

## CHAPTER 7

### LAND AND SEA BREEZES

#### 7.1 INTRODUCTION

A significant wind pattern in the UAE is that of the diurnal land and sea breeze circulation (U.A.E. Climate 1996). This circulation affects most of the country almost on a daily basis, the exception being during the passage of major weather systems, which produce pressure gradients that disrupt and often overwhelm the thermal gradients.

The alignment of the UAE Gulf coast in the east is south-west to north-east, which means that land breezes arrive from a south-easterly direction and sea breezes from the north-west. These are the two dominant wind directions and it is no coincidence that the airport runways in the region are aligned north-west to south-east. For example,  $310^{\circ}/130^{\circ}$  at ADIA and  $300^{\circ}/120^{\circ}$  at Dubai. To the west of ADIA the coast is oriented west to east and the land and sea breezes tend to be northerly and southerly, respectively.

Numerous references to literature have been made in previous chapters in connection with land and sea breezes at ADIA. These will not be discussed again in this chapter, except where necessity dictates.

#### 7.2 SCOPE OF THE STUDY

This chapter examines land and sea breezes at ADIA during the 12 months from September 2002 to August 2003. Shamal and southerly desert winds due to synoptic pressure systems were ignored, although some were difficult to separate. The dynamics, statistical occurrence (including wind roses at ADIA) and general characteristics of land and sea breezes are discussed with examples and a case study presented. Attention is drawn to their effect inland in the desert at Al Ain, the Abu Dhabi Emirates second international airport, as well as an anabatic and katabatic effect there. Finally, a forecast methodology is proposed.

#### 7.3 DYNAMICS

The coastline marks the boundary between markedly different sea and land temperatures. These differences give rise to land and sea breezes. Bradbury (1989), Hsu (1988) and Riehl (1979), among others, explained how the land/sea breeze is driven by the diurnal diabatic heating/cooling of the land adjacent to the ocean and will not be repeated here. Suffice to say that the diabatic heating of the surface air over the deserts surrounding the Arabian Gulf play an important role in the wind experienced at ADIA.

Land and sea breezes are more common in summer in higher latitudes, but all year round in the tropics (Miller 1966). The latter is especially true along the UAE Gulf Sea coast where land and sea breezes are virtually a daily occurrence.

Sea breezes are strongest when the thermal difference between the land and sea are greatest. This is typically in the early summer period when inland temperatures have begun to increase and sea temperatures, which typically lag behind the air temperature, are still relatively low (Bradbury 1989).

The extent of the circulation varies according to different sources. It may extend about 20 kilometres seaward and 60 to 70 kilometres inland (Miller 1966), or not more than 50 kilometres according to Critchfield (1974), while Hsu (1988) defines the vertical extent as being up to 700 hPa.

Due to thermal stability, usually in the form of a surface temperature inversion, the land breeze is usually very shallow. Ground friction tends to restrict the wind to 2 to 4 knots (about 1 to 2  $\text{ms}^{-1}$ ), whereas the sea breeze usually attains speeds of 10 to 20 knots ( $\pm 5$  to 10  $\text{ms}^{-1}$ ). The sea breeze accelerates until ground friction is sufficient to counter the pressure gradient, or the circulation weakens (Riehl 1979).

The prevailing wind has an effect on the land and sea breeze (Bradbury 1989 and Riehl 1979). In the UAE a north-westerly Shamal wind will strengthen the sea breeze, but it will suppress, or obliterate, the land breeze. Similarly, the southerly desert wind, such as east of an approaching low, which can result in a dust storm, will strengthen the morning land breeze.

#### 7.4 STATISTICS AND GENERAL CHARACTERISTICS

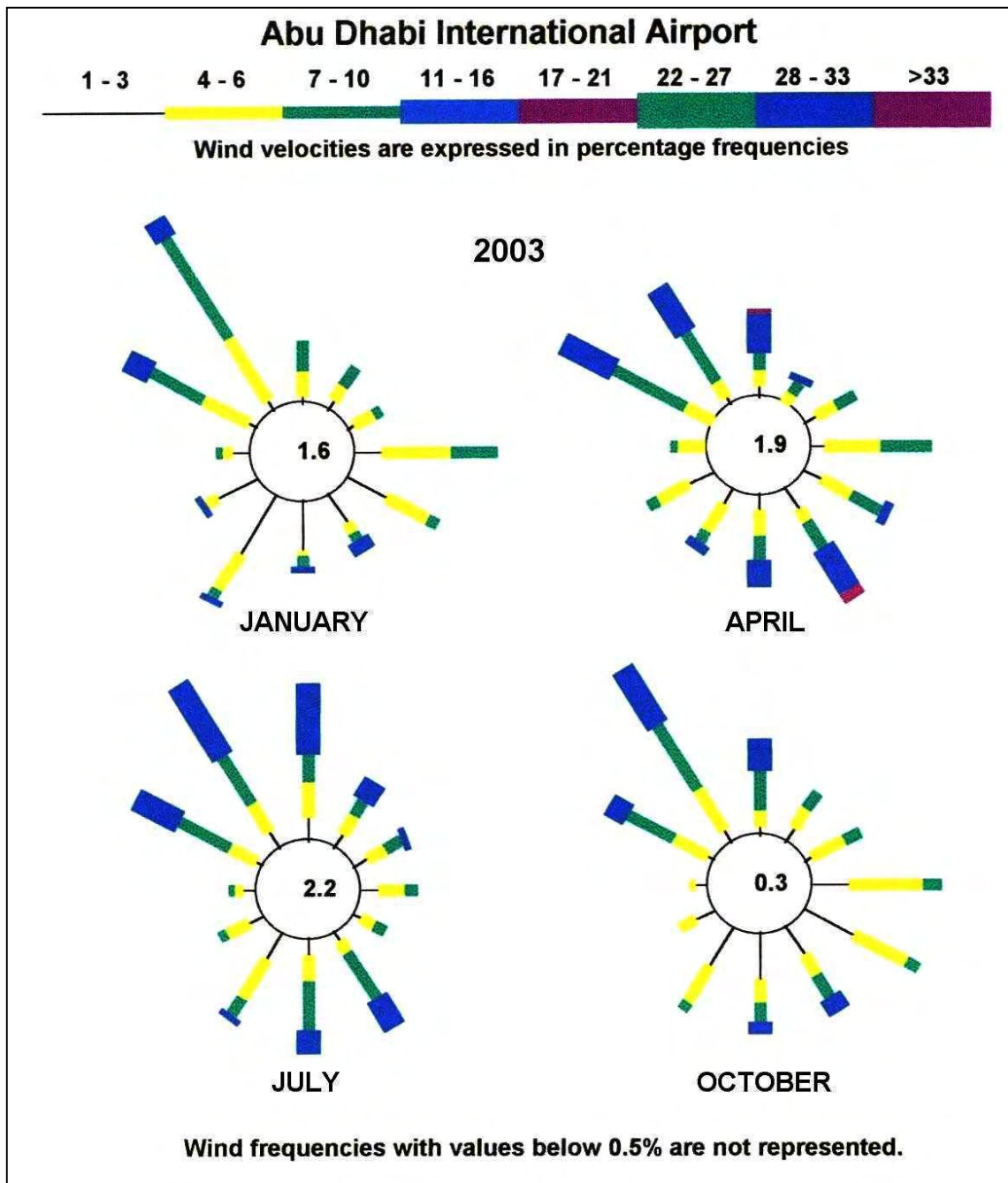
The research indicated that on average, during the 12 months, the sea breeze can be expected to start at 0830 UTC (12:30 pm), the average wind speed being 11 knots reaching a maximum at about 1030 UTC (14:30 pm). The lighter land breeze is most likely to begin at 0100 UTC (05:00 am), blow at about 4 knots and reach a maximum at about 0450 UTC (08:50 am).

