CHAPTER 9

CONCLUSION

9.1 GENERAL

The principal objective of this thesis is to provide comprehensive documented forecast material for aviation forecasters in the Emirates and in particular at ADIA. With this in mind, significant weather phenomena and systems of the region have been identified, their development described and researched through case studies and the results summarised in each chapter. Based on the research, forecast methodologies, or checklists, were developed and presented at the end of each relevant chapter. These are summarised in the sections in 9.3 that follow.

Post-processing macros were developed to identify and assess the particular weather phenomena and their use was instituted in the ADIA forecast office in 2002 to 2004.

The secondary objective was to describe the general seasonal climate sequence in the UAE and its immediate surroundings. This was achieved in chapter 3. The main climate factors are summarised in paragraph 9.2.

9.2 GENERAL CIRCULATION: A SUMMARY

The weather experienced in the Arabian Peninsula, is strongly influenced by the summer and winter Monsoon over Asia and the annual reversal of trans-equatorial flow of air at the surface and the upper troposphere, as well as associated changes in velocity divergence and convergence. The primary effect is the surface transition from winter high pressure to summer low pressure.

In winter the passage of mid-latitude low pressure cells in association with upper air troughs, are important weather and rain and thunderstorm producers. Interspersed with the passing lows, latitudinal movement of the surface anticyclonic cell over Arabia results in alternating dry and hot southerly to south-easterly winds and cooler northerly Shamal winds.

The summer circulation, dominated by the position of the Asia low, results in a consistent northerly to north-westerly Shamal wind with high temperatures. While water vapour advection, into the low from the Arabian Gulf causes very humid conditions and can provide enough water vapour for the development of thunderstorms, which are driven to the UAE west coast by the mid-level easterly circulation.

In spring rapid land surface heating causes the development of shallow cyclonic circulation systems. They accentuate the shallow, near sub-synoptic depressions arriving from north-west Africa. These shallow low pressure cells are preceded by southerly winds with intense heat waves and sandstorms.

By virtue of its location straddling the Tropic of Cancer, the subtropical anticyclone in the lower atmosphere dominates the weather and climate of the UAE. This results in predominantly weak pressure gradients and subsiding air. Combined with the warm Gulf Sea and marked land/sea temperature differences, this makes the region ideal for consistent land and sea breeze conditions and overnight fog. In early summer, large daytime temperature difference between the land and the still lower Gulf Sea temperatures, cause intensified land and sea breeze circulation. The lower sea temperature is also influential in increased fog.

9.3 SIGNIFICANT WEATHER PHENOMENA AND SYSTEMS

To the author's knowledge documented aviation weather research, indeed any research, in the UAE and ADIA in particular, is non-existent. The little aviation forecast information that was available was anecdotal and limited to a few pages of notes. Research that does exist relates to weather further afield and it is not aviation specific. These are Shamal studies done by Membery (1983) at Bahrain and Rao, et al (2001) at Doha in Qatar; sea breezes across the UAE coast (Eager et al, 2005); waterspouts (Jackson, 1987 and Davey, 1987). More relevant, but still not aviation specific is thunderstorm and enhancement of precipitation research in the nearby Hajar Mountains (Breed et al, 2005 and 2002; Jensen et al, 2005; Bruintjes and Yates 2003 and Al-Brashdi, 2007). Therefore, the research in the weather phenomena chapters, for the greater part, covers new ground.

9.3.1 FOG

Fog is the most serious disrupter of aviation activity at ADIA and, although there is a higher frequency in autumn and winter it occurs often enough to be a continual source of concern to the aviation forecaster throughout the year. The fog forms as result of advection and radiation processes. Moist air is advected from the Gulf during the afternoon and evening. During the latter part of the night radiation cooling causes the fog to form over the land. It then expands toward, or drifts over, the airport on its way to the coast, borne by a light early morning land breeze (figure 9.1).

Figure 9.1. Early morning Stratus cloud and fog drifting into the island city of Abu Dhabi from the direction of ADIA further inland (2004-03-07).

Clear night and weak pressure gradient conditions aside, the wind is the most critical factor for determining whether fog will occur or not. Fog is most likely after a Shamal has been blowing for some time and then dies away and veers to a light south-easterly land breeze around sunrise. The ideal situation being after the passage of a trough and a slow moving following anticyclone maintains a north-westerly wind off the Gulf Sea and then settles over the UAE. Significantly it rarely occurs when the wind backs through westerly during the night with a longer period blowing off the desert to ADIA.

