METEOROLOGY AND AIR QUALITY OF THE PILBARA REGION

William L. Physick

CSIRO

CSIRO Atmospheric Research
PMB1 Aspendale, Vic 3195 Australia
Phone: (03) 9239 4636
Fax: (03) 9239 4688
Email: bill.physick@dar.csiro.au

May 2001

This Report is a public version (slightly modified) of the previously-issued restricted-access Report ‘A Preliminary Analysis of Pilbara Region Meteorology and Air Quality’.

Table of Contents

1. Introduction

An abundant supply of offshore gas from the North-west Shelf region of Western Australia (WA) has been the catalyst for industrial development on the Burrup Peninsula near the towns of Dampier and Karratha (Figure 1.1). This area is about 220 km west of another industrial town Port Hedland, a processing and shipping centre for ore from the Hamersley Range. Although the Burrup Peninsula development is not large at present, it is likely to grow steadily. Applications for new or expanded industries in the region must undergo assessment by the Environmental Protection Authority, which includes an evaluation of the impact of the industry on the air quality of the region. As input to an air quality management plan for the Pilbara, and to enable a greater understanding of the fate of emissions in this region, where the meteorology at scales important for dispersion is virtually unknown, the WA Dept. of Environmental Protection have initiated two Studies; (1) to analyse the existing meteorological and air quality data in the region, and (2) to evaluate the ability of various dispersion models to simulate the air quality of the region. The two Studies are linked as the important dispersion processes identified in the first Study will aid in understanding the model performances in the second. This Report presents the results of the data analysis Study, which was completed in 1999 and presented in the form of a preliminary report at that time.

A previous study into sea breezes along the Pilbara coast by Tapp (1996) presents monthly statistics of surface wind behaviour at five stations between Dampier and Port Hedland. Surface winds at these stations for a number of case studies are also presented. Some upper-air wind data are also analysed. While our results naturally are consistent with those of Tapp (1996), our Study also examines the implications of our findings for pollutant dispersion and uses modelling to expand the analysis to areas where there are no data. In addition, we examine temperature and moisture profiles from radiosonde flights, and also analyse data from two air quality monitors.

The aims of the Study, as set out in the original proposal, are to

- document and obtain an understanding of the year-round meteorology in the coastal area extending from the Burrup Peninsula to Port Hedland. Particular attention will be paid to those mesoscale characteristics of the meteorology that are important for the dispersion of emissions from local industry,
- summarise the air quality data from the monitors at Dampier and Boodarie, and to relate any elevated levels to the prevailing meteorology,
- assess the adequacy of the current meteorological and air quality network,
- select days that can be used as worst-case scenarios for the evaluation of models, and for modelling the impact of modified or additional sources in the region,
- discuss which models are suitable for impact assessments in the region, and whether there are restrictions on the conditions under which they may be valid.

The data sets are described in Section 2, with analysis results in Section 3. Further insight into the meteorology of the region is presented in Section 4 where some modelling simulations are discussed. Results of an analysis of the air quality data are found in Section 5, with a summary of overall findings in Section 6.

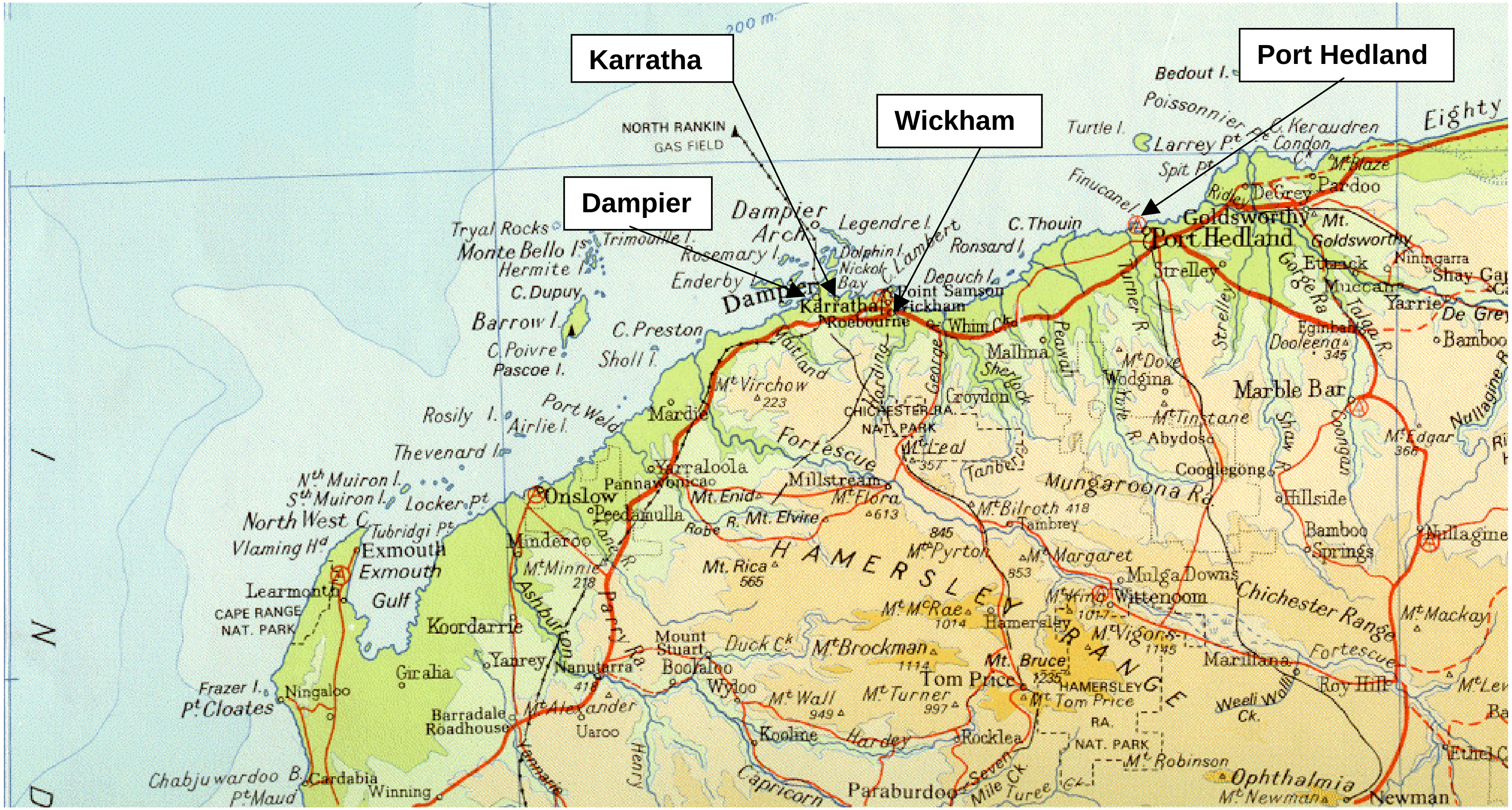


Figure 1.1: The Pilbara region of north-western Australia. In this Report, meteorological data are analysed from a site at Wickham.

2. Data

Data from all months of 1998 and January 1999 have been analysed. Some Bureau of Meteorology stations measured data prior to 1998, but these have not been used in this Study. Surface and upper-air meteorological data and air quality data were analysed from sites near Karratha (Figure 2.1) and Port Hedland (Figure 2.2). The Wickham site is shown in Figure 1.1. At some sites, measurements did not begin until later in 1998. These sites are indicated in Table 2.1, which summarises the number of days per month for which data were available.

Figure 2.1: The Burrup Peninsula region, including the data sites Legendre Island, Dampier, Karratha and Maitland.

2.1 Surface meteorological data

Legendre Island (Bureau of Meteorology station)
At a height of 10 m, 10-minute averages of wind speed and direction.
At a height of 2 m, 10-minute averages of temperature, dewpoint, and relative humidity
Surface pressure (10-minute averages).

Karratha (Department of Environmental Protection station)
At a height of 10 m, 10-minute averages of wind speed and direction, standard deviation of wind direction, temperature, and relative humidity.
At a height of 2 m, 10-minute averages of temperature.
Surface pressure and shortwave radiation (10-minute averages), and rainfall (total over 10 minutes).

Dampier (Department of Environmental Protection station)
At a height of 10 m, 10-minute averages of wind speed and direction, standard deviation of wind direction, temperature, and relative humidity.
Surface pressure and shortwave radiation (10-minute averages), and rainfall (total over 10 minutes).

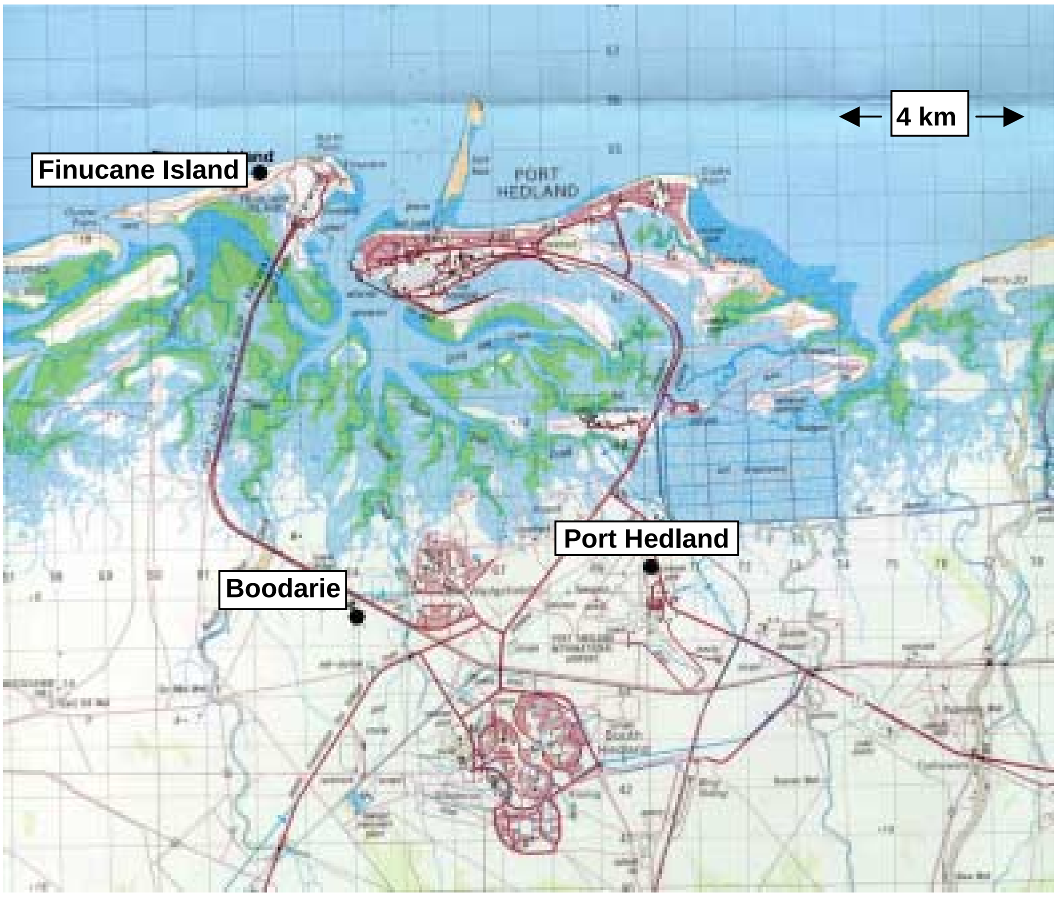


Figure 2.2: The Port Hedland region, including the data sites Finucane Island, Boodarie and Port Hedland.

Maitland (Woodward-Clyde station)
At a height of 10 m, 10-minute averages of wind speed and direction, standard deviation of wind direction, temperature, and relative humidity.

Wickham (Department of Environmental Protection station)
At a height of 10 m, 10-minute averages of wind speed and direction, standard deviation of wind direction, temperature, and relative humidity.

Boodarie (BHP station)
At a height of 30 m, 10-minute averages of wind speed and direction, and standard deviation of wind direction.
At a height of 10 m, 10-minute averages of wind speed and direction, standard deviation of wind direction, temperature, and relative humidity.
Surface pressure and shortwave radiation (10-minute averages), and rainfall (total over 10 minutes).

Port Hedland (Bureau of Meteorology station)
At a height of 10 m, 30-minute averages of wind speed and direction.
At a height of 2 m, 30-minute averages of temperature, and dew point.
Surface pressure (30-minute averages), and rainfall (total over 30 minutes).

2.2 Upper-air meteorological data

Karratha (Department of Environmental Protection station)
30-minute averages of wind speed and direction at height intervals of 25 m, from 50 m to 775 m above the ground from a Sodar instrument.

Dampier (Department of Environmental Protection station)
Radiosonde data (wind speed and direction, temperature, dewpoint, relative humidity and pressure at approximately 11-m intervals) from early-afternoon flights on nine occasions during November, December 1998 and January 1999.

Port Hedland (Department of Environmental Protection station)
Plots of radiosonde data (wind speed and direction, temperature, dewpoint, relative humidity and pressure at approximately 11 m intervals) from mid-afternoon flights on six occasions from Finucane Island (Port Hedland) in September and October 1996.

Port Hedland (Bureau of Meteorology, airport station)
Radiosonde data (wind speed and direction, temperature, dewpoint, relative humidity and pressure at approximately 11 m intervals) from 0700 WST and 1900 WST flights during January 1999.

2.3 Surface air quality data

Dampier (Department of Environmental Protection station)
10-minute averages of ozone, nitric oxide, nitrogen dioxide, carbon monoxide, and particulate matter with diameter less than 10 μm (PM10).
Hourly averages of PM10.

Boodarie (BHP station)
10-minute averages of ozone, nitric oxide, nitrogen dioxide, nitrogen oxides, sulphur dioxide, hydrogen sulphide, PM10, and particulate matter with diameter less than 2.5 μm (PM2.5).

2.4 Processing of data

Much of the analysis presented in this Report uses 'hourly-averaged' values. For meteorological data, this means the averaged value corresponding to the integer hour in the original data file. For example, the 0500 WST value used is an average over 0450 to 0500 WST for a 10-minute averaged file, or from 0430 to 0500 WST for a 30-minute averaged file. For the air quality data, hourly-averaged values have been calculated by averaging the six ten-minute values prior to the hour. At Dampier, the measured hourly-averaged data for PM10 was used.

Table 2.1: The number of days per month for which data were available at the various sites.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Jan-99*
Boodarie	31	28	31	30	28	30	31	31	30	31	30	31	31
Dampier	0	0	0	0	31	30	31	31	30	31	30	31	31
Dampier sondes	0	0	0	0	0	0	0	0	0	0	2	1	6
Karratha	0	6	31	30	31	30	31	31	30	31	30	31	31
Karratha sodar	0	18	31	27	0	10	26	31	19	31	30	26	31
Legendre Island	31	28	31	30	31	0	0	9	27	20	19	26	27
Maitland	0	0	0	0	0	0	0	0	11	29	29	31	31
Port Hedland	31	24	30	28	31	30	31	30	29	31	30	28	31
Port Hedland Sondes	0	0	0	0	0	0	0	0	0	0	0	0	31
Wickham	0	0	0	0	0	0	0	0	0	0	6	21	26

3 Analysis of meteorological data

3.1 Winds at 10 m

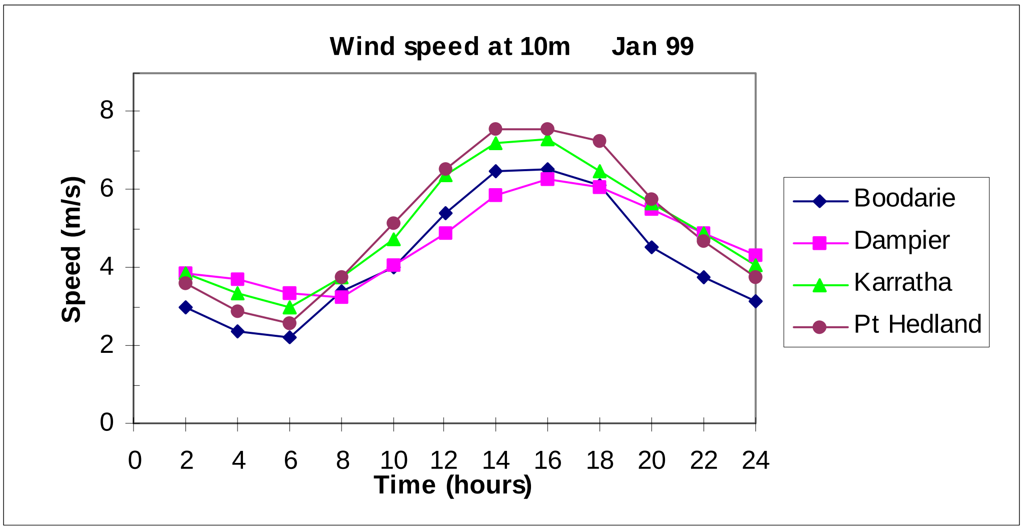
For each site, monthly averages of wind speed and direction at 2-hourly intervals have been calculated for the period February 1998 through to January 1999. This is an efficient way to examine the seasonal behaviour of the surface winds in the region and also the variability between sites. Figures A.1 and A.2 in Appendix A show the diurnal variation of the monthly averages for two stations (Port Hedland and Boodarie) in the Port Hedland region. The corresponding data for four stations in the Burrup Peninsula area, 220 km to the west along the coastline, are shown in Figures A.3-6 (Karratha, Legendre Island, Dampier and Maitland). Data from Wickham, about 50 km east of Burrup Peninsula, are shown in Figure A.7.

While examination of these plots shows a strong seasonal variation of the monthly-averaged winds at each site, there is little difference in the winds from site to site for any given month. This is especially so for wind direction. This can be seen more clearly in Figures 3.1a-d where monthly-averaged speed and direction from four of the stations are displayed on the one plot for each of January, May, July and September. Small systematic differences in wind speed (e.g. Port Hedland usually registers higher and Dampier lower than the majority of sites) are most likely due to local site characteristics. At all sites except Legendre Island, winds decrease at night to about half their daytime maximum, which is invariably in the afternoon and associated with a sea breeze. At Legendre Island, where there is little diurnal variation in speed and presumably atmospheric stability, the wind behaviour is more characteristic of winds over the sea than over land. As found by Tapp (1996), strongest winds occur in spring and early summer, with weaker winds in autumn and winter. Our analysis is also consistent with Tapp's conclusion that sea breezes occur on 50% of days in winter and on 80% in summer, where a sea breeze is defined by Tapp as an onshore wind.

The diurnal variation in the monthly-mean direction is most interesting, and is observed at all sites including Legendre Island, which has been shown to behave differently than the others as far as wind speed is concerned. In the warmer months, October through to February, the mean direction remains in the two western quadrants over the diurnal period, switching to onshore, and its most northerly direction, by mid- to late morning as the land warms. The direction then slowly backs through west until it is offshore again by midnight.

Similar, but converse, behaviour is observed in May, June and July when the mean direction remains in the two easterly quadrants with a switch to onshore mid-morning, but a switch back to offshore winds by early evening. Also, the most northerly direction is reached in mid-afternoon, in contrast to that in the warmer months. This latter observation is a direct consequence of the Coriolis force continually acting to turn winds in an anti-clockwise direction while the sea-breeze pressure gradient acts normal to the coastline (from north to south in this case).

In the transition months March, April, August and September (and October at two sites), the behaviour of the wind direction can be termed 'around the clock', meaning that it steadily rotates in an anti-clockwise direction with a 24-hour period. At midnight, the wind is typically from a south-southwest direction for each site.



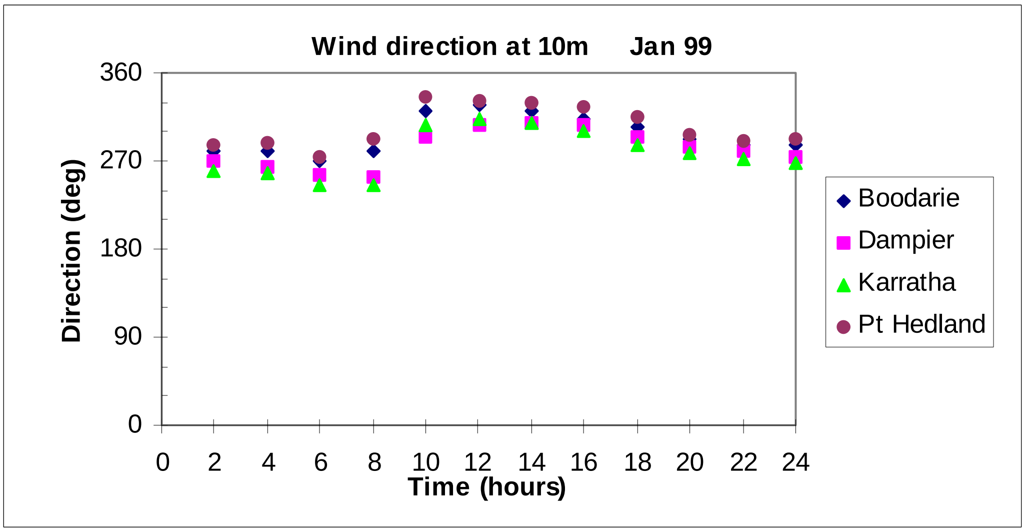
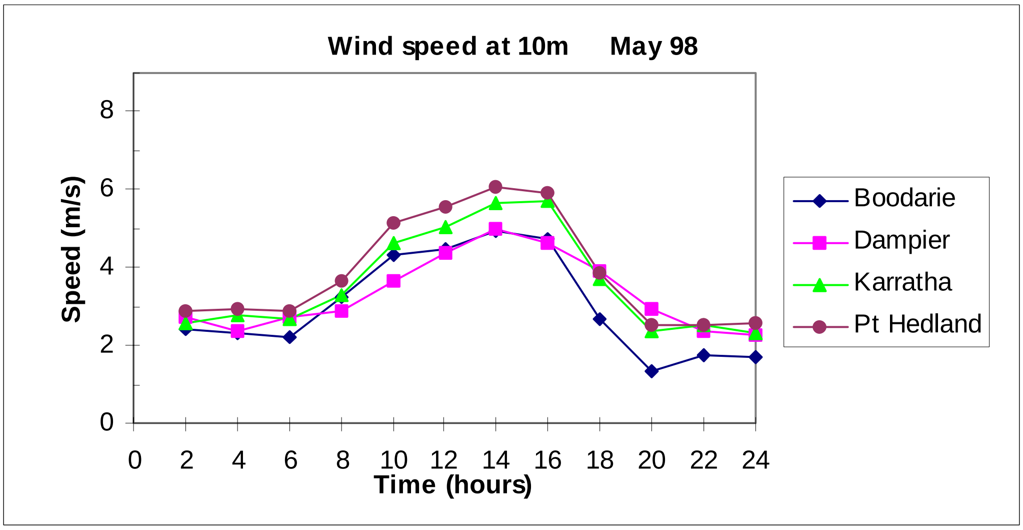


Figure 3.1a: Monthly-mean wind speed and direction at a height of 10 m at four stations for January 1999.



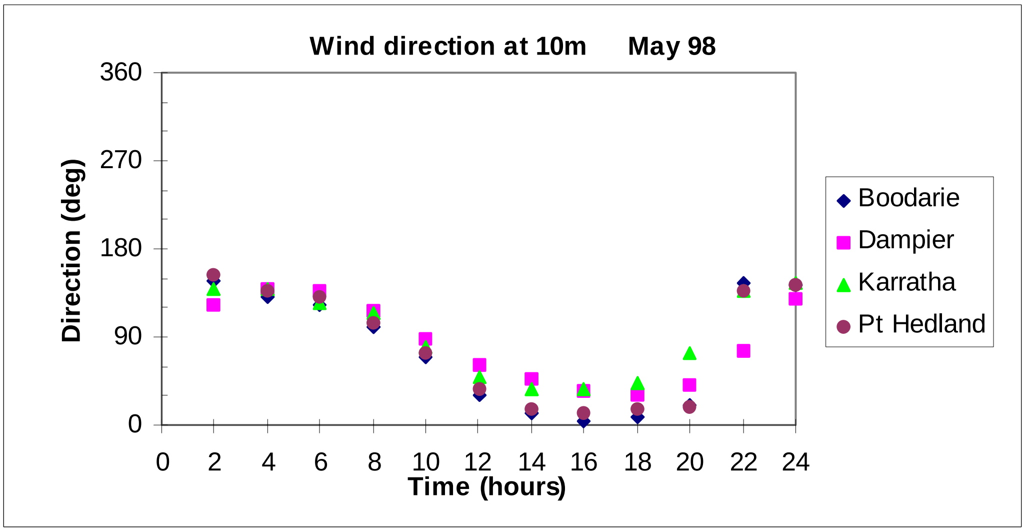
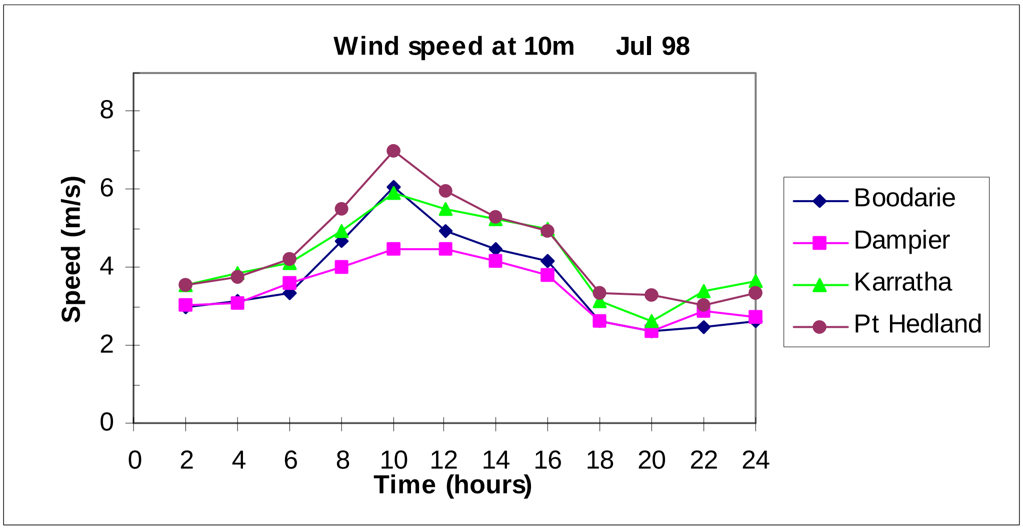


Figure 3.1b: Monthly-mean wind speed and direction at a height of 10 m at four stations for May 1998.



