Dust storms and dust at Abu Dhabi International Airport

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Estimates have been made that, annually, up to about two billion tons of dust are carried up into the atmosphere, mainly by dust storms. One dust storm can lift and deposit more than 200 tons of dust (Griffin *et al.,* 2002). The Arabian Peninsula has been listed as one of five major dust-producing regions (Idso, 1976), while Goudie (1983) adds that dust storms are frequent in the area.

Apart from being a hazard and a nuisance to the general public, dust storms and sand storms are hazards to aviation. Poor visibility and gusty winds are a danger to aircraft landing and taking off at Abu Dhabi International Airport (ADIA) in the United Arab Emirates (UAE). This can lead to diverted flights, delayed departures and attendant airport operational problems. Other effects include the scouring of aircraft surfaces and damage to engines as well as hampering ground operations.

A dust storm, or sand storm, is a collection of particles of dust, or sand, vigorously lifted to great heights by a strong and turbulent wind and the visibility is reduced to below 1000m (UKMO, 1991). The visibility is most likely to be at its worst during daylight hours when the wind is at its strongest (UKMO, 1994).

At ADIA little differentiation is usually made between whether the event is caused by dust or by sand, until the visibility falls below 1000m when it is reported as a sand storm by the observers at ADIA. Safar (1985) uses the same stipulations, but adds that when the visibility falls below 200m, the storm is classified as severe. The more general convention seems to be simply to refer to dust haze and dust storms (Safar, 1985).

To the authors' knowledge no analysis has been made as to when dust events and dust storms occur at ADIA. This paper examines statistically when dust events and dust storms occurred at ADIA during the ten years from 1994 to 2003, a dust event being when the visibility was reduced to 5000m, or less.

Dynamics

Although little distinction is usually made between whether the cause of the poor visibility is dust or sand, there is a difference. The diameter of grains of desert sand usually varies from 0.15mm to 0.3mm with the lower limit being 0.08mm. A diameter below 0.08mm is defined as dust. Dust is more likely to be found in and around inhabited areas where human and vehicular activity tends to break and crush sandy soil to produce finer sand or dust (UKMO, 1994).

The conditions that allow dust to be raised in suspension in the atmosphere for prolonged periods are dry soil, strong winds and a deep and well-mixed boundary layer with a nearly dry adiabatic lapse rate (Blair, 1957; Safar, 1985; Jauregui, 1989). Obvious-ly, the drier and sandier, or rather dustier, the surface the better.

Surface turbulence is normally too weak to raise grains of sand more than about a metre above the ground until the 10-m wind speed reaches 20kn. Sand lifted by the wind is then carried across the surface, but tends to fall back to the ground where the grains bounce back into the air and in the process disturb other grains of sand on the ground, a process known as saltation. The sand falls quickly to the ground when the wind drops and the visibility immediately improves. Depending upon the condition of the surface and instability, dust, on the other hand, can be easily raised to great heights and, long after the surface wind has dropped, be held in suspension in the atmosphere for hours and even days before settling. Dust grains start to lift when the 10-m wind speed reaches 15kn. Larger parti-cles, in falling back to the ground, also disturb smaller particles, which are lifted higher into the air by turbulence and remain in suspension longer (UKMO, 1994).

Two mechanisms that provide a wind strong enough to lift dust and sand are thunderstorms and the synoptic situation when there is a strong pressure gradient between an anticyclone and a cyclone (WMO, 1983; Wheaton and Chakravarti, 1990). In a thunderstorm, dust is raised by the ascent of air in convective thermal currents, as well as severe turbulence and vertical motion induced by the strong wind at the storm's gust front. In the synoptic situation, where there is stable thermal stratification at the edge of the anticyclone, lifting is due to the steep pressure-gradient-induced geostrophic wind along the pres-sure contours. Raised dust permeates upwards in small turbulent eddies that move up through one thermal layer to the next. Dust raised this way is much more extensive than that raised by thunderstorms and can cover over a million square kilo-metres (WMO, 1983).