This normal daily interchange between the land and sea breeze is depicted in figures 4.8 to 4.12 of chapter 4 that details the four days with fog on the 18<sup>th</sup> to the 22<sup>nd</sup> July 2002 when fog occurred on four consecutive days under weak surface pressure gradient conditions. Notice the regular and rapid change from a land breeze to sea breeze in about an hour.

Based on weather observations at ADIA from 1995 to 2002, Eager et al (2005) found that sea breezes occur on more than 90% of the days from March to December while land breezes occur on over 90% of the days in May to December. The lowest recorded frequencies of daily sea breezes and land breezes were 77% and 71%, respectively, in February. The consistency of the land and sea breezes during most of the year is evident in the wind roses in figure 7.1. Winds from the north-west and the south-east dominate. What is also apparent is the overall directional dominance of the north-westerly sea breeze and its strengthening by the Shamal. In summer this happens when the Shamal tends to prevail most of the time and in winter when the north-westerly wind is associated with winter troughs (Rao, et al 2001 and Membery 1983). Data for the 12 month study period at ADIA revealed that 73% of the time the land breeze veers from a directly offshore south-easterly to south-west, while 65% of the time sea breeze veers through north to south-east as it subsides in the evening. This is to be expected due to the action of the Coriolis force, which deflects the wind to the right in the

northern hemisphere (Holton 1992). The Coriolis is dependent on the Sinus of the latitude and it is therefore small at the latitude of the UAE (Holton 1992, Bradbury 1989)

By early summer inland desert temperatures have climbed well into the mid 40's. However, sea surface temperature typically lags a month or so behind the rapidly rising air temperatures. Bradbury (1989) stated that sea breezes peak during the early summer when thermal gradients between the land and sea are the greatest. The wind roses in figure 7.1 show that this is equally valid at ADIA with a higher frequency of strong north-westerly to northerly sea breezes in April compared with July.



**Figure 7.1.** Wind roses at ADIA for January, April, July and October, 2003, compiled from hourly observations. The percentages when the wind was calm are entered in the centre circles.

If the sea level pressure is higher south of the UAE, this will enhance the land breeze during the morning and cause higher than normal daytime temperatures. This pressure gradient will also oppose the land/sea thermal gradient due to solar heating of the land heating and therefore delay the onset of the north-westerly sea breeze. Under these circumstances the beginning of the sea breeze can be sudden, strong and gusty. Examples can be seen on the 12<sup>th</sup> and 13<sup>th</sup> June 2003 in figures 4.33 and 4.34, chapter 4. The build up of the thermal gradient is sometimes big enough to cause a sea breeze strong enough lift dust and reduce the visibility. Occasionally isolated cumulus clouds will form along the sea breeze gust front as it travels inland.

With high pressure to the south the synoptic scale pressure gradient may on occasions overwhelm the thermal gradient caused by daytime heating of the land surface. The sea breeze is suppressed and a southerly wind continues throughout the day and night. This wind may become light in the evening and overnight, when the lower layer of the atmosphere becomes stable and suppresses the vertical transport of wind momentum. The sea breeze is also suppressed when a surface low pressure cell approaches the UAE from the west. For example, on the 12<sup>th</sup> and 13<sup>th</sup> March 2003 (figure 6.17 and 6.18, chapter 6) the synoptic scale pressure gradient was able to suppress the sea breeze for all but the two hours between 1300 and 1500 UTC on the 12th.

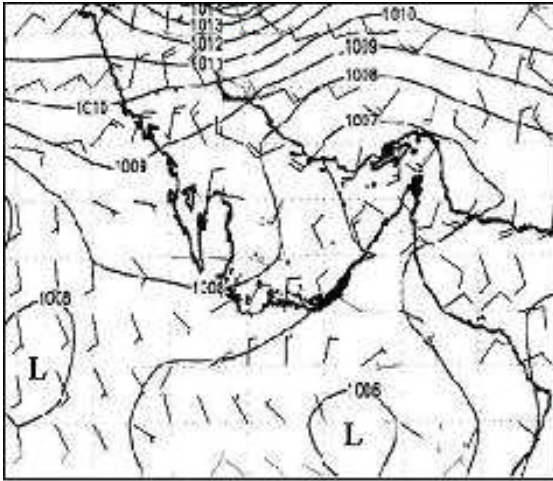
On the other hand if the surface pressure increases to the north-west the synoptic scale pressure gradient reverses and the opposite situation applies. If this pressure gradient is strong enough to overcome the overnight thermal gradient, a north-westerly wind may blow throughout the night completely suppressing any land breeze. Under these circumstances, night temperatures tend to be higher than usual, but daytime temperatures tend to be lower due to the advection of maritime air over the land. In the afternoon this pressure gradient will support the thermal gradient and the sea breeze will add its strength to the prevailing onshore flow resulting in an onshore wind speed greater than due to the pressure gradient alone. The case study in chapter 5 on the 15<sup>th</sup> and 16<sup>th</sup> November 2003, depicted by figures 5.9 and 5.10 illustrates this phenomenon.

## **7.5 LAND AND SEA BREEZE: 10<sup>TH</sup> TO 11<sup>TH</sup> MAY 2003**

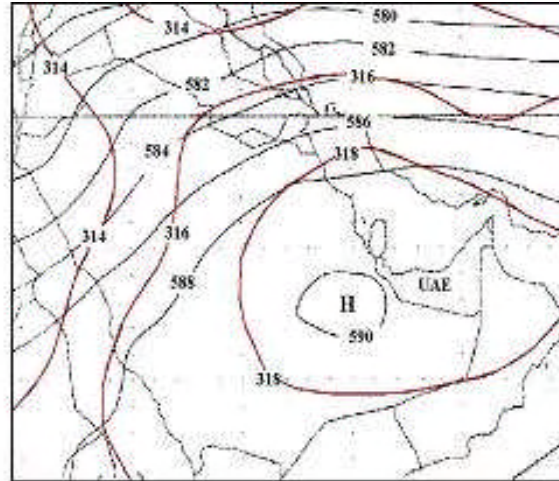
Analysis of wind data at both Al Ain and ADIA revealed that the wind inland at Al Ain is sometimes surprisingly stronger than at the coast. This gusty and turbulent wind at Al Ain can be strong enough to raise sand and dust, drastically reducing the visibility at Al Ain. This phenomenon is illustrated by a case study of the land and sea breeze interaction with the synoptic scale flow that happened on the 10<sup>th</sup> and 11<sup>th</sup> May 2003. Also of interest is the change in vertical air movement below 700 hPa over the land and sea as indicated by the ETA model data.

### **7.5.1 SYNOPTIC SITUATION**

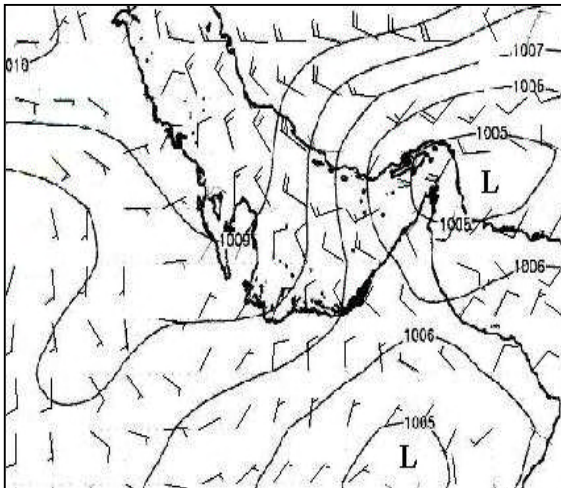
On the 10<sup>th</sup> at 1200 UTC (T+12), the Eta NWP model data (figure 7.2) indicated that a surface pressure ridge would develop over Qatar and northward to western Iran, with an area of generally low pressure over the southern Arabian Peninsula. Low pressure cells were also predicted over the Strait of Hormuz with a trough extending to the south of the UAE as well as another to the south-west. A weak 1 to 2 hPa surface pressure gradient is indicated over the



