



A climatological study of the sea and land breezes in the Arabian Gulf region

Rebecca E. Eager,^{1,4} Sethu Raman,¹ Adrienne Wootten,¹ Douglas L. Westphal,² Jeffrey S. Reid,² and Abdulla Al Mandoos³

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[1] This study focuses on observations of the sea and land breeze circulations in the southern Arabian Gulf. During the summer months, the Indian monsoon creates light northwesterly winds over the Arabian Gulf, allowing for the formation of thermally driven circulations. Observations from a network of stations are used to develop a wind climatology for the Arabian Gulf region. Characteristics of the sea and land breeze circulations, such as onset time, duration, and horizontal and vertical extent are described. The dense network of surface stations in the United Arab Emirates (UAE) allows for a fine-scale observational study in this region. It is found that the sea breeze occurs during all seasons of the year in this region. It occurs in the late afternoon and continues through the evening. A land breeze sets in during the night. Surface offshore winds in the land breeze are strong probably due to drainage flow down the inland hills.

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1. Introduction

[2] During the summer months of June through September, southwest Asia is dominated by the southwest Indian monsoon. The pattern includes the low-level southwesterly winds from the Somali Jet over the Arabian Sea, an upper-level high pressure system and the Arabian heat low stretching from northern Africa to Iran and Pakistan. The heat low creates light northwesterly winds over the Arabian Gulf, with wind speeds of about 3 m s^{-1} . This weak synoptic forcing associated with the southwest monsoon allows for the formation of thermal circulations, namely sea and land breezes. Sea breeze circulations have been studied extensively through theoretical and observational studies in regions throughout the world such as southeastern Australia [Physick and Abbs, 1991], Indonesia [Hadi *et al.*, 2002], Brunei Darussalam [Hassan and Raman, 2003], California [Wilczak *et al.*, 1991; Banta, 1995], Florida's Atlantic and Gulf coasts [Boybeyi and Raman, 1992; Wakimoto and Atkins, 1994], Chile [Kalthoff *et al.*, 2002], Sardinia [Melas *et al.*, 2000], and southern France [Drobinski *et al.*, 2006], among others.

[3] The presence of these circulations in the Arabian Gulf has previously been documented in the literature. Zhu and

Atkinson [2004] found the sea breeze and land breeze circulations to be perennial features over the Arabian Gulf, with seasonally and diurnally varying depth and horizontal extent. They noted the difficulty in making a clear identification of the sea and land breezes due to the ambient northwesterly winds over the Gulf. The depth of the planetary boundary layer over the northern Arabian Gulf was decreased by the sea breeze circulation, which advected cooler maritime air over the land [Warner and Sheu, 2000]. On the west side of the Arabian Gulf, numerical simulations showed effects of the maritime air inland up to 100 km during the late winter and early spring [Warner and Sheu, 2000]. The presence of mountains in Oman and Iran create additional features of thermally driven anabatic and katabatic winds. These features may augment the sea and land breezes, similar to that found in the numerical simulation studies in Brunei [Hassan and Raman, 2003] and Sardinia [Melas *et al.*, 2000].

[4] Although several case studies of sea and land breeze circulations exist in the literature, systematic climatological analysis of the sea and land breeze circulations are rare. Climatological observations of the characteristics of sea and land breezes provide crucial information such as the horizontal extent of the sea breeze inland, time of onset of both breezes, and the intensity of the breezes on a timescale that can show persistence on weekly to monthly timescales. Such a study in the UAE region also can provide information on offshore characteristics of the sea and land breezes due to the availability of offshore island weather stations. The topography and the surface characteristics of the UAE region being predominantly sand raise questions on their effects in sea and land breeze initiation and maintenance. In addition, absence of strong synoptic scale forcing is helpful in identifying the sea and land breeze circulations with confidence.

¹Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina, USA.

²Marine Meteorology Division, Naval Research Laboratory, Monterey, California, USA.

³Department of Atmospheric Studies, Ministry of Presidential Affairs, Abu Dhabi, United Arab Emirates.

⁴Now at Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland, USA.

Joint Frequency Distribution Abu Dhabi

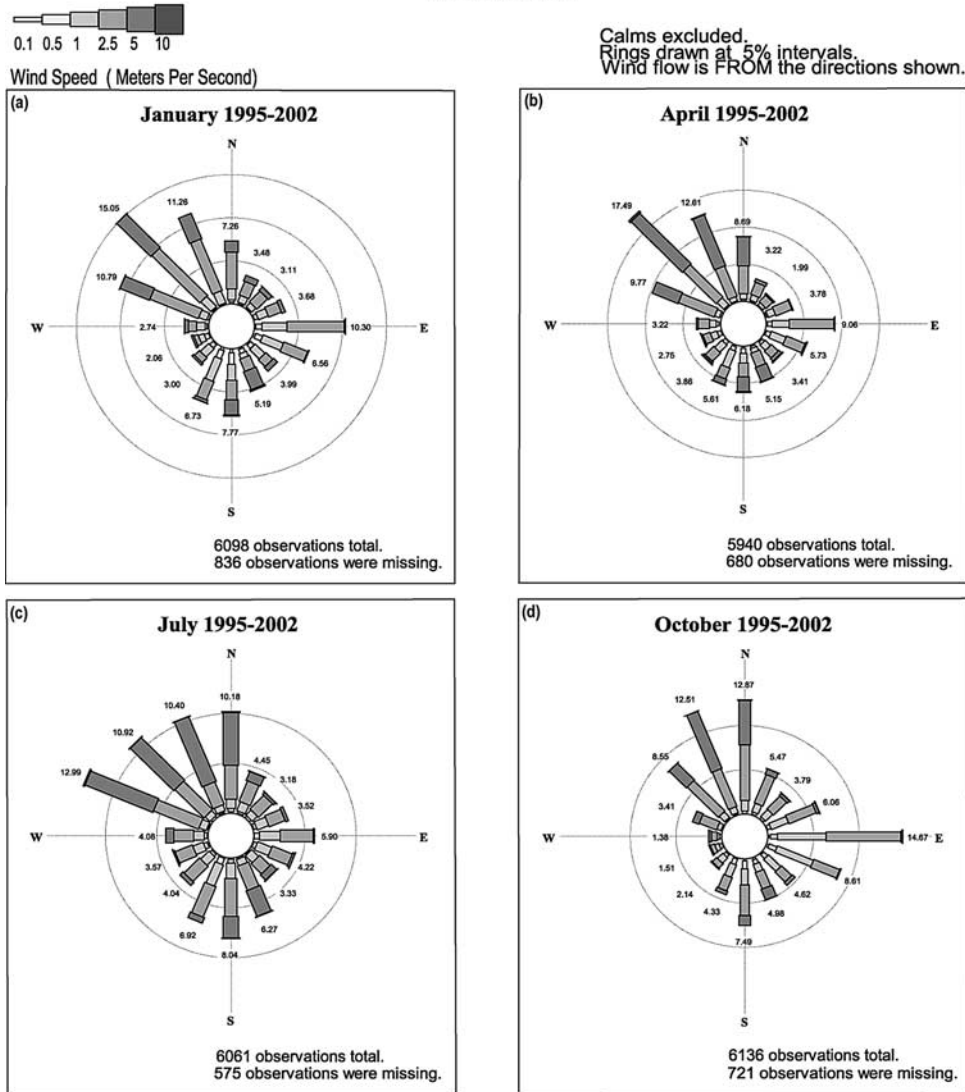


Figure 2. Wind direction frequency for Abu Dhabi for (a) January, (b) April, (c) July, and (d) October 1995–2002 (data from NCDC).

fall, and winter) or south (summer). Wind speeds are typically 5–10 m s⁻¹. This northwesterly flow over the Arabian Gulf is due to the southwest monsoon and the onshore sea breeze flow. The secondary maximum of winds from the offshore direction indicates the presence of the nighttime land breeze. These wind distributions are similar to those found by *Zhu and Atkinson* [2004] using one year of data from 2002. In all four seasons, winds perpendicular to the coastline are most common, in part due to the year-round prevalence of sea breeze and land breeze circulations.