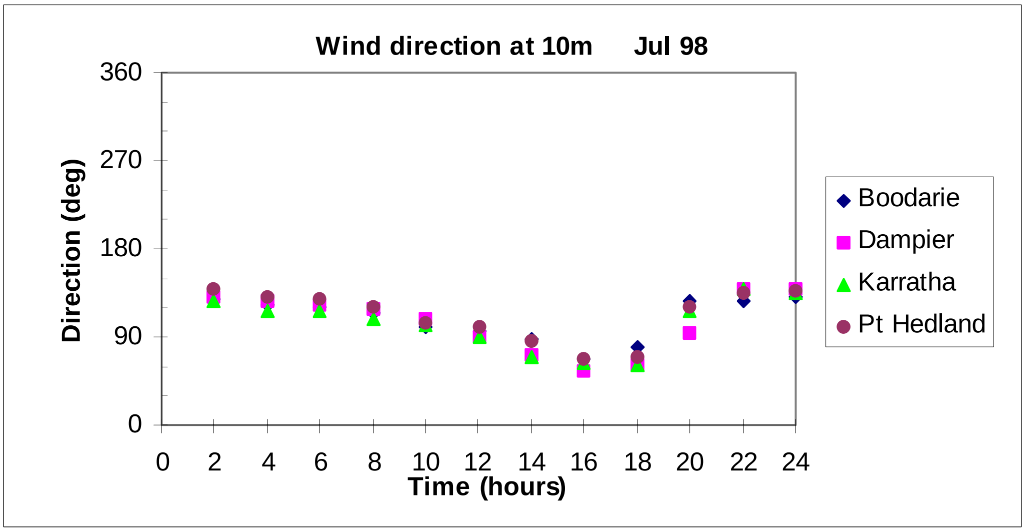
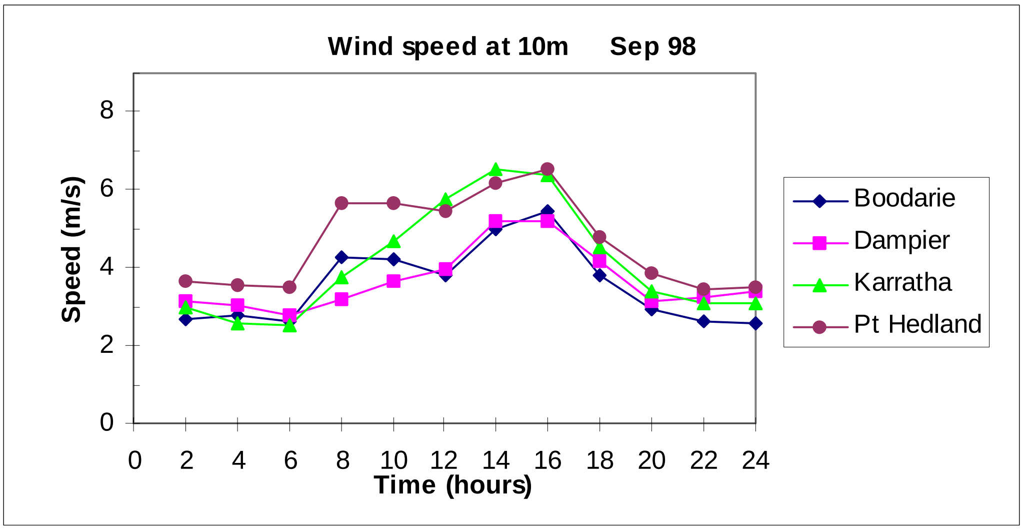


Figure 3.1c: Monthly-mean wind speed and direction at a height of 10 m at four stations for July 1998.



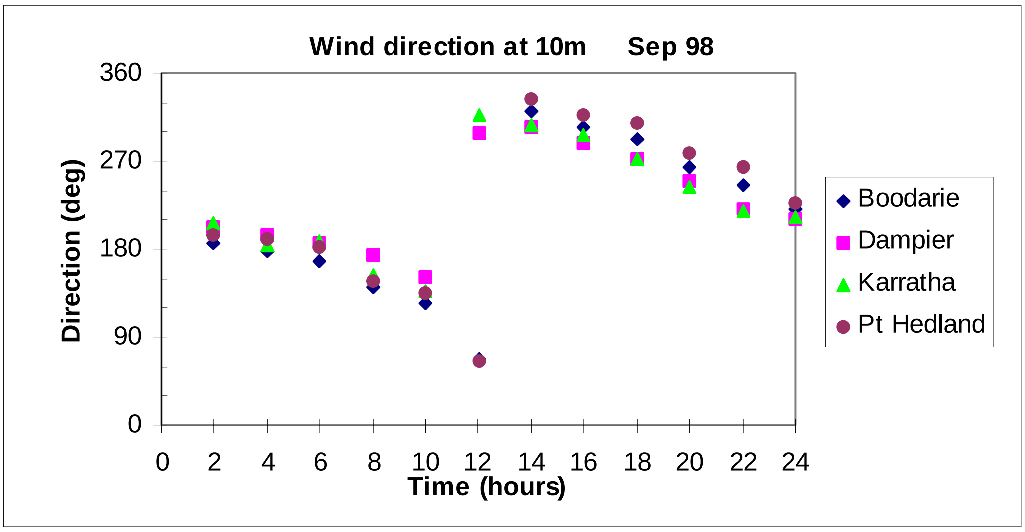


Figure 3.1d: Monthly-mean wind speed and direction at a height of 10 m at four stations for September 1998.

Monthly means usually indicate the most common value (median) found during the month, but this is not always the case and cannot be assumed. Figures 3.2a-d show the surface wind speed and direction at Karratha for each day of January 1999 and April, July and October 1998. Note that the last panel of each plot shows the monthly mean value. For January (Figure 3.2a), the direction on the vast majority of days reflects the mean value, with westerly-component winds occurring all day on twenty three occasions. Interestingly though, there are six days on which ‘around the clock’ behaviour is observed. Similarly in July (Figure 3.2c), there are four occasions when the wind direction rotates anti-clockwise over the 24-hour period, but once again most days reflect the monthly mean. On three days, winds have a westerly component all day.

For April (Figure 3.2b), the winds remained in the westerly quadrants all day on seven occasions and in the eastern quadrants on three days, but on the remainder of the days the wind direction covered all four quadrants in a similar manner to the mean. In October (Figure 3.2d), the winds on the majority of days resembled those in January, i.e. predominantly westerly winds with a deviation to the northwest quadrant during the day (onshore winds) and to the southwest in the early morning hours (offshore winds). However there were eleven days on which ‘around the clock’ behaviour was observed.

Summarising, it has been found that surface winds are invariably onshore from the northwest quadrant during the daytime in the months of September through to April. By midnight, and usually earlier, they have turned to offshore with a southerly component. The wind usually remains in the southwest sector during the night, but can turn to the southeast in the transition months. During May to August, the daytime onshore winds are from the northeast sector and at nighttime from the southeast. However, for all months of the year it was found that there are days, and series of days, on which the wind direction rotates steadily through 360 degrees over 24 hours. These days, which are more frequent in March, April, August and September, may be especially important for the recirculation of pollutants and are investigated further later in this Report.

3.2 Upper-level winds at Karratha.

Winds from the acoustic sounder at Karratha have been analysed for the period February 1998 to January 1999. Figures 3.3a-d show wind speed and direction at heights of 300 m and 700 m above the ground for January, April, July and October. By comparing these to the mean surface winds at Karratha in Figure A.3, it is apparent that the latter do not always reflect what is happening above the ground. In January, April and October, the morning switching of the wind from offshore to onshore occurs a couple of hours later at upper levels than at the surface. In July the direction at 300 m remains constant throughout the day and night, suggesting that the direction perturbation is quite shallow. As will be seen later, there is very little change in direction in July, even at a height of 50 m, though at 700 m, there is a late afternoon switch to the southeast (from east) for a few hours.

The minimum wind speed occurs at quite different times for surface and upper winds. While it is a night-time occurrence at the surface for all months, it occurs in the daytime morning hours in January and October, and in the late afternoon in July. In April, wind at 300 m is fairly constant and at 700 m there is no definite maximum and minimum pattern. The strongest upper-level winds are found in July, whereas winds are strongest at the surface in the late spring/summer months.

Characteristics of the wind behaviour above the ground can also be analysed by examining vertical profiles at different times of the day. Monthly-mean profiles from the acoustic sounder data at 6-hourly intervals are plotted in Figures 3.4a-d for four different months. In July, strong nocturnal jets are evident above the surface, with much weaker winds during the daytime. Wind direction does not change much over the 24-hour period, generally staying around east, and it appears that there is a decoupling of the surface winds from the flow at 50 m and above during the night-time and early morning. In fact in all months there are discontinuities between the speeds and directions at 10 m and 50 m. This may be an artifact of the different observing platforms, or it may be a real effect, and should be examined further. Generally speaking, all months except July show winds increasing in the afternoon with the sea breeze (and continuing to increase into the early evening in January and October) before weakening through the night. In these three months too, the diurnal rotation of the winds, previously found in the analysis of the surface winds, is also evident to the upper limit of the sounder (750 m). There is very little directional shear with height, leading to the conclusion that in the coastal region of the Pilbara on many single and consecutive days of the year there is a mass of air at least 750 m deep rotating with the diurnal period. Although the data analysis cannot shed light on the depth or the inland extent of this phenomenon, results from some modelling experiments, which allow a further insight, are presented in Section 4.

3.3 Analysis of Port Hedland and Dampier radiosonde data

Temperature, relative humidity, and wind data were available from radiosonde flights at Port Hedland at 0700 and 1900 WST on 25 days in January 1999. Monthly-mean profiles for the two flight times were calculated, but comparison of these with individual flights showed that the temperature and relative humidity means were not representative of any days. These will be discussed later. However, the mean wind speed and direction profiles, shown in Figure 3.5, were typical of many days. At 0700 WST, surface winds in the southwest quadrant slowly backed with height through south (by 1400 m) to reach east-southeast at a height of 2000 m. There were also flights for which the wind turned through north (between 700 and 1000 m) instead of south, but still became easterly or east-southeasterly by 2000 m. On some days the low-level winds at 0700 WST were in the northwest quadrant (eight occasions compared to fifteen in the southwest quadrant and two in the northeast). There is more variability from day to day in the speed profiles at 0700 WST than in the direction profiles, but the shape of the mean profile is quite representative, with a jet in the lowest 500 m decreasing to a minimum between 1500 and 2000 m before increasing again to stronger speeds aloft.

The signature of the sea breeze, a daily occurrence in January 1999, is clearly evident in the 1900 WST mean profiles. From the direction profiles in Figure 3.5, it can be concluded that the sea-breeze circulation is about 2000 m deep in January. The speed maximum at a height between 200 and 400 m and the minimum between 1200 and 1400 m are evident on virtually every day. Sometimes the maximum speed is as high as 11 m s^{-1} and on such occasions the minimum is as low as 2 m s^{-1}. The mean wind direction up to about 800 m is west-northwest, above which the wind backs through south until it reaches southeast by about 1400 m. Inspection of individual flights shows that on the vast majority of days the wind actually turns through north with height rather than south. The turning through south in the mean profile is a result of averaging over many days on which the turning from the west-northwest direction begins at different heights.

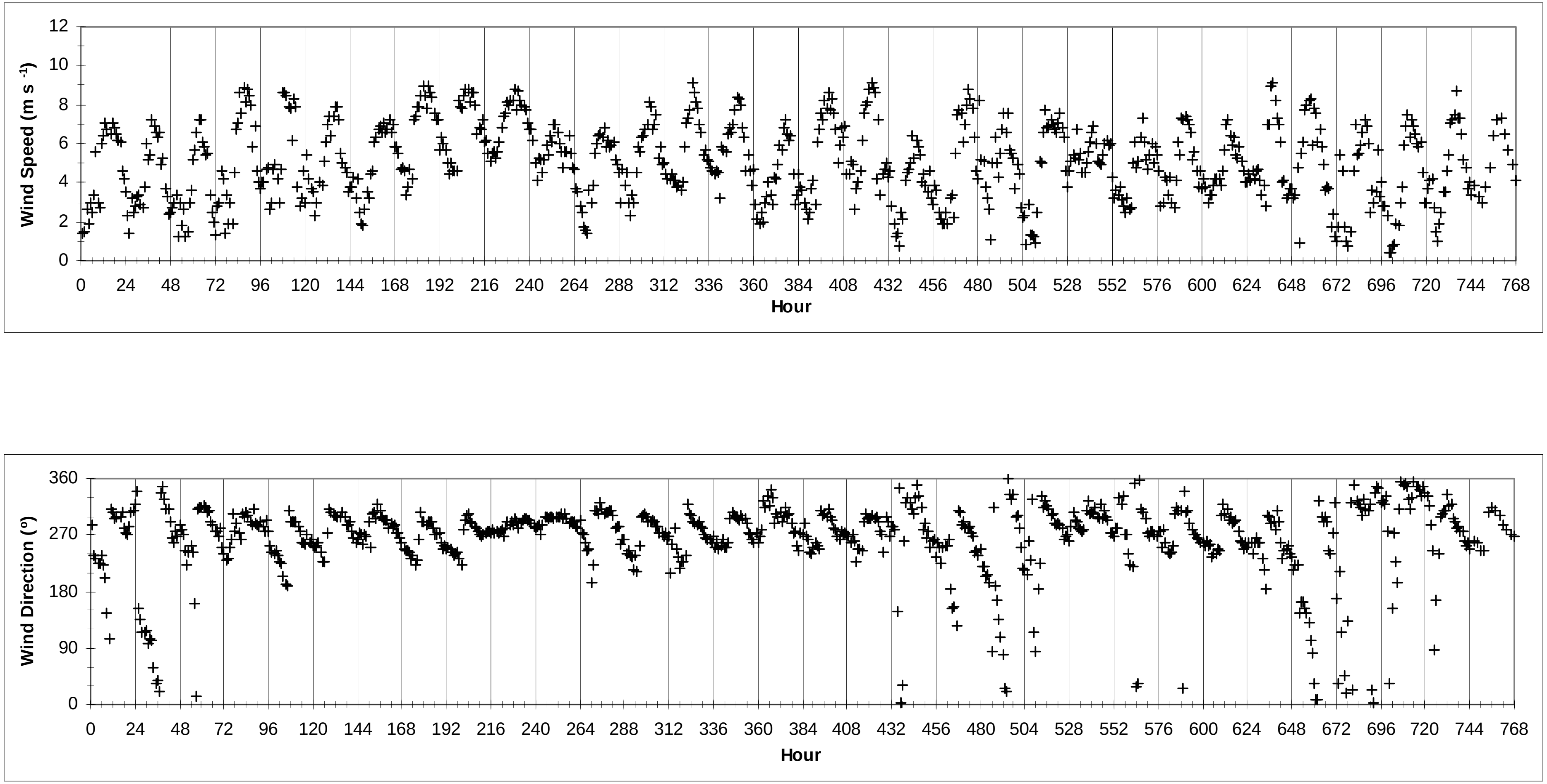


Figure 3.2a: Wind speed (m s^{-1}) and direction (degrees) at Karratha for 1-31 January 1999 at 10 m above the ground. The final panel (744-768 hours) on each plot shows the mean values for the month.

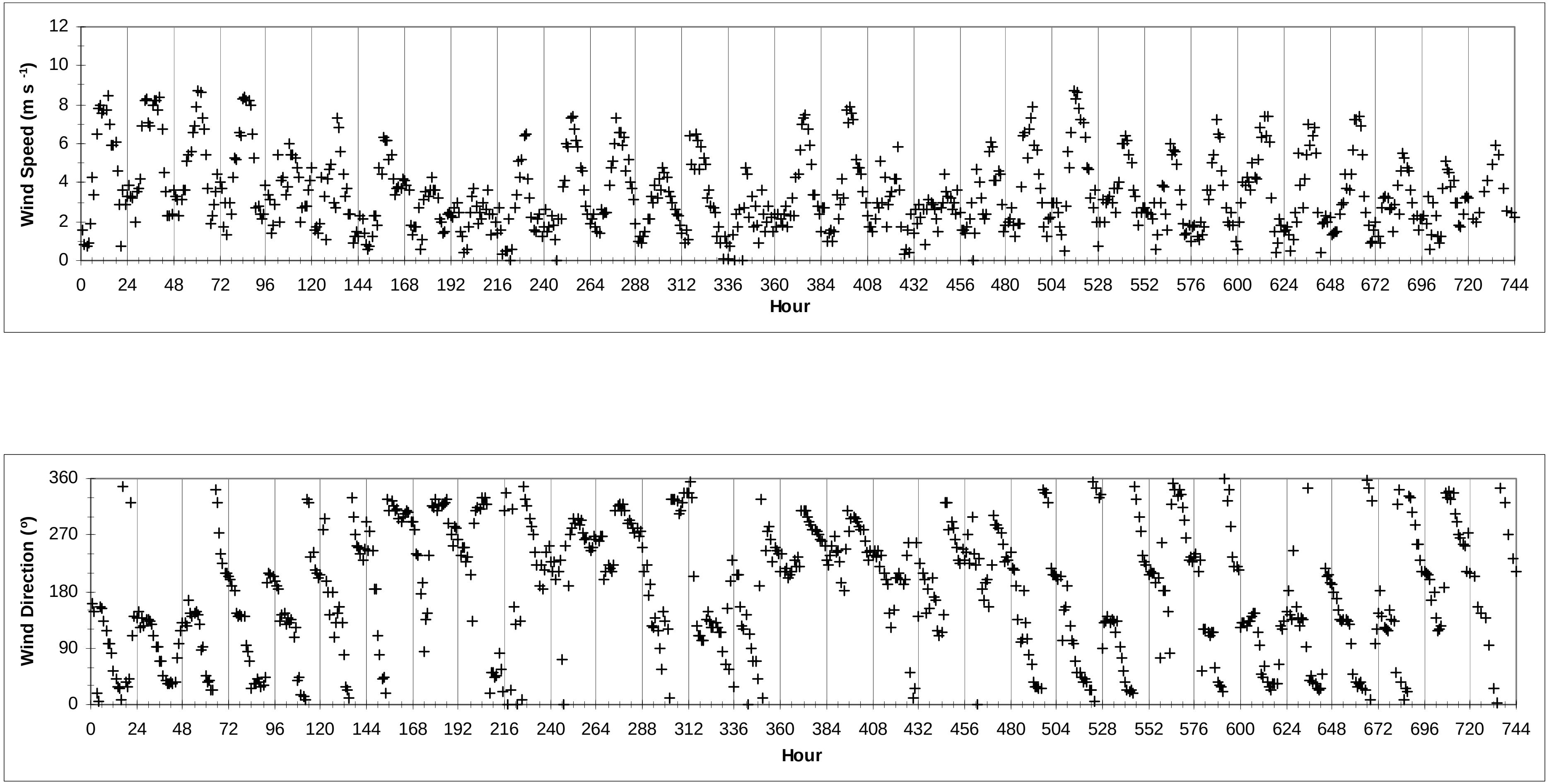
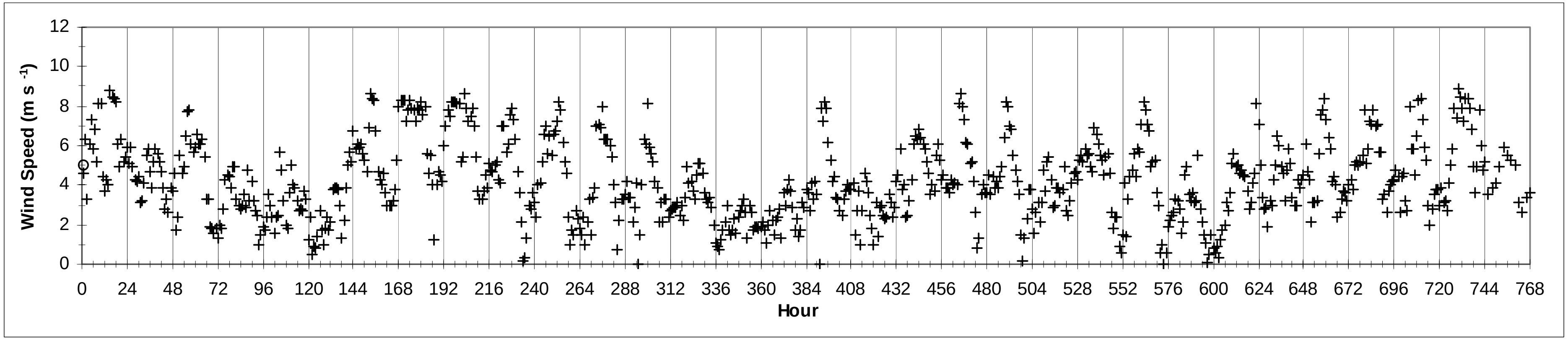


Figure 3.2b: Wind speed (m s^{-1}) and direction (degrees) at Karratha for 1-30 April 1998 at 10 m above the ground. The final panel (720-744 hours) on each plot shows the mean values for the month.



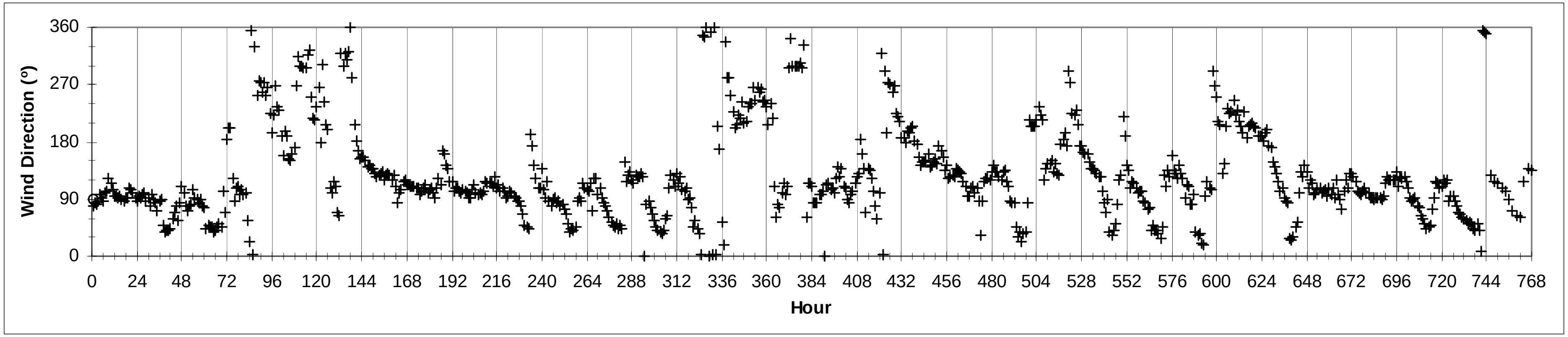
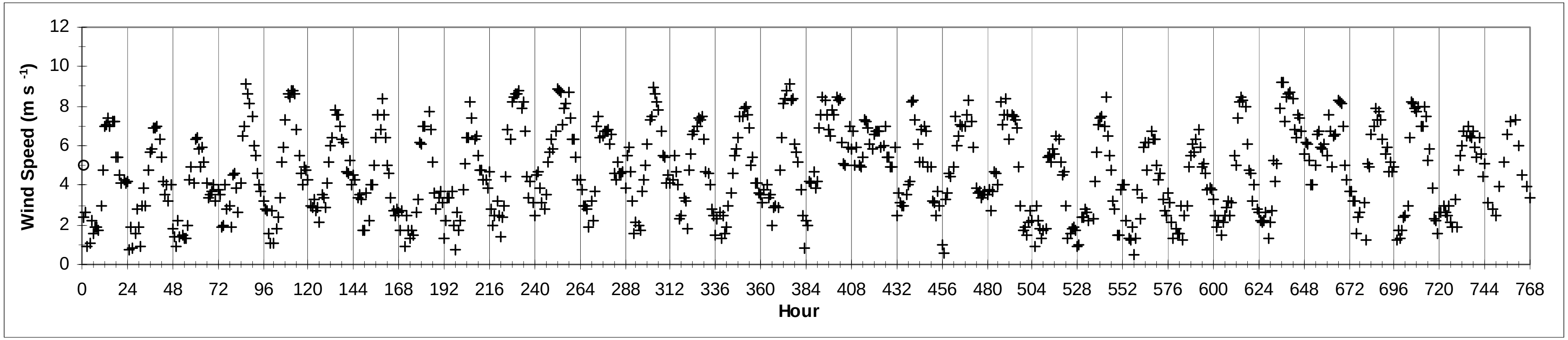


Figure 3.2c: Wind speed (m s^{-1}) and direction (degrees) at Karratha for 1-31 July 1998 at 10 m above the ground. The final panel (744-768 hours) on each plot shows the mean values for the month.