**Figure 7.2.** 2003-05-10 Eta GFS surface pressure and wind on 2003-05-10 at 1200 UTC (T+12).



**Figure 7.3.** Eta GFS 700 hPa and 500 hPa gpm heights in decametres on 2003-05-10 at 1200 UTC (T+12).



**Figure 7.4.** As figure 7.2, but for 2003-05-11.

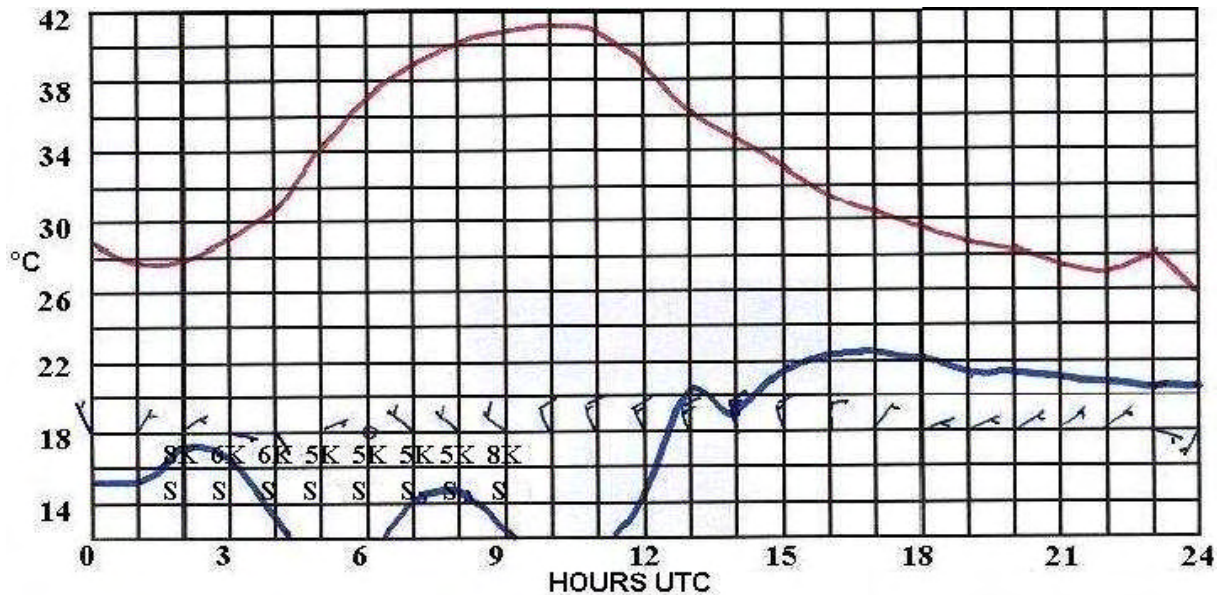
UAE (figure 7.2). Figure 7.3 shows how the anticyclonic circulation supersedes the cyclonic circulation by 500 hPa (U.A.E. Climate, 1996).

Later the following day the model indicated that the upper-air anticyclone would still be over the Emirates, but at the surface an increased pressure gradient, associated with a ridge of high pressure, would develop over the western part of the Gulf and that the low pressure cell over the Strait of Hormuz, as well as the low south of the UAE would deepen somewhat (figure 7.4) and a small col forms in the vicinity of ADIA. This synoptic

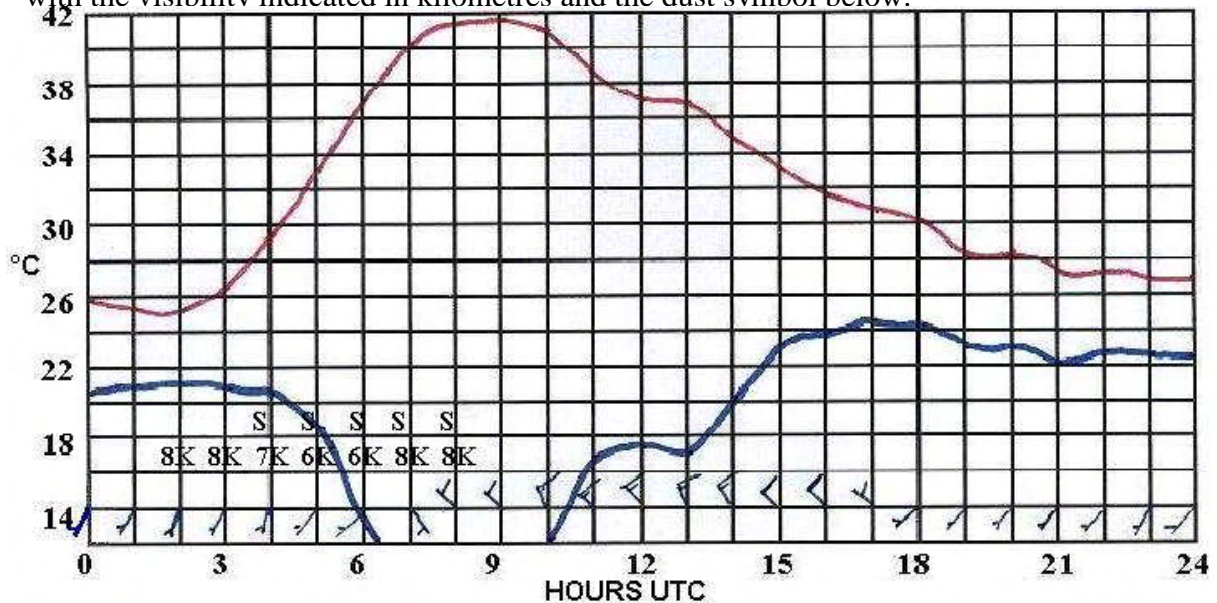
scale circulation indicates that north-westerly Shamal conditions would develop and strengthen over the western Gulf during the 11<sup>th</sup>, but that it should not have a significant effect on the land and sea breeze circulation at ADIA. It will be shown that the north-westerly sea breeze was stronger on the 10<sup>th</sup>, when a weaker pressure gradient existed than on the 11<sup>th</sup>.

## 7.5.2 SURFACE OBSERVATIONS

Most of the night of 9<sup>th</sup>/10<sup>th</sup> at ADIA, the wind blew from the sea and briefly turned to a light land breeze between 0200 and 0500 UTC (6-9 am) at about 3 knots (figure 7.5). A light variable wind preceded a light to moderate sea breeze that began at 0700 UTC (11 am), reaching a maximum of 14 knots at 1100 UTC (3 pm). Notice the gradual veering change from a sea breeze to a land breeze overnight on the 10<sup>th</sup>/11<sup>th</sup>. On the second night the wind veered through north-east to a south-east land breeze and then south-west by 2400 UTC (4 am). Within an hour, at about 0800 UTC (12 noon) the land breeze changed to a sea breeze, reaching a maximum of 13 knots at 1100 UTC (figure 7.6).



**Figure 7.5.** Surface observations graph at ADIA on 2003-05-10. The air temperature (°C) is indicated in red, dew point temperature in blue (°C). The wind feathers are in tens of knots with the visibility indicated in kilometres and the dust symbol below.