It is equally important to know when fog will not occur. It does not occur when the wind persists from the north-west to north-east, such as during a Shamal, no matter how much water vapour is available. Although not affecting ADIA, prior to this research, it was not known that well inland this wind can become light enough for fog to form at the Liwa Oasis on the edge of the Empty Quarter. Fog also does not occur when the wind persists off the desert, which happens when there is a low pressure to the west. However, the forecaster must also be wary of the sea breeze during the day, bringing increased water vapour, which then ceases with a light land breeze around sunrise.

The fog very quickly becomes thick enough for the visibility to decrease below the CAT3A ILS 200 m minimum, resulting in aircraft diversions. During the winter months fog tends to occur earlier in the night and clear later than in summer. It is so frequent later in the night and around sunrise between 2200 and 0300 UTC (0200 and 0700 local time) that scheduled flights into ADIA virtually cease between these times.

A significant discovery, and contrary to local weather lore, is that fog is unlikely to occur on two, or more, consecutive nights. It does happen, but the likelihood is less than 18% and the risk of fog during four or more consecutive days is 1%. Another research result relates to the local belief that 80% or higher surface relative humidity at 1800 UTC (2200 local time) is a precursor to fog. This factor was found to be a useful, but not an infallible, nowcasting tool, The research showed that 90% of the study fog events occurred when the relative humidity was ≥ 73% at this time. On the other hand, the relative humidity also exceeded 80% on some nights and then fog did not form by the next morning. A far more reliable indicator was found to be whether the minimum surface air temperature, later in the night, will drop to, and below, the maximum surface dew-point temperature that occurred late the previous afternoon, or early evening.

A detailed forecast methodology to pursue is provided in chapter 4, but taking everything into consideration the most important fog forecasting criteria at ADIA are:

- Clear sky expected.
- Pressure gradient ≤ 1 hPa over the UAE (surface anticyclone or col present).
- Shamal ceases during the afternoon, or evening.
- Very misty evening conditions brought by the sea breeze or Shamal.
- Surface relative humidity ≥ 73% by1800 UTC and ≥ 90% at 0000 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.
- ≥ 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.

9.3.2 SHAMAL

The Shamal is the only wind in the region that can routinely last for several days, brings cooler, but still humid air to ADIA and promotes fog formation. Over the Gulf Sea the Shamal can reach strong to gale force, causing a very rough sea and disrupt helicopter flights to the oil rigs. The wind develops in the northerly flow east of a surface anticyclone that approaches over Saudi Arabia and follows a low pressure cell over southern Iran, or the Strait of Hormuz.

As described by Membery (1983) at Bahrain and Rao, et al (2001) at Doha (Qatar), the wind is most prevalent in summer and most persistent during the summer months of May to July with a secondary maximum in winter from November to March. The wind is strongest during the afternoon from 1000 to 1500 local time when it is reinforced by the sea breeze.

Strong Shamal winds can carry sand from Iran and Saudi Arabia over the Gulf Sea to the UAE and cause poor visibility. The visibility tends to be worst over the eastern UAE where there is a shorter sea traverse and less time for the dust to fall out of the atmosphere before reaching the oilrigs offshore and the UAE coast.

The wind can be stronger and gustier inland at Al Ain in the afternoon than at ADIA. It is suggested that this is probably because of enhanced cyclonic circulation due to the hotter conditions inland and upslope (anabatic) wind along the western slope of the Hajar Mountains to the east of Al Ain. This contribution by the land breeze may also help to overcome the retarding friction effect of the land as the air penetrates inland from the sea. This strong and gusty wind lifts dust and reduces the visibility.

At night, during persistent Shamal conditions, the wind tends to become lighter and may even back to south-westerly, due to the influence of the overnight land breeze effect, but may persist from the north-west, or the west-north-west, when synoptic scale surface pressure gradients dominate.

Strong upper air subsidence above the surface heat low means that this (superior) air is usually too dry for low cloud to develop, but in winter with cooler and moist air off the sea, scattered low cloud often occurs over the coast, but less often further inland. The cloud, formed as a result of turbulent mixing of maritime air beneath a temperature inversion, is usually about 2500 feet to 3000 feet above ground level.

The most important considerations when forecasting a Shamal are:

- Wind speed ≥ 17 knots.
- Surface ≥ 5 hPa pressure gradient across the UAE.
- A surface low, or trough, passing to the east.
- A surface anticyclone to the west of the UAE and/or a deepening of the surface low over Iran.
- Wind shear. A low level jet developing overnight, 30–40 knots ± 300 metres MSL.
- Poor visibility. The Shamal can carry dust from far away in Saudi Arabia and Iran.