Statistics

Observational records kept at ADIA from 1982 to 2001 show that while haze – due to dust, commercial pollutants, or moisture – is very common and occurs on average on 242 days per year, dust storms are far less preva-lent, the average being three per year with the most being eight in 2003. By way of comparison, inland at Al Ain and using data from 1994 to 2001, haze occurs on an average of 304 days per year. Dust storms average four days per year with a maximum of seven in 1994.

A total of 173 events (141 dust events and 32 dust storms) were identified during the period from 1994 to 2003 (Table 1). These were divided into three groups according to when the wind direction was from the south-east to west-south-west, or from the west to west-north-west, or north to east-south-east (Table 2). The logic behind these divisions being that wind from the south-east to west-south-west blows from the desert areas to the south-east to south-west. It also blows when a low pressure cell, or trough, approaches from the west. Wind from the west to west-north-west has a track mainly down the length of the Arabian Gulf during post-trough, or low-pressure, situations and high pressure building to the west, while that from the north to east either comes from the mainland of Iran to the north and north-east, or had to come across the Gulf of Oman Sea and over the penin-sula to the east. Northerly to east-southeasterly events were difficult to categorize. These winds are most likely when low pressure/ trough systems and the building anticyclone are more to the north-east, or east, of the UAE. There were borderline instances that were difficult to categorize, such as when the wind blew from a northerly direction and it was possible that the wind was a northwesterly Shamal that with time veered to the north. Rao *et al.,* (2001) define the Shamal as a north to northwesterly wind with a mean hourly speed of 17 kn, or more, that blows for at least three hours in a day. The *UKMO Meteorological Glossary* (1991) adds that it Uis a hot and dry wind.nderstandably, the visibility was most often reduced at ADIA when the wind was from the south-east to west-south-west and therefore has a long track off the desert. It is less often reduced when the wind arrived from across the length of Arabian Gulf to the north-west, or the Gulf of Oman to the east and the much narrower sea in the vicinity of the Strait of Hormuz to the north-east (Table 2), such as the cold and dry north-easterly wind from Iran to the north, known locally as the Nashi (UAE Ministry of Communications, 1996). The total 95 southeasterly to west-southwesterly events in Table 2 constitute 45% of the total 211 observations (Figure 3). Similarly 42 westerly to west-northwesterly events and 103 observations represent 41% and 36 out of 57 northerly to east-southeasterly events is 63% (Figures 4 and 5). Looked at from this point of view dust events from the north to east-south-east are far more frequent than previously imagined. The obvious conclusion is that if the wind blows strong enough from inland, dust haze and dust storms must be expected.

There is a close association between dust in suspension and vertical instability (Chepil and Woodruff, 1957). It is therefore not surprising to note that there were often instances when a dust storm was associated with the presence of thunderstorm cumulonimbus (Cb) cloud, or cumulus congestus (Cu), and always with a high base (±1500m). Consequently, the wind direction and strong speed were often of a very temporary nature as was the poor visibility. Of the 32 dust storms, convective cloud was present on 15 occasions and most often with northerly to east-southeasterly winds (Table 3).

The average duration (to the nearest 5 minutes) of visibility at, or below, 1000m at ADIA in a dust storm was found to be 1 hour and 15 minutes with the maximum time being 4 hours 30 minutes. The average time when the visibility was at, or below, 3000m was 3 hours 45 minutes with the longest time being 15 hours. Taking all 173 dust events into consideration the average time when the visibility was at, or below, 5000m is 3 hours 30 minutes and the most 21 hours. On average, thunderstorm gusts reduced the visibility to duststorm levels for 37 minutes with the longest time being nearly 60 minutes. These poor visibility periods due to dust during a thunderstorm are conservative, because observations when rain was present with dust during a thunderstorm were excluded, even though the main cause of the poor visibility could still be dust in suspension.