**Figure 7.6.** As figure 7.5, but for 2003-05-11.

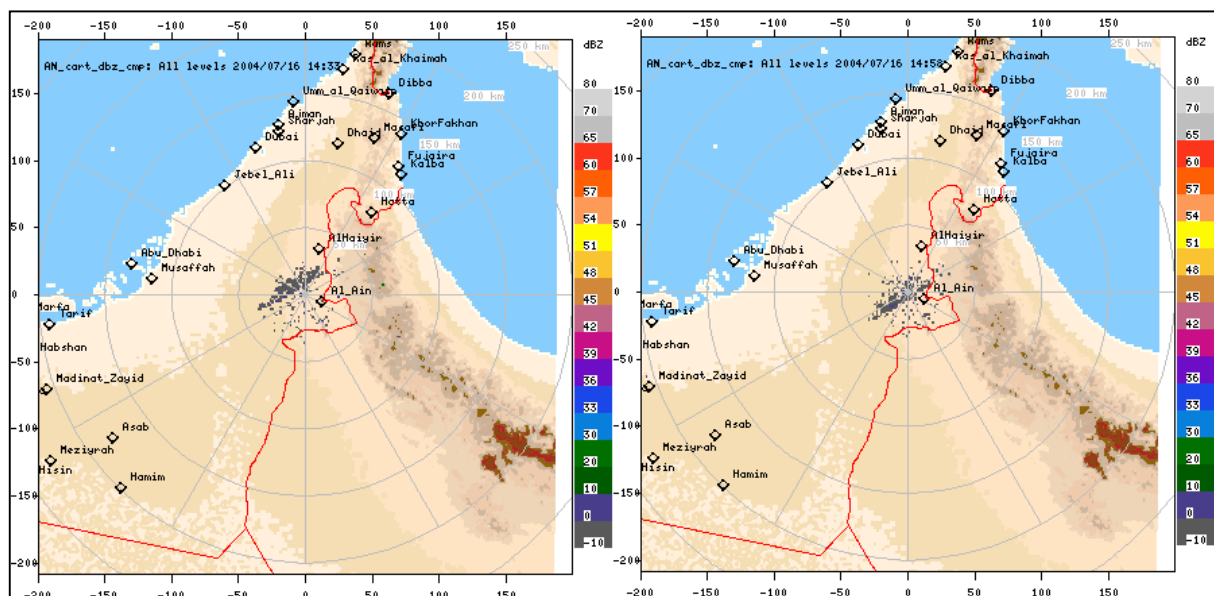
Inland at Al Ain on the 10<sup>th</sup> the wind was south-easterly to southerly at 3 to 7 knots up to 0700 UTC (1 pm) when it became light variable. On the 11<sup>th</sup> the wind was north-easterly at 7 to 9 knots for most of the night, becoming south-easterly to southerly at 0400 UTC to 0600 UTC (8-10 am).

Of particular interest is that on both days the land breeze at Al Ain was stronger than at ADIA. The same applied to the sea breeze. The sea breeze reached Al Ain on the 10<sup>th</sup> at 1300 UTC (5 pm) and blew from 310° at 9 knots and changed to 340° 17 knots by 1336 UTC (5:36 pm) when it was strong enough to lift sand off the desert and reduce the visibility to 4000 metres. As happened at the coast on the 11<sup>th</sup>, the wind turned to north-westerly earlier in the day. At 0900 UTC (1 pm) it became 330° 9 knots with temporary gusts up to 22 knots at 1100 UTC (3 pm). Thereafter, it averaged 14 to 15 knots with the direction varying through

north between 270° and 060° and the visibility down to 4500 metres. A gusty and directionally variable wind is characteristic of the sea breeze (Miller 1966) and it is usually more so at Al Ain than at ADIA, as evidenced by the above comparative wind and visibility data depicted by figures 7.5 and 7.6.

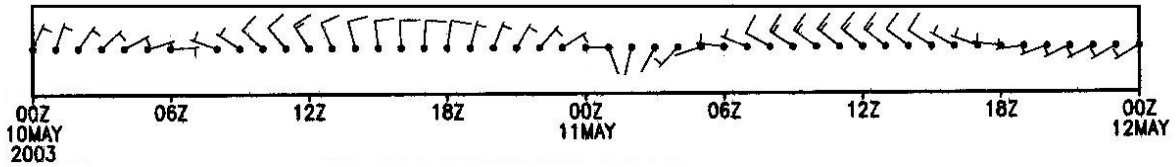
On both days at ADIA the visibility became unlimited when the clear sea air arrived with the sea breeze. However, there is much more extremely dry desert dust and sand between Al Ain and the coast with ample opportunity for the wind to whip up the dust. When, at about 1600 UTC (8 pm), the wind became light at Al Ain, it enabled the visibility to improve to about 7000 metres, but no better than this due to the amount of dust remaining in suspension in the air.

Bradbury (1989) and Riehl (1979) state that due to the Coriolis force, in middle latitudes the sea breeze is deflected to the right (veers) and to the left (backs) in the northern and southern hemispheres, respectively, to the point that the wind, in time, blows parallel to the coast, thereby limiting sea breeze penetration to about 20 to 50 kilometres inland. Approaching the equator the magnitude of the Coriolis force eventually diminishes to zero. This means that near the equator the wind follows the direction of the pressure gradient and this allows the sea breezes to penetrate further inland in the tropics. This, along with a fairly even desert surface, may account for the penetration of the sea breeze as far Al Ain, which is about 150 km inland. It is worth noting that Eager et al (2005) found that the sea breeze can penetrate up to 130 km inland, while Zhu and Atkinson (2004) found that landward penetration along the UAE coast is over 250 km. On a different occasion, penetration of the sea breeze inland to Al Ain could be tracked inland on Radar by the movement of anomalous propagation echoes caused by refractive index variations at the cooler sea breeze front (figure 7.7).

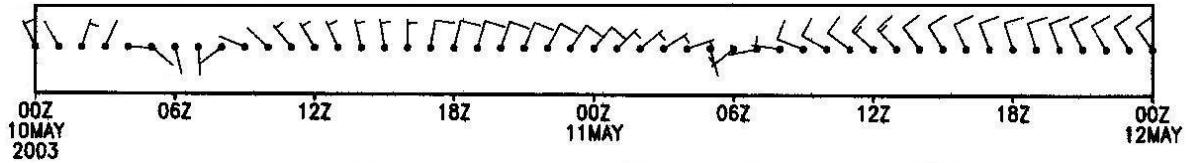


**Figure 7.7.** Sea breeze approaching Al Ain on 2004-07-16. As seen in the form of clutter (Collier 1989, Rhome 2003) on the UAE Department of Water Resources radar at 1433 UTC (6:38 pm) on the left and 1458 UTC (6:58 pm) on the right. The wind changed from 280° 07 knots at 1400 UTC (6 pm) to 340° 14 knots gusting to 25 knots at 1500 UTC (7 pm).

The Eta surface wind prognosis for ADIA and Al Ain bears testimony to the accuracy of the model data with respect to the onset of the sea breezes (figures 7.8 and 7.9).



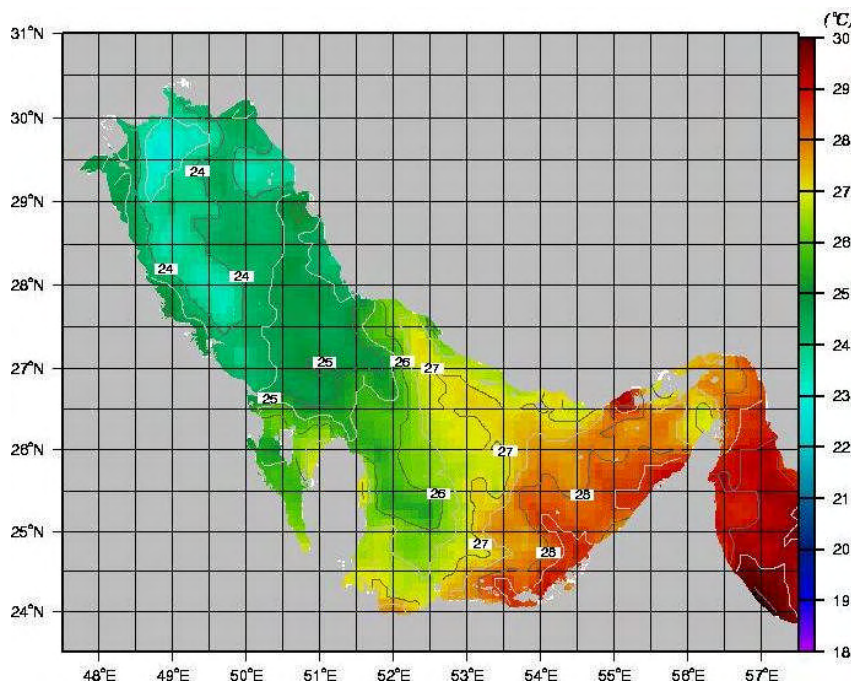
**Figure 7.8.** Eta GFS 2003-05-10 0000 UTC surface wind prognosis at ADIA up to T+48.