9.3.3 DUST STORMS

Dust storms at ADIA occur either as a result of a thunderstorm gust front, or in the synoptic scale when a strong surface pressure gradient develops over the UAE. This often happens when a low pressure system advances from the west and it is further enhanced by diabatic heating over the desert. The enhanced gradient causes a strong to gale force gusty and turbulent wind and dust may be lifted from afar and transported to the UAE.
Dust storms, when the visibility is below 1000 metres, are not as common as legend would have it. Owing to the geographical location of the UAE, the average is only 3 per year. However, dust events when the visibility is reduced to less than 5000 metres are more common and occurred on 141 occasions from 1994 to 2003.

The duration of dust storms, when the visibility is below 1000 metres, is not long. The average duration was found to be about 1¼ hours and the longest 4½ hours. On average thunderstorm gusts reduce the visibility to dust storm levels for 37 minutes with the longest time being nearly 60 minutes. Dust events, when the visibility is ≤ 3000 metres, last on average 3¾ hours with the maximum duration 15 hours. The longest period, when the visibility remained ≤ 5000 metres due to dust, was 21 hours.

Dust events and dust storms are most likely when the wind blows from the desert to the south. With Shamal conditions the dust has to be transported from the north-west and a considerable distance across the Gulf Sea with the result that the visibility is seldom seriously reduced. Dust storms are even less likely from the north-east, or east. The exceptional Nashi wind dust storm that reached the UAE happens very seldom, and no literature reference to such an event could be found. Weather forecasters need to consider the risk of dust transport to the UAE whenever model prognoses indicates strong turbulent winds over the desert to the south and west as well as over southern Iran.

Poor visibility is most likely when thermally induced eddies reduce stability and increased mixing with the air aloft. This happens most often during the morning and the early afternoon. The peak time is at 0600 UTC (1000 local time). This also coincides with the regular early morning land breeze that reinforces any southerly, pressure gradient forced, wind off the desert. By way of contrast the Shamal, or a strong sea breeze, penetrating inland, is most likely to cause poor visibility during the afternoon.

There is negative correlation between wind speed and dust reduced visibility. As a predictive tool, this correlation is not worth much due to other factors. These include poor visibility due to dust in suspension after the wind has dropped, or dust carried aloft from elsewhere, while the local wind speed remains low and also the effect of a low sun with haze or dust in suspension. Other factors are the dust source region and type, such as finer dust in the vicinity of ADIA and more sandy soil at Al Ain (section 6.6.1.3). However, there are some loose conclusions that can be made. At wind speeds above 15 kn the visibility can generally lower to below 8000 m and it is often reduced to below 5000 m. Above 20 kn the visibility will frequently be less than 2000 m, but most likely be below 1000m. For wind speeds above 30 kn the visibility will be less than 1000 m.

The most important forecasting considerations are;-

- Strong wind from the south-east to west-south-west .

- Strong outflow from thunderstorms creating a turbulent and gusty wind at the outflow leading edge.

These two mechanisms are considerably enhanced when:

- The environmental lapse rate approaches the value of the dry adiabatic in the lower layers.
- The dryness of the surface dust/sand.

However, the visibility improves when:

- The southerly dust generating wind veers to north-westerly after the passage of a surface low system.
- An afternoon sea breeze develops
- At night when the wind speed decreases.

Other factors to be considered are:

- The transport of dust from further afield by the Shamal and north-easterly Nashi.
- Dust and dust storms in southerly winds are most likely between 0300 UTC to 1200 UTC and most prevalent at 0600 UTC.
- Dust and dust storms in a Shamal are most likely between 0800 UTC to 1300 UTC.
- Thunderstorm associated dust storms last ± 30 minutes and hardly ever more than 60 minutes.

9.3.4 LAND AND SEA BREEZES

The very consistent sea breeze at ADIA can be expected to start at 0830 UTC (1230 UAE time) and average about 11 knots, reaching a maximum at about 1030 UTC (1430 UAE time). The equally regular, but much lighter, land breeze is most likely to begin at 0100 UTC (0500 local time), blow at about 4 knots and reach a maximum at about 0450 UTC (0850 local time). The change from a land breeze to sea breeze usually occurs within about an hour, whereas the overnight change from a sea breeze to a land breeze is more gradual. Generally, the Eta GFS NWP model surface wind time section fields give a good indication of the strength and timings of sea and land breezes.