Diurnally, with south-east to west-south-westerly winds, dust reduction of the visibility to below 5000 m was most frequent during the morning and most of the afternoon. This coincides with the regular morning land breeze that would reinforce any southerly flow due to the synoptic pressure pattern, such as a low pressure cell, or trough, to the west (Figure 1). Conversely, dust-reduced visibility associated with a west-northwesterly flow was most likely during the mid and later afternoon when a northwesterly Shamal would be strengthened by the sea breeze. A possible explanation for the greater frequency of northerly to east-southeasterly events in the late afternoon and early evening is that this is the time when the sea breeze begins to veer towards the east prior to the morning south-easterly land breeze. It could also be the Coriolis force taking effect and deflecting the wind to the right, but this is weak at this latitude (Bradbury, 1991). More likely, the increased frequency is due to increased wind speed caused by deepening of the diurnal heat low over the Empty Quarter to the south-west (Rao *et al.*, 2003).

There is a remarkable frequency increase in dust-reduced visibility during the day and decrease at night (Figure 1). Night cooling of the ground and the air immediately above it by radiation, results in increased stability that suppresses the vertical movement of wind eddies, uncouples the surface wind from the stronger wind aloft, and allows surface friction to further reduce the near surface wind speed. Dust is therefore given time to settle. During the day, increased heating and thermally induced turbulent eddies reduce stability and increase mixing with the air aloft, which increases the wind speed and lifts dust (Kessler, 1985).

Correlation between wind speed and visibility was difficult to establish as the scatter graph depicting the relationship for the 32 dust storm events shows (Figure 2). This is attributed to the visibility remaining poor due to dust remaining in suspension in the atmosphere after the wind has dropped, as well as poor visibility in low sun conditions, particularly at sunrise. Another contributing factor is dust brought aloft from afar by a synoptic system, such as the trough that

Table 1

Events when dust haze, or dust storms, were observed at ADIA and the visibility was ≤5000 metres from 1994 to 2003.

Year	*Dust events*	*Dust storms*	*Total*
1994	10	5	15
1995	16	2	18
1996	13	1	14
1997	10	2	12
1998	12	2	14
1999	18	7	25
2000	15	3	18
2001	10	0	10
2002	17	2	19
2003	20	8	28
Total	141	32	173

Table 2

Frequency of dust events with the visibility <5000 metres according to wind direction, 1994 to 2003

Direction	*Dust events*	*Dust storms*	*Total*
SE-WSW	83	12	95
W-NNW	33	9	42
N-ESE	25	11	36
Total	141	32	173

Table 3

Frequency of dust storms with convective cloud, 1994 to 2003

	SE-WSW	*W-NW*	*N-ESE*
Dust storm with Cb	2	2	6
Dust storm with Cu	1	3	1

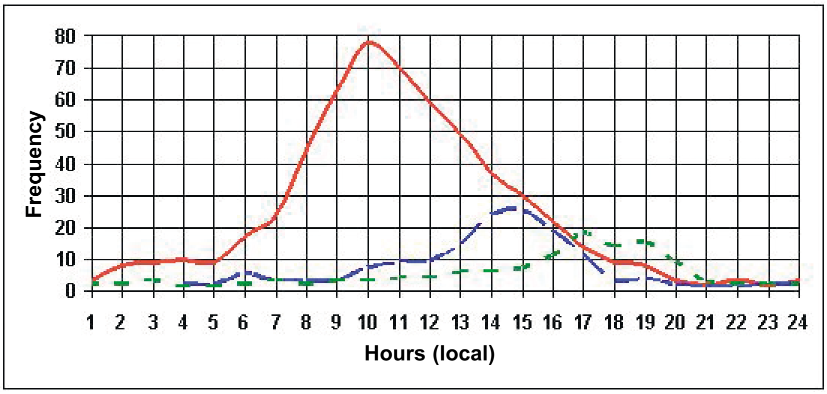

Figure 1. Diurnal frequency of dust events (visibility ≤5000 m) from 1994 to 2003, inclusive. southeast-west-southwesterly wind events – solid red line, west-north-northwesterly – blue long dashed line, north-east-south-easterly – green short dashed line. Annually the sunrise varies from 0530 (summer) to 0700 (winter) local time and sunset from 1900 (summer) to 1730 (winter) local time.