**Figure 7.9.** As figure 7.8, but for 3002-05-10 at Al Ain.

### 7.5.3 SEA TEMPERATURE

Sea and land breezes owe their existence to the contrast between land and sea surface temperature (SST) (UKMO 1997, Bradbury 1989, Hsu 1988). There was a marked contrast between surface 1.2 m air temperatures and SST during the days in question. Surface air temperatures reached 42°C and 43°C during the early afternoon at ADIA on the 10<sup>th</sup> and 11<sup>th</sup>, respectively. At Al Ain temperatures reached 44°C and 43°C on the two days. Conversely, the Gulf SST adjacent to the UAE were about 28°C to 29°C. Figure 7.10 shows the SST on the 11<sup>th</sup>. These are very similar to those of the 10<sup>th</sup>, except the area where the temperature exceeded 28°C, close to the UAE coast, was more prominent than on the 10<sup>th</sup>.



**Figure 7.10.** Sea surface temperature in the Gulf Sea on 2003-05-11. US Navy Oceanographic Office Multi-Channel Sea Surface Temperature (MCSST) K10 global 1/10th degree grid satellite SST composite updated daily from Polar-orbiting Operational Environmental Satellites.

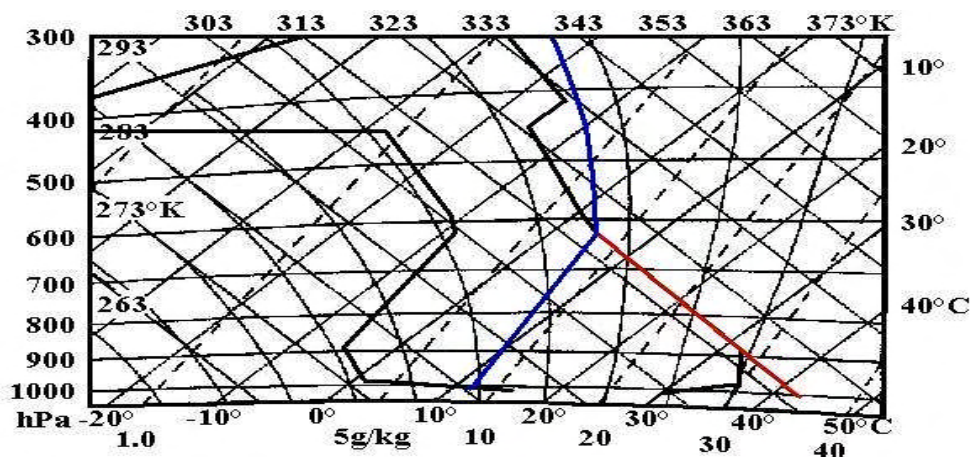
On the other hand early morning minimum temperatures were very similar to the sea temperature. At Abu Dhabi these were about 28°C on the 10<sup>th</sup> and 25°C on the 11<sup>th</sup> (figures 7.5 and 7.6). This probably accounts for a very light land breeze on the first day and slightly stronger wind on the second day. However, it does not explain why the early morning wind was stronger at Al Ain, as stated in the previous section, and where the early morning minimum temperature was 29° and 27°C on the two days.



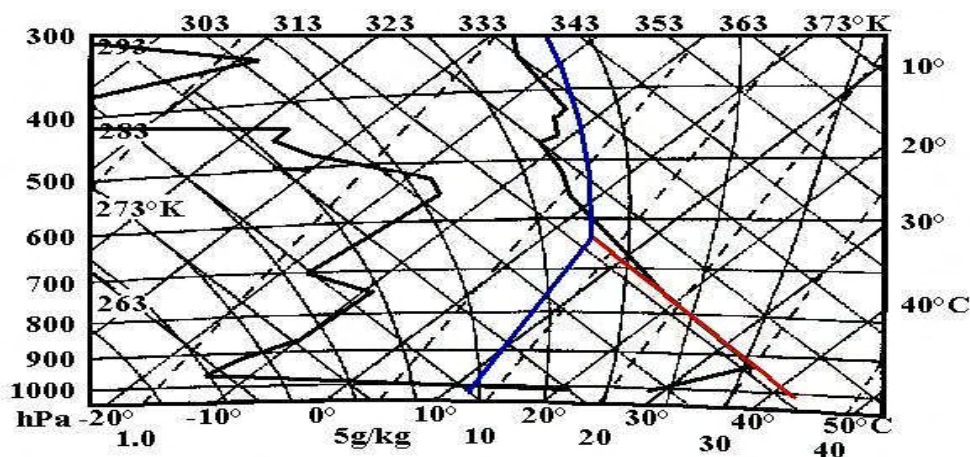
### 7.5.4 UPPER AIR

At ADIA the wind changed from a land breeze (of less than 4 knots) to a sea breeze when the surface temperature reached 38°C on the 10<sup>th</sup> and 41°C on the 11<sup>th</sup> (figures 7.5 and 7.6, respectively). Based on the morning atmospheric soundings (in the absence of afternoon soundings), this was when the temperature lapse rate from the surface to the top of the surface temperature inversion became dry adiabatic (figures 7.11 and 7.12).

Onset of the north-westerly sea breeze at ADIA was earlier on the 10<sup>th</sup> than on the 11<sup>th</sup>. It turned to 310° 5 knots at 0700 UTC and from 1000 UTC increased to 10 to 14 knots from 340°. However, on the 11<sup>th</sup> it began at 0800 UTC, but decreased to 7 to 12 knots, temporarily reaching 13 knots (figures 7.5 and 7.6). The earlier start of the sea breeze can probably be ascribed to the much shallower surface temperature inversion and the higher minimum temperature on the 10<sup>th</sup> (figure 7.11) than on the 11<sup>th</sup> (figure 7.12). On the 10<sup>th</sup> the inversion top was at 980 hPa ( $\pm$ 265 metres MSL) with a minimum temperature of just under 28°C, while on the second day saw the inversion top at 930 hPa ( $\pm$ 722 metres MSL) and the minimum temperature was about 25°C. The implication being that less radiation heating was needed to dissipate the inversion on the 10<sup>th</sup> and allow turbulent mixing with the air above the inversion and the start of the sea breeze than on the 11<sup>th</sup>.



**Figure 7.11.** Atmospheric profile at ADIA with the low surface temperature inversion on 2003-05-10 0000 UTC. Normand's theorem adiabatic lapse rate line in red and constant mixing ratio in blue below the lifted condensation level at  $\pm$  625 hPa.



**Figure 7.12.** As figure 7.11, but for 2003-05-11 0000 UTC. Note the higher surface temperature inversion.

Referring to table 1, lower level winds at ADIA, on the 10<sup>th</sup>, were from the north to north-east. These appear to have been influenced by the low pressure cell to the south of the UAE with a shallow sea breeze below 500 feet in the afternoon of the 11<sup>th</sup>. The winds aloft became more northerly on the 11<sup>th</sup>, probably due to the increasing pressure gradient between the ridge to the west and the low to the east.