This research revealed that the marked thermal difference between the sea temperature and maximum land temperatures causes the sea breeze to penetrate up to about 150 kilometres inland to Al Ain and the Liwa Oasis. Most references to the extent of sea breezes inland limit this to 20 to 70 kilometres (Bradbury 1989, Riehl 1979, Critchfield 1974 and Millar 1966), while only Eager et al (2005) claimed that they can be penetrate up to 130 kilometres inland.

Another factor that this research revealed was that the sea breeze can be stronger and gustier inland at Al Ain than at ADIA accompanied by worse visibility due to wind blown dust. The stronger wind at Al Ain is considered to be due to the anabatic upslope wind driven by the daytime heated slopes of the Hajar Mountains. The land breeze at Al Ain was also found to be stronger than at the coast. This is probably due to the night time cold air drainage (katabatic effect) of the western slopes of these mountains.

Dry air entrainment from near the top of the boundary layer can maintain low humidity and produce a “dry” sea breeze. A peculiar temporary dip that has been noted in the rising humidity shortly after the sea breeze begins and this is attributed to dry air that is advected to sea by the upper diverging branch of the inland convergence zone. It then sinks and is carried back onshore by the sea breeze.

Important forecasting considerations:

The sea breeze.

- Will be enhanced and start earlier in a northerly synoptic scale flow. This happens due to the strong gradient between a surface low pressure in the east and or an anticyclone approaching from the west. This pattern suppresses the land breeze. It will be weaker, start later and may not occur at all.
- It is most likely to veer overnight through easterly to become a south-easterly land breeze.
- Dust raised by the land breeze clears when the sea breeze begins.
- It can penetrate up to about 150 kilometres inland.
- In the summer the sea breeze is usually free of low cloud
- In winter low cloud with the sea breeze is more common. The cloud base is generally between about 600 to 1200 metres (2000 feet to 3500 feet).
- At Al Ain the sea breeze is often stronger and gustier.

The land breeze.

- Will be enhanced by the synoptic scale southerly flow when a surface low pressure cell lies to the west. The land breeze will start earlier and in this case the sea breeze will be suppressed, start later, or not at all.
- It is most likely to veer through south-westerly to a north-westerly sea breeze.
- The land breeze is often stronger at Al Ain than at the coast at ADIA, but not as strong and gusty as the sea breeze.

9.3.5 RAIN TROUGHS, THUNDERSTORMS AND TROPICAL DEPRESSIONS

Thunderstorms, embedded in the south-westerly flow ahead of eastward moving upper air troughs in winter, are the main producers of rain in the vicinity of ADIA. Thunderstorm precipitation can be heavy and result in brief flash floods. However, rain depth of around 10 mm to 20 mm is most common. Hail is vary rare with no recorded incidence at ADIA. Wind shear parameters obtained from the Eta NWP model at the time of the 18th March 2002 thunderstorm (Chapter 8.4.3), indicated the potential for enough wind shear to foster vigorous development, but not enough to produce a supercell thunderstorm.

To a lesser extent, diurnal thermal heating and orographic forcing cause afternoon summer thunderstorms to develop on the Hajar Mountains. Echoes of up to 50 dBZ are not uncommon with thunderstorms tops up to about 45000 feet (13716 metres). They develop in a north-easterly steering flow along the eastern edge of an upper air anticyclone situated to the north and west of the UAE. Surface low level moisture is advected from the Arabian Sea and the Gulf of Oman and carried aloft by synoptic scale ascent. Under these circumstances the majority tend to be on the Oman part of the mountains south of Al Ain where the mountains are nearly perpendicularly to the lower level north-easterly flow. Sometimes they develop in the far north on the mountains in the Musandam Peninsula and an easterly 500 hPa steering wind causes the storms drift to Ras Al Khaimah, Dubai and Sharjah on the west coast, but rarely, to ADIA. It is possible that the afternoon sea breeze gust front, meeting thunderstorms on higher ground toward the mountains, adds impetus to the thunderstorm development.

The passage of a trough system is normally marked by a short period of cloudy weather of less than 24 hours, but, occasionally cloudy periods lasting up to about 8 to 10 days do occur. Intense and slow moving mid-tropospheric trough systems, on occasion, have the potential to produce severe convective weather. When this happens fresh to strong, hot and dry southerly desert winds precede the thunderstorm line squall. Visibility is reduced to below 2000 metres by a combination of wind blown dust and rain. Visibility, below 1000 metres, occurs in the wind blown dust at the thunderstorm gust front and improves in the following rain. Cloud bases remain high enough so that they rarely hamper landing aircraft.

