inversion at 70% to 85% relative humidity, this is not much moister than the previous afternoon ascent and not sufficiently moist for fog to form. A higher temperature inversion was at 945 hPa (±400 metres AGL) with the wind between the two inversions off the sea from the west to west-north-west at 10 to 12 knots.



In view of the change from a weak pressure gradient with fog to Shamal conditions and air transported from the north over the UAE, it was thought that there might have been a change of air mass. In order to determine this, the wet bulb potential temperature (WBPT) at 850 hPa was calculated from the Abu Dhabi soundings at the time of the fog and afterwards. The WBPT was chosen because it is conservative with respect to dry and moist adiabatic processes (Hess 1959) and the 850 hPa level was selected, because it is high enough to eliminate boundary layer influences such as surface heating and cooling (Galvin 2003). It was found that there was very little change in value from the 8th to the 9th, with the temperature varying between

289°K and 290°K.

With this in mind the WBPT was determined at the time of the previous case studies. Once again the variation was found to be very small in every episode, being less than 3°K, apart from 4°K during the case study of the 8th to 11th January 2003. Therefore the conclusion is that there is no marked change in air mass during fog events and that fog formation is rather due to smaller scale boundary layer influences.

4.7.6.4 Summary

One must not fall into the trap of simply forecasting fog because it occurred the previous morning. Persistence forecasting of fog will fail.

Although inspection of the 850 hPa wet bulb potential temperature leads one to believe that there is no change of air mass during fog events, developing synoptic processes and smaller scale boundary layer influences must be taken into consideration.

The model data clearly show a change in synoptic circulation, therefore fog was not to be expected. Although the moisture fields were at times misleading, the main considerations were the increased pressure gradient and stronger north-westerly to south-westerly wind due to the development of a low pressure to the north-east.

Fog is highly unlikely when the wind backs from north-westerly to south-westerly. This situation arises when there is a low pressure cell to the north-east, particularly a developing low pressure cell. The reason is that the resulting pressure gradient over the UAE generates a wind that is strong enough to maintain turbulent mixing. In this situation the surface wind at night becomes uncoupled from the circulation around the low above the boundary layer and backs from north-west to south-west.

The moderating influence of the Gulf Sea, brought by the wind from the north-west and possibly curving to south-west along the coast, maintains warmer overnight surface temperatures. This, combined with turbulent mixing, prevents, or inhibits, nocturnal radiation cooling of the air.

4.8 RESULTS

4.8.1 GENERAL

Typically, fog at Abu Dhabi forms at night in a clear sky with a weak pressure gradient, light winds and sufficient moisture, that is, radiation fog, although a preceding advection process plays a supporting role by bringing moisture from the sea. A secondary observed form of advection is that the fog often appears to form over the southern inland part of the airport and drift, or expand, coastward on a light southerly wind off the desert.

Seasonally, the highest frequency of fog is in the autumn months of September and October and the least in summer. It tends to form earlier in the evening during the winter months and last longer after sunrise than in the summer. The 10 year study of the winter months of January and

February revealed that fog occurred between 1800 to 0700 UTC and most frequently between 2200 to 0500 UTC. In summer (July and August) fog occurred between 2200 and 0400 UTC and most of it between 0000 and 0300 UTC. More often than not the fog clears within about 2 hours after sunrise. The earliest fog occurred during the study period from 1983 to 2002 was 1800 UTC and the latest was 0700 UTC.

Inspection of the fog events for the ten-year period from 1993 to 2002 revealed that there is only an 18% chance of fog on two consecutive days, while the risk of fog three days in a row is 6% and 2% and 1% for four and five days, respectively. These figures emphasise that one must not go the persistent forecasting fog. Consideration must be given to changing circumstances and conditins. A case in point is the non-occurrence of fog on the 6th October 2003.

Although inspection of the 850 hPa wet bulb potential temperature leads one to believe that there is no change of air mass during fog and no fog events, developing synoptic processes and smaller scale boundary layer influences must be taken into consideration.

4.8.2 PRESSURE AND PRESSURE PATTERNS

Fog forms in a weak pressure gradient across the UAE, usually 1 hPa, or less, particularly after persistent Shamal winds, or sea breezes, with attendant high humidity.

Fog does not occur when a surface low pressure cell is situated to the west of the UAE, or over the western part of the UAE. It produces a dry offshore southerly flow that strengthens the early morning land breeze and delays the onset of the sea breeze until late in the afternoon and can prevent it from extending too far inland. The stronger and earlier beginning of the land breeze causes turbulent mixing of the surface air with drier air aloft, thereby prematurely curtailing the radiation cooling effect and prevents fog formation.

The presence of an anticyclone over southern Iran and the Strait of Hormuz also produces a southerly flow over the UAE and produces the same effect.