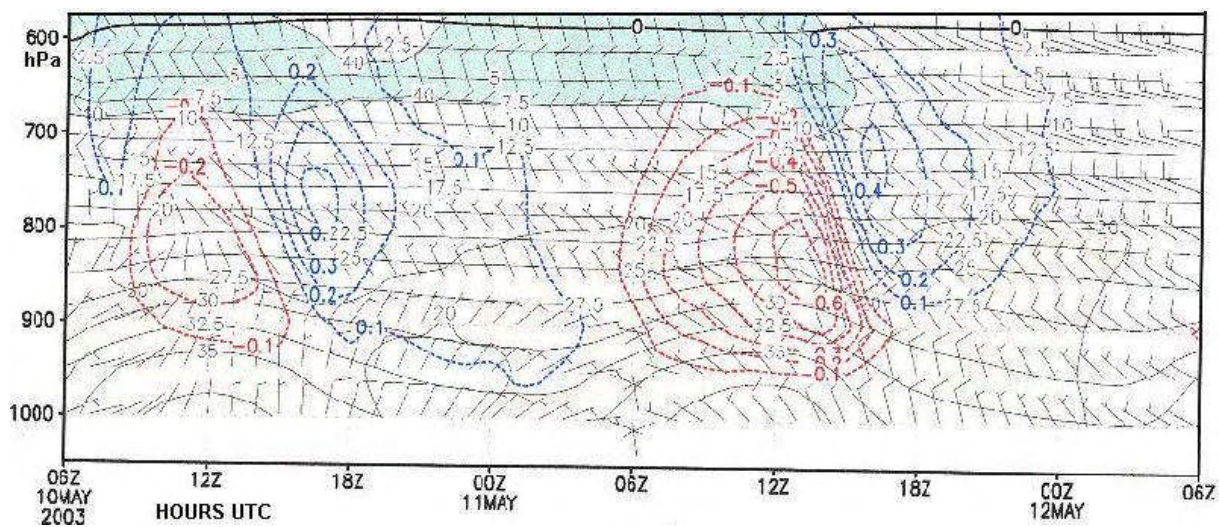
**Table 7.1.** Radiosonde wind observations at ADIA. Wind direction in degrees true and speed in knots.

metres MSL	2003-05-10		2003-05-11	
	0000 UTC	1200 UTC	0000 UTC	1200 UTC
150	020°11	050°10	010°15	345°11
300	005°14	055°08	350°18	350°11
600	055°03	225°02	350°09	360°16
900	360°08	130°04	360°10	005°21
1200	330°12	120°02	005°08	010°16

### 7.5.5 VERTICAL VELOCITY

Bearing in mind that the upper air circulation was anticyclonic and general subsidence could be expected, the time cross section at Al Ain shows that upward vertical velocity ( $w > 0$ ;  $w = -g\rho\omega$  and  $\omega = dp/dt$  (pressure coordinate system)) below 700 hPa was predicted for both afternoons with sinking air overnight (figure 7.13). This is consistent with the land and sea breeze circulation described by Hsu (1988).

The 1000 hPa wind prognosis (figure 7.13) bears testimony to the vertical movement. A northerly sea breeze is indicated in the afternoon from 1200 UTC on the 10<sup>th</sup> in association with upward motion ( $\omega$  negative on the figure), changing to an easterly to south-easterly land breeze later in the night and a switch to descending ( $\omega$  positive) vertical motion. This was followed by a return to a north-westerly sea breeze on the 11<sup>th</sup> with even stronger upward motion.

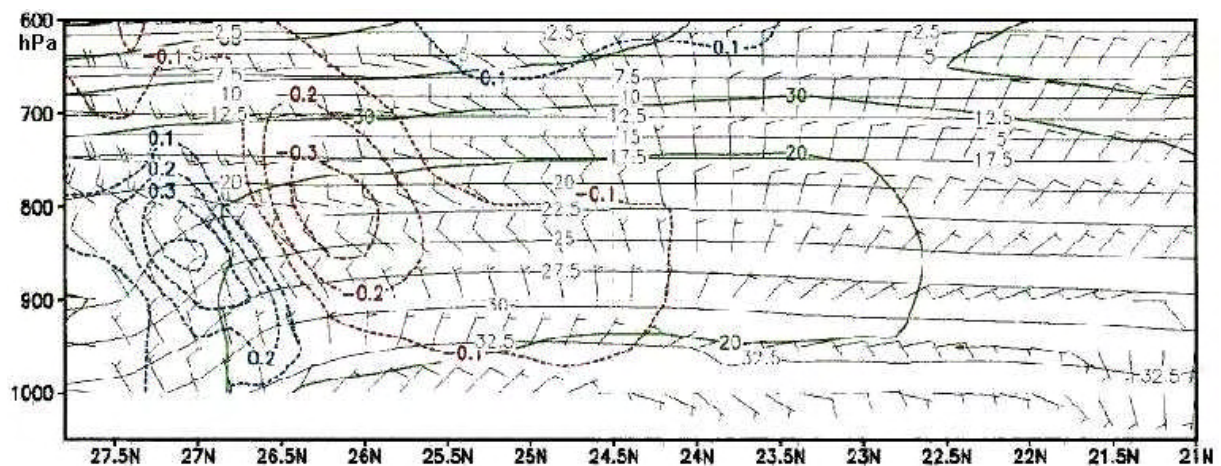


**Figure 7.13.** Eta GFS model run vertical motion at 2003-05-10 0600 UTC. Upward vertical motion (negative red values) of 0.6 microbars  $s^{-1}$  (0.06 Pa  $s^{-1}$ ) is indicated on both afternoons, with sinking air developing overnight (positive blue lines).

It is worth noting that the model indicated stronger vertical velocity ( $0.06 \text{ Pa s}^{-1}$ ) on the afternoon of the 11<sup>th</sup> than on the 10<sup>th</sup> ( $0.02 \text{ Pa s}^{-1}$ ). This is contrary to what was expected but it should be borne in mind that the magnitude of the vertical motion is a function of the divergence field not dealt with here. On the 11<sup>th</sup> the predicted vertical velocity for the afternoon was  $0.03 \text{ Pa s}^{-1}$ . The magnitude of the model derived vertical motion is very small but in phase with the expected secondary (vertical) circulation branch of the land sea breeze system.

North to south cross sections slightly west of ADIA, at  $54^\circ\text{E}$  on the 11<sup>th</sup>, illustrates another view of the land and sea interaction (figures 7.14 and 7.15). The sea is north of  $24^\circ\text{N}$  on the cross section. At about an hour and a half after sunrise, at 0300 UTC (figure 7.14), weak upward motion is indicated below 800 hPa accompanied by a 1000 hPa south-easterly to easterly land breeze blowing from inland up to about  $1^\circ$  (100 km) out to sea (right to left). No subsiding air is indicated over the land.