[10] The frequency of sea breezes and land breezes at Abu Dhabi International Airport was determined quantitatively using the same 1995–2002 NCDC hourly surface observation data set. The sea breeze at Abu Dhabi is assumed to occur when the wind direction is onshore for four or more hours, with a diurnal change in wind direction. The land breeze is assumed to occur when the wind direction is offshore for four or more hours. For days when wind direction was not reported, a significant change in

wind speed in the surface layer was used to determine the presence of the sea and land breezes. Sea breeze formation at Abu Dhabi increases the surface wind speed during the daytime because both the prevailing winds and the sea breeze are from the northwest. The land breeze circulation acts to oppose the prevailing winds, leading to a weakening or reversal of the low level winds. The land breeze in this region is strong due to the added effect of katabatic flow resulting in the delay of the onset of the sea breeze. The main topographical features in the UAE are the Al-Hajar Mountains that extend from the peninsula in northern UAE into Oman, as shown in Figure 1. These mountains reach a height of about 1700 m. The rest of the UAE is mostly flat with a slow upslope toward the south.

[11] The percentage of days each month when a sea breeze circulation and a land breeze circulation developed for 1995–2002 is shown in Table 1. Sea breezes occurred more than 77% of the time during all months of the year, while land breezes occurred more than 70% of the time.

Table 1. Percentages of Days Per Month When Sea Breeze and Land Breeze Circulations Develop^a

Month	Sea Breeze Frequency	Land Breeze Frequency
Jan	82	81
Feb	77	71
Mar	81	71
Apr	93	84
May	96	95
Jun	99	94
Jul	99	96
Aug	96	97
Sep	99	99
Oct	98	100
Nov	92	93
Dec	90	91

^aSea breeze and land breeze frequency: Abu Dhabi, 1995–2002.

In the months of April through December, sea breezes occurred 90–99% of all days. Land breezes occurred 90% of the days from May through December. The month of February had both the lowest percentage of days having sea breezes (77%) and days having land breezes (71%). Two factors that allow for sea breeze development throughout the year include the weak year-round synoptic forcing in this tropical region, and the relatively consistent difference between the sea surface temperature and temperature over land during the year.

4. Summer Weather Conditions in 2004

[12] Hourly wind speed and wind direction observations from UAE DWRS meteorological stations were used to investigate the near-surface wind field over the region

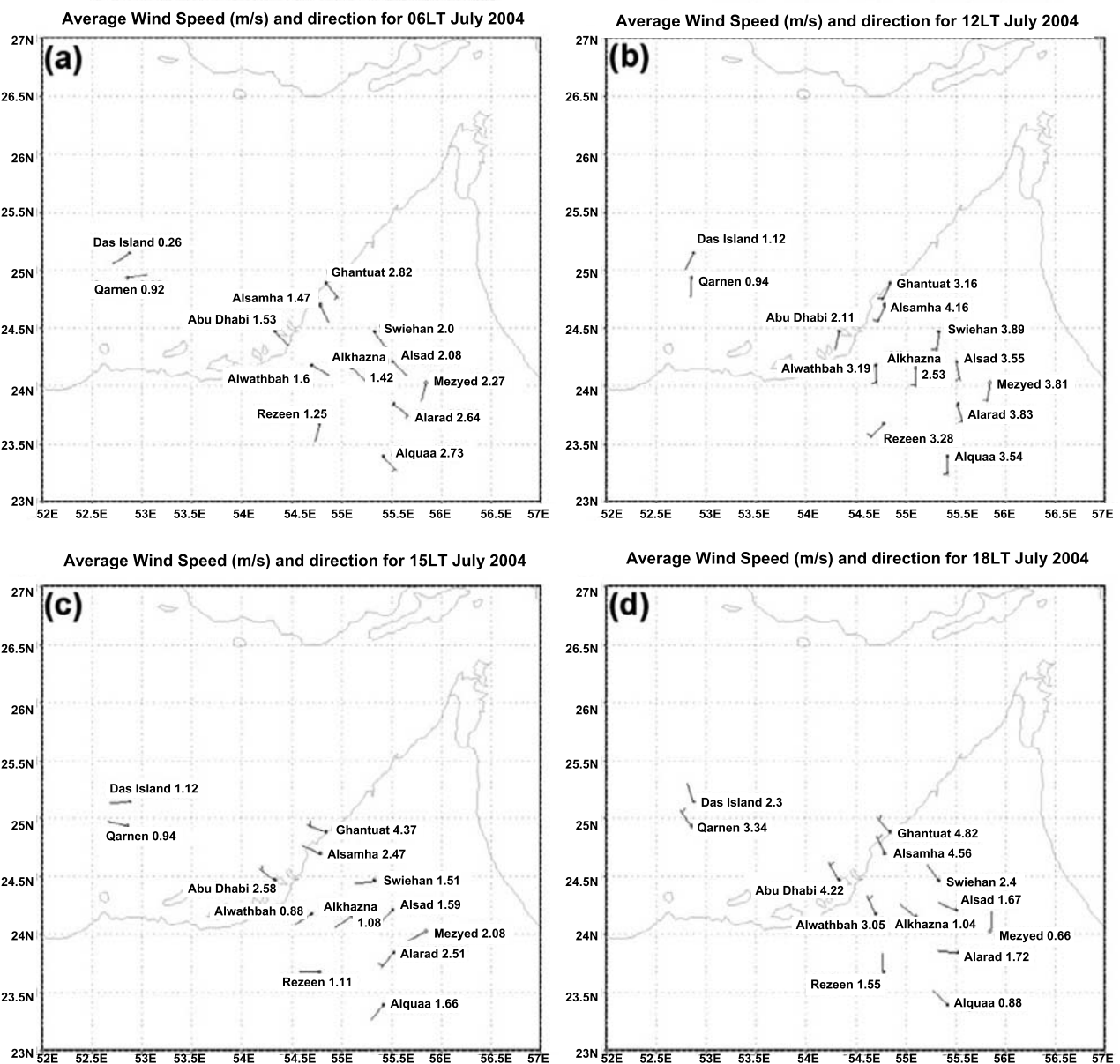


Figure 3. Average wind speed ($m s^{-1}$) and wind direction for July at (a) 0600 LT, (b) 1200 LT, (c) 1500 LT, and (d) 1800 LT. The wind speed is noted after the station name.