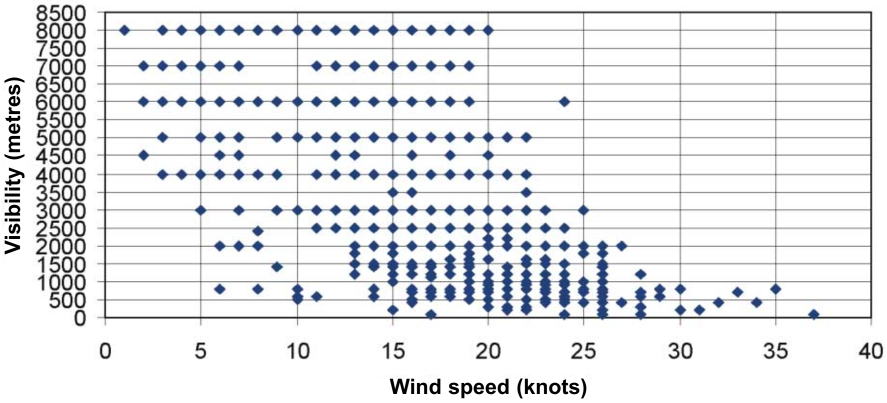

Figure 2. Scattergraph of visibility and wind speed (kn) recorded (715 observations) during 32 dust storms for ten years from 1994 to 2003 when the visibility was ≤8000 m. (correlation, –0.64.)

caused a persistent 5-day Shamal from 16 to 20 May 2003, which carried dust from eastern Saudi Arabia across the Arabian Gulf to ADIA and reduced the visibility to 3000 m. Nevertheless, the Pearson product-moment co-efficient of correlation (Harper, 1977) yields a commendable correlation of –0.64.

Figure 2 shows that the greatest concentration of events is when the wind speed exceeds 15 knots and the visibility is less than 3000 m. Below 15 kn most of the events are present when visibility is greater than 4000 m, although a considerable number are present in an area where the visibility is greater than 4000 m and the wind is between 15 and 20 kn. Bear in mind that wind direction, such as a shorter track off the sea, has not been taken into consideration. However, there are some loose assumptions that can be made:

i Above 15kn the visibility can be below 8000 m and is often less than 5000 m; i
ii Above 20kn the visibility will be less than 5000 m and is often less than 2000m, but most likely below 1000m;
iii Above 25 kn the visibility will be less than 2000m and is more likely to be below 1000m;
iv Above 30 kn the visibility will be less than 1000m.

Scattergraphs were compiled of dust events during 2003 according to the three wind direction groups. Of the 28 identified during the year, 17 were associated with the southerly sector, eight from the north-west sector and three from the north-east sector (Figures 3, 4 and 5).

Of the three wind direction groups, the best correlation between the wind and visibility existed when there was a southerly desert wind, the correlation being –0.67 (Figure 3). For the most part at 5kn the visibility was never below 6000m and at 10 kn the minimum visibility was 3000 m. A wind speed above 15kn accounted for most of the observations when the visibility was below 3000 m. Above 20 kn the visibility was below 1000 m.

The correlation between visibility and wind speed for northwesterly winds was poor, namely –0.41 (Figure 4). The most probable explanation is that the dust arrived after passing over a broad expanse of water. The visibility was therefore more dependent on how much dust was still in suspension and not the wind speed.

Strictly speaking there were too few events for a reasonable analysis to be made of the northeasterly wind group (Figure 5). Nevertheless, the scattergraph is interesting. Note, although classified as two calendar day events, two consecutive days were associated with dust that arrived from the north-east after travelling a considerable distance from Iran (13 and 14 December 2003), the so-called Nashi wind. The wind at ADIA was generally below 13kn (with one observation of 17 kn). Winds below this magnitude do not usually cause serious visibility reduction. However, in this instance there were numerous observations when the visibility was below 5000m and even less than 1500m with the wind below 7kn. Clearly the dust was not raised locally, but brought from far afield over Iran.