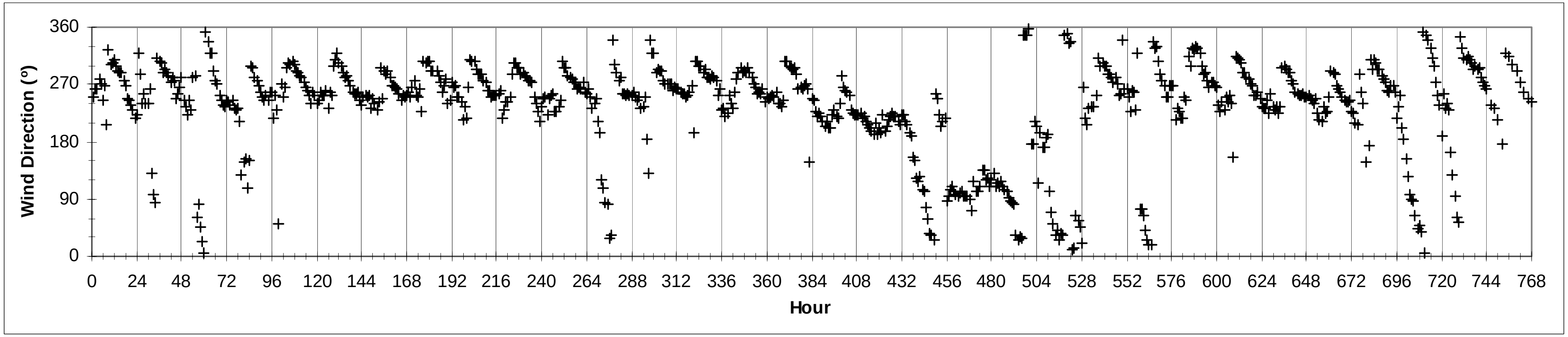
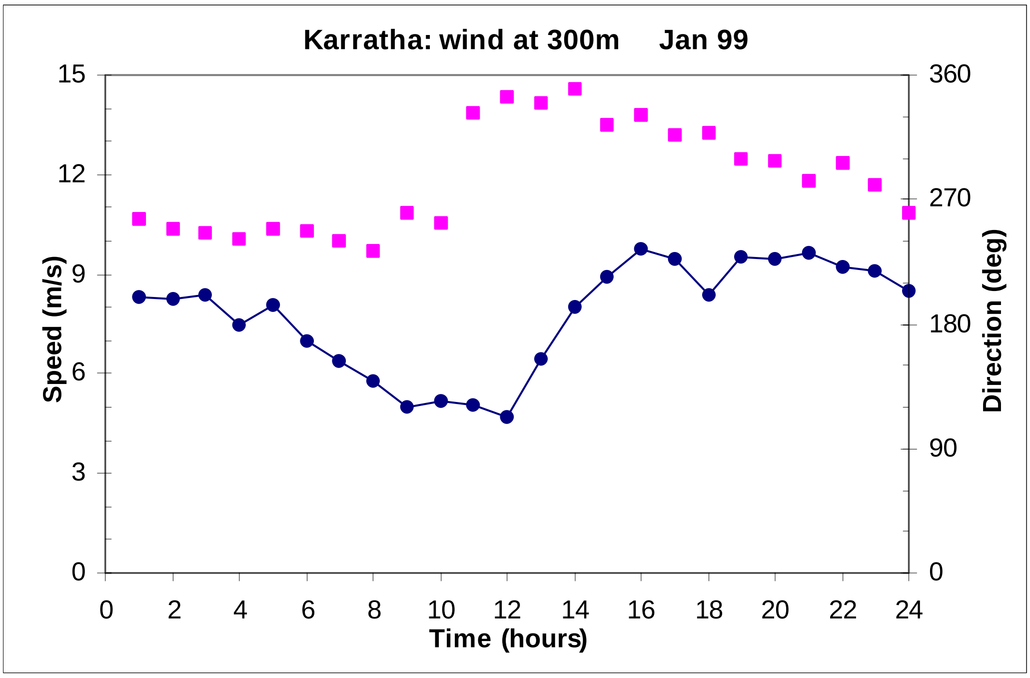


Figure 3.2d: Wind speed (m s^{-1}) and direction (degrees) at Karratha for 1-31 October 1998 at 10 m above the ground. The final panel (744-768 hours) on each plot shows the mean values for the month.



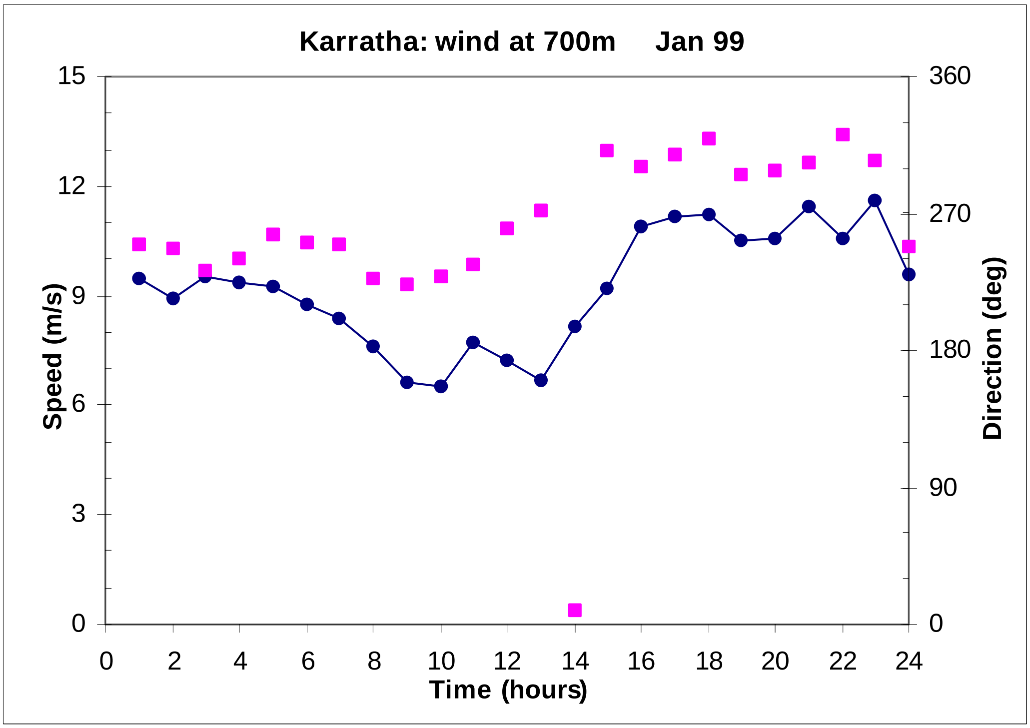


Figure 3.3a: Monthly-mean wind speed (●) and direction (■) at heights of 300 m and 700 m above the ground for January 1999.

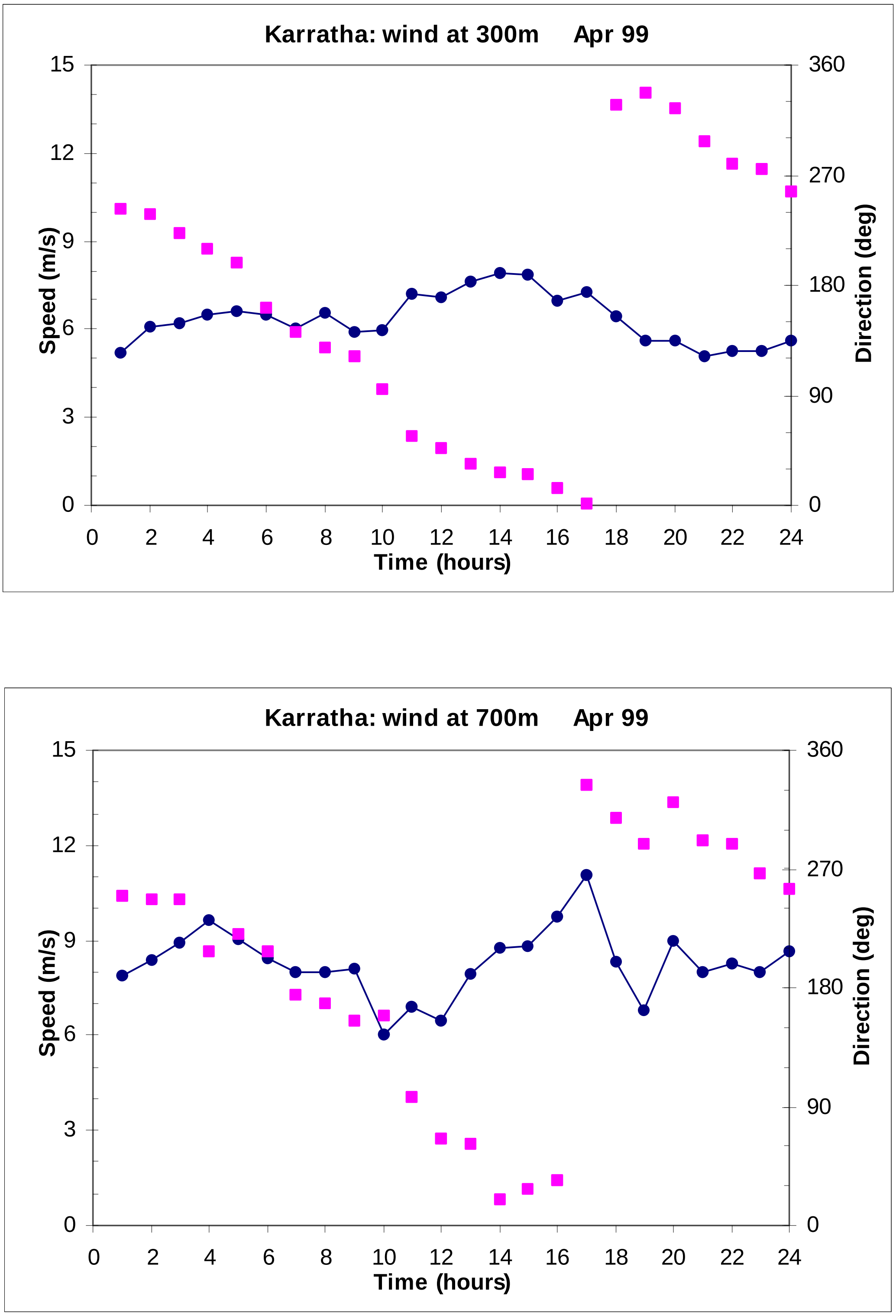
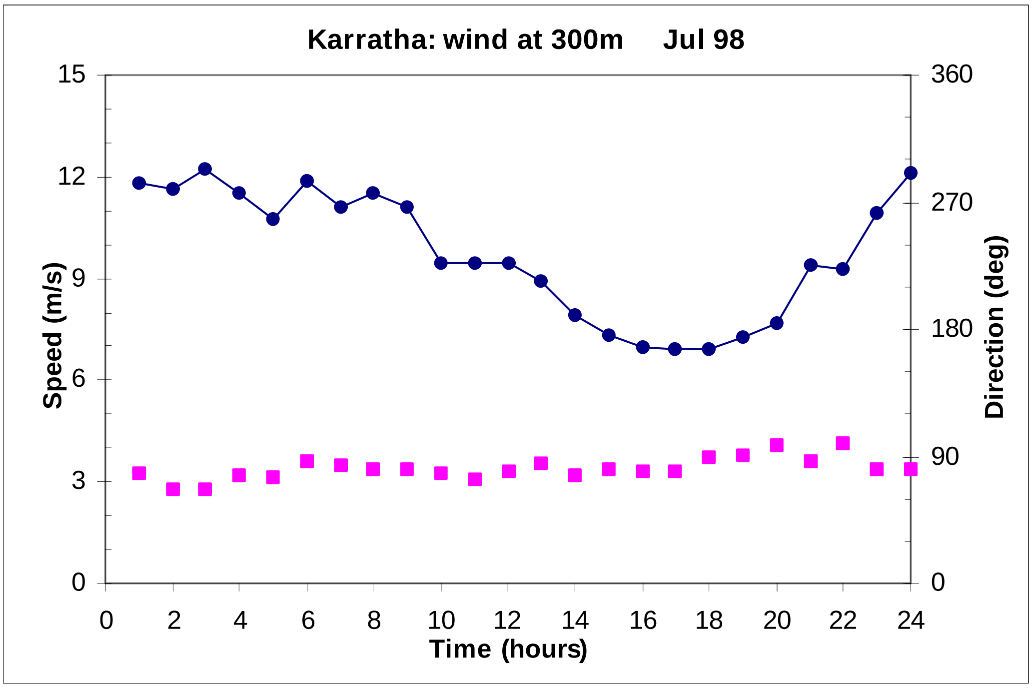


Figure 3.3b: Monthly-mean wind speed (●) and direction (■) at heights of 300 m and 700 m above the ground for April 1998.



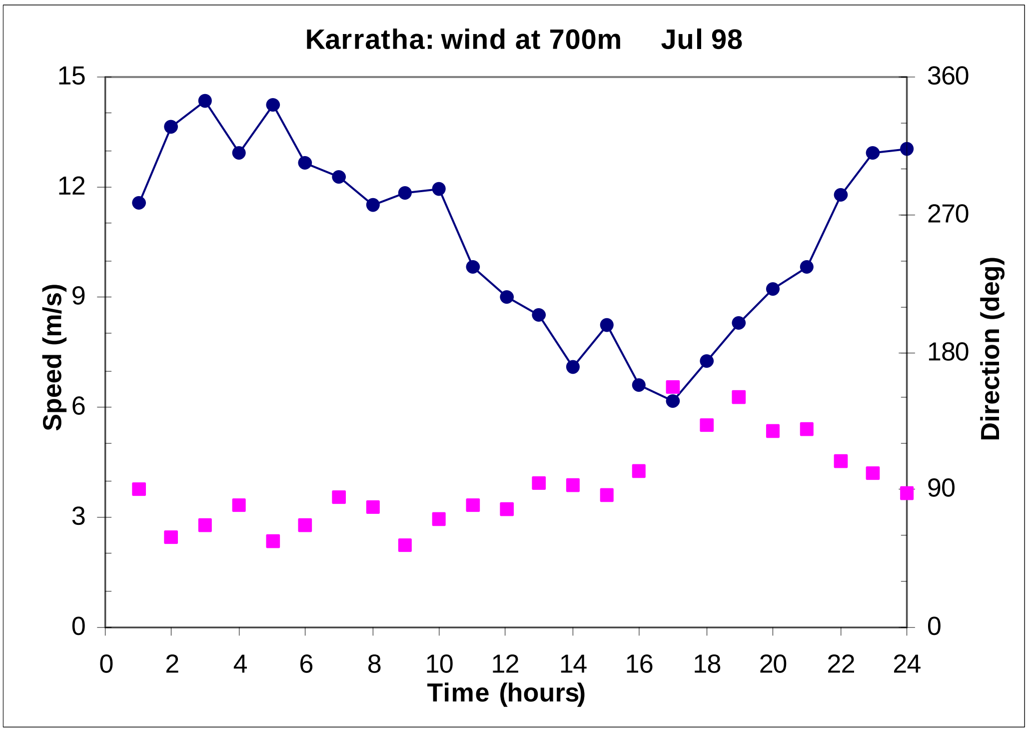
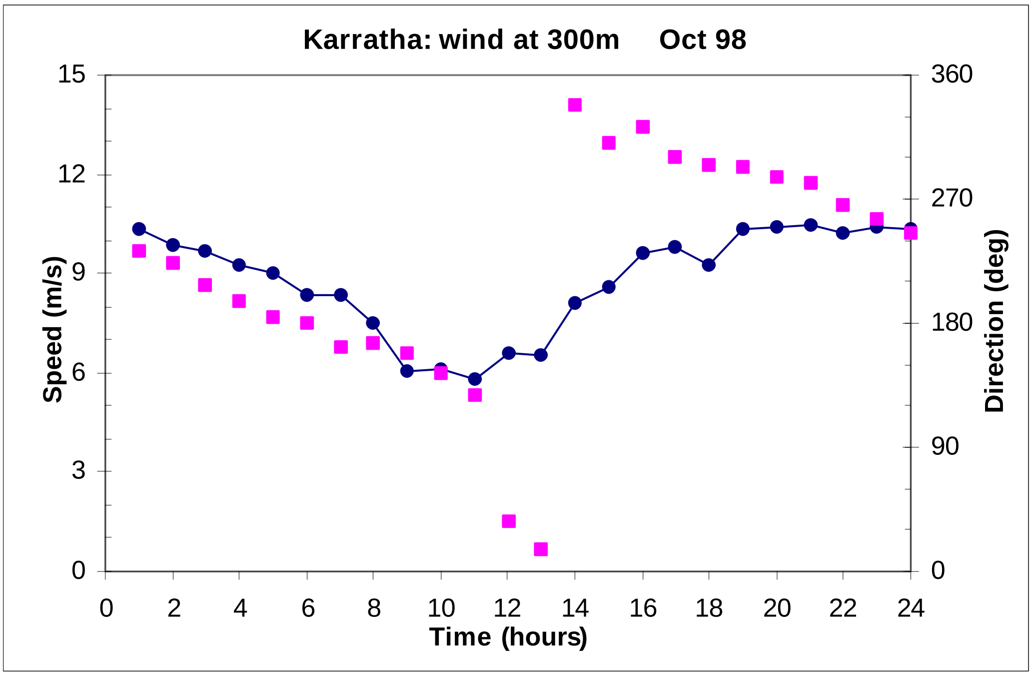


Figure 3.3c: Monthly-mean wind speed (●) and direction (■) at heights of 300 m and 700 m above the ground for July 1998.



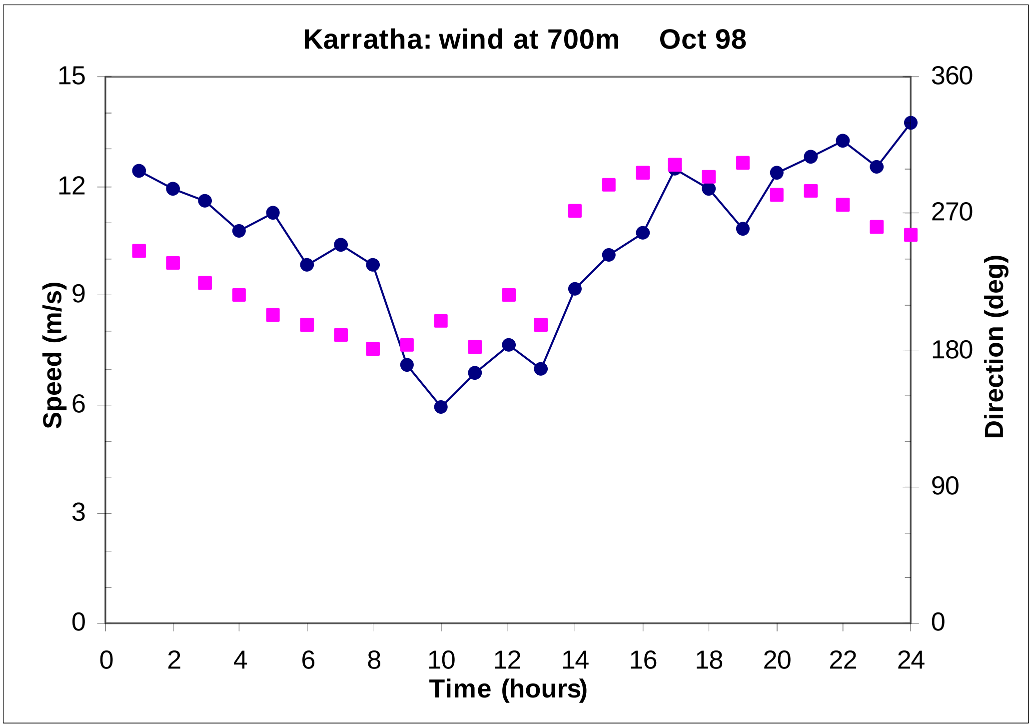
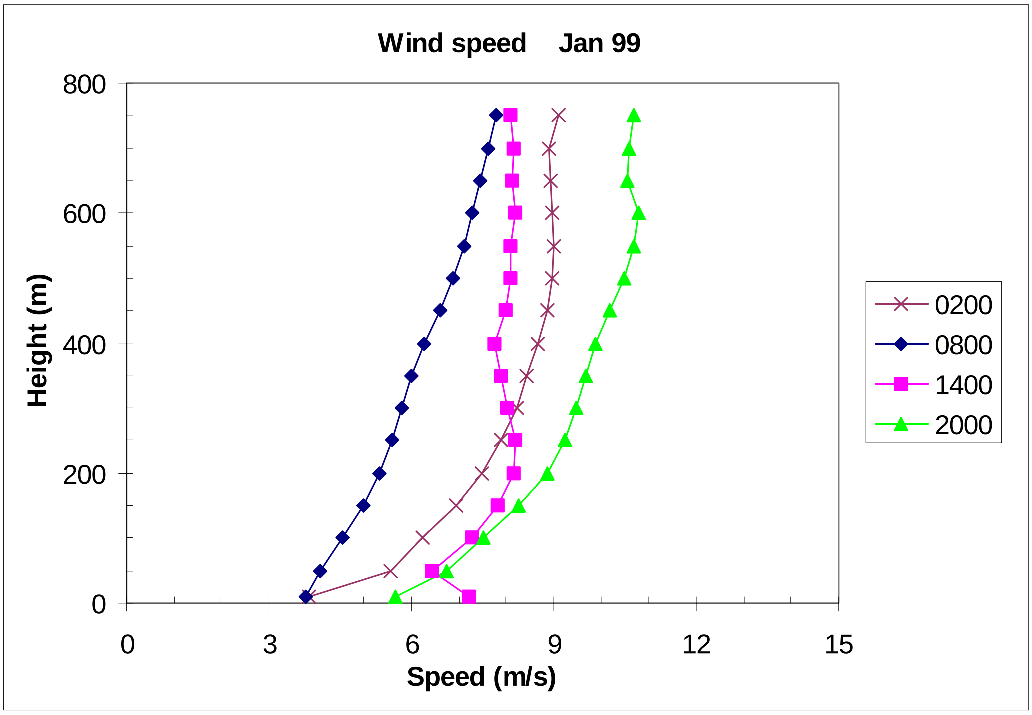


Figure 3.3d: Monthly-mean wind speed (●) and direction (■) at heights of 300 m and 700 m above the ground for October 1998.



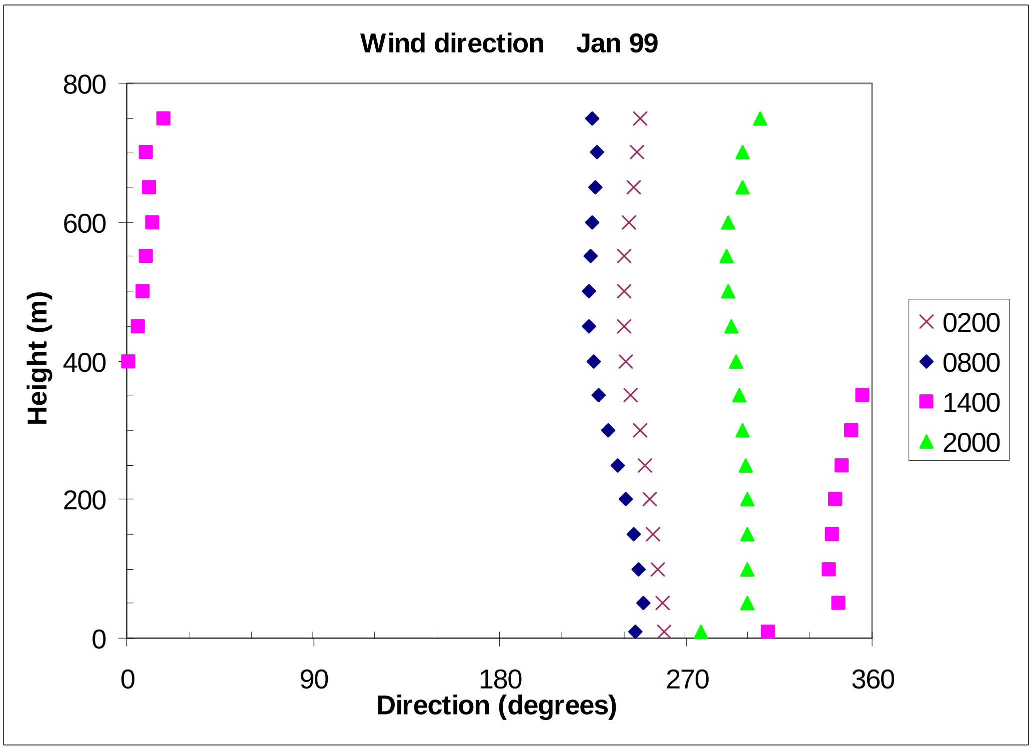
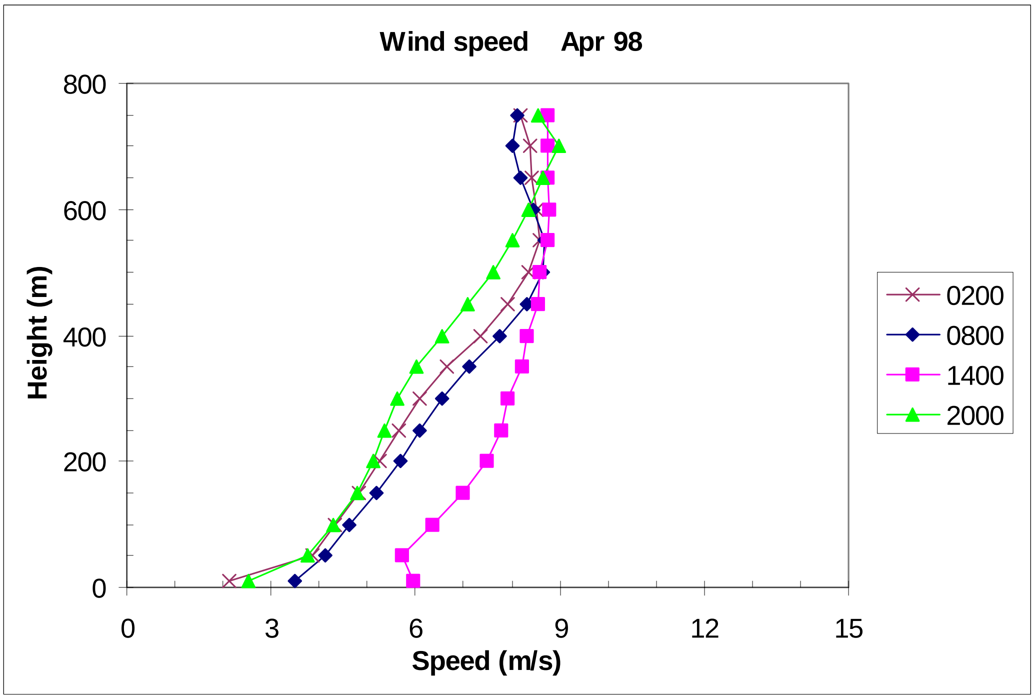


Figure 3.4a: Mean wind speed and direction profiles at 0200, 0800, 1400 and 2000 WST for January 1999.