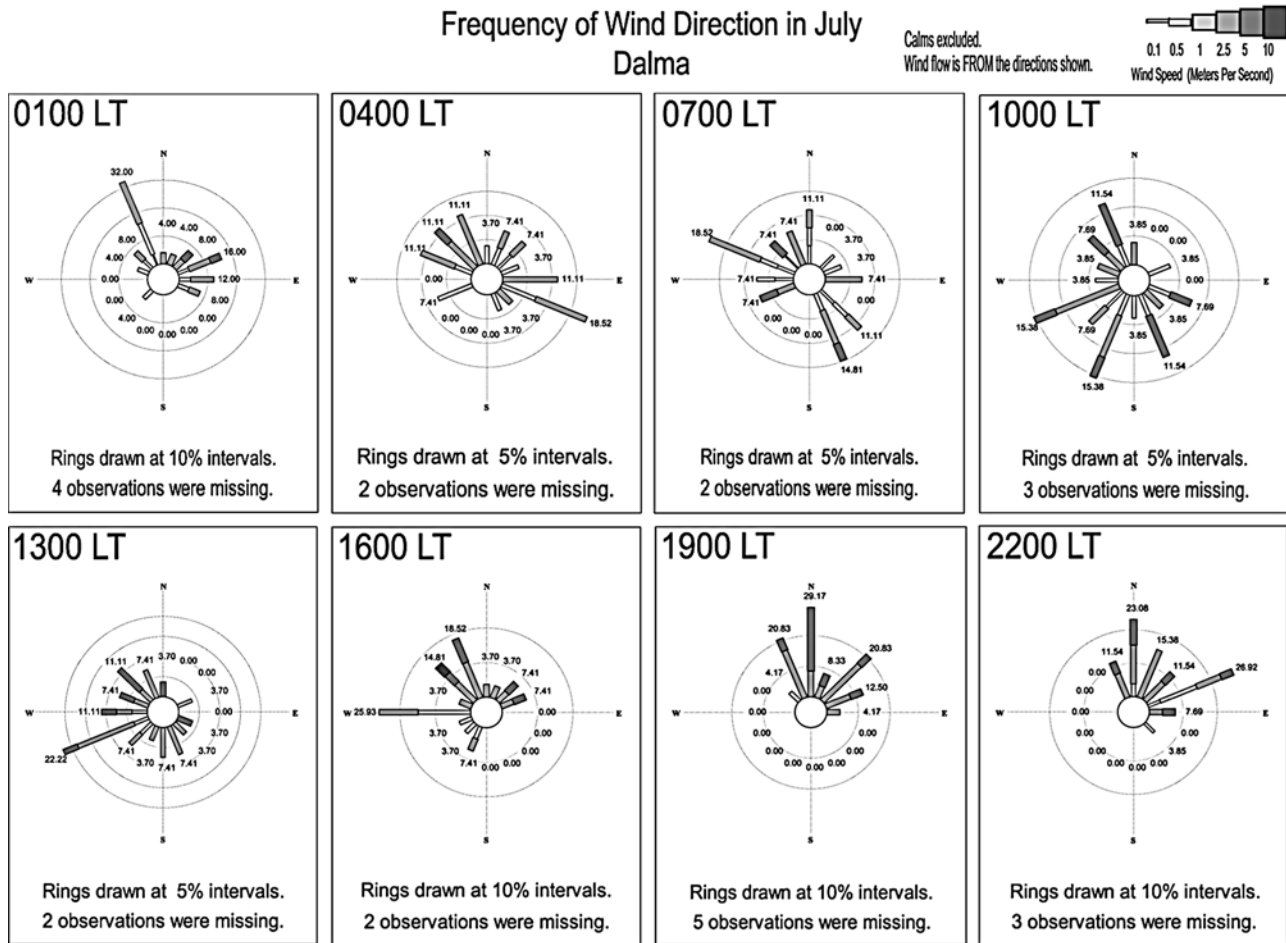


Figure 4. Wind direction frequency distributions every 3 h at Dalma. The percentage of observations from each direction is indicated at the end of each wind barb. The number of missing observations for each hour is given.

during the summer of 2004. The wind speed and direction at thirteen stations along a northwest to southeast cross-section through Abu Dhabi, including offshore, coastal, and inland stations, has provided fine-scale spatial information about the average diurnal variation of the sea and land breeze circulations.

[13] Spatial plots of average wind speed and direction at several locations are shown in Figure 3 for 0600, 1200, 1500, and 1800 LT. The data used was from the month of July. Plots of June, August, and September reveal similar patterns to those seen in July. The station names and the wind speed (in $m s^{-1}$) at each station are labeled near the respective wind barb. The diurnal variation of the horizontal extent of the sea breeze can be clearly seen. At 0600 LT, the surface winds over the UAE are southeasterly offshore winds, indicative of a land breeze, possibly augmented by downslope flow from the mountains (Figure 3a). The winds are onshore or parallel to the coast at 1200 LT (Figure 3b). At 1500 LT the sea breeze front has moved onshore about 15 to 20 km, as seen in Figure 3c, with the shift in wind direction at Abu Dhabi, Alsamha, and Ghantuat stations. By 1800 LT the sea breeze has moved further inland to about 160 km with onshore winds evident at all stations (Figure 3d). The wind speed maximum is located at the

coast, even after the sea breeze front has moved further inland. With the increase in surface roughness over land, the wind speed decreases inland. Spatial distribution plots of temperature and humidity did not show the sea breeze extent as clearly. The air-sea temperature differences were calculated for the stations shown in Figure 3. During the summer, the water temperature of the southern Arabian Gulf is quite warm, about $34^{\circ}C$, with similar air temperatures at stations near the coast and slightly higher temperatures further inland. Between 0600 LT and 1500 LT, the air-sea temperature difference increases, but from 1500 LT to 1800 LT the difference remains relatively constant and even decreases at some stations. This suggests the possibility of slow moderating effects of the sea breeze circulation on the near-surface air temperature due to the advection of relatively cool maritime air inland. This effect of the sea breeze on the temperature may be seen more clearly on studies of individual days.

[14] Time series of wind roses were developed to show the diurnal evolution of wind directions and investigate the timing of the sea and land breezes at locations in various parts of the country representing offshore, coastal, inland, and mountainous regions. Wind roses were made every 3 h beginning at 0100 LT for stations representing the various