Another interesting aspect of Figure 5 is that all the winds above 17 kn were observed during brief periods of less than half an hour when there were thunder-storms at and near the airport. In these instances the dust was clearly locally generated by outflow from the thunderstorms.

Temperature and visibility change in a southerly wind and following Shamal

Dust storms from the south are associated with the approach of a low-pressure system, or trough, from the west and bring sharp changes in temperature and humidity. Such a storm occurred on 12 and 13 March 2003. The surface synoptic situation as predicted by the Global Forecast Service numerical weather prediction model is shown in Figure 6.

Visibility on the 12th at ADIA deteriorated to 1000 m in a southerly wind that averaged

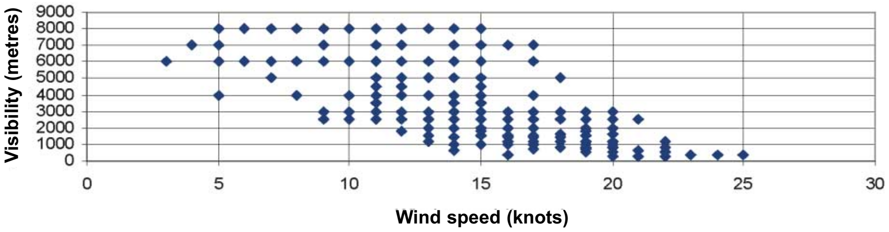

Figure 3. Scattergraph of visibility and wind speed recorded (211 observations) during dust events in 2003 when the wind was south-east to west-south-west and the visibility was ≤8000 m. (correlation, –0.67.)

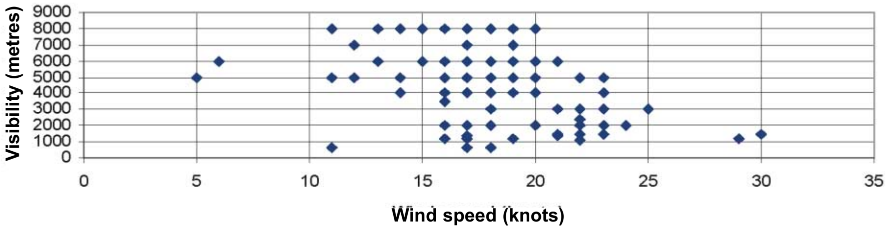

Figure 4. Scattergraph of visibility and wind speed recorded (103 observations) during dust events in 2003 when the wind was west to north-northwest and the visibility was ≤8000 m. (correlation, –0.41.)

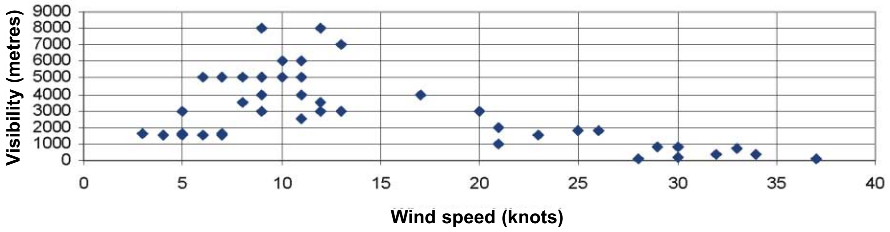

Figure 5. Scattergraph of visibility and wind speed (kn) recorded (57 observations) during dust events in 2003 when the wind was north to east-southeast and the visibility was ≤8000 m. (correlation, –0.53.)

15 to 20 kn (Figure 7). At Al Ain International Airport (about 150km inland from ADIA in Figure 6) the visibility fell to 3500m in a gusty wind that reached an average speed of 25kn. On the second day at ADIA the average wind was 20 to 25 kn and the observed visibility intermittently reduced to between 300 and 600 m for nearly 7 hours during daylight, while at Al Ain the still gusty wind reached 29 kn with the visibility down to 1200 m. In total the visibility deteriorated to 1000 metres, or less, for about 5 hours on the 12th and 6 hours on the 13th.