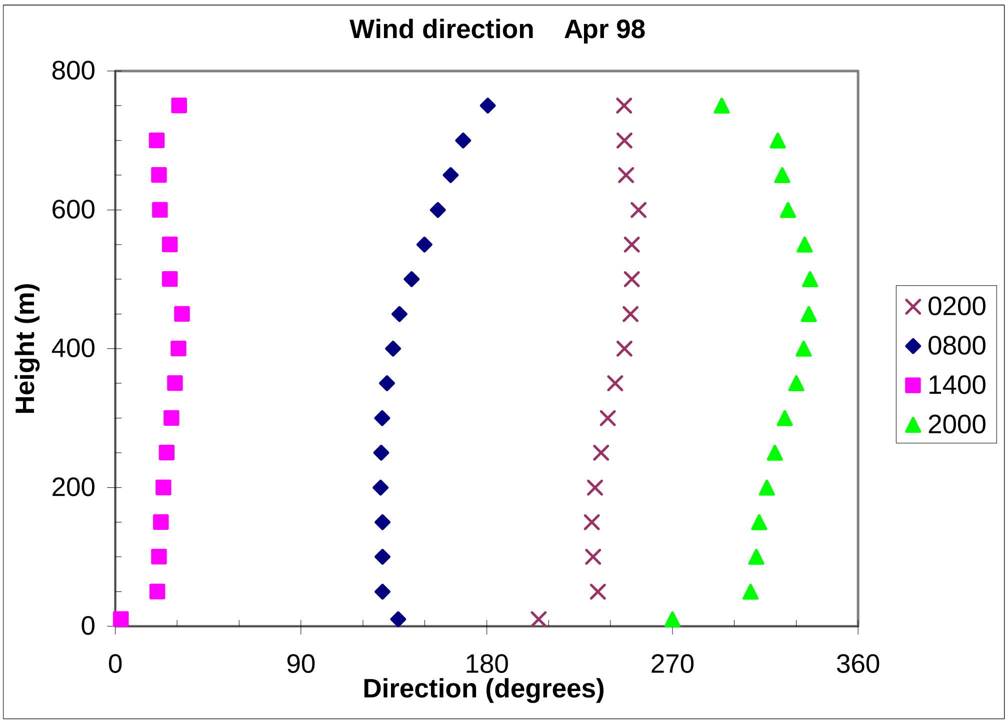
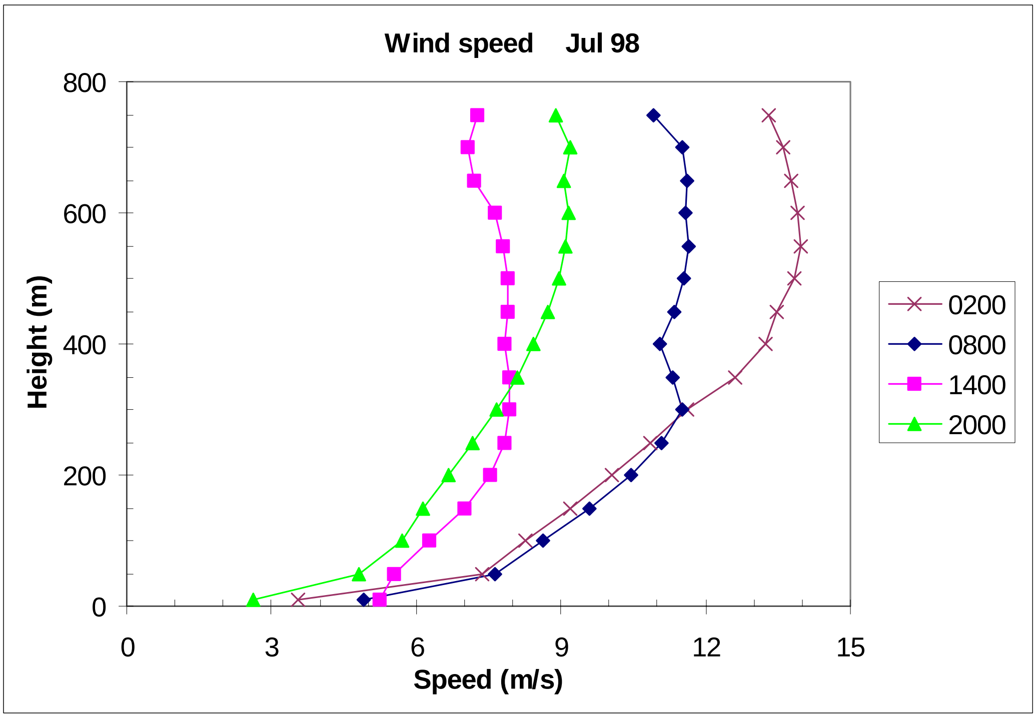


Figure 3.4b: Mean wind speed and direction profiles at 0200, 0800, 1400 and 2000 WST for April 1998.



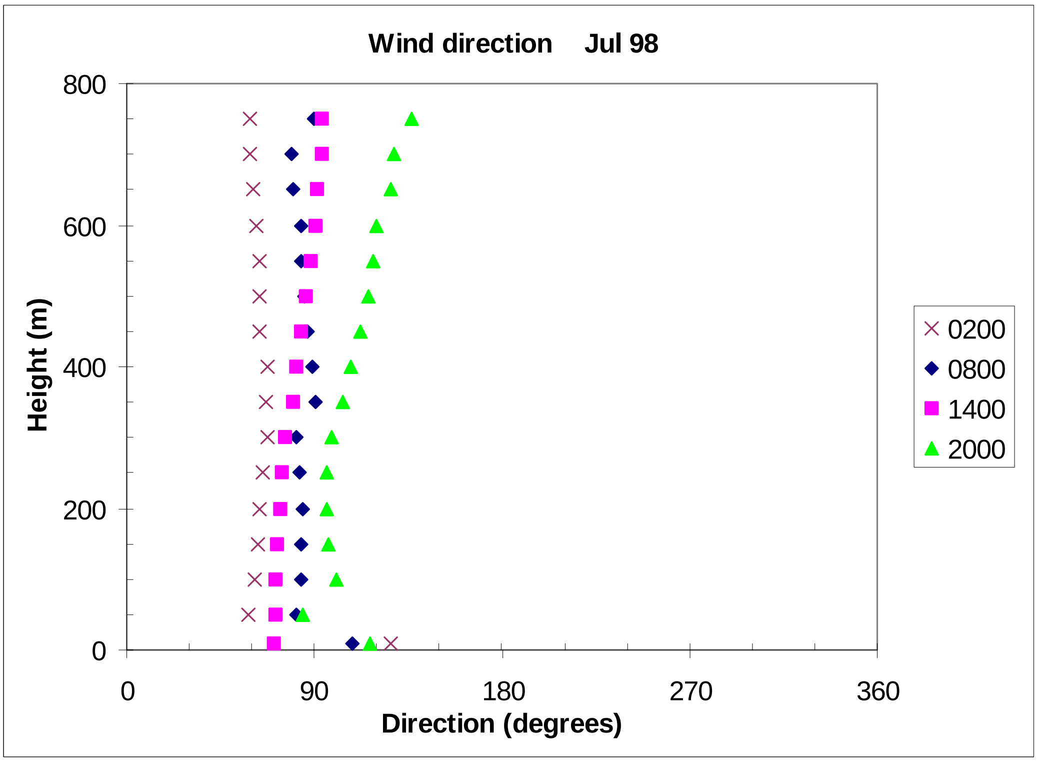
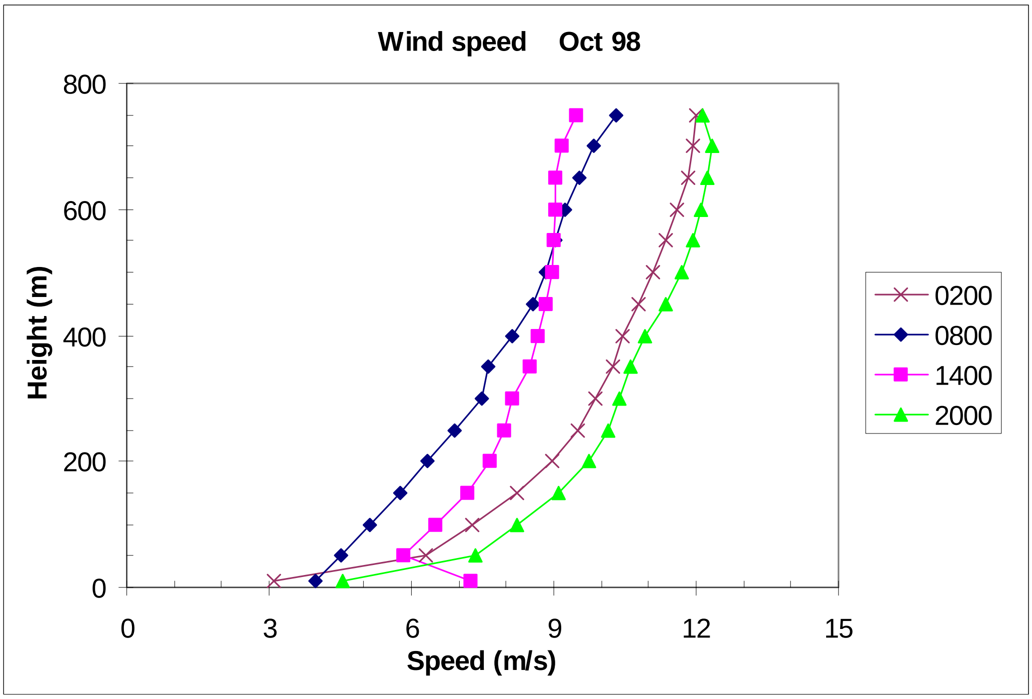


Figure 3.4c: Mean wind speed and direction profiles at 0200, 0800, 1400 and 2000 WST for July 1998.



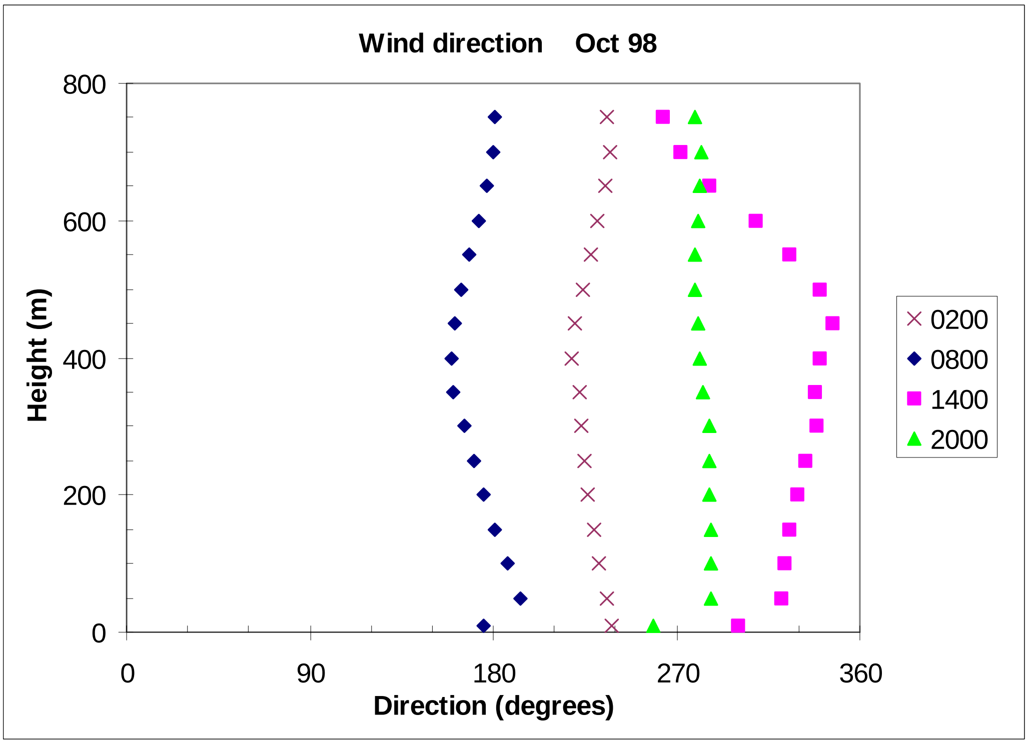
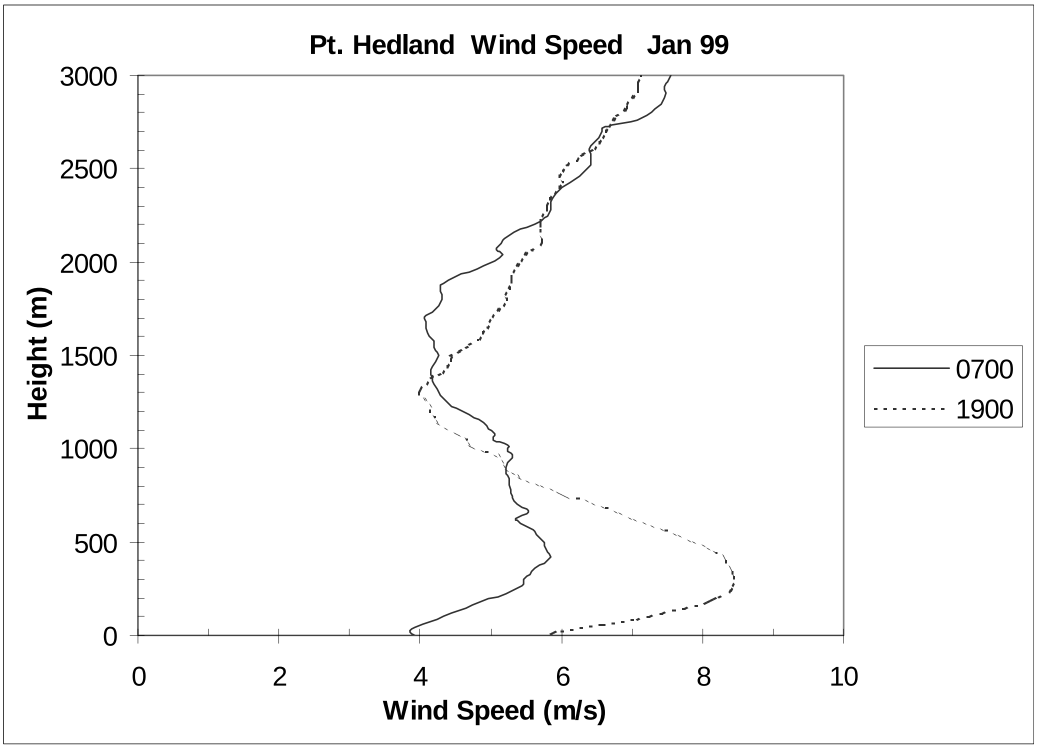


Figure 3.4d: Mean wind speed and direction profiles at 0200, 0800, 1400 and 2000 WST for October 1998.



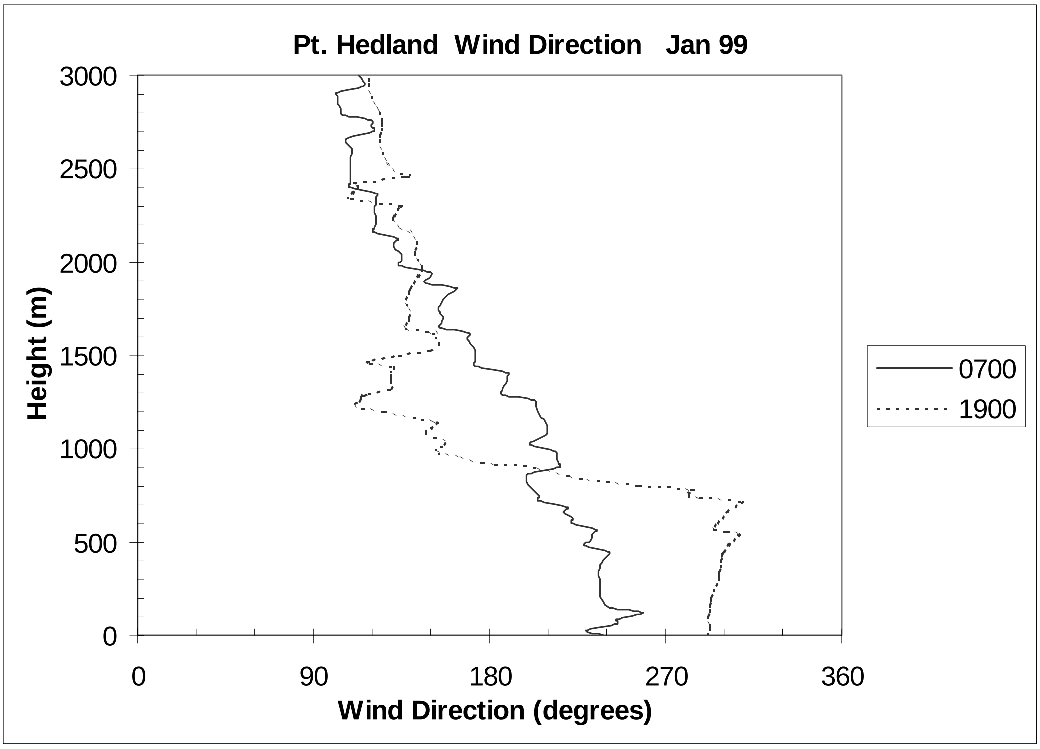


Figure 3.5: Monthly-mean profiles of wind speed and direction at Port Hedland for 0700 WST and 1900 WST for January 1999.

The 0700 WST temperature profiles showed a surface-based mixed layer on every day except one (which occurred when the low-level wind was from the northeast). A frequency distribution of the depth of the mixed layer is shown in Figure 3.6, from which it can be seen that the most common value is 500 m and that layers as shallow as 100 m can occur. Above the mixed layer, a strongly stable layer lies beneath a less stable layer. Relative humidity in the mixed layer (typically between 65 and 80%) increases linearly with height, and above the mixed layer rapidly decreases to much smaller values with height.

All mixed layers deeper than 500 m occur when the low-level winds are from the northwest quadrant; no layers shallower than 400 m are found under this wind direction. This is probably due to the longer time spent over the sea by air reaching Port Hedland from this direction than when the winds are from the southwest quadrant. This is based on the assumption that the mixed layer arises from cool air travelling over a warmer sea, although it is not immediately obvious as to why air arriving from the southwest soon after sunrise should be well mixed to heights of up to 500 m. The mixed layer is probably a residual from the previous day, which has remained mechanically mixed through the night, or it may be that radiatively-cooled layers near the surface have been dissipated by heating from below in the short time between sunrise and 0700 WST.

The 1900 WST profiles all show a mixed layer below the strongly stable layer. On the majority of days the depth is the same as found for the 0700 WST profile, but on some occasions it is lower. On one day it was higher.

An example of winds, potential temperature and relative humidity profiles is shown in Figure 3.7. Apart from being representative, 22 January 1999 was chosen because a radiosonde was also released at Dampier on this day at 1400 WST. The potential temperature data suggest that, as far as the most important features of the profiles are concerned, there is little change either during the day or between the two locations. Although temperature decreases by two degrees between 0700 and 1900 WST, the depth of the mixed layer (about 350 m) and the overlying stability (an increase of about 6 K over a 200 m deep layer) change very little. Similarly, the relative humidity profiles show the typical pattern of moist air in the mixed layer giving way to quite drier air with height. The higher values of relative humidity at 1900 WST are a consequence of the cooler air at this time.

There is not a lot of similarity between the speed profiles at the different times and locations, although the maximum and minimum pattern seen in the mean speed profile (Figure 3.5) is evident. Wind direction profiles at 1900 WST on this day at Port Hedland are typical of those for most days, with northwesterly winds in the mixed layer turning through north to east-southeast by 2000 m. The 0700 WST low-level winds are also from the northwest quadrant, a situation observed on eight mornings in this month. Interestingly, the Dampier profile at 1400 WST is very similar to the 1900 WST monthly-mean profile at 1900 WST, with winds turning through south above the mixed layer.

A further comparison between Dampier and Port Hedland upper-air data is shown in Figure 3.8. On this day, a radiosonde was released at the two sites at 1440 WST and 1400 WST respectively. There were no wind data at Port Hedland. While this day was not a typical January day in terms of mixed-layer depth and associated winds, surface observations show that sea breezes were evident at both locations. With the shallow mixed layer (100 m), the wind maximum was at 75 m, but the minimum occurred at a height of 1300 m in agreement with days with deeper mixed layers. The potential temperature profiles are very similar below 500 m, but air above this height at Dampier is about 2 K warmer than at Port Hedland. At Dampier, this leads to the strongly-stable region above the mixed layer becoming deeper (600 m) than at Port Hedland (450 m). Relative humidity profiles at both sites show shallow humid air beneath much drier air, with a sharper transition at Port Hedland than at Dampier.

From the profiles of wind, temperature and relative humidity for 22 and 28 January 1999 (Figures 3.7 and 3.8), it can be concluded for this month that there are no important differences in the dispersion meteorology between Dampier and Port Hedland. Given the similarity in the surface winds at both locations for November through to February, the above conclusion could perhaps be extended to these months too, although it is recommended that the fine-resolution radiosonde flights at both locations continue to be carried out.

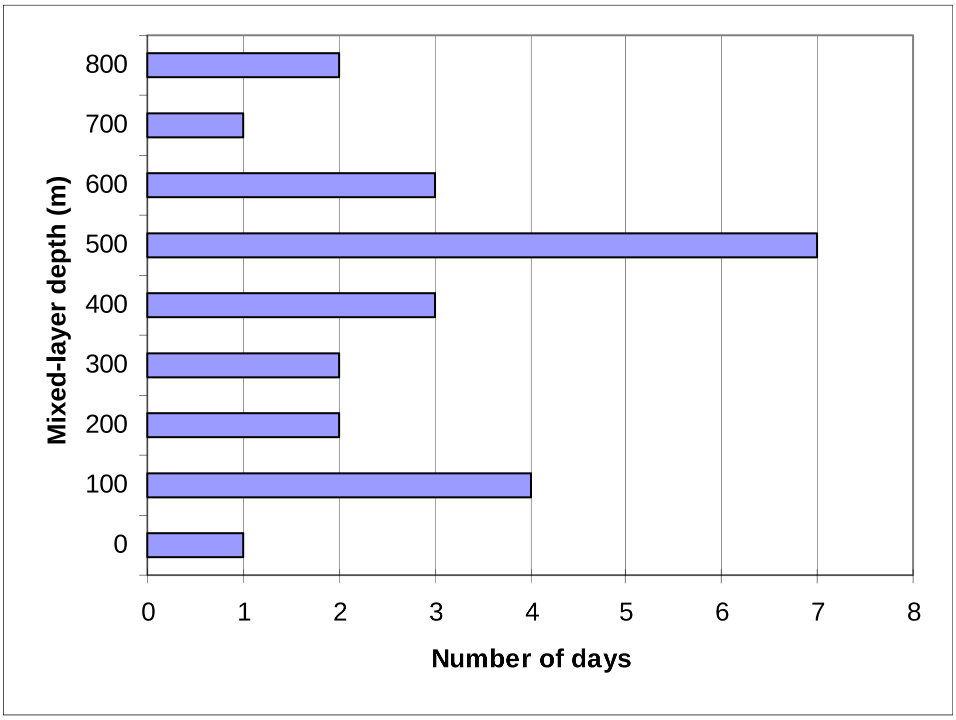
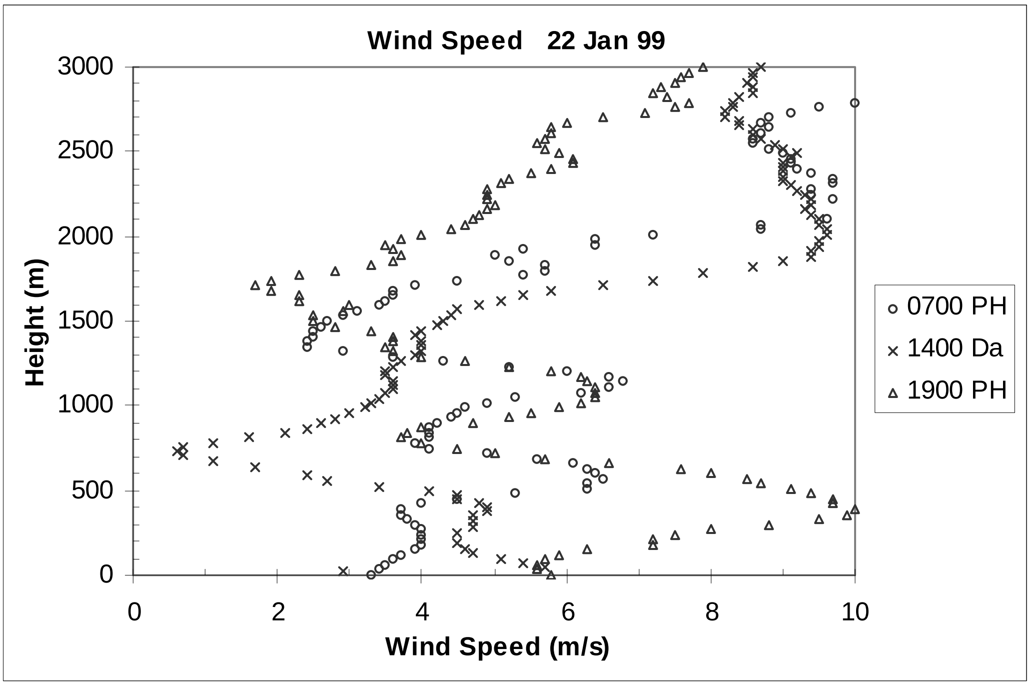


Figure 3.6: Frequency distribution of mixed-layer depths at 0700 WST at Port Hedland for January 1999.