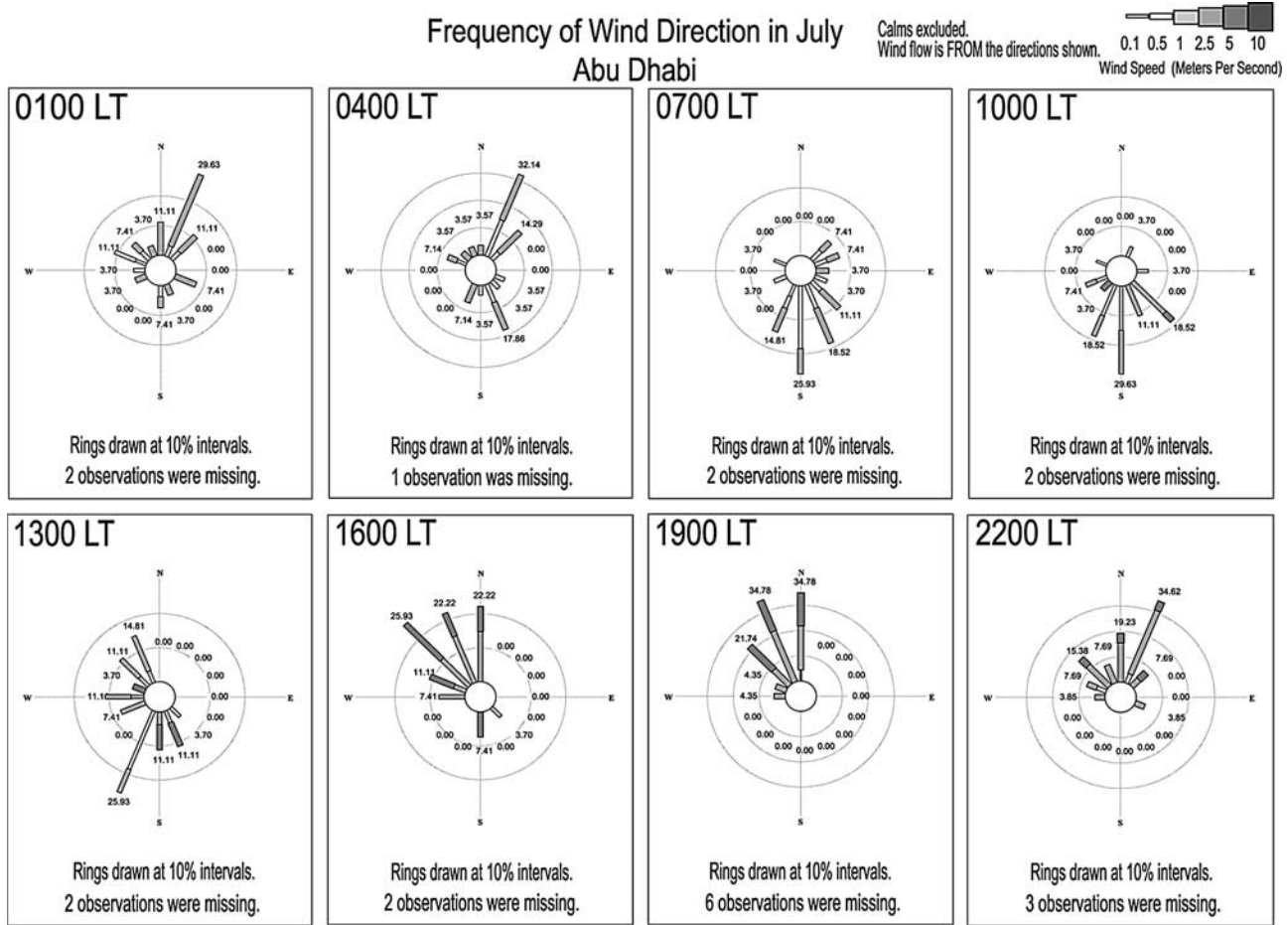


Figure 5. Same as Figure 4, but for Abu Dhabi.

geographic locations of the stations in the DWRS network. Time series for four stations are shown in this paper. In the morning hours, winds over the southern Arabian Gulf are southerly, indicating offshore flow, as seen in Figures 4 and 5, and Figure 6 for Dalma (55 km offshore), Abu Dhabi (along the coast), and Alkhazna (74 km inland). At the coast, the sea breeze forms between 1300 LT and 1600 LT when the winds turn onshore at coastal stations such as Abu Dhabi (Figure 5). Stations further inland and offshore experience the sea breeze later in the afternoon, for example the sea breeze reaches the offshore station of Dalma by 1600 LT (Figure 4) and the inland station of Alkhazna after 1600 LT (Figure 6). The sea breeze continues until sunset with winds remaining northerly after sunset due to the onshore synoptic flow. The time series of the winds at the Abu Dhabi DWRS station is similar to that shown in the surface climate summary maintained by the Fleet Numerical Meteorology and Oceanography Detachment (FNMOD) and NCDC. FNMOD reports the July daily average wind speed is a maximum at 1600 LT, with a speed of 6.5 m s^{-1} . The DWRS data indicates an average wind speed of 4.7 m s^{-1} at 1600 LT in July 2004. FNMOD daily time series show that the sea breeze, or onshore flow, in July develops by 1300 LT and continues until 2200 LT. The land breeze begins around 0100 LT and continues through the night and morning until the sea breeze develops in the early after-

noon. DWRS data for July 2004 indicates a slightly later sea breeze onset time, sometime between 1300 LT and 1600 LT. The FNMOD analysis of the winds and the DWRS wind data for August and September exhibit similar patterns as those found for July.

[15] The winds at Abu Dhabi are northeasterly (parallel to the coastline) during the overnight hours of 2200 to 0400 LT with lighter wind speeds than during the day. These wind speeds are similar to those found by *Zhu and Atkinson* [2004], who found the monthly mean hourly wind speed to increase from $1\text{--}2 \text{ m s}^{-1}$ during the night to $5\text{--}8 \text{ m s}^{-1}$ during the day in 2002. They also found that speeds are at the higher end of these ranges during the summer months. The land breeze flow may be augmented by katabatic flow from the mountains along the UAE-Oman border.

[16] In addition to the sea breeze along the Arabian Gulf, one can also form along the Gulf of Oman coast. Onshore easterly flow is indicative of the sea breeze, while westerly flow is offshore. The station of Al Heben is located just inland of the Gulf of Oman coast in the Al-Hajar Mountains at an elevation of 933 m (Figure 1). Figure 7 shows the diurnal evolution of the winds at this location. Interaction with the Gulf of Oman (rather than the Arabian Gulf) is expected to dominate the wind pattern at Al Heben. From 0700 LT until 1900 LT, the winds are southeasterly with speeds of $5\text{--}10 \text{ m s}^{-1}$. At 1900 LT and continuing until