The wind off the hot and dry desert caused the temperature to peak at 42 °C and 41 °C on the first and second day respective-ly at ADIA, with the relative humidity down to 5% and never above 20% during the day (Figure 7). The mean maximum temperature in the UAE in March is about 30 °C, so the days were certainly hotter than normal. Temporary cooler and moister conditions occurred during the intervening night when the north-westerly sea breeze managed to break through in the late afternoon (1700 local time (1300 UTC)), but by 2300 h (1900 UTC), the southerly wind was already beginning to make itself felt again.

Finally, late on the 13th, the northerly Shamal in the wake of the low brought clear and more humid air from the Arabian Gulf and a considerable drop in temperature (Figure 7). The maximum temperature on the third day (the 14th) being 25°C at ADIA and 26°C at Al Ain. Of interest is the fact that when the Shamal started at ADIA, the visibility temporarily deteriorated in the strong wind before improving.

An ambiguity is that on both days the maximum wind was stronger inland at Al Ain than at ADIA and yet on both days the visibility was not as poor at Al Ain as at ADIA. The reason for this is not certain. It could be that being nearer to the rocky Hajar Mountains they caused some descending motion, which suppressed the lifting of dust. Another, more likely explanation is that the sand is different. On trips inland to Al Ain it was noted that the sand is a fine, white and salty dust deposit along a wide coastal strip that becomes a distinct red/brown-coloured and much coarser desert sand as one approaches Al Ain, it being more difficult for the wind to lift the sand at Al Ain than the dust at ADIA. Furthermore, smaller particles more effectively reduce visibility than larger particles (Robinson, 1968), thereby accounting for the poorer visibility at ADIA.

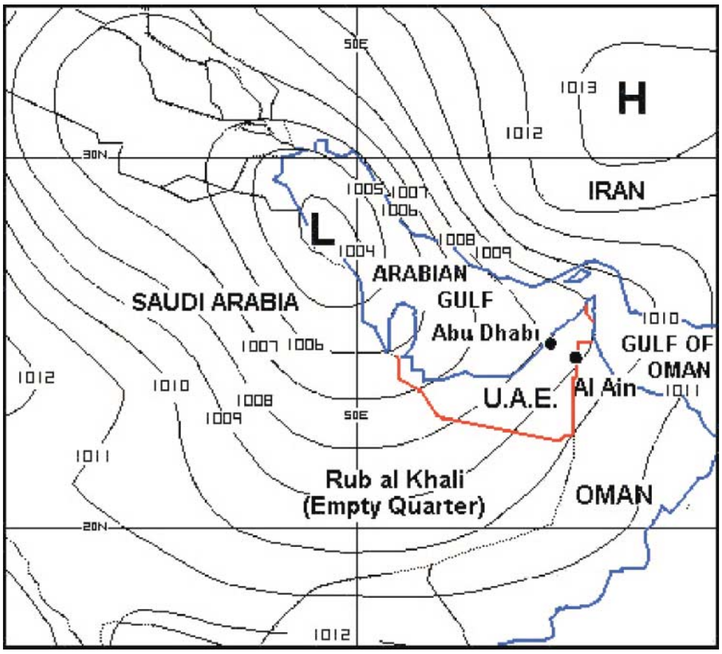

Figure 6. Forecast MSL pressure (hPa) at 0been made as to when dust events and dust storms occur at ADIA.This paper600 UTC (T+6) 12 March 2003. (GFS model data)

Conclusions

Dust storms are not as common as one would think, given the geographical location of the UAE, the average being only three per year. However, dust events when the visibility is reduced to less than 5000 m are more common and occurred on 141 occasions from 1994 to 2003 as opposed to 32 dust storms.