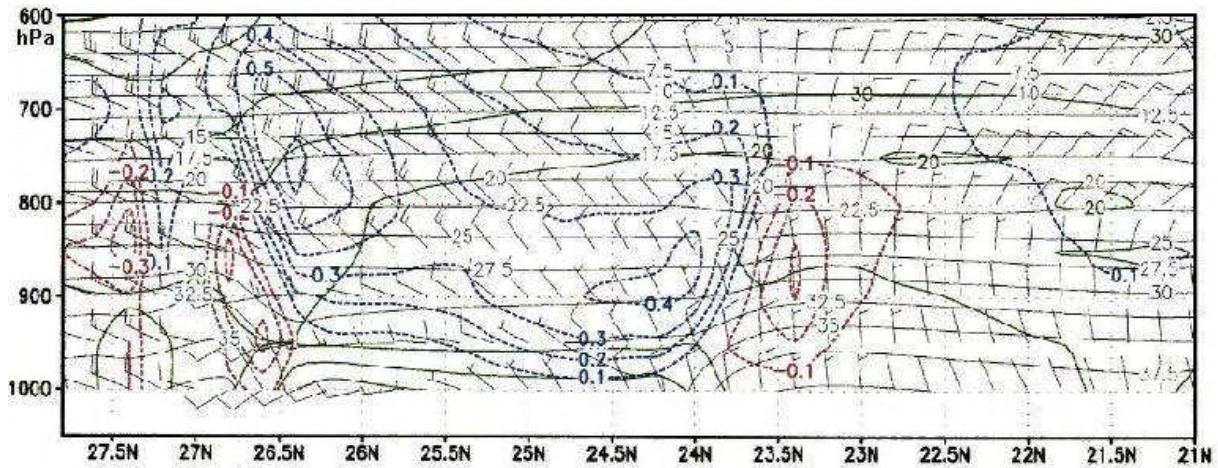
Hsu (1988) claimed that by late afternoon, “because of (wind) velocity divergence and relatively dry air in the upper return flow of the sea breeze, there is a subsidence phenomenon near the coastal area.” This is borne out by the subsiding air (positive values) indicated immediately seaward of the coast in the model prognostic cross section at  $54^\circ\text{E}$  at 1200 UTC (figure 7.15), with rising air (negative values) over the land south of  $24^\circ\text{N}$ . The model also predicted the spread of a 1000 hPa northerly to north-north-westerly sea breeze inland to about  $23\frac{1}{2}^\circ\text{N}$  to  $23^\circ\text{N}$ .



**Figure 7.14.** Eta GFS 0000 UTC model run cross section at T+3 at  $54^\circ\text{E}$  on 2003-05-11. Weak rising air (negative, red) is indicated below 800 hPa north of the coast at  $24^\circ\text{N}$  with a 1000 hPa south-easterly to easterly land breeze blowing about  $1^\circ$  out to sea.

## 7.5.6 INSTABILITY

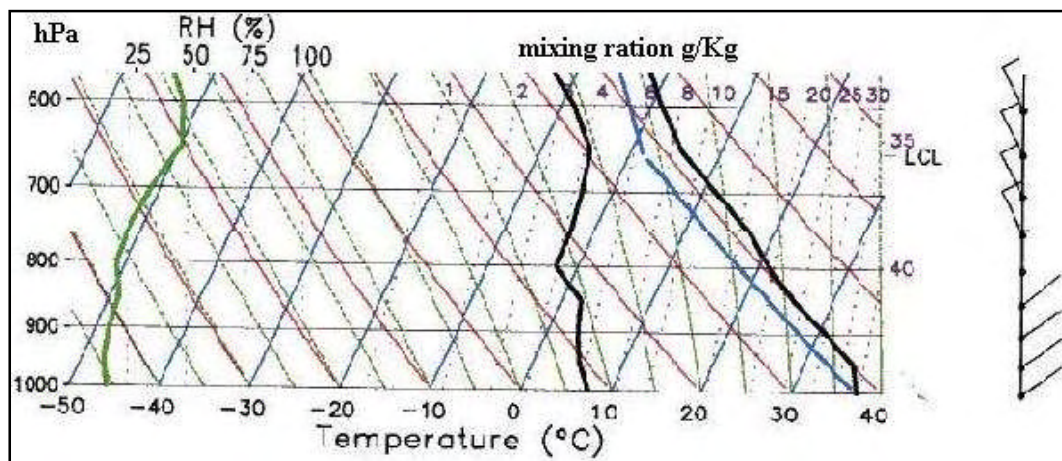
The depth of the unstable layer has an effect on the distance of inland penetration of the sea breeze. Bradbury (1989) states that the best penetration occurs with dry convection from  $\pm 1830$  to 2740 metres (6000 to 9000 feet), while the UKMO Source book to the forecaster’s reference book (1997) specifies dry convection up to 1500 metres (4000 feet). It goes on to add that if there is a very shallow convection layer, there will be virtually no inland penetration of the sea breeze regardless of the land and sea temperature difference.



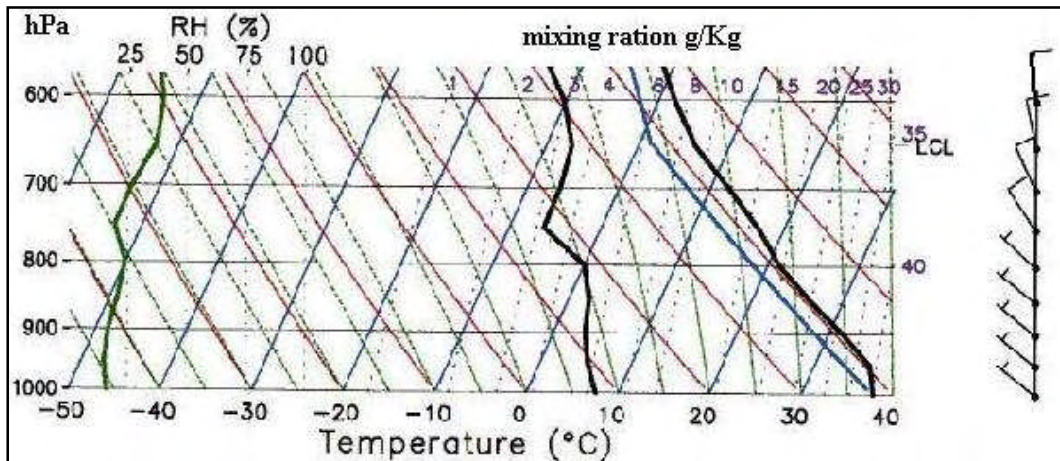
**Figure 7.15.** Eta GFS 0000 UTC model run cross section at T+12 at 54°E on 2003-05-11. Rising air (negative, red) is indicated below 800 hPa south of the coast at 24°N over the land with weak sinking air over the sea north of the coast.

Consider the model projected tephigrams at 0900 UTC on the 10<sup>th</sup> (figure 7.16) and 0900 UTC on the 11<sup>th</sup> (figure 7.17). Both of them reveal that with a surface temperature of 43°C, or 44°C, on either day, it was hot enough for dry air convection up to a lifted condensation level (LCL) of about 650 hPa ( $\pm 3660$  metres, 12000 feet). This is considerably more than the limits required for inland penetration of the sea breeze as specified by Bradbury (1989) and the UKMO (1997). Despite this the sea breeze still reached Al Ain. The atmospheric soundings at 0000 UTC on the 10<sup>th</sup> (figure 7.11) and 11<sup>th</sup> (figure 7.12) at ADIA confirms this and show that deep instability in very dry air occurred later in the day. On the 10<sup>th</sup> the LCL was about 625 hPa ( $\pm 3700$  metres), but somewhat lower on the 11<sup>th</sup> at about 750 hPa ( $\pm 2500$  metres).

The UKMO Source book to the forecaster’s reference book (1997) also specifies that inland spread of the sea breeze “is only likely” if the wind is less than 10 knots at 900 metres (3000 feet). This was probably so during this event if one considers the predicted wind at about 900 hPa in figure 7.14 and 7.15 between 25°N and 24°N. The observed winds at 0000 UTC on the 11<sup>th</sup> were indeed light enough, being 8 to 10 knots between 600 to 1200 metres, with 10 knots already at 900 metres. Furthermore, on the morning of the 10<sup>th</sup> the winds were 3 to 12 knots with 8 knots at 900 metres (table 7.1).