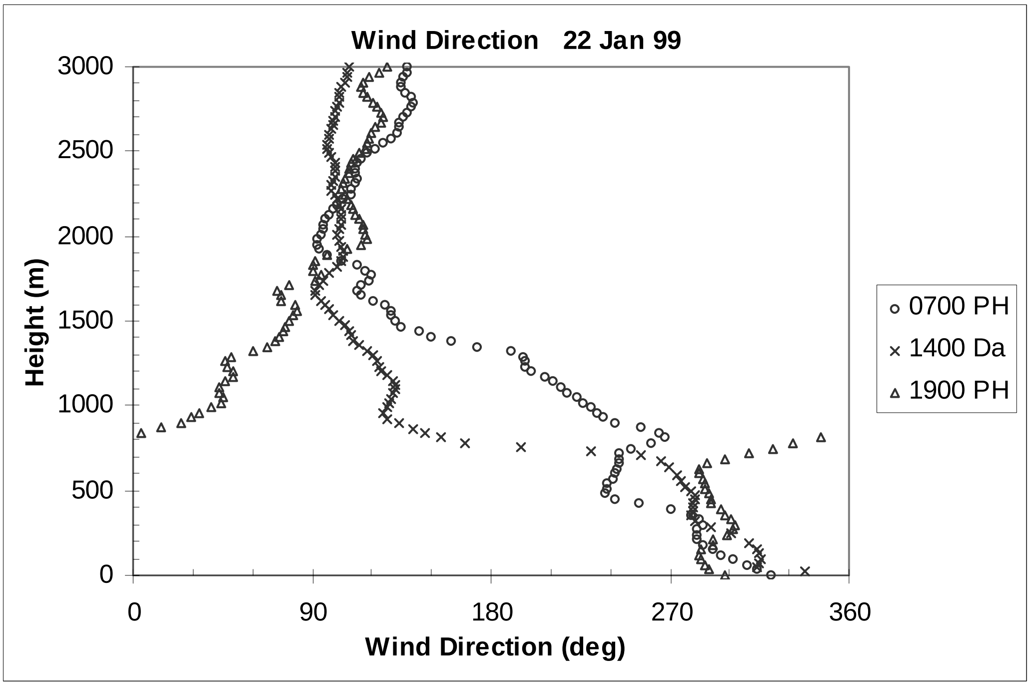
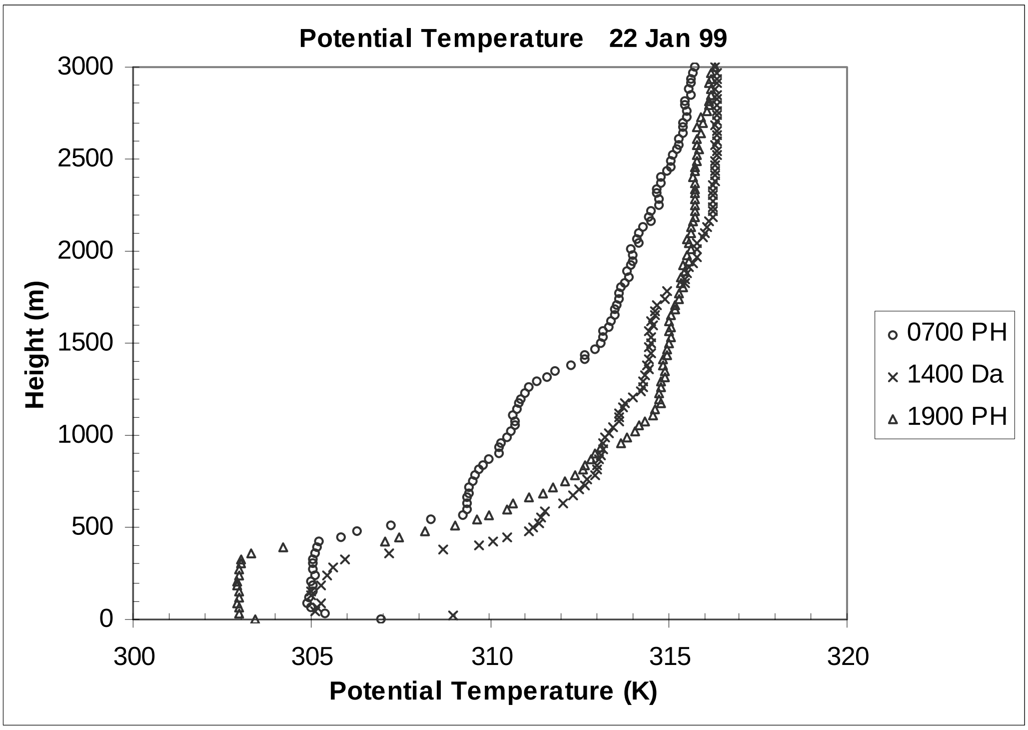


Figure 3.7a: Wind speed and direction profiles on 22 January 1999 at Port Hedland (0700 WST and 1900 WST) and Dampier (1400 WST).



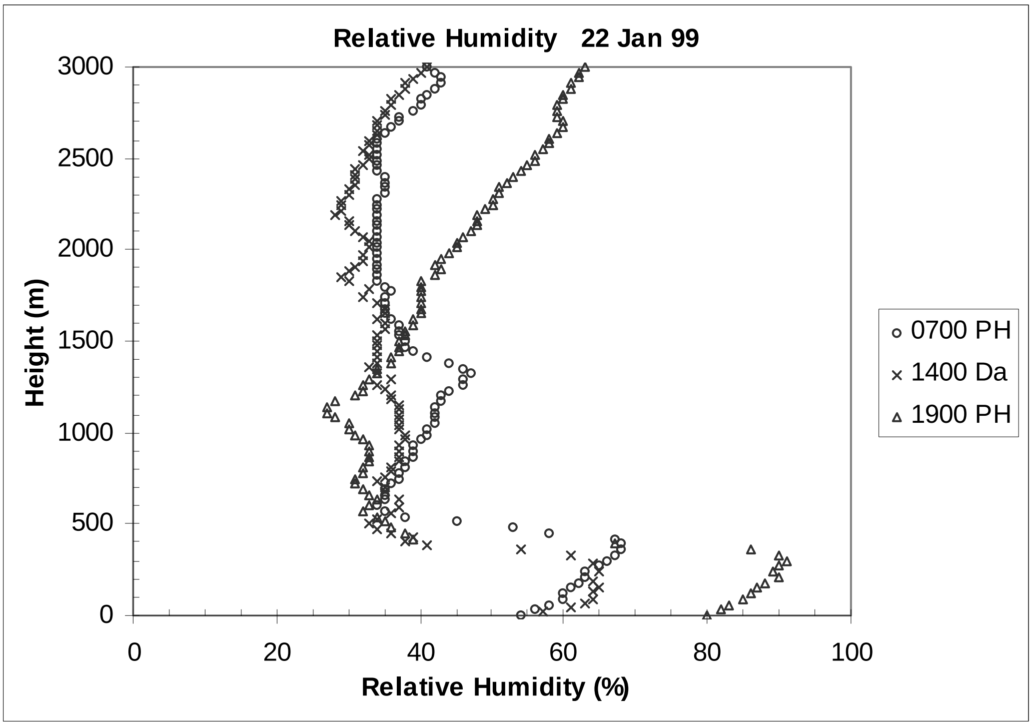
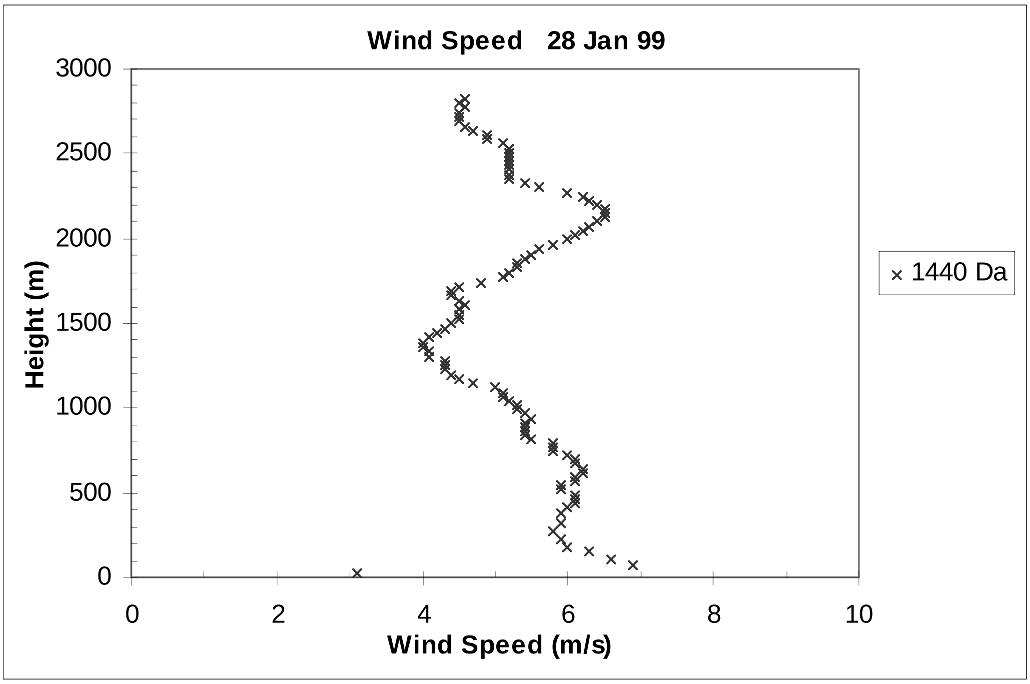


Figure 3.7b: Potential temperature and relative humidity profiles on 22 January 1999 at Port Hedland (0700 WST and 1900 WST) and Dampier (1400 WST).



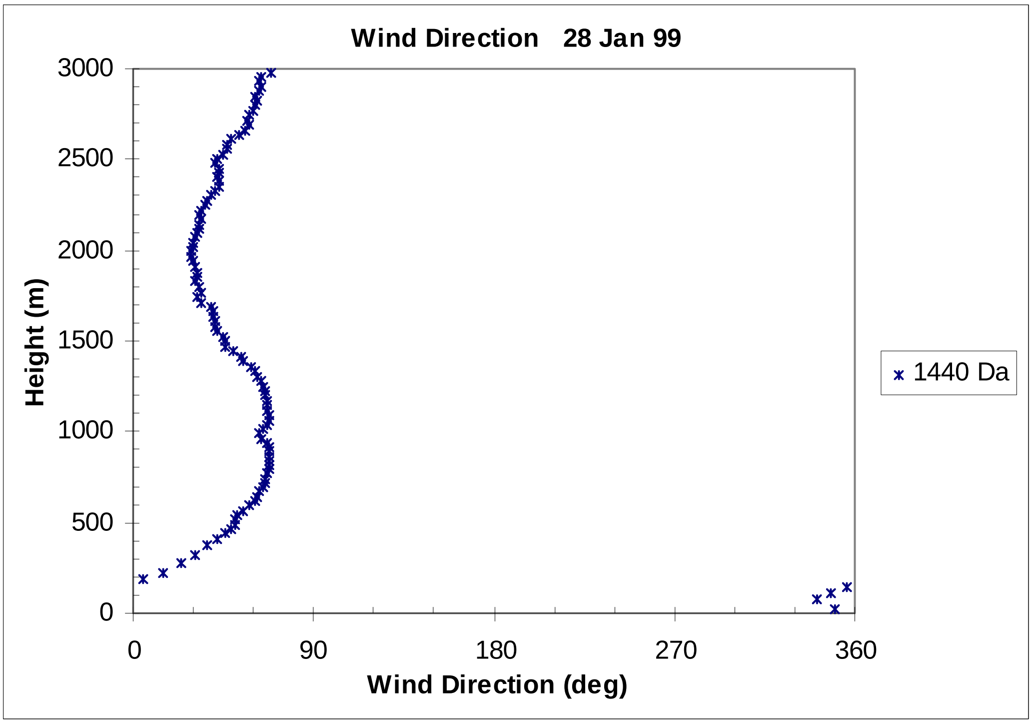
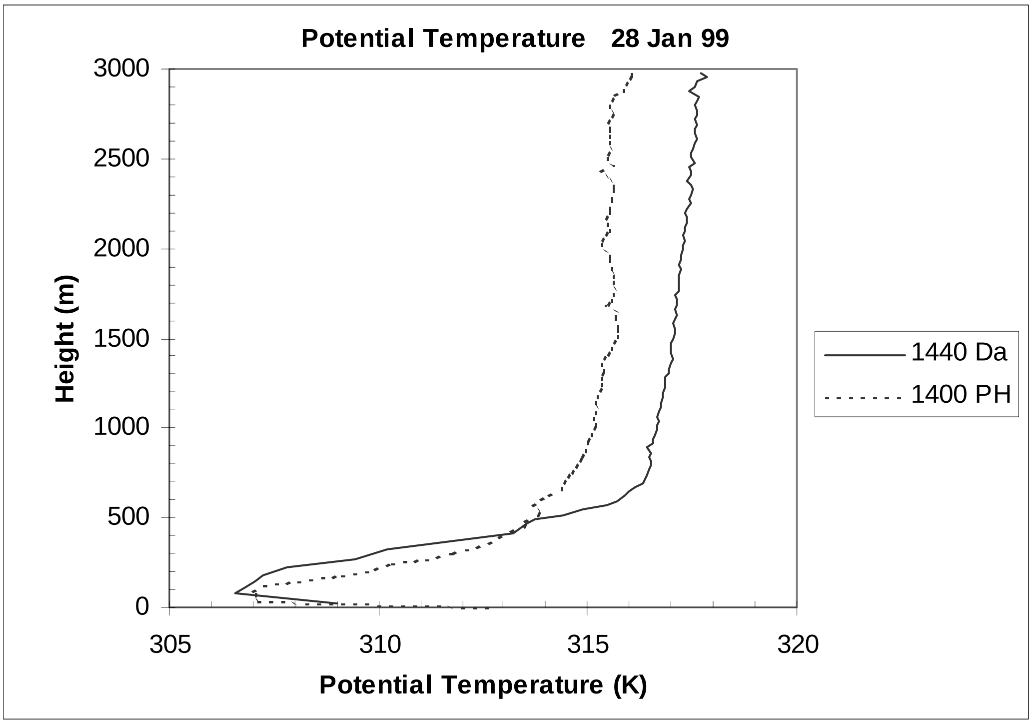


Figure 3.8a: Wind speed and direction profiles at Dampier (1440 WST) on 28 January 1999.



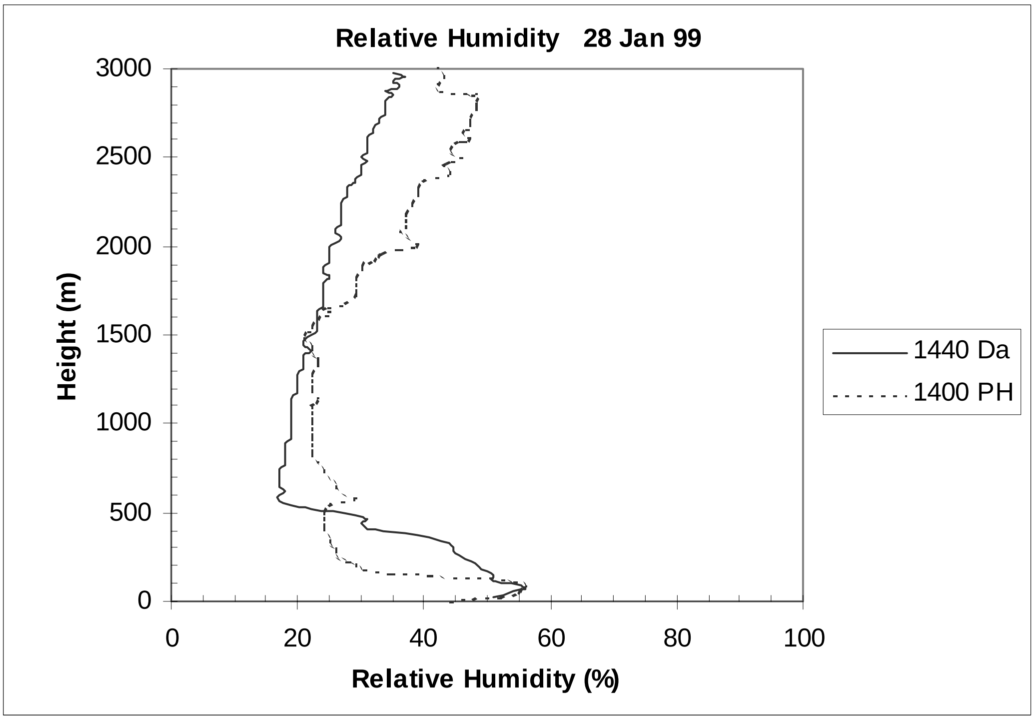


Figure 3.8b: Potential temperature and relative humidity profiles at Dampier (1440 WST) and Port Hedland (1400 WST) on 28 January 1999.

Characteristics of the data from the fifteen flights on various afternoons at Dampier and Finucane Island (Port Hedland) (see Section 2.2 for dates) are consistent with the above analysis of the Port Hedland data for January 1999. Sea breezes from the northwest sector are evident on every occasion and mixed-layer heights vary from 0 m (on one occasion) to 800 m (also on one occasion). A very strong stable layer above the mixed layer is present on nearly every day. There is an indication that shallower mixed layers occur in the September/October data than in the summer data, but the small number of flights for the former period (six) does not allow any conclusion involving seasonality to be made.

4. Modelling

Simulations were carried out with the mesoscale model TAPM (The Air Pollution Model) to complement the data analysis of the previous section. This approach allows further insight into the meteorology of the Pilbara region in those areas where there are no observations.

4.1 Model formulation and experimental setup

TAPM (Hurley, 1998) was developed at CSIRO Atmospheric Research and consists of prognostic meteorological and air pollution modules that can be run for multiply-nested domains. The meteorological module is an incompressible, non-hydrostatic, primitive equation model for three-dimensional simulations. It predicts the three components of the wind, temperature, humidity, cloud and rain water, turbulent kinetic energy and eddy dissipation rate, and includes a vegetation/soil scheme at the surface and radiation effects. The model is driven by the Bureau of Meteorology's LAPS (Limited Area Prediction System) analysis fields (on a 75 km-spacing grid) of winds, temperature and specific humidity, which account for the larger-scale synoptic variability. TAPM is run for much finer grid spacings and predicts the meteorology at smaller scales.

The air pollution module, not used in this Study, solves prognostic equations for pollutant concentration using predicted fields from the meteorological module. It includes gas- and aqueous-phase chemical reactions based on an extended version of the Generic Reaction Set (GRS) developed at CSIRO Energy Technology, a plume-rise module, and wet and dry deposition effects.

The simulations were carried out on two nests (each 40 x 40 x 20 gridpoints) with grid spacings of 10 km and 3 km and centred on Karratha. Vertical grid levels were at heights above the ground of 10, 50, 100, 150, 200, 300, 400, 500, 750, 1000, 1250, 1500, 2000, 2500, 3000, 4000, 5000, 6000, 7000 and 8000 m. Monthly simulations were done for months in the summer (January 1999), winter (July 1998) and the transition seasons (April and October 1998).

4.2 Comparison with observations

Before model predictions can be used to supplement observations in data-sparse areas, the model must be shown to have some skill. This Study is not concerned with a full validation of the model, but a comparison of surface and upper-wind predictions at

Karratha with observations does show that the model is reproducing the dominant characteristics of the wind fields in the region. The comparison for the monthly-mean winds at heights of 10 m and 200 m above the ground (from the 3-km spacing run) is shown in Figures 4.1a – d for the four simulated months.

Prediction of wind speed magnitude at both heights is good, although the January winds are underestimated by about 2 m s^{-1} in the afternoon and evening. The diurnal pattern of the speed is observed to vary greatly between months, and between the two heights, and the model has reproduced this variation well. The simulations also capture very well the considerable variation in wind direction throughout the day and night and from month to month. In particular, the 'round the clock' rotation of the winds over 24 hours in April has been simulated, not only in the monthly means, but also for individual days of the month (not shown here).

4.3 Further analysis of modelled wind fields

The analysis of Section 3 has shown that there are three dominant wind patterns in the coastal region of northwest Australia between Karratha and Port Hedland: an *easterly* pattern in which winds vary between northeast and southeast over the diurnal period, a corresponding *westerly* pattern in which the winds vary from northwest to southwest, and a *rotation* pattern in the which the wind direction rotates anti-clockwise through 360 degrees over 24 hours. While the easterly flow occurs predominantly in the cooler months, the westerly in the warmer months, and the rotation pattern in the transition (autumn/spring) months, all patterns can be found at any time of the year. Three days that are representative of these wind regimes have been modelled, and predicted surface wind fields from the 3-km spacing grid are shown at four times of the day in Figures 4.2 to 4.4.

An interesting aspect of the easterly and westerly simulations (Figures 4.2 and 4.3), which are almost reflective, is that at any particular time there is very little variation of the winds across the land gridpoints, especially given that there is terrain and a varying coastline in the region. This is consistent with the analysis in Section 3 of surface winds from near-coastal sites, and suggests that for these types of days, which constitute a clear majority over a year, the complex variation in the coastline in the vicinity of the Burrup Peninsula may not be relevant from a pollutant transport point of view. Certainly, recirculation of pollutants back to the Peninsula source region does not appear to be a possibility under these regimes.

Results from the third regime in which the coastal wind direction rotates steadily throughout the day are shown in Figure 4.4. From a dispersion point of view, the wind patterns that develop under this regime are potentially the most important. Between mid-morning and midday, when the northerly sea breeze is forming and moving onshore against the prevailing easterly wind, flow fields in the coastal region become quite complex (see 1100 LT (Local Time) plot of Figure 4.4). In this situation, the potential exists for emissions from Burrup Peninsula sources earlier in the morning to move back onshore and combine with recently emitted pollutants. The winds over land acquire a northerly component everywhere by 1300 LT, although the actual sea breeze does not reach the boundary of the 3-km grid, a distance of 60 km inland, until 1600 LT.

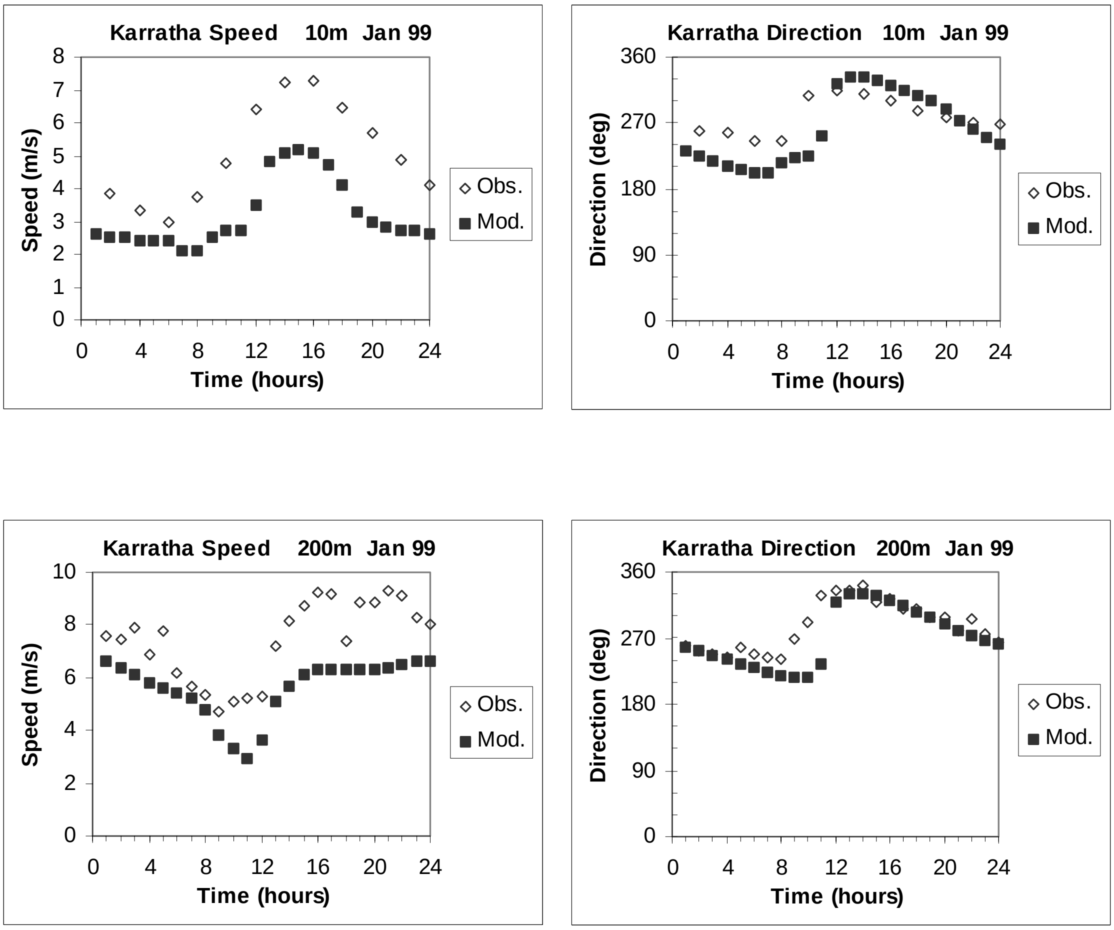


Figure 4.1a: Observed and modelled monthly-mean wind speed and direction at heights of 10 m and 200 m at Karratha for January 1999.