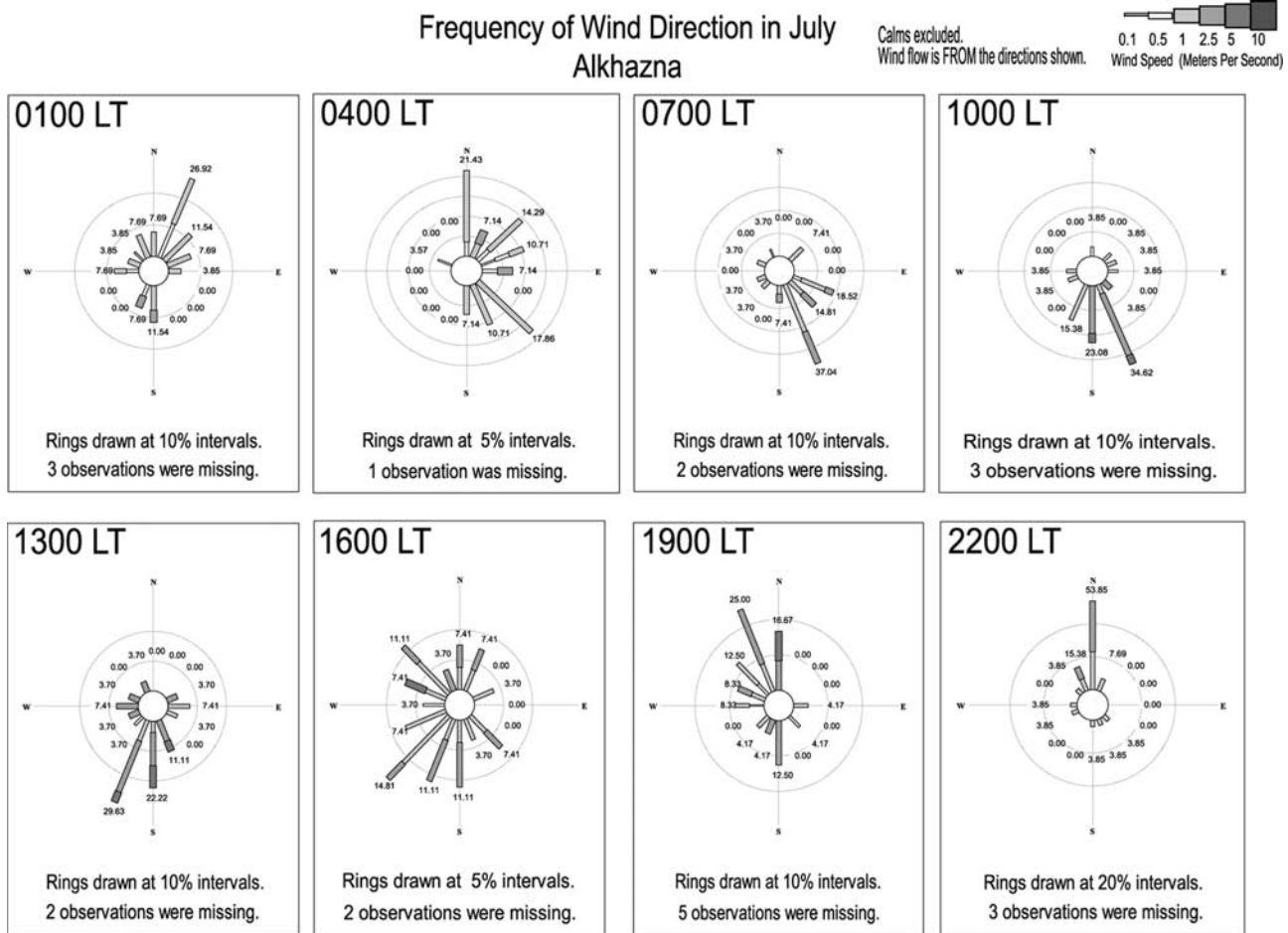


Figure 6. Same as Figure 4, but for Alkhazna.

0400 LT, the winds are equally from either the northwest or the southeast. In this area of the UAE, the distance from the Gulf of Oman to the Arabian Gulf is about 100 km. Al Heben could be influenced by flow from either coastline, depending on the blocking effects of the mountains and the intensity of the sea breeze from either coast. Along this coast, the coastal circulations may also be augmented by mountain-forced flows during both the night and day.

5. Evolution of the Sea Breezes

5.1. Horizontal Structure of the Sea Breeze

[17] The horizontal extent of the sea breeze circulation is variable and depends on many factors, including the strength and direction of the synoptic winds. DWRS observations were used to determine the horizontal extent of the sea and land breeze circulations during the summer of 2004. Stations oriented along a north-south line were selected to demonstrate the evolution of the horizontal extent of the sea breeze over the Arabian Gulf and inland over the UAE. These stations, shown in Figure 1, include Das Island (115 km offshore), Qarnen (85 km offshore), Dalma (55 km offshore), Sir Bani Yas (15 km offshore), Alqlaa (on coast), Owtaid (80 km inland), and Mukhariz (130 km inland). The coastline is oriented approximately west to east, with northerly sea breeze winds and southerly

land breeze winds. The sea breeze forms near the southern coastline of the Arabian Gulf and expands inland and offshore with time, reaching its maximum width in the late afternoon.

[18] One 48-h period was selected to investigate the possible differences in the inland extent of the sea breeze for two consecutive days. Wind direction measurements for 3–4 September 2004 are shown in Figure 8. Onshore winds occur at the beginning of the time period. Offshore winds form between 0100 LT and 1000 LT, and continue through the morning until 1500 LT, when the sea breeze forms at the Sir Bani Yas and Dalma stations, located at 15 km and 55 km offshore, respectively. By 1600 LT the sea breeze has developed at the coast and at the two islands further offshore. Southerly winds remain throughout the day at the inland stations of Owtaid and Mukhariz, which suggest that the sea breeze did not reach these locations. The maximum daily temperature occurs at 1500 LT at stations affected by the sea breeze. At Owtaid, which is not affected by the sea breeze, the maximum temperature occurs at 1700 LT. The relative humidity also increases as the sea breeze front passes these stations. The sea breeze lasts until about 2300 LT, when offshore winds are noted on the coast at Alqlaa. The horizontal extent of the sea breeze on 3 September was at least 115 km offshore, although no observations are available north of Das Island. The onshore

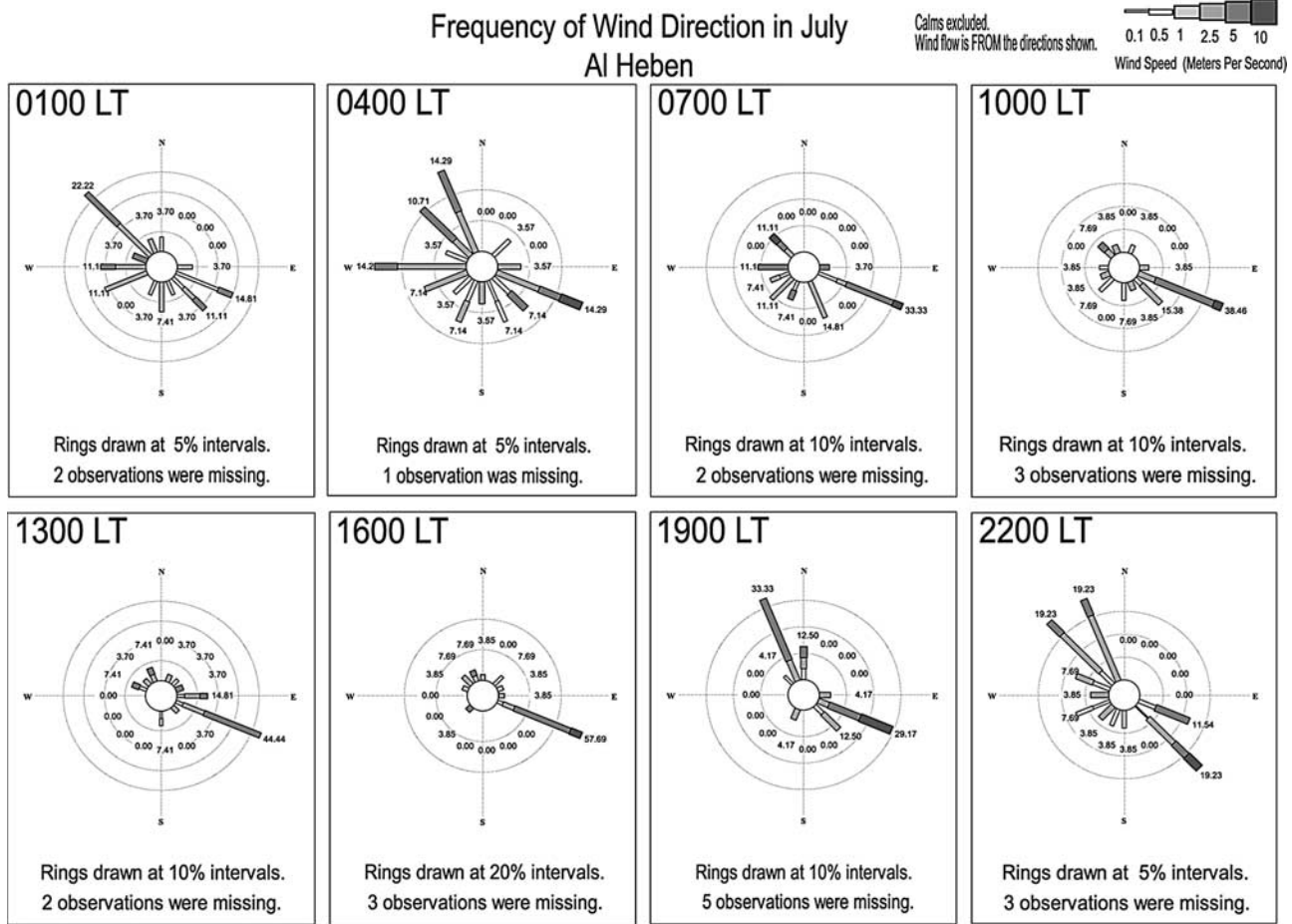


Figure 7. Same as Figure 4, but for Al Heben.

extent is estimated to be less than 80 km. Thus the total width of the sea breeze was at least 195 km. There are no stations between Alqlaa and Owtaid to determine the onshore extent more precisely.