When the wind remains from the north-west to north-easterly throughout the night, due to a surface low pressure cell to the south, or south-east, fog does not occur. The steady wind off the sea is also usually strong enough to maintain turbulent mixing, thereby preventing fog formation. Air off the sea, being less influenced by nocturnal surface radiation cooling maintains warmer conditions than when it arrives from the cooler desert, with less likelihood of the air cooling to its condensation level. If the wind does swing to the south-east, due to the synoptic circulation, and increased radiation cooling over the land, it is usually too late to enable the air to cool to below the dew-point temperature.

Under Shamal conditions, such as when a surface low pressure cell is to the north-east of the UAE, fog does not form. The low level winds at night, which become light south-westerly to westerly and may even remain north-westerly, maintain warm Gulf air in circulation relative to the cooler overnight land air. Turbulent mixing of the warm and moist air from the Gulf Sea may cause a thin layer of stratocumulus, or stratus cloud, to form under a temperature inversion in the approximately 900 metres (3000 feet) atmospheric boundary layer, with sea haze moderately reducing the visibility.

4.8.3 TEMPERATURE

It was noted that fog forms when the air temperature falls to, or below, the maximum dew-point temperature that occurred in the previous late afternoon, or early evening. This is significant enough to be taken into consideration when determining the overnight minimum temperature. Fog does not always form immediately the air temperature has fallen to, or below, the maximum dew-point temperature earlier in the day. It can form up to a few hours later. This is not an absolutely reliable indicator, as the air temperature can fall below this level with no fog formation.

4.8.4 HUMIDITY

As a rule the chance of fog later in the night is very good if the surface humidity exceeds the specific hourly values during the preceding evening, as indicated in figure 4.1. However, it is by no means a rigid rule, as it can be lower, particularly during the early evening. Certainly if the surface relative humidity is expected to reach, or exceed, 95%, fog must be considered.

4.8.5 WIND

The 10 m wind often falls to 2 knots, or less, about an hour prior to the fog forming. Allowing for surface friction effect, it can be assumed that the wind at about 2 m decreases to less than this and possibly calm at this time, which is favourable for initial fog development.

Fog is most likely (87% of the time) when the wind veers during the night from north-westerly through easterly to a calm or light east-south-easterly or south-easterly wind. It is most unlikely, but not impossible, when the wind backs to south-westerly to southerly.

Fog does not occur when Shamal conditions exist and the surface wind persists from the west through north-west to north-east during the night, or most of the night before possibly becoming a temporary light south-easterly land breeze around sunrise.

From the ground up to the temperature inversion the wind tends to back from south-easterly to north-north-easterly in fog conditions, but this is not always true. As the case study for the 9th to the 11 January showed, the wind can remain easterly. A southerly wind brings dry desert air and no fog. The critical factor remains the strength of the wind, a wind of around 5 knots, or less, being the most productive.

4.8.6 VISIBILITY

The visibility during fog events normally rapidly deteriorates to less than 200 metres, on some occasions as low as 50 metres. Visibility less than 200 metres is most prevalent between 2200 UTC and 0500 UTC. 200 metres is a critical visibility level at ADIA and determines whether the airport remains operational, or not.

Misty conditions and/or low stratus cloud in the afternoon or evening, are a useful visual indicator of fog later, but are not infallible.

4.8.7 ATMOSPHERIC SOUNDINGS

The extreme dryness of the air above a temperature inversion, in the atmospheric soundings, epitomise the prevailing presence of a continental anticyclone with strong subsidence and creating so called superior air.

The soundings reveal profiles around the time of fog formation at 0000 UTC that conform closely to those suggested by Stull and the UK Met Office in figure 4.1.

An ideal fog profile at 12 UTC that is indicative of fog later in the night is more difficult to categorise. However, the ambient air temperature profile most likely to be a precursor to fog formation later in the night, is one that indicates the base of a temperature inversion somewhere in the layer between the surface and 960 hPa. This pressure level is approximately 270 metres (900 feet) AGL in summer to about 490 metres (1600 feet) AGL in winter.

Morning soundings show that fog most often forms when the temperature inversion base is about 171 metres (560 feet) AGL, or lower, but can be up to about 1000 feet AGL. This implies that sinking of the inversion toward the ground occurs in the evening, or a new ground inversion develops in conjunction with nocturnal surface radiation cooling. Wind shear is not always present at the temperature inversion.

Preferably, the pre-fog afternoon dew-point temperature profile will reflect moist air with markedly dry air above. Greater than 50% relative humidity, from the surface to the base of the temperature inversion, or at least up to 100 metres above the ground is a good indicator, but it is not an infallible indicator. On occasion relative humidity, at the time of the sounding, has been as low as 30%.

On summer afternoons the cooler sea breeze tends to carve a very prominent wedge into the very hot dry adiabatic lapse rate temperature profile, with a near surface superadiabatic lapse rate. In winter the afternoon soundings differ in that, due to the lower winter land temperatures, the wedge of sea breeze air is less pronounced. The morning winter upper air profiles generally had shallow surface inversions The winter upper air profiles also often had difficult to discern near surface inversions topped by an isothermal layer. This is in complete contrast to the marked summer temperature inversion. Winds below the inversion tend to back from south-easterly to north-easterly irrespective of the season.