**Figure 7.16.** Eta GFS 2003-05-11 0600 UTC model projected atmospheric profile at 0900 UTC (T+3).



**Figure 7.17.** Eta GFS 2003-05-11 0000 UTC model projected atmospheric profile at 0900 UTC (T+9).

### 7.5.7 ANABATIC AND KATABATIC EFFECTS

In section 7.4.2 and 7.4.6 it was pointed out that the land and sea breezes were stronger inland at Al Ain than at Abu Dhabi on the coast. It is unclear to what extent anabatic and katabatic winds on the Hajar Mountain's western slopes influenced the land and sea breeze. Riehl (1954) stated that strong land breezes are common where anabatic, or katabatic, winds reinforce the thermal effect.

About 30 nm to the east of Al Ain are roughly north to south oriented Hajar mountain range. At Al Ain the early morning south-easterly to southerly land breeze was up to 7 to 9 knots while it was no stronger than 3 knots at ADIA. The difference could be due to the katabatic wind (UKMO 1997). Sinking of cool, mountain slope air at night would foster land breeze development at night. While across the flat desert to the coast, ground friction would retard the wind, as would the lack of a significant thermal gradient.

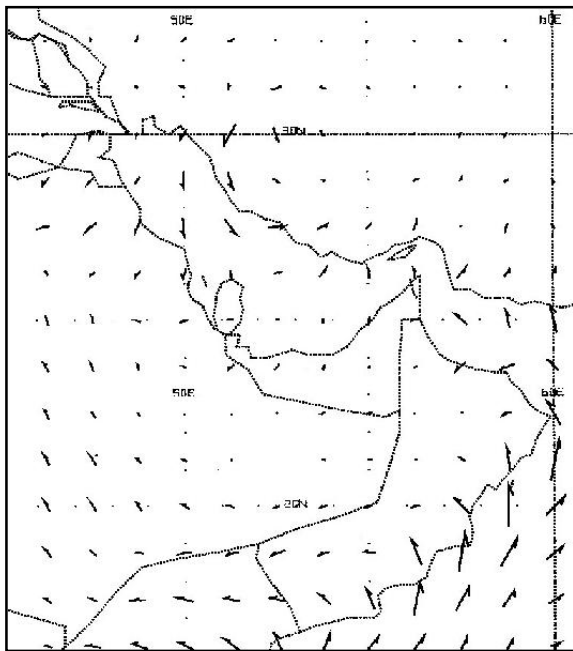
In the afternoon the western slopes of the mountain range are more perpendicularly aligned to the sun's rays than the desert floor. This results in hotter slopes, heated and less dense air in contact with the slope and an up-slope anabatic wind (Miller 1966). This could assist sea breeze penetration and account for the 3 to 4 knots stronger wind with 22 knot gusts experienced at Al Ain as opposed to ADIA.

### 7.5.8 DRY SEA BREEZE

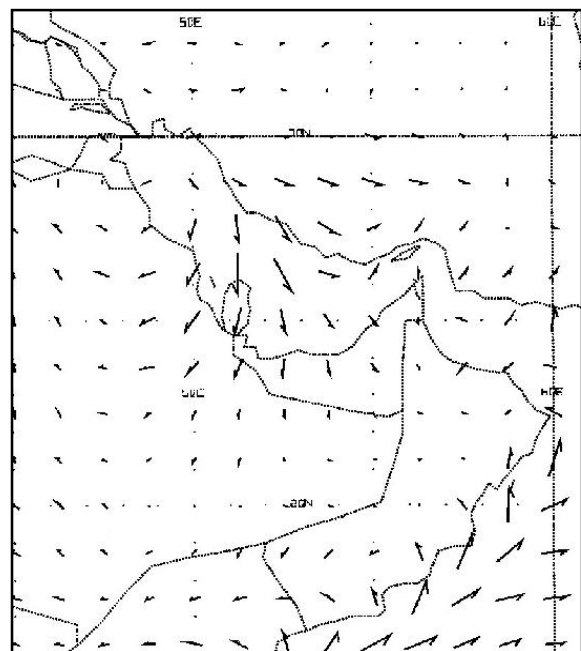
On occasion the onset of the breeze at ADIA fails to increase the relative humidity. On both the 10<sup>th</sup> and the 11<sup>th</sup> the air remained dry (figures 7.5 and 7.6) with the relative humidity remaining below 20% until well after the wind increased to 14 knots and in this case the humidity remained at around 40% until the evening when air temperatures fell. The low relative humidity is attributed to the subsidence taking place in the anticyclonic circulation aloft. The atmospheric soundings at 0000 UTC on the 10<sup>th</sup> and the 11<sup>th</sup> indicate that the air was very dry immediately above the surface, particularly on the 11<sup>th</sup> (figures 7.11 and 7.12) and that this subsiding dry air mixed with the moister maritime air from the Gulf when turbulent mixing began after the demise of the surface inversion. Furthermore, boundary

layer moisture flux fields at 1200 UTC on the 10<sup>th</sup> and the 11<sup>th</sup> also confirm that the air was very dry on both days (figures 7.18 and 7.19, respectively). Lee and Shun (2003) explained that it took some time for dry continental air, already in place, to be replaced by moister maritime air.

Another peculiarity that often occurs after the sea breeze begins at ADIA, is that there is a temporary dip in the increasing humidity recorded at ADIA. This dip can be seen in the dew point temperature trace in figure 7.5 and figure 4.9 in chapter 4. An explanation for this is that the convergence zone inland carries dry air aloft and out to sea in the upper part of the circulation, where it sinks and is carried back onshore by the sea breeze (Riehl 1954).



**Figure 7.18.** Eta GFS surface moisture flux analysis at 1200 UTC (T+00) on 2003-05-10.



**Figure 7.19.** Eta GFS 2003-05-10 1200 UTC model run moisture flux prognosis at 1200 UTC (T+24) on the 11<sup>th</sup>.

## 7.6 FORECAST CHECKLIST

Use of the Eta NWP model post processing products give ample indication of the onset and demise of land and sea breezes.

Of particular use for forecasting the onset of land, or sea breezes, are the Eta surface wind time cross sections. In this respect the forecaster must be aware of the prevailing synoptic condition and whether this will cause the wind to blow earlier, later, stronger, or weaker.

Important considerations:

The sea breeze.

- The average sea breeze start time is 0830 UTC (12:30 local time).
- It is most likely to blow at 11 knots reaching a maximum at about 1030 UTC (14:30 local time).

- The sea breeze will be strengthened by a northerly flow such as when there is a surface low pressure cell to the east, or an anticyclone approaching from the west and will start earlier. However, under these conditions the land breeze will be weaker, start later and may not occur at all.
- The sea breeze is most likely to veer overnight through easterly to a south-easterly land breeze.
- Night minimum temperature is higher when the north-westerly wind persists throughout the night.
- Dust raised by the land breeze clears when the sea breeze begins.
- The sea breeze penetrates far inland, up to about 150 kilometres to Al Ain. This is probably due to thermal heating and the anabatic effect of the Hajar Mountains.
- The summer sea breeze is usually free of low cloud
- Low cloud that does accompany the sea breeze, more likely in winter, is usually at about 600 to 1167 metres (2000 feet to 3500 feet).

The land breeze.

- The land breeze is most likely to begin at 0100 UTC (05:00 local time)
- It is most likely to blow at about 4 knots and reach a maximum at about 0450 UTC (08:50 local time).
- The land breeze is most likely to veer late morning through south-westerly to a north-westerly sea breeze.
- The land breeze will be strengthened by the southerly flow ahead of a surface low pressure cell to the west and start earlier. However, a sea breeze will then be weaker, start later, or not at all.
- The land breeze is often stronger at Al Ain than at the coast and the sea breeze stronger and gustier. This is probably due to katabatic effect of the Hajar Mountains.

Wind strength, and its effect on the visibility, has been discussed in the chapter on dust storms.