Over the UAE, tropical depressions are very rare severe weather and rain producers. In 2002 one tropical depression (number 01-A) reached the UAE in a much depleted state in and one other rapidly degenerating cyclone 02-A Gonu passed well east of the UAE east coast in 2007.

Important considerations:

- The passage of upper air troughs during winter.
- Thunderstorms are likely to occur embedded in cloud ahead of these troughs.
- Summer thunderstorms are rarely reach ADIA when they drift westward from the Hajar Mountains.
- When the 500 hPa steering winds are from the north-east the summer storms drift away to the Empty Quarter.
- Tropical depressions are extremely rare and move from the south-east over southern Oman, or move northward over the Gulf of Oman.

9.4 GUIDELINES ON THE USE OF THIS THESIS

Apart from a copy of this thesis being made available to the UAE Federal Meteorological Service and to the Abu Dhabi Directorate of Civil Aviation, the recommendation is that copies of the forecast methodologies, or checklists, be placed in a ready reference file and kept at the work station as a decision making tool.

The research detailed in this thesis could also provide the basis for an operations and training manual.

To assist forecasters in decision making, macros, based on this research, currently in operational use, can be updated using new post-processing technology.

9.5 THE FUTURE OF UAE AVIATION WEATHER FORECASTING

One tends to view the desert environment as one with little in the way of weather. The disruption to airport operations and diverted flights due to fog, dust storms, thunderstorms and wind disprove this.

Commercial aviation in the UAE is a rapidly growing and expanding industry, particularly at ADIA and Dubai. Airport passenger and cargo hubs are continually being enlarged with the aim of being global centres. An all new airport, Al Maktoum International Airport at Jebel Ali on the coast near Dubai, will be operational by 2010 and before the recession of 2009, it was projected to be the biggest in the world by 2015. Commercial aircraft flying to and from the UAE, such as the A340-500, already have flight endurance of 19 hours, while the A380 typically carries 525 passengers and can carry up to 555.

Aviation weather forecasting in the UAE will become more important and the emphasis will be on greater forecasting accuracy for longer forecast periods. Better understanding of weather phenomena detrimental to aviation will become more important and the author trusts that this thesis will contribute.

9.6 RECOMMENDED FUTURE RESEARCH

Fog is the most serious form of weather detrimental to aviation in the UAE, particularly along the Gulf Coast. Some fog forecasting indices in use elsewhere in the world, such as Saunders and the Craddock and Pritchard methods (UKMO 1997), were briefly tested during research for this thesis and found to be unsuitable for the weather conditions in the UAE. The surface wet-bulb temperature at 0000 UTC and the 1200 UTC dew point temperature showed promise. The invention of a reliable local fog index would be of great benefit to the forecaster at ADIA and at Dubai.

As producers of severe weather over the UAE, thunderstorms in association with the passage of upper air troughs deserve further research. This also holds for the summer westward displacement of thunderstorms to the Emirates coast by 500 hPa steering winds. Closer scrutiny is recommended of the relationship between low level water vapour flux from the south and south-east and passing trough systems as a thunderstorm rain producer in support of the pioneering research by Al-Brashdi (2007).

The little known Nashi wind is certainly worthy of further statistical and analytical research, as is the role played by the diurnal land and sea breeze effect on the strength and direction of the Shamal.

A useful area of research would be the anabatic and katabatic effects of the Hajar Mountains on the land and sea breezes. As well as the peculiar temporary dip in humidity often noted at ADIA shortly after the onset of the sea breeze. Is this due to dry air carried out to sea aloft, then sinking and brought back to the coast on the sea breeze? Of additional interest is the effect of land and sea temperature differential on the strength and onset of the land and sea breezes and whether the sea breeze penetrates further than 150 km inland.

Although the primary mechanisms of the weather in the UAE are known and understood, there are synoptic and mesoscale characteristics and circulatory systems that need further investigation. For example, the semi-permanence of the winter, surface anticyclonic cell over Arabia and the transitory spring desert depressions with their attendant sand storms. It would also be beneficial to examine the extent to which the zone of 200 hPa convergent air at about 40°E is a compensatory effect for the upward flow at 70°E, as well as to what extent the subsiding air below this convergent zone contributes to the dry summer weather over the Arabian Peninsula.