4.8.8 FOG INDICES

Generally, fog indices, developed elsewhere, yielded erratic results when applied at ADIA. The Saunders and Craddock and Pritchard methods were derived in the United Kingdom for a wetter and milder climate and did not fare well in the much drier conditions immediately above the surface layer at ADIA. The same applies to using the 850 hPa wet-bulb potential temperature (WBTP). The fact that these indices gave more realistic values in the cooler and moister winter conditions at ADIA supports this assumption.

The two locally developed WBPT methods fared better. One method uses the 1200 UTC surface WBPT as the forecast the fog temperature. The second method uses the 0000 UTC surface temperature and the 1200 UTC surface dew point temperature to calculate a forecast surface WBPT, or fog temperature for the following night. The second method has promise with the application of exception stipulations, but it requires further investigation.

4.8.9 NWP MODEL DATA

Larger scale synoptic patterns that do not produce fog are easy to identify. These include; Shamal conditions with a low pressure cell to the east, or north-east, a southerly wind off the desert in association with a low pressure cell to the west and south, or an anticyclone to the north and east of ADIA. The problem arises when the pressure gradient is weak, such as when an anticyclone or col is over the UAE. Whether condensation will be in the form of dew or fog then depends on the delicate balance between moisture available and the wind, a condition that is still beyond the ability of current NWP models.

Model data can give misleading clues as to whether fog would form or not. Model conflicts include indicating fog favourable light south-easterly to southerly winds, but with insufficient moisture, or on the other hand, high moisture content, but with a light wind from the wrong direction. Another problem with model data is predicting high moisture content at longer lead times and then scaling it down closer to the target time. The conclusion is that model prognoses relative humidity and wind fields must not be used in isolation and other fog indicators must also be taken into consideration.

Prognostic atmospheric profiles, particularly those from finer resolution NWP models, can give a good indication the environmental lapse rate that is expected and the presence of a boundary layer temperature inversion as well as low level winds.

In spite of NWP models correctly predicting a weak surface pressure gradient, high relative humidity and light low level wind, fog may still not occur. Under these circumstances consideration must be given to the predicted pressure pattern.

4.9 FORECAST CHECKLIST

A fog forecast checklist has been established to help the forecaster decide whether fog will occur. Taking into consideration that forecasts can be required up to eleven to thirteen hours before the flight arrives at ADIA, the checklist has been divided into separate short (<12 hours) and long term (>12 hours) checks.

Long term (>12 hours)

Favourable for fog

- Clear sky expected.
- A weak pressure gradient of 1 hPa, or less.
- Surface col, or anticyclone, over the UAE.
- Shamal ceases during the afternoon, or evening.
- $\geq$ 90% surface relative humidity indicated in the night at 0000 UTC and 0300 UTC.

- ≤ 5 knots surface winds and in the atmospheric boundary layer expected.
- Surface wind expected to veer from north-west to south-easterly.
- A surface, or near surface temperature inversion expected overnight, preferably ≤ 168 metres (± 550 feet) above MSL.

Unfavourable for fog

- Wind ≥ 5 knots.
- A southerly offshore surface wind.
- Low level southerly to south-easterly wind (≥ 5 knots).
- Early surface land breeze expected.
- Pressure gradient > 1 hPa.
  The above conditions occur with:
  - a) A low pressure cell to the west.
  - b) An anticyclone over southern Iran and/or the Strait of Hormuz.
- Shamal wind.
- Low pressure cell to the south, south-east, or east with a ≥ 5 knots easterly to north-easterly wind.
- Surface winds expected to back from north-west to south-west, or southerly.

Short term (< 12 hours)

Favourable

- Afternoon sounding has;
  a) A near surface temperature inversion ±270 m, 885 ft (summer) ±490 m, 1607 ft (winter).
  b) ≥ 50% relative humidity within ± 100 metres of the surface.
- Forecast minimum temperature lower than, the maximum dew point temperature the previous late afternoon or evening.
- Hazy visibility late afternoon and/or evening.
- Early evening low stratus cloud.
- Relative humidity ≥ 73% by 1800 UTC.

Unfavourable

- The afternoon sounding has;
  a) A surface temperature inversion higher than 960 hPa.
  b) ≤ 50% relative humidity within a few hundred feet of, the surface.
- The forecast minimum temperature is higher than, the maximum dew point temperature the previous late afternoon and evening.
- Clear and crisp late afternoon and evening visibility conditions.
- ≥ 5 knots southerly surface desert wind begins early in the night.
- Surface wind backs to south-westerly instead of south-easterly.

Imminent

- The 10 m wind is light variable and approaches calm.
- The 2 metres wind falls below 2 knots, or calm (and increases again).
- The observed surface relative humidity ≥ 95%.