Dust events are most likely when the wind is off the desert to the south, considerably less so when the wind is from the north-west with Shamal conditions and dust has to be transported a considerable distance across the Arabian Gulf. They are less likely when the wind is from the north-east to east, such as when the Nashi wind brings cold air from Iran. However, this is more likely attributable to the lower frequency than the direction. The distribution of dust storms according to the wind direction is much more random. The problem with forecasting dust storms associated with Shamal and Nashi winds is that the storms are not common. The forecaster therefore needs to be more vigilant when model data indicate strong winds from further afield.

Dust storms, when the visibility is ≤1000 m, do not last long. The average duration is 1 hour 15 minutes and 4 hours 30 minutes at the most. Duration is even shorter during thunderstorms when the average is near to 40 minutes with the longest time being nearly 60 minutes. Poor visibility (≤3000 m) during the build-up and lingering aftermath lasts about 3 hours 45 minutes, but has lasted 15 hours,

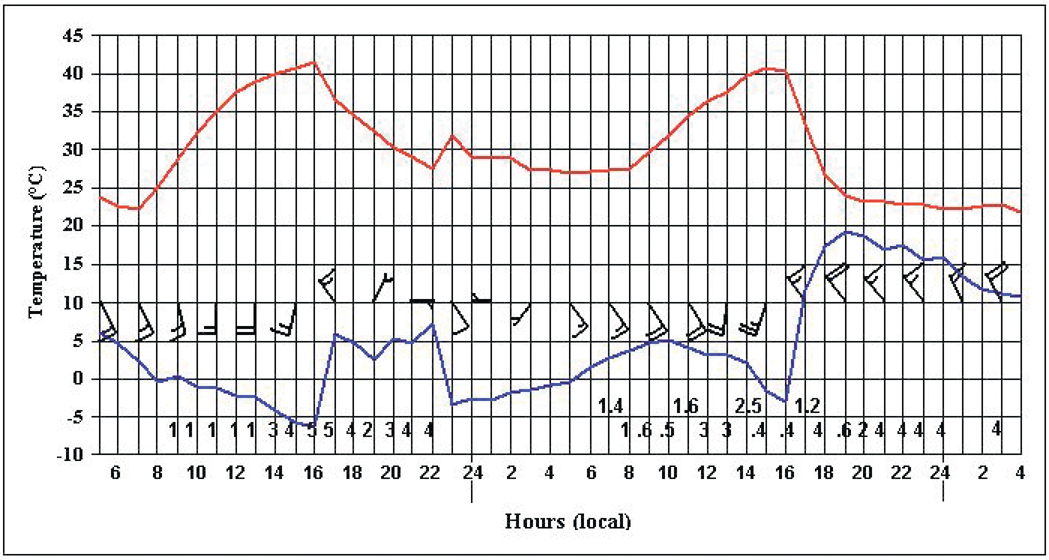

Figure 7. Air temperature (upper line) and dew-point temperature (lower line) at ADIA on 12 and 13 March 2003, from 0500 h on the 12th. The main graph shows the extremely dry conditions during the desert wind and much cooler and moister conditions when the Shamal blows. The graph also shows wind barbs (kn) every 2 hours and periods when the visibility ≤5 km.

while visibility ≤5000 m can last up to 21 hours.

Poor visibility is most likely from after sunrise during the morning and the early afternoon during the time of surface heat-ing and when thermally induced eddies reduce stability and increase mixing with the air aloft. The peak time is at 10 00 local time. This also coincides with the regular morning land breeze that would reinforce any southerly flow off the desert.

There is a distinct negative correlation of −0.64 between wind speed and visibility. That is, the greater the wind speed, the poorer the visibility is likely to be. It is diffi-cult to establish a clear relationship, due to other factors. These include poor visibility due to dust in suspension after the wind has dropped, or dust carried aloft from elsewhere and the effect of a low sun. The source region of the dust and the type of dust are other factors. However, there are some loose assumptions that can be made. Above 15 kn the visibility can be below 8000 m and is often less than 5000 m. Above 20 kn the visibility will often be less than 2000 m, but most likely below 1000 m and above 30 kn the visibility will be less than 1000 m.

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