[19] The sea breeze begins on 4 September at 1200 LT and reaches the inland stations by 1700 LT and the furthest island station by 2200 LT. Stronger prevailing winds over the southern Arabian Gulf may have prevented the seaward penetration of the sea breeze until later in the afternoon as compared to the inland penetration. Because no stations are north of Das Island or south of Mukhariz, the horizontal extent of the sea breeze on 4 September can only be determined to be at least 115 km offshore and at least 130 km onshore, for a total width of at least 245 km. The difference in the horizontal extent of the sea breeze between the two days appears to be due to low-level southerly winds over the southeastern Arabian Peninsula on 3 September, inhibiting the southward penetration of the sea breeze front. On both days, a similar trend in sea breeze circulation development is observed. Onshore winds form earliest along the coast or just offshore. Throughout the afternoon the sea breeze circulation increases in horizontal extent and moves further inland and offshore. During the summer of 2004, the total width of the sea breeze varied from about 195 km to 245 km on the days investigated. The onshore extent of the sea breeze ranged from less than 80 km to

more than 130 km, while the offshore extent ranged from 85 km to 115 km.

5.2. Vertical Structure of the Sea Breeze

[20] The variation in the vertical extent of the onshore winds was determined using 51 soundings taken at 1600 LT (1200 UTC) at Abu Dhabi during the months of August, September and October 2004. In five of these soundings, the winds near the surface were offshore, indicating a sea breeze did not form on those days. The remaining 46 soundings showed onshore winds throughout the depth of the boundary layer, sometimes extending above the boundary layer. These soundings have a vertical resolution of about 100 m, which leads to some difficulty in determining the exact vertical extent of the onshore winds and the boundary layer height. The vertical extent of the onshore winds varies daily and ranges between 750 m and 1500 m. Located above the onshore winds is the offshore return branch of the sea breeze.

[21] The virtual potential temperature (θ_v) and wind direction profiles at Abu Dhabi at 1600 LT (1200 UTC) on 4 September 2004 plotted in Figure 9 show both the onshore and return (offshore) flows. Evidence of a thermal internal boundary layer (TIBL) can be seen in the lowest 30 m of the θ_v sounding. The onshore winds at this location cause a modification of the near-surface air temperature. Onshore winds occur from the surface to a height of about

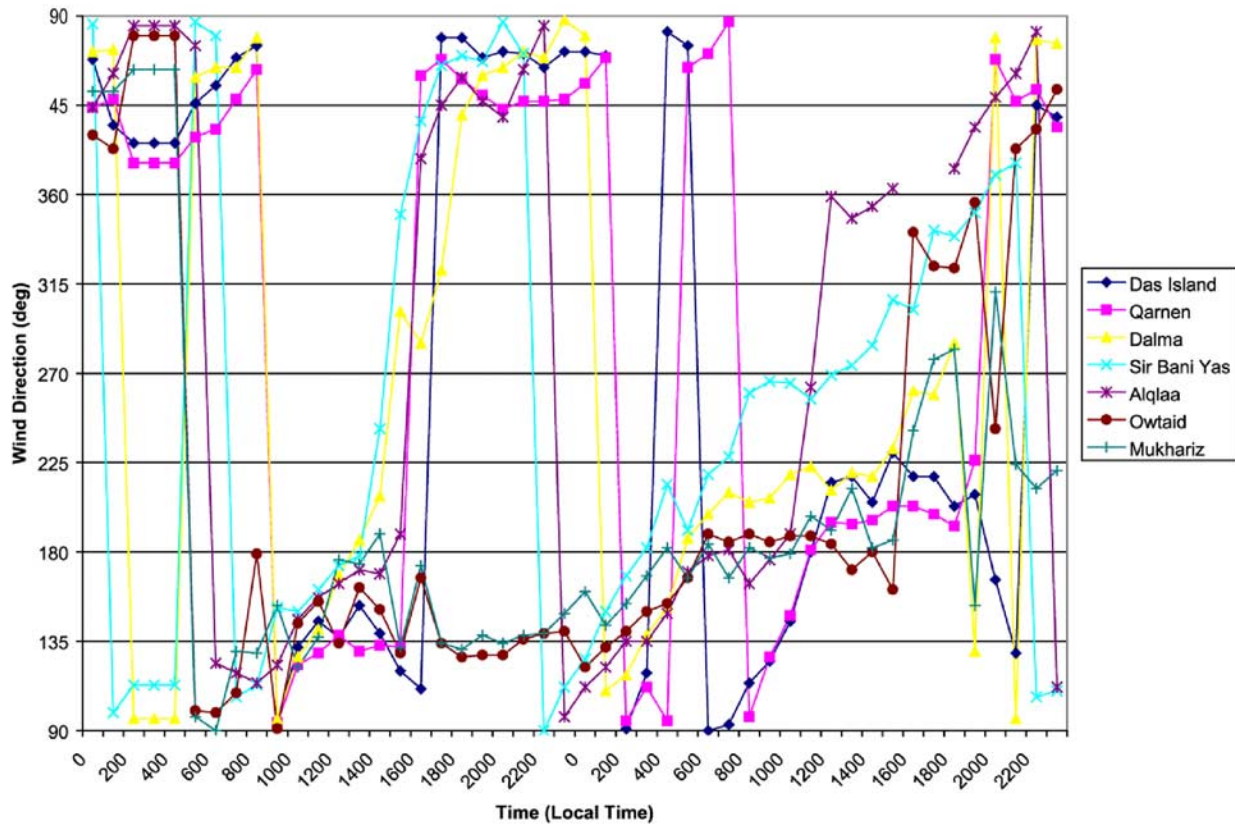


Figure 8. Wind direction beginning at midnight local time 3 September 2004 through midnight local time 5 September 2004 at Das Island, Qarnen, Dalma, Sir Bani Yas, Alqlaa, Owtaid, and Mukhariz. Time is in local time (UTC + 4 h).