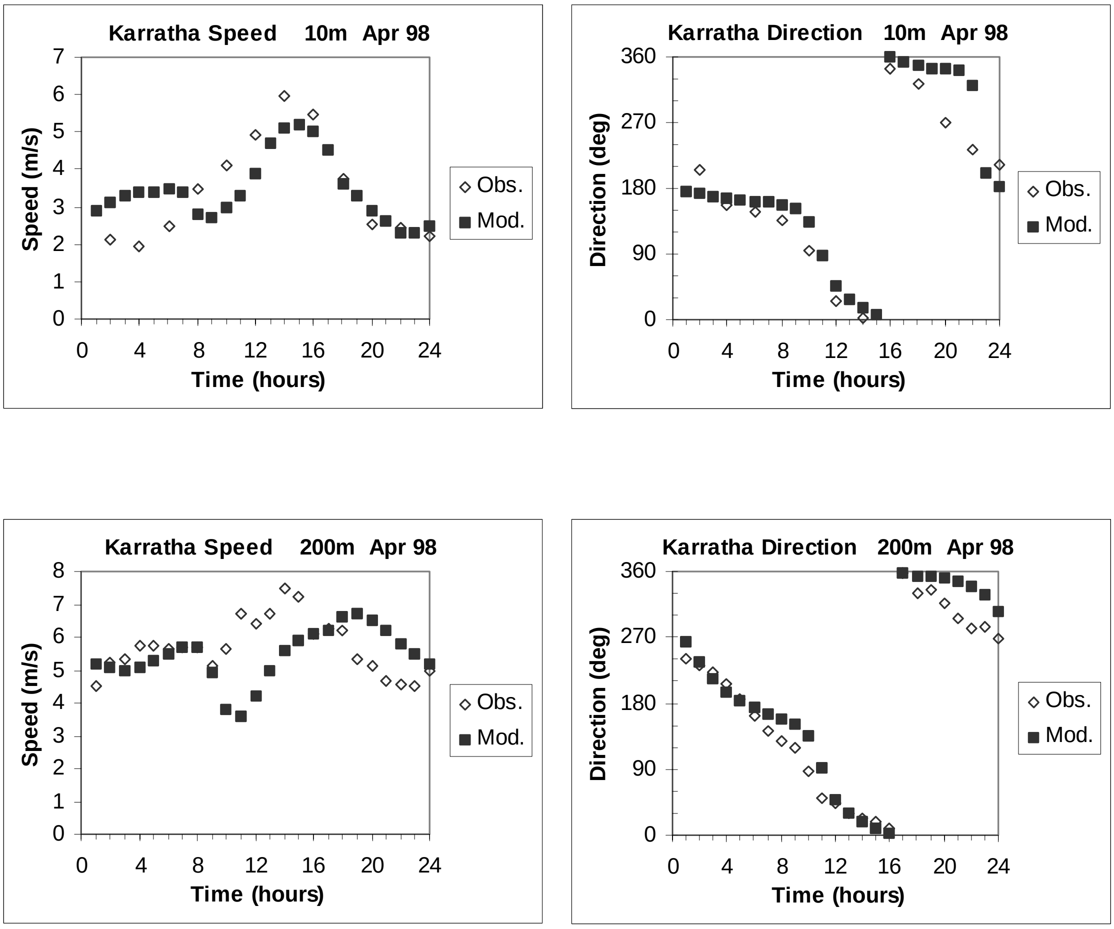


Figure 4.1b: Observed and modelled monthly-mean wind speed and direction at heights of 10 m and 200 m at Karratha for April 1998.

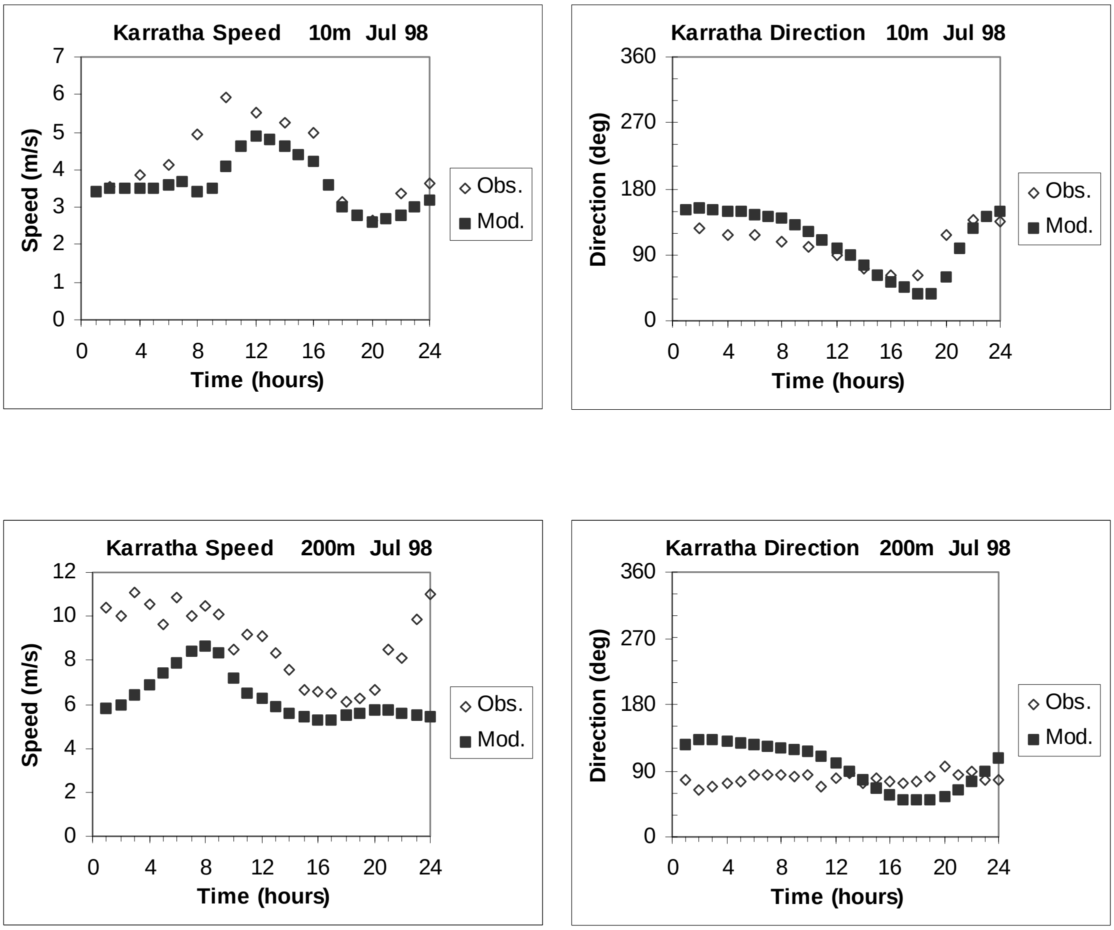


Figure 4.1c: Observed and modelled monthly-mean wind speed and direction at heights of 10 m and 200 m at Karratha for July 1998.

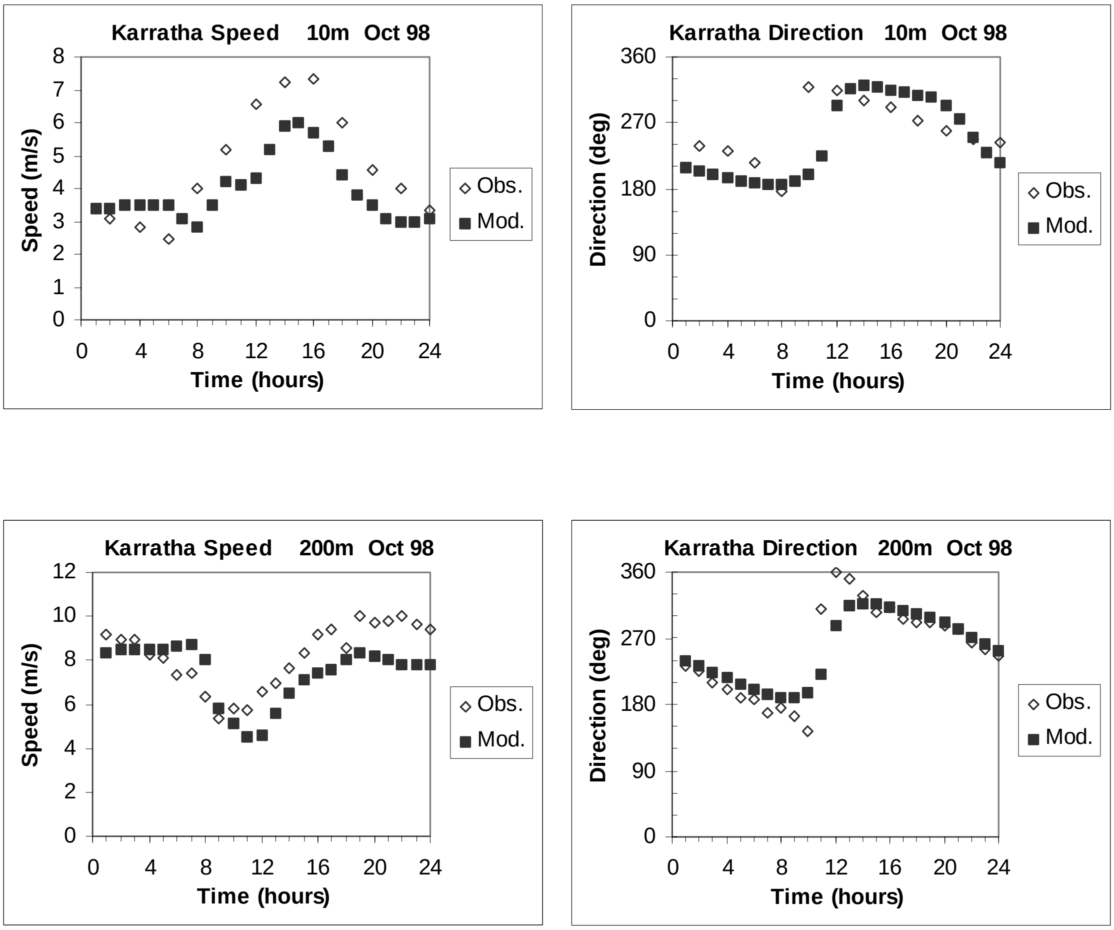


Figure 4.1d: Observed and modelled monthly-mean wind speed and direction at heights of 10 m and 200 m at Karratha for October 1998.

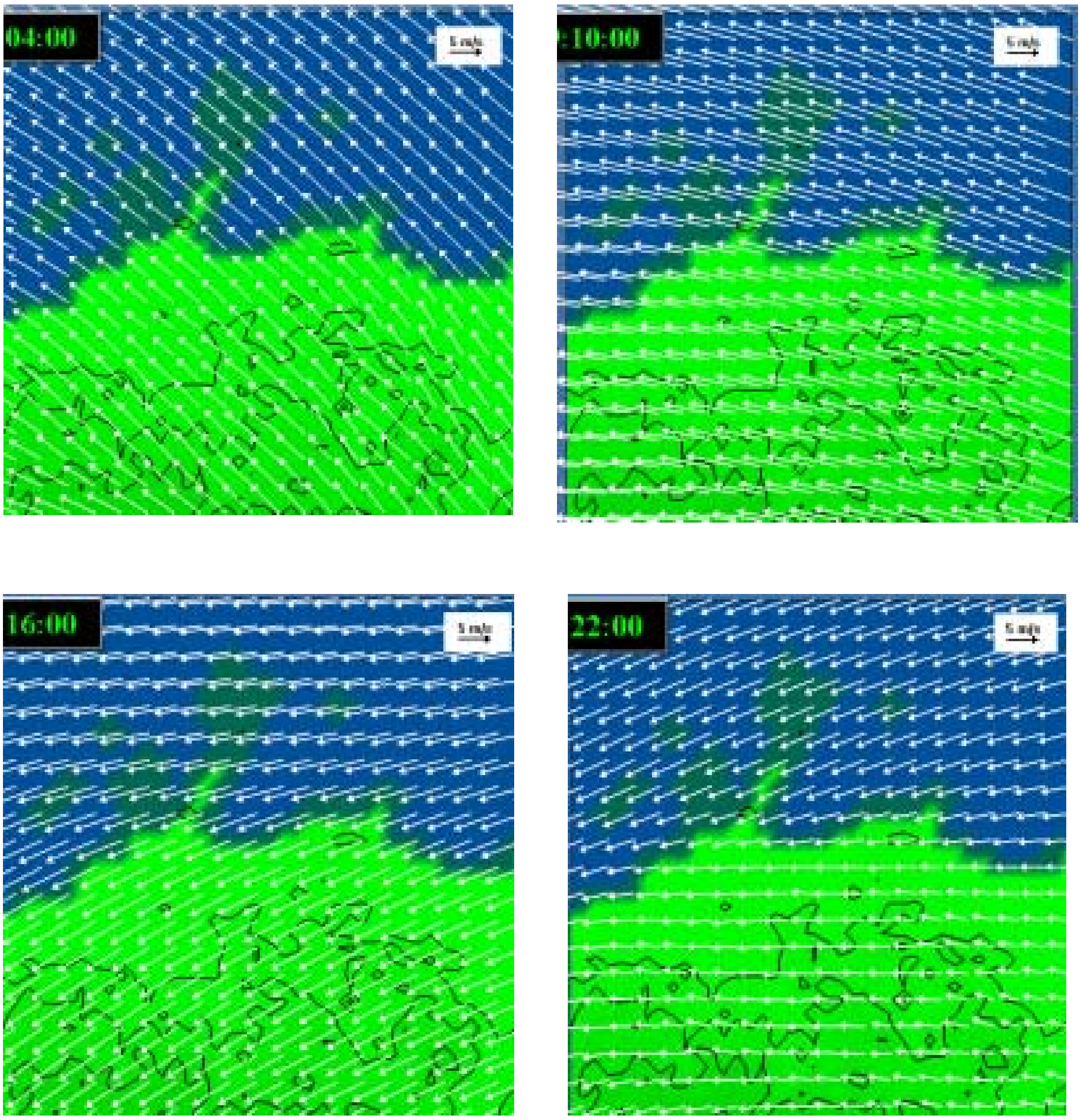


Figure 4.2: Modelled winds at a height of 10 m for 30 July 1998 at 0400, 1000, 1600, and 2200 Local Time The contours denote terrain height at 50 m, 100 m and then at a contour interval of 100 m. The domain size is 117 x 117 km^2.

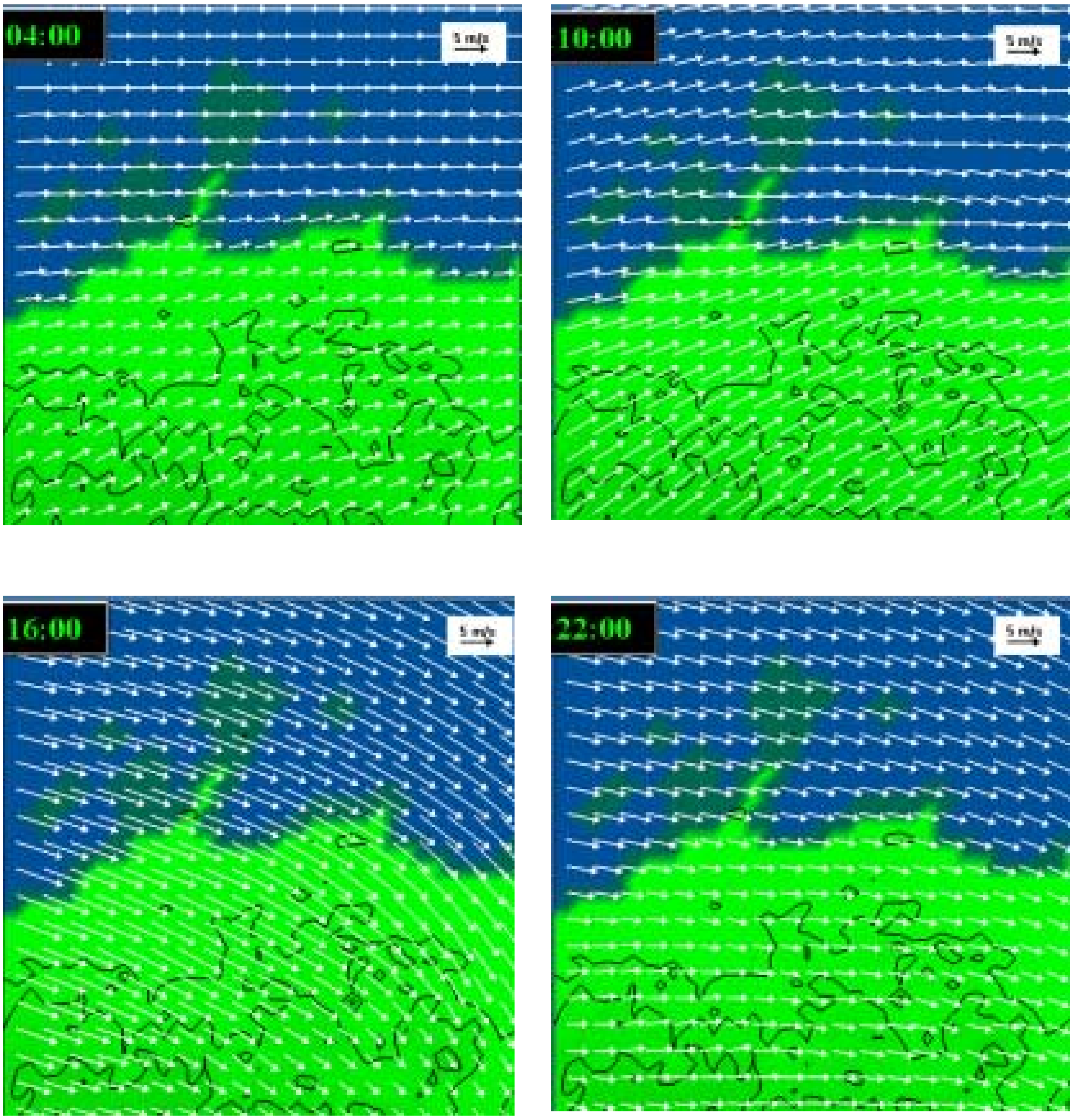


Figure 4.3: Modelled winds at a height of 10 m for 8 January 1999 at 0400, 1000, 1600, and 2200 Local Time The contours denote terrain height at 50 m, 100 m and then at a contour interval of 100 m. The domain size is 117 x 117 km^2.

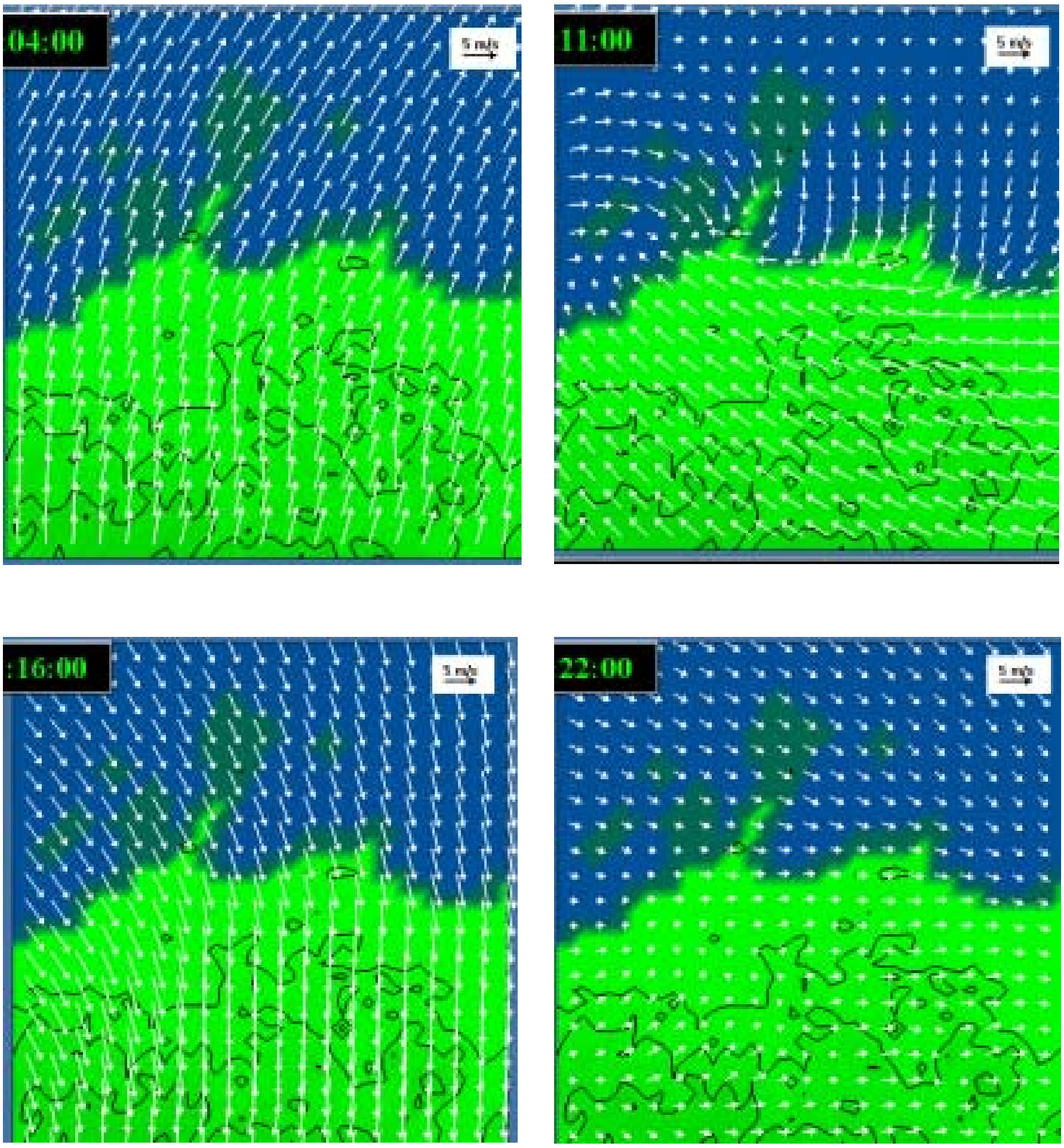


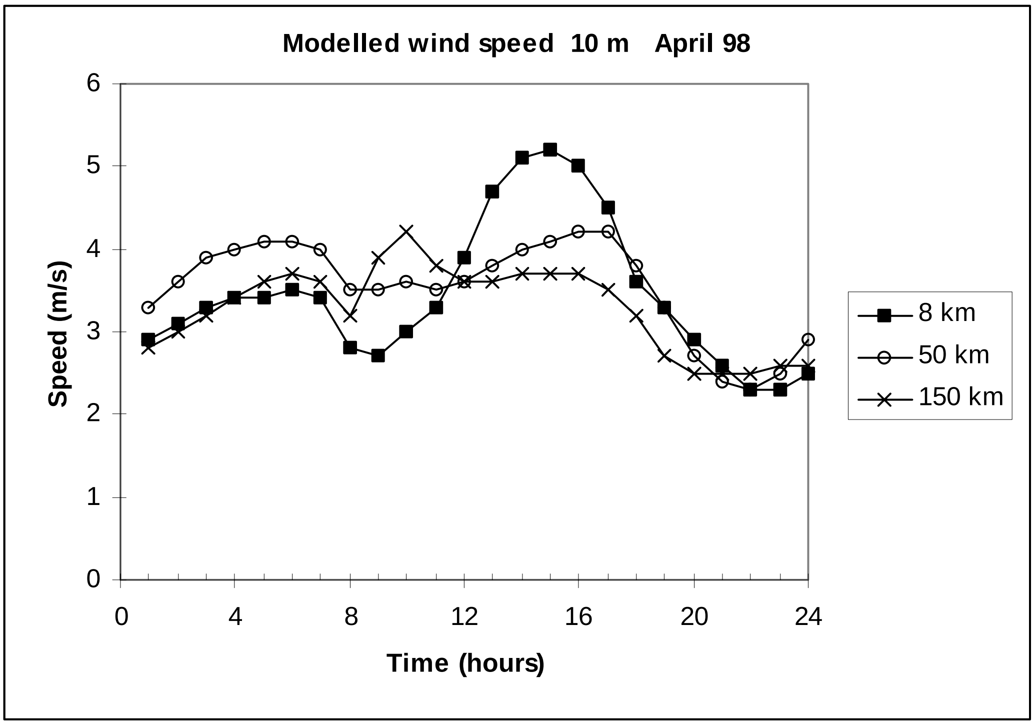
Figure 4.4: Modelled winds at a height of 10 m for 12 October 1998 at 0400, 1000, 1600, and 2200 Local Time. The contours denote terrain height at 50 m, 100 m and then at a contour interval of 100 m. The domain size is 117 x 117 km^2.