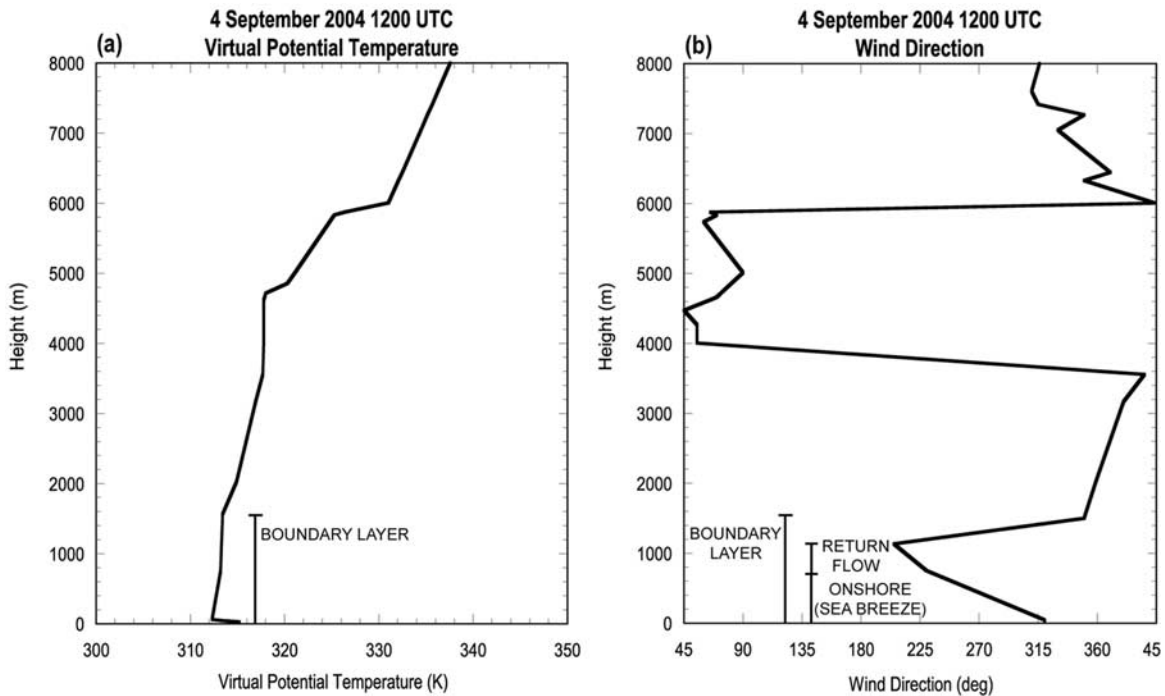


Figure 9. (a) Virtual potential temperature and (b) wind direction profiles at 1600 LT (1200 UTC) on 4 September 2004 at Abu Dhabi. The height of the boundary layer, the height of the onshore sea breeze flow, and the location of the return flow is indicated.

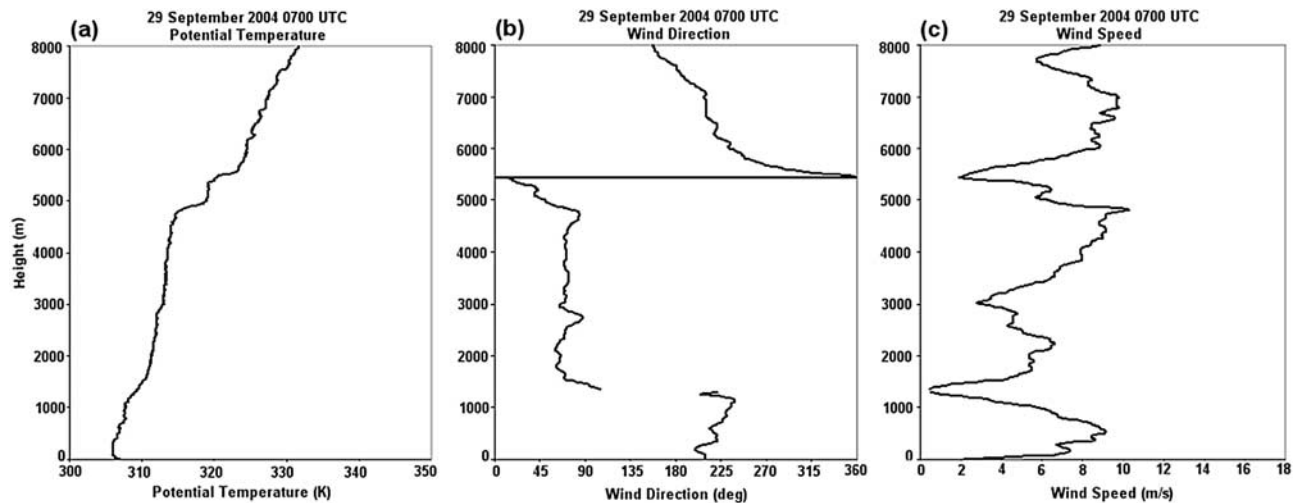


Figure 10. (a) Potential temperature, (b) wind direction, and (c) wind speed profiles at MAARCO for 29 September 2004 at 1100 LT (0700 UTC).

750 m, with the return flow above extending to around 1100 m. This gives the sea breeze circulation a height of 1100 m. Air within the TIBL (surface to 30 m) is unstable, while it is stable in the onshore layer above the TIBL from 30 m to 500 m, representative of the conditions over water. However, the air in the return-flow layer above 500 m is well-mixed, representing conditions over land. Higher values of water vapor mixing ratio are located up to 500 m, due to the advection of maritime air by the sea breeze. Above the boundary layer, mixing ratio values decrease by a factor of two (not shown).

[22] During the UAE² experiment, additional soundings were taken between 11 September and 1 October 2004 at the MAARCO site (24.70°N, 54.66°E), located to the northeast of Abu Dhabi near Alsamha (Figure 1). Onshore winds at this location are from the southwest through the northeast. These soundings have a much finer vertical resolution, with measurements available every 2–5 m. The MAARCO data indicates that the sea breeze typically

formed between 1100 LT and 1300 LT at this site. Potential temperature, wind direction, and wind speed profiles on 29 September at 1100 LT (0700 UTC), 1300 LT (0900 UTC), and 1500 LT (1100 UTC) are shown in Figures 10, 11, and 12, respectively. At 1100 LT, winds in the lowest 1 km are south-southwesterly offshore winds with speeds of 2 m s^{-1} near the surface increasing to 8.6 m s^{-1} at a height of 360 m (Figure 10). The developing daytime convective boundary layer can be seen in the lowest 100 m. Above 1 km, the winds were east-northeasterly to an altitude of 5 km. By 1300 LT the winds backed to southeasterly to be parallel to the coast or slightly onshore in the lowest 430 m with wind speeds of 7 m s^{-1} (Figure 11). The winds were offshore above this layer to a height of 554 m. At 1500 LT onshore winds extended to a height of 655 m (Figure 12). The wind speed near the surface was 6 m s^{-1} . By 1600 LT (not shown) a well-mixed layer had formed in the lowest 200 m and onshore winds extended to 614 m, with wind speeds of about 5 m s^{-1} . The 1600 LT wind direction