As with the easterly and westerly regimes discussed earlier, the winds at any particular time over land are quite horizontally homogeneous. To explore this further, we have computed the monthly-mean surface winds for the April simulation at two inland locations. One is 50 km from the coastline, directly south of Karratha, and the other is 150 km inland, also south of Karratha and located about 500 m above sea level in the Hamersley Range. Winds at the latter site are taken from the simulation with 10-km grid spacing. The results are plotted in Figure 4.5, along with the mean-monthly winds predicted for Karratha (8 km from the coast). A striking feature of the wind behaviour is that the direction rotates through 360 degrees over a diurnal period at not only the coastal site but at the two inland sites as well. This also occurs on individual days of the month. The conclusion to be drawn is that the rotation is a synoptic-scale feature of the region, rather than being only a consequence of sea and land breezes in the coastal area. The effect of the sea breeze can be seen in the plot for Karratha which has stronger winds and a more northerly direction than the other two sites between 1200 and 1800 LT. The departure between the directions at 50 km and 150 km at 2100 LT may indicate that this is the mean arrival time of the sea breeze at 50 km inland. This interesting finding will not be explored further in this Report, but may be a consequence of an inertial oscillation or the daily convective mixing to the surface of higher level winds with a different direction.

Future modelling work should involve dispersion of pollutants from Burrup Peninsula sources under the three main wind regimes. However, some preliminary results are presented here to illustrate the trajectories of emissions under the rotating wind regime. In the early testing stages of TAPM, a meteorological simulation was done for the period 23-25 September 1996 – radiosonde data were obtained on 25 September from a flight from Finucane Island near Port Hedland and showed a sea breeze with associated mixed layer and capping inversion. Figure 4.6 shows the surface wind behaviour over the three days at the Dampier gridpoint, and it can be seen that the winds in this period for the first two days can be categorised under the rotation regime. On the third day, while still rotating through almost 180^{o}, the wind pattern resembles the westerly regime.

Figure 4.7 shows the trajectory of emissions released from Dampier at a height of 10 m at 0600 LT and at 1500 LT on the first day. Note that the trajectories are two-dimensional, i.e. the emissions are assumed to remain at a height of 10 m over the three days. Emissions released at 0600 LT initially move out to sea, but return towards land in the sea breeze and cross the coast 80 km east of Dampier at 2000 LT (the numbers on the trajectory denote hours after the start of the simulation, i.e. midnight). The emissions cross the coast again further east just prior to sunrise on the second day before moving back onshore in mid afternoon, and eventually travelling about 90 km inland. The trajectory of the 1500 LT emissions takes them 80 km inland by 2200 LT, at which time they turn and head back towards the coast, moving offshore at about 0700 LT and then crossing back onto land again in early afternoon.

For both the illustrated release times (and many others not shown), an emissions parcel spends long periods over the sea, where secondary pollutants such as ozone are not lost by deposition. Over the land, further precursors may be emitted into the parcel as it passes over any other sources (including, perhaps, biogenic). These possibilities suggest that long-range transport and recirculation of emissions may lead to elevated levels of photochemical smog in the region and should be investigated further in more detailed modelling studies. From the trajectories beginning at many times, including those of Figure 4.7, it is interesting to see that the sea air that moves onshore during the daytime has spent the previous night over the land, subjected to radiative-cooling effects. Therefore it may be that the mixed layers seen in the coastal sea breezes in this region are a result of heating of the lower layers of the nocturnally-cooled air by the warmer sea-surface temperature, in combination with the residual mixed layer from the previous day at higher levels. This is an interesting problem, which can be investigated further with an appropriate model.



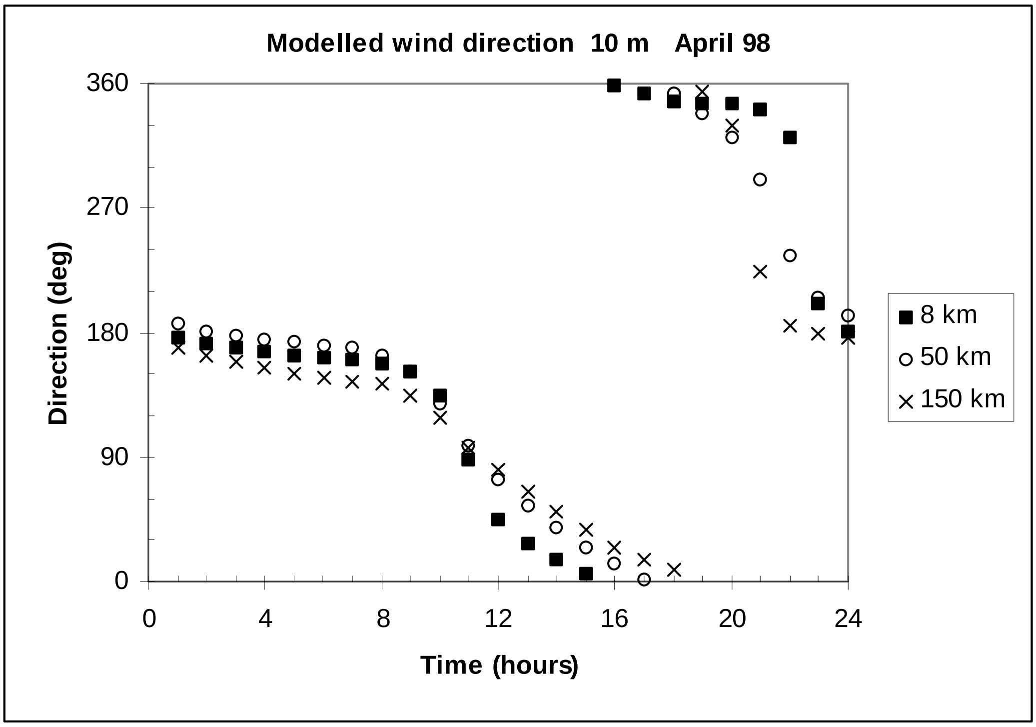
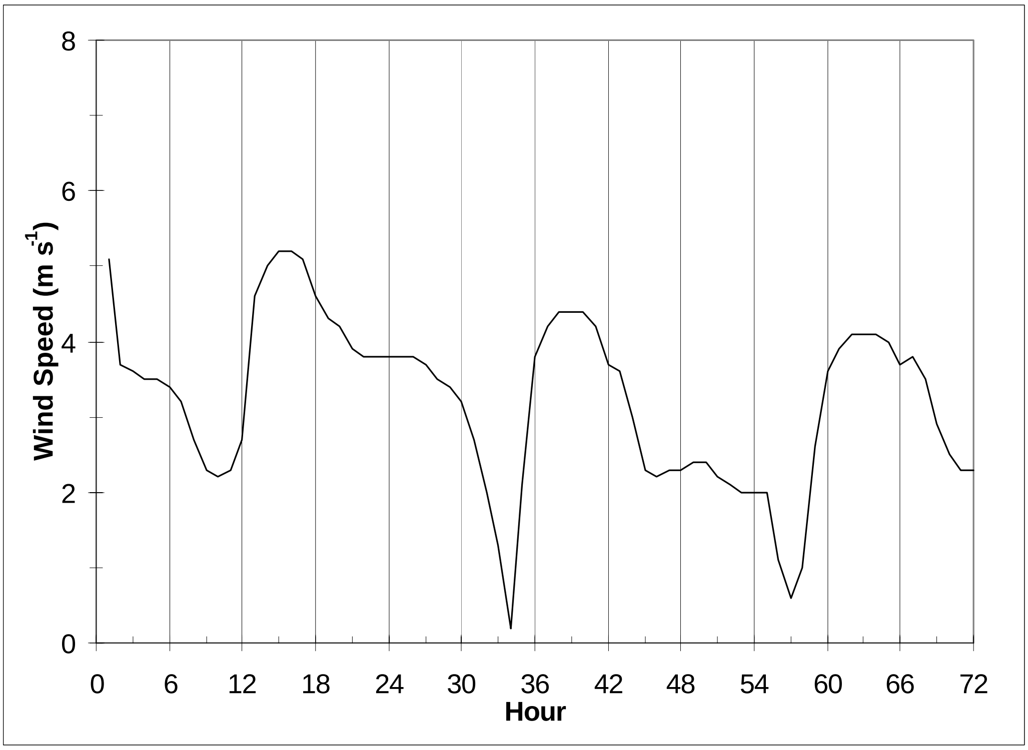


Figure 4.5: Modelled mean-monthly wind speed and direction at 10 m for April 1998 at three gridpoints 8 km (Karratha), 50 km and 150 km inland from the coastline.



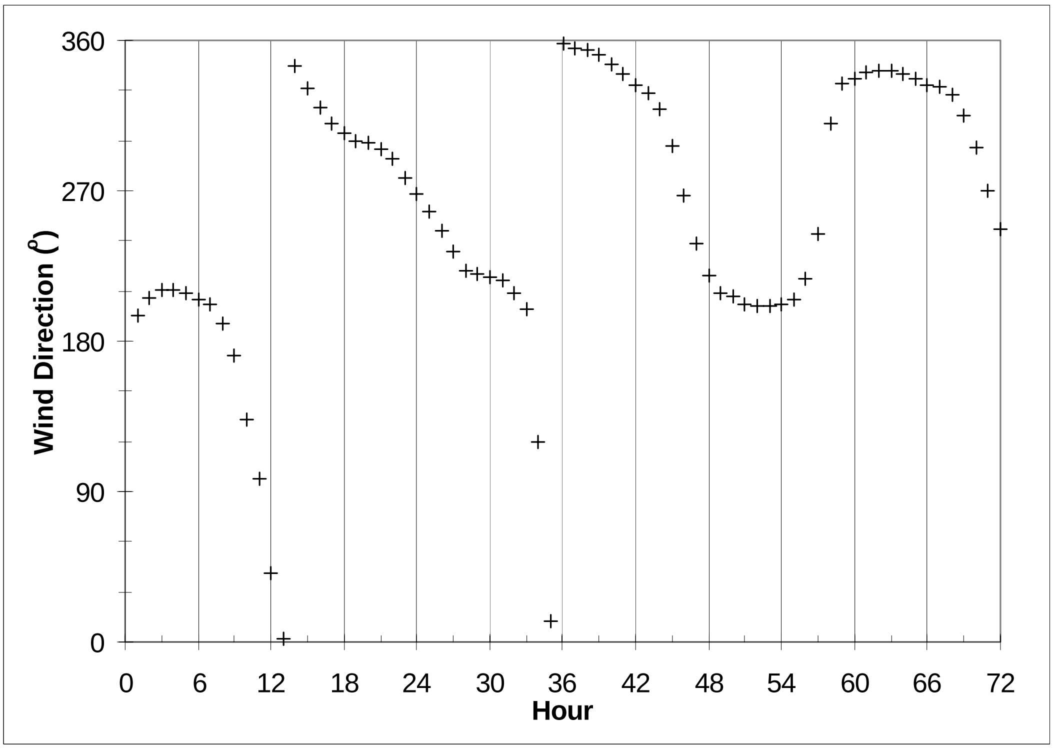
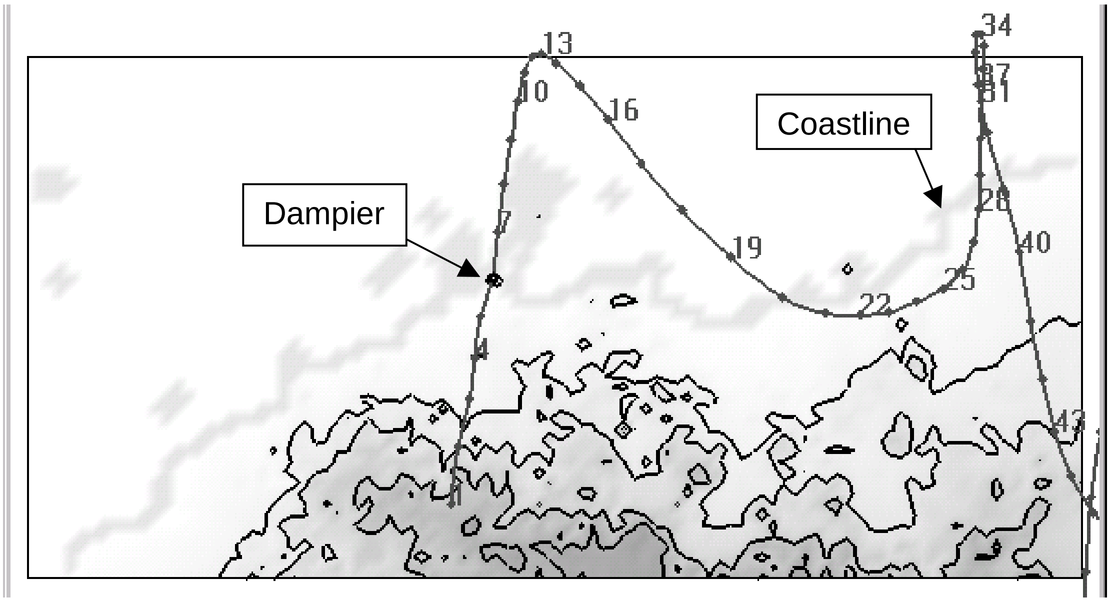


Figure 4.6: Modelled wind speed and direction at a height of 10 m at Dampier from 23 – 25 September 1996.



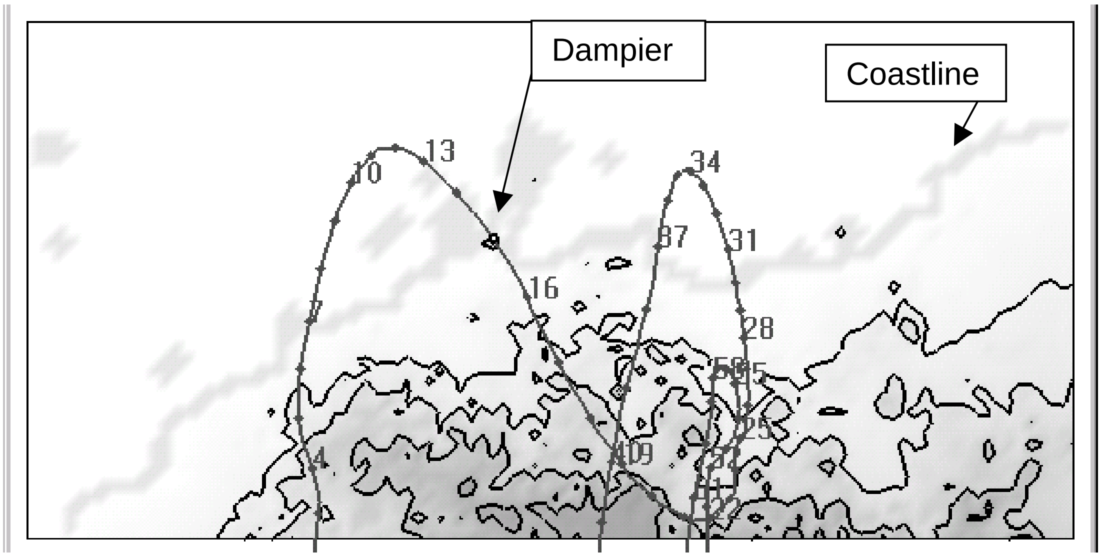


Figure 4.7: Trajectory of a marked particle released at a height of 10 m from Dampier at 0600 LT (top) and 1500 LT (bottom) on day 1 of the 3-day simulation of the period 23-25/9/96. Numbers on the trajectory denote hours from 0000 LT on day 1.

5. Air pollutant levels

For each month from May 1998 to January 1999, the highest observed hourly-averaged concentrations of ozone, nitrogen dioxide and carbon monoxide, and 24-hourly averaged concentrations of PM10 at Dampier are shown in Table 5.1. The NEPM standards are also shown in the Table. The monitor is less than 2 km from Hamersley power station and about 9 km from the Woodside LNG plant, both to the northeast.

The secondary pollutants O_3 and NO_2 are formed from NO_x and volatile organic compounds (VOCs) in the presence of sunlight, although a small percentage (probably about 10% for current Pilbara industries) of emitted NO_x is NO_2. However, NO_2 forms quickly from NO and background ozone soon after being emitted. The process for ozone is slower and the largest regional values for ozone would not be expected at the Dampier monitor. The maxima of Table 5.1 are certainly not high values when compared to the NEPM standards, with the O_3 concentrations not greatly above the background concentration, which ranges from about 14 ppb in May to 21 ppb in January.

There is always the possibility of recirculation of emissions back to the source area, in which case higher values of O_3 and NO_2 are likely as the chemistry has then progressed further than for the case of a direct trajectory from source to monitor. To explore this possibility further, the twenty highest concentrations each month are plotted in Figure 5.1 against the corresponding wind direction at the monitor. For NO_2, the direct trajectory from source to monitor is evident in the clustering of values about the northeast direction. However, many of the highest values occur for directions ranging from southeast clockwise around to north. The dominant directions for ozone maxima are north and west, both off the sea, and occur from about midday to early evening. Ozone maxima associated with winds from the southwest sector arrive between 1900 and 2400 WST. These plots suggest that further work should be done on the trajectory of the ozone parcels, using a mesoscale model with photochemistry, such as TAPM, for case-study days.

Table 5.1: Maximum hourly-averaged concentration of ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO) and 24-hour averaged concentration of particulate matter (diameter less than 10 μm) observed at Dampier for each month from May 1998 to January 1999. The last row contains the NEPM standard for each pollutant.

	O_3 (ppb)	*NO_2 (ppb)*	*CO (ppb)*	*PM10 ($\mu g\ m^{-3}$)*
May	27	-	167	36
June	30	13	233	22
July	30	14	617	40
August	34	15	250	27
September	32	17	233	36
October	35	15	667	39
November	34	9	200	36
December	37	14	370	44
January	41	16	183	40
NEPM	**100**	**120**	**3000**	**50**

Table 5.2: Maximum hourly-averaged concentration of nitrogen dioxide (NO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and 24-hour averaged concentration of particulate matter PM10 (diameter less than 10 μm) and particulate matter PM2.5 (diameter less than 2.5 μm) observed at Boodarie for each month from January 1998 to January 1999. The last row contains the NEPM standard for each pollutant.

	NO_2 (ppb)	*NO_x (ppb)*	*SO_2 (ppb)*	*PM10($\mu g\ m^{-3}$)*	*PM2.5 ($\mu g\ m^{-3}$)*
January	16	53	4	147	35
February	12	35	2	88	26
March	14	35	2	47	16
April	20	45	5	35	8
May	22	58	5	30	11
June	17	79	6	22	10
July	22	80	25	21	8
August	21	110	9	46	13
September	16	42	6	21	9
October	10	23	17	35	13
November	14	21	3	28	12
December	12	21	2	69	10
January	10	17	1	49	15
NEPM	**120**	**-**	**200**	**50**	**-**

Carbon monoxide maxima occur for all wind directions, but they are very low compared to the NEPM standard. 24-hour mean PM10 concentrations in Table 5.1 are closer to the NEPM standard than any of the other pollutants. As the highest hourly-averaged values are highly correlated (positively) with wind speeds, it is most likely that dust is the dominant source of PM10, especially as there are only small sources involving internal combustion engines and the use of gas as an industrial fuel does not produce particles. The clustering of hourly-averaged PM10 maxima between 250 and 270 degrees in Figure 5.1 is probably due to dust emissions from the Hamersley ore loading facility on East Intercourse Island, about 4 km west of the monitor.

Table 5.2 shows the monthly variation of the maxima for various pollutants at Boodarie. NO_2 concentrations are a little higher than at Dampier, but still well below the NEPM standard. SO_2 values are also low. The one larger reading for SO_2 in July occurred at 2200 LT in light winds from the east-northeast. The considerably high 24-hour mean PM10 values occurred on days with high winds, with PM2.5 to PM10 ratios on these days of about 0.2, strongly suggesting that dust was the dominant contributor to the maxima. For the whole monitoring period, the average ratio is 0.58. Figure 5.2 shows that the largest PM10 concentrations occur when the wind is from the east, although a westerly wind can sometimes produce high readings. SO_2 and PM2.5 maxima are found for virtually all wind directions, as are NO_2 maxima although the majority occur when the wind has an easterly component. Interestingly, all NO_2 maxima occur between 1600 WST and 0900 WST the following day, suggesting that an ozone monitor in the area would provide valuable data.

In summary, air quality levels in the vicinity of the sources in the Pilbara are comfortably below NEPM standards, and are probably so throughout the region.

However, the data analysis at both locations has suggested the existence of recirculating flows with the potential to return pollutants to the sources and towns.

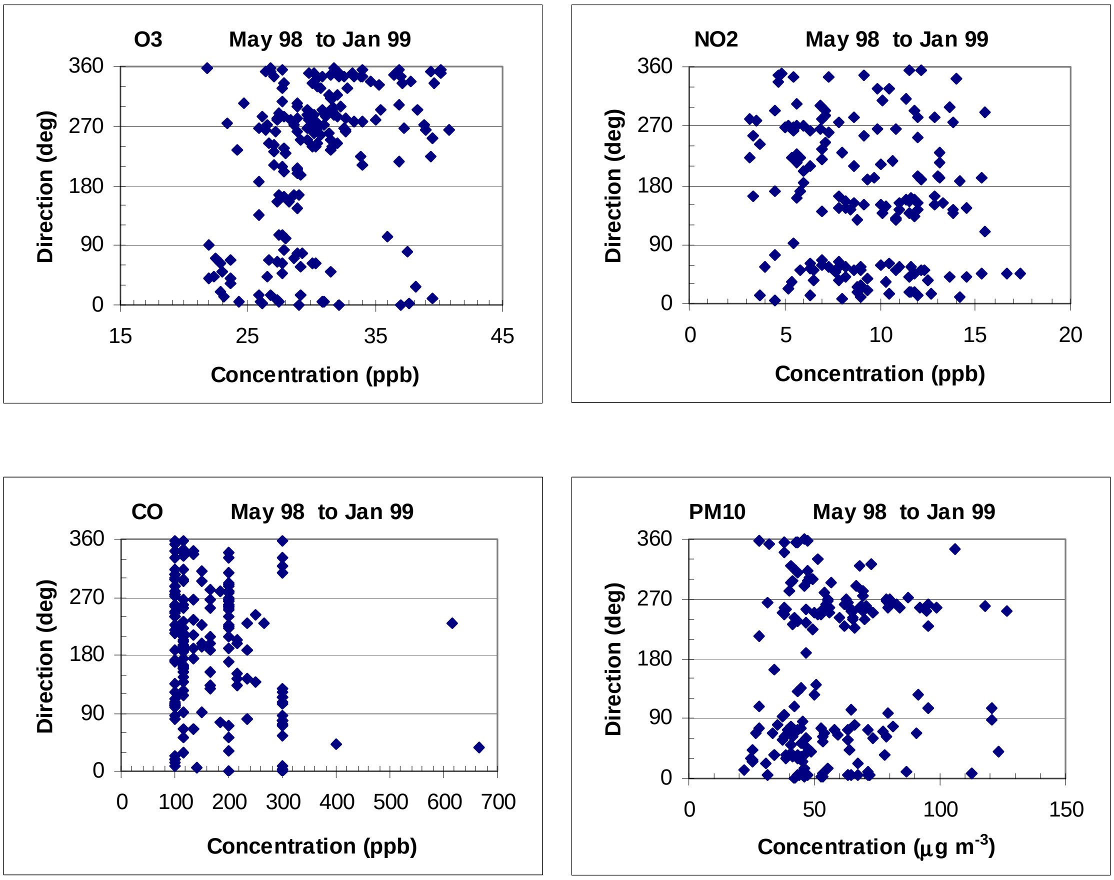


Figure 5.1: Wind direction plotted against the highest twenty hourly-averaged concentrations each month of ozone, nitrogen dioxide, carbon monoxide and PM10 at Dampier. Data range from May 1998 to January 1999.