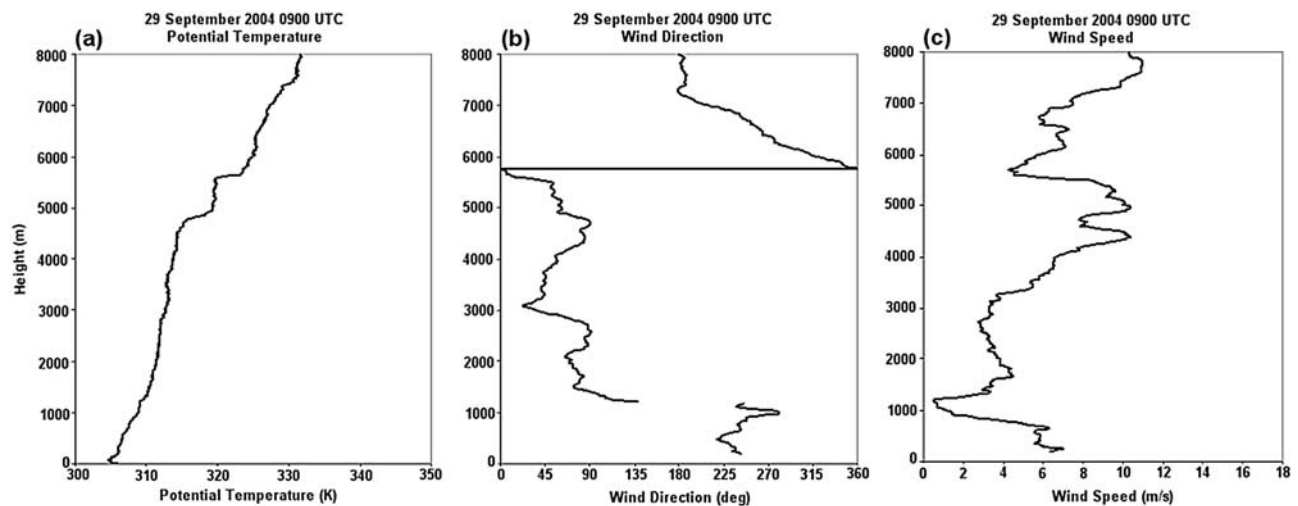


Figure 11. (a) Potential temperature, (b) wind direction, and (c) wind speed profiles at MAARCO for 29 September 2004 at 1300 LT (0900 UTC).

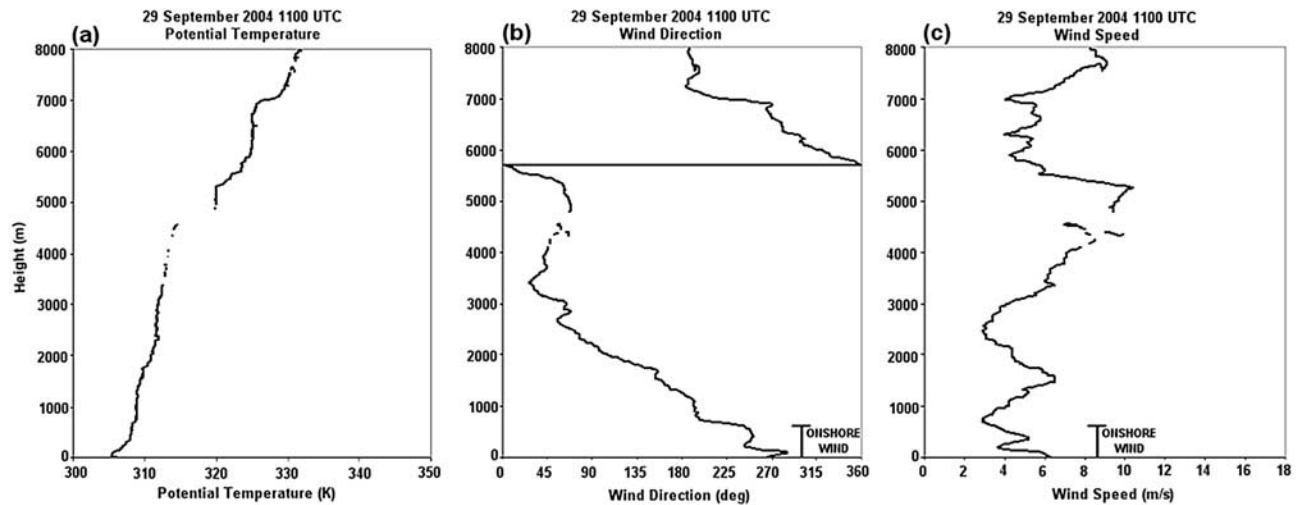


Figure 12. (a) Potential temperature, (b) wind direction, and (c) wind speed profiles at MAARCO for 29 September 2004 at 1500 LT (1100 UTC) with the vertical extent of the onshore winds marked on the wind profiles.

profile at Abu Dhabi (not shown) also indicated onshore winds to an altitude of 776 m. The soundings at MAARCO show that the sea breeze has an onset time at this location similar to that at Abu Dhabi and Alqlaa, which is around 1400 LT.

6. Summary

[23] This paper provides an overview of the sea and land breeze climatology of the UAE region. Both surface and upper-air observations were utilized to characterize the wind patterns over the region. The regional sea and land breeze circulations are imbedded within the northwesterly winds of the southwest Indian monsoon flow. It was shown by *Arriitt* [1993] that thermally forced flows are greatly suppressed by onshore flows greater than 3 m s^{-1} . During the monsoon season, the prevailing winds are near that threshold during sea breeze development. The sea breeze circulation is an important characteristic feature of the regional climate as sea and land breezes occur in all months of the year, most frequently during the summer months. This being a location in a tropical area, the difference between the sea surface temperature and land temperature does not vary much throughout the year, allowing for the sea breeze to occur in all months. The synoptic forcing is also very weak throughout the year. The late onset time of the sea breeze previously noted was a surprising find, as most other sea breeze studies indicate a much earlier onset time. Monthly average spatial distributions during the summer months, in addition to hourly variations for several days were investigated, and both the results indicate a late onset at the southern Arabian Gulf coast, between 1300 LT and 1400 LT. The late onset time could be due to strong downslope offshore winds remaining from the previous night acting against the sea breeze. Once the sea breeze sets in it continues until sunset, at which time prevailing onshore synoptic winds continue through about 2200 LT when the onshore flow ceases at inland stations. Southerly land breeze winds form overnight once the desert cools and continue until the sea breeze develops on the following day. Our modeling study [*Eager*,

2005] also indicates formation of the sea breeze circulations along the northern side of the Arabian Gulf.

[24] The horizontal and vertical extent of the sea breeze circulation was examined using surface data and radiosonde profiles. Along the southern Arabian Gulf coast, the sea breeze forms first near the coast and expands inland and offshore, reaching its maximum width late in the afternoon. The data from the DWRS stations showed the total horizontal extent of the sea breeze inland and offshore varied from about 195 km to 245 km on the days investigated. These values are somewhat similar to the onshore extent of 300 km and offshore extent of 80 km found by *Zhu and Atkinson* [2004]. *Drobinski et al.* [2006] found onshore sea breeze extents of 50 to 150 km over southern France; however, the relatively flat topography of most of the UAE and the large scale background onshore winds may allow for further inland penetration of the sea breeze. The vertical extent of the sea breeze as determined by daily radiosonde profiles at Abu Dhabi, and select days and times at the MAARCO site varied between 750 m and 1500 m with return offshore flow evident above the onshore flow near the surface. These vertical extents are very similar to values of 700 m to 1500 m found by *Drobinski et al.* [2006].

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- A. Al Mandoos, Department of Atmospheric Studies, Ministry of Presidential Affairs, Abu Dhabi, United Arab Emirates.
- R. E. Eager, Applied Physics Laboratory, The Johns Hopkins University, 11100 Johns Hopkins Road, Laurel, MD 20723, USA. (rebecca.eager@jhuapl.edu)
- S. Raman and A. Wooten, Department of Marine, Earth, and Atmospheric Sciences, 2800 Faucett Drive, Jordan Hall, North Carolina State University, Raleigh, NC 27695–8208, USA.
- J. S. Reid and D. L. Westphal, Marine Meteorology Division, Naval Research Laboratory, 7 Grace Hopper Ave., Stop 2, Monterey, CA 93943, USA.