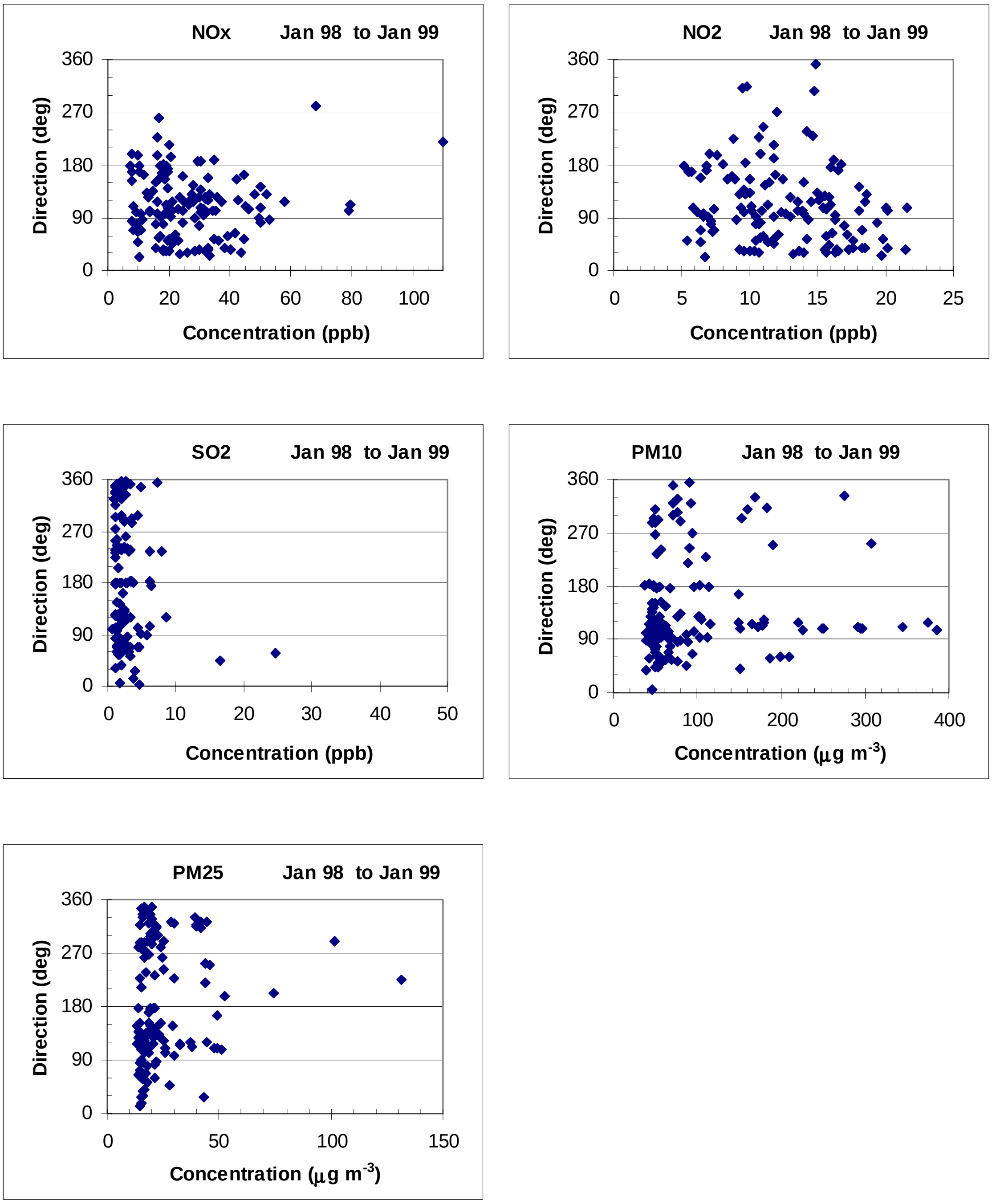


Figure 5.2: Wind direction plotted against the highest twenty hourly-averaged concentrations each month of ozone, nitrogen dioxide, carbon monoxide, PM10 and PM2.5 at Boodarie. Data range from January 1998 to January 1999.

6. Summary and Discussion

A summary of the findings and further discussion are presented by addressing the aims of the Study, which were to

- *document and obtain an understanding of the year-round meteorology in the coastal area extending from the Burrup Peninsula to Port Hedland. Particular attention will be paid to those mesoscale characteristics of the meteorology which are important for the dispersion of emissions from local industry.*

For six sites, monthly averages of wind speed and direction at 2-hourly intervals were calculated for the period February 1998 through to January 1999. This is considered an efficient way to examine the seasonal behaviour of the surface winds in the region and also the variability between sites. While examination of these plots showed a strong seasonal variation of the monthly-averaged winds at each site, there was little difference in the winds from site to site for any given month. This was especially so for wind direction.

It was found that there are three dominant wind patterns in the coastal region of northwest Australia between Karratha and Port Hedland: an *easterly* pattern in which winds vary between northeast and southeast over the diurnal period, a corresponding *westerly* pattern in which the winds vary from northwest to southwest, and a *rotation* pattern in the which the wind direction rotates anti-clockwise through 360 degrees over 24 hours. Surface winds are invariably onshore from the northwest quadrant during the daytime in the months of September through to April. By midnight, and usually earlier, they have turned to offshore with a southerly component. The wind usually remains in the southwest sector during the night, but can turn to the southeast in the transition months. During May to August, the daytime onshore winds are from the northeast sector and at night-time from the southeast. However, for all months of the year it was found that there are days, and series of days, on which the *rotation* pattern prevails. These days, which are more frequent in March, April, August and September, are likely to be important for the recirculation of pollutants.

Upper winds to a height of 750 m from a sodar system were examined for January, April, July and October. Onshore/offshore surface perturbations to the generally easterly flow in July were observed to less than a height of 100 m, but for the other three months, the diurnal rotation of the winds, previously found in the analysis of the surface winds, was also evident to the upper limit of the sounder (750 m). There was very little directional shear with height, leading to the conclusion that in the coastal region of the Pilbara on many single and consecutive days of the year there is a mass of air at least 750 m deep rotating with the diurnal period. Results from some modelling experiments with a mesoscale model (TAPM) suggest that the rotation extends only to about 1000 m and may be a synoptic-scale feature of the region, rather than being only a consequence of sea and land breezes in the coastal area. Trajectories at a height of 10 m from a simulation over a three-day period in which the winds rotated diurnally showed that emissions from the Burrup Peninsula can meander up the coast to Port Hedland, moving onshore and offshore with sea breezes and the nocturnal flow off the land.

Analysis of daily 0700 WST and 1900 WST radiosonde flights from Port Hedland in January 1999 revealed that the sea-breeze circulation is about 2000 m deep, with a speed maximum at a height between 200 and 400 m and a minimum between 1200 and 1400 m. The 0700 WST temperature profiles showed a surface-based mixed layer on every day except one (which occurred when the low-level wind was from the northeast). The most common depth of the mixed layer was 500 m. It is likely that the mixed layer arises from cool air (radiatively cooled over land at night?) travelling over a warmer sea, although it is not immediately obvious as to why air arriving from the southwest soon after sunrise should be well mixed to heights of typically 500 m. This is one of a number of questions that can be examined further with a modelling approach. Above the mixed layer, a strongly stable layer (a typical increase of 6 K potential temperature over 200 m) was found beneath a less stable layer. Relative humidity in the mixed layer (typically between 65 and 80%) increased linearly with height, and decreased to much smaller values rapidly at higher levels.

The 1900 WST profiles all showed a mixed layer below the strongly stable layer. On the majority of days the depth was the same as found for the 0700 WST profile, but on some occasions it was lower. On one day it was higher.

From the profiles of wind, temperature and relative humidity for two January days on which sondes were released from both Dampier and Port Hedland, it was concluded for this month that there are no important differences in the dispersion meteorology between Dampier and Port Hedland. Given the similarity in the surface winds at both locations for November through to February, the above conclusion could perhaps be extended to these months too, although it is recommended that the fine-resolution radiosonde flights at both locations continue to be carried out.

- *summarise the air quality data from the monitors at Dampier and Boodarie, and relate any elevated levels to the prevailing meteorology.*

For all pollutants except PM10, air quality levels in the vicinity of the sources in the Pilbara are comfortably below NEPM standards, and are probably so throughout the region. The maximum concentration (hourly-averaged) recorded for ozone was 41 ppb, for nitrogen dioxide 17 ppb at Dampier and 22 ppb at Boodarie, and for sulfur dioxide 25 ppb. The 24-hour averages for PM10 at Dampier are below the NEPM standard, but the monthly maximum at Boodarie exceeds it for three months. The maxima can be attributed to dust raised from the surface.

The data analysis at both locations suggested the existence of recirculating flows with the potential to return pollutants to the sources and towns. Ozone maxima at Dampier occur in the afternoon when the wind is from the northwest sector (off the sea), and in the evening when the wind has backed to the southwest sector. At Dampier and Boodarie, nitrogen dioxide maxima were found not only as a result of direct trajectories from source to monitor, but also from westerly directions, which must involve recirculating flows.

- *assess the adequacy of the current meteorological and air quality monitoring network.*

It is not possible to recommend a final expanded network until substantial modelling work is done, but the data analysis has already shown the importance of specific observations. The high-resolution radiosonde flights each morning and evening from Port Hedland are yielding very important wind and stability data, and if a 12-month data set can be obtained, can form an important part of an annual meteorological file for models such as DISPMOD and AUSPLUME. Continuation of sonde flights from Dampier will yield valuable data for comparison with the Port Hedland measurements. If more simultaneous flight times can be arranged, the comparison would give greater insight into the validity of using the daily Port Hedland data in a meteorological file for running models at Dampier. The overwhelming majority of days examined so far exhibit early-morning mixed layers at least 100 m deep and it is important to see whether this is the situation for all months of the year.

At Dampier, sonde flights from more than one location on the same day would be desirable to obtain data on the growth of the thermal internal boundary layer (TIBL) with distance inland. The current sonde site and the Karratha site would be quite suitable, and perhaps another site further inland if possible. Also, more than one flight (e.g. early morning and mid-afternoon) from the same location would provide additional data on the time-varying nature of the sea breeze.

The town of Karratha would appear to be downwind of the emission sources in sea-breeze conditions for much of the year, at least as often as Dampier, and may receive elevated concentrations due to either fumigation or the convective knockdown of plumes within the TIBL. An air quality monitor in the town would be useful.

Another meteorological station and air quality monitor further inland (25-30 km) would provide information on the penetration of the sea breeze and the development of photochemical smog. Site selection should perhaps wait until modelling work has been carried out.

Mixed layers in onshore flow was also a finding from the Kwinana field experiment in 1995. However, the Kwinana data showed that the mixed layer at the coast was not turbulent over its full depth, an important finding for plume dispersion. Measurements should be undertaken to determine whether the same situation occurs in the Pilbara region.

The acoustic sounder provided valuable and reliable data and should be continued.

Sea-surface temperatures used in TAPM are long-term monthly averages on a 1^o x 1^o lat-long grid, but higher resolution daily data would be useful both for modelling and for determining the relative temperatures of surface air over land and over sea.

- *select days which can be used as worst-case scenarios for (a) the evaluation of models, and (b) for modelling the impact of modified or additional sources in the region.*

Data analysis has shown that most days have winds off the sea and that the air crossing the coast is well-mixed to a height of at least 100 m, with a very strong stable layer above. A stable profile was observed at the ground on only two out of 42 morning flights. Days to be modelled should be chosen from those on which there are upper-air sonde data, and should be divided into two categories. The first category should include those days for which the winds, at least for part of the day, are directing emissions towards the monitor. This situation should test the ability of a model to simulate the convective mixing and fumigation processes. The second type of day chosen should be those on which recirculation of pollutants occurs, either back to the source or further along the coast.

Annual modelling should also be done with different models, as recommended below.

- *discuss which models are suitable for impact assessments in the region, and whether there are restrictions on the conditions under which they may be valid.*

The data analysis has shown that at nearly all times throughout the year, winds are generally onshore in the daytime and offshore at night. Temperature profiles at Port Hedland (7 km inland) and Dampier (on the coastline) show that the onshore winds are characterised by a mixed layer capped by a very strong stable layer, implying that coastal fumigation must be a regular occurrence. An adequate parameterisation of this process is essential in any model to be used for evaluating the impact of emissions in the vicinity of the source. This includes modelling the growth of the TIBL with distance inland and incorporating the strong stable layer above. One model that has a good parameterisation of the fumigation process is DISPMOD, which is used to set emission limits for industry at Kwinana, located on the coast south of Perth. Models such as AUSPLUME and AUSPUFF/CALPUFF may produce valid predictions on those occasions when sources emit into the mixed layer and do not rise through the capping layer, but will not model fumigation situations properly.

TAPM is able to simulate fumigation and convective mixing properly, but uses predicted values for the meteorological variables whereas the other models use observations. In the related Study evaluating air quality models in the Pilbara, it is planned to produce a 12-month meteorological file using TAPM, and use it to run DISPMOD and AUSPLUME, comparing the results to a TAPM run, and to runs of the models with an observed meteorology file. This will give some insight into the use of TAPM in data-sparse areas to produce meteorological files for simpler models.

Models such as DISPMOD, and AUSPLUME cannot model situations when emissions are brought back to near the sources by re-circulating flows, nor are they, along with AUSPUFF/CALPUFF, suitable when photochemistry is important. Under these conditions, it is necessary to use an air chemistry model (e.g. CIT, SAQM) coupled to a prognostic mesoscale model (e.g. TAPM, DARLAM, MM5), or the LADM system with its simpler (IER) chemistry. TAPM, which uses the GRS mechanism of Azzi *et al.* (1992) for gas-phase photochemistry and also includes aqueous phase reactions, is also a suitable model, especially given its coupling to the Bureau of Meteorology LAPS analyses and its significant speed advantage over the other models. It is the most appropriate model to use where simulations involve many days.

7. References

Azzi, M., Johnson, G.M., and Cope, M.E. (1992). 'An introduction to the generic reaction set photochemical smog mechanism.' *Proceedings of the 11th Conference of the Clean Air Society of Aust. and New Zealand, Brisbane, July, 1992.*

Hurley, P.J. (1998). 'Model any region for EIAs on a PC.' *Preprints of the 14th Conference of the Clean Air Society of Aust. and New Zealand, pp 551-555, Melbourne October, 1998.*

Tapp, R. (1996). 'A brief investigation of sea breezes along the Pilbara coast between Port Hedland and Dampier.' *Climate and Consultancy section, Bureau of Meteorology, Perth. Report to Department of Environmental Protection, Western Australia, September 1996.*

APPENDIX A

Plots of monthly-averaged surface wind speed and direction at 7 sites in the Pilbara.

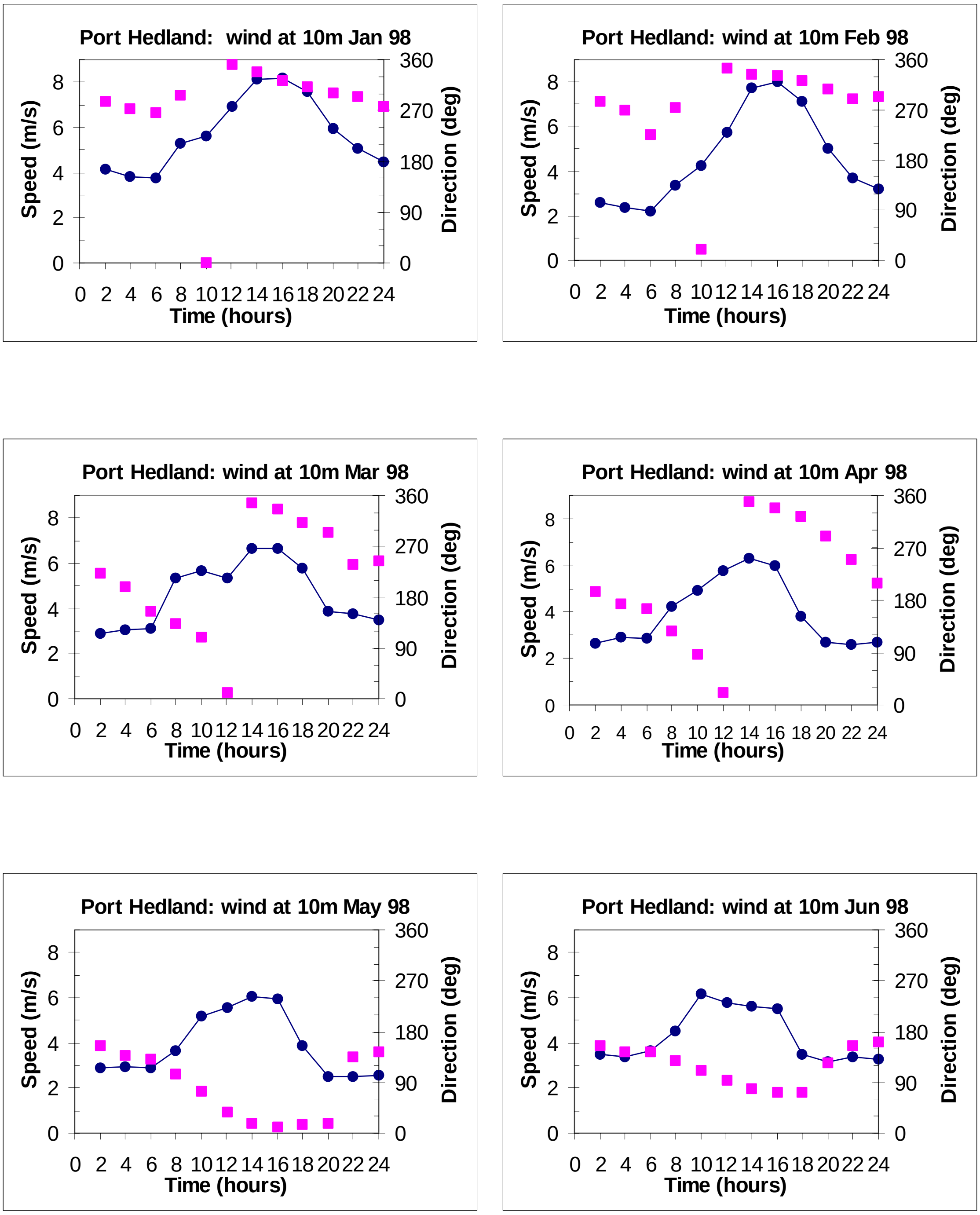
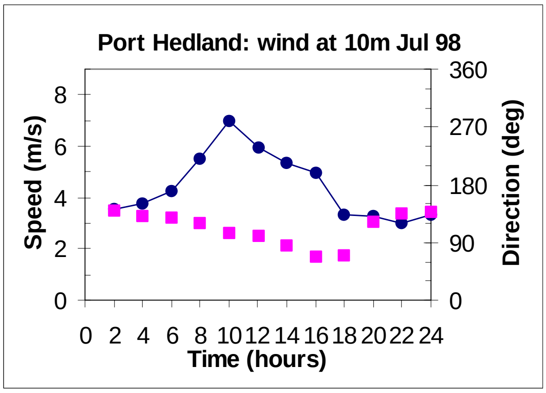
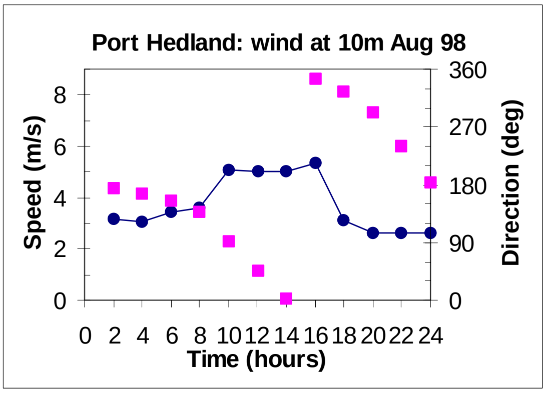
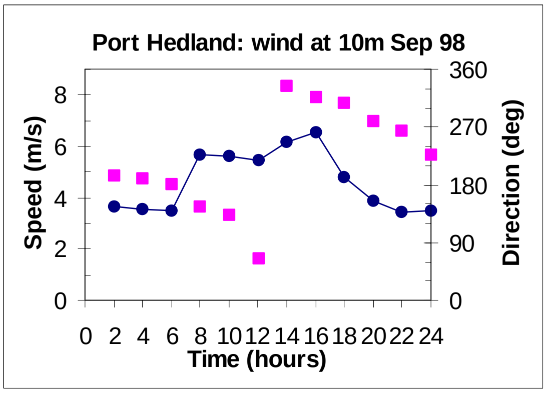
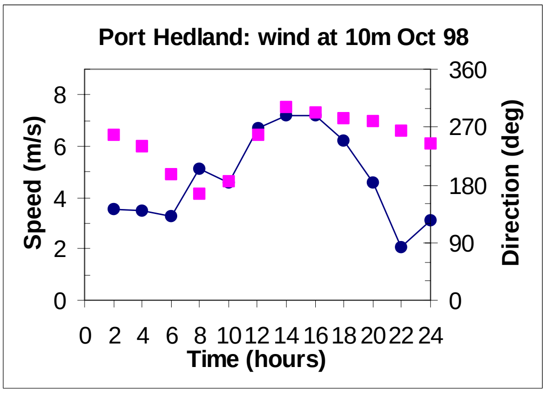


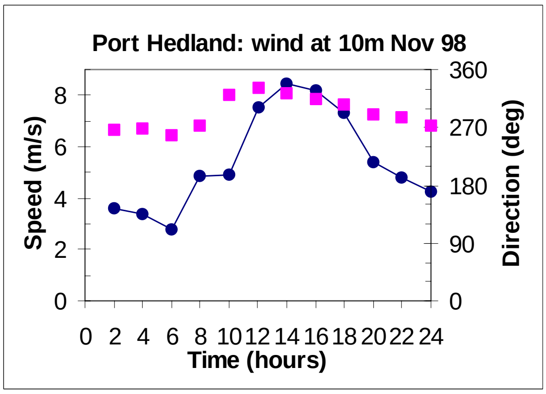
Figure A.1: Monthly-averaged surface wind speed (●) and direction (■) at Port Hedland for January 1999, and February through to December 1998.











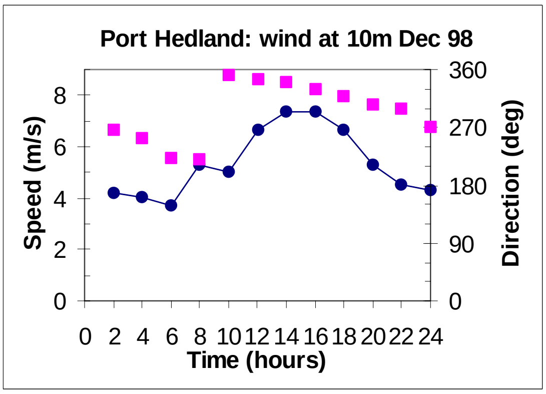


Figure A.1 (continued).

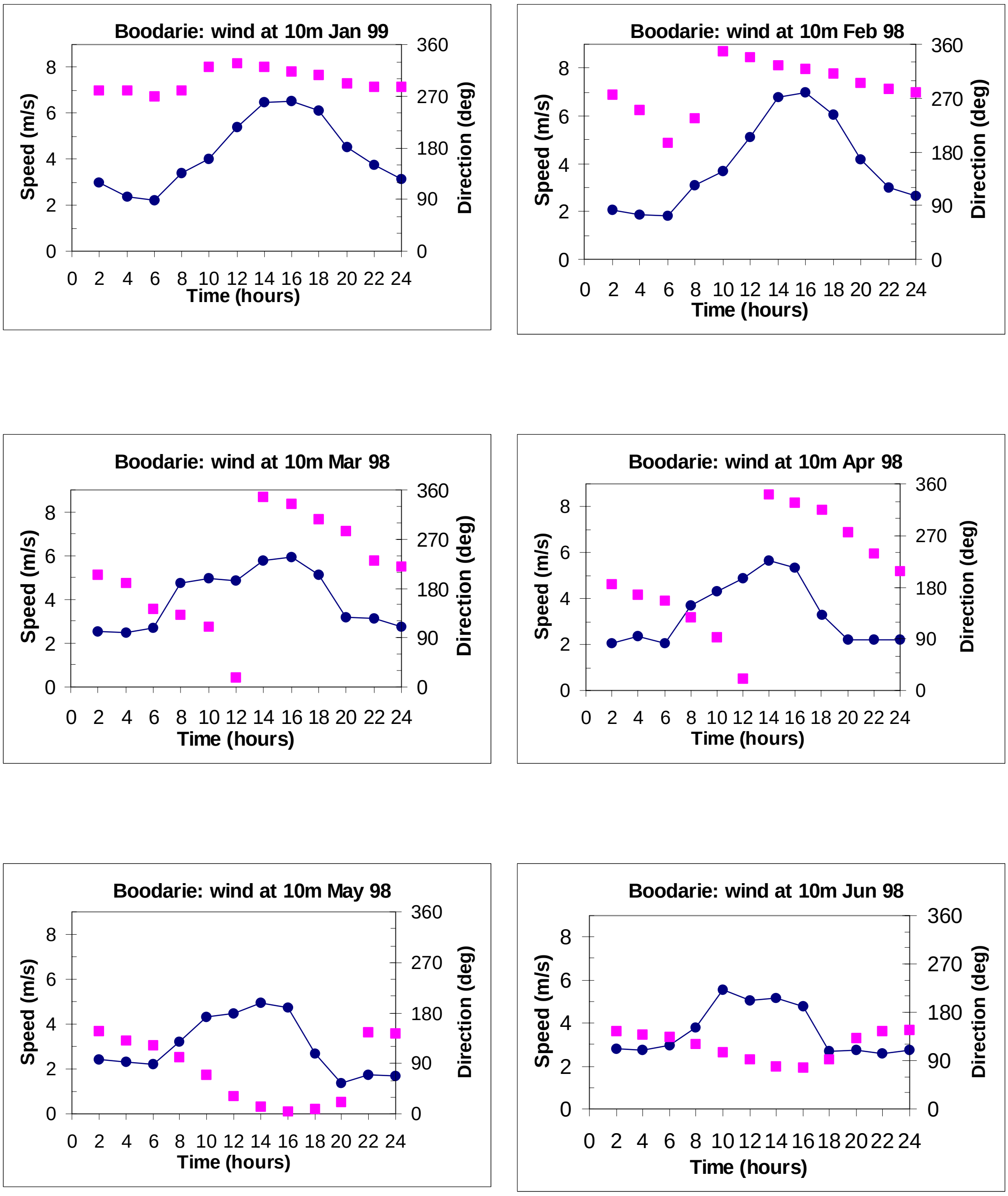


Figure A.2: Monthly-averaged surface wind speed (●) and direction (■) at Boodarie for January 1999, and February through to December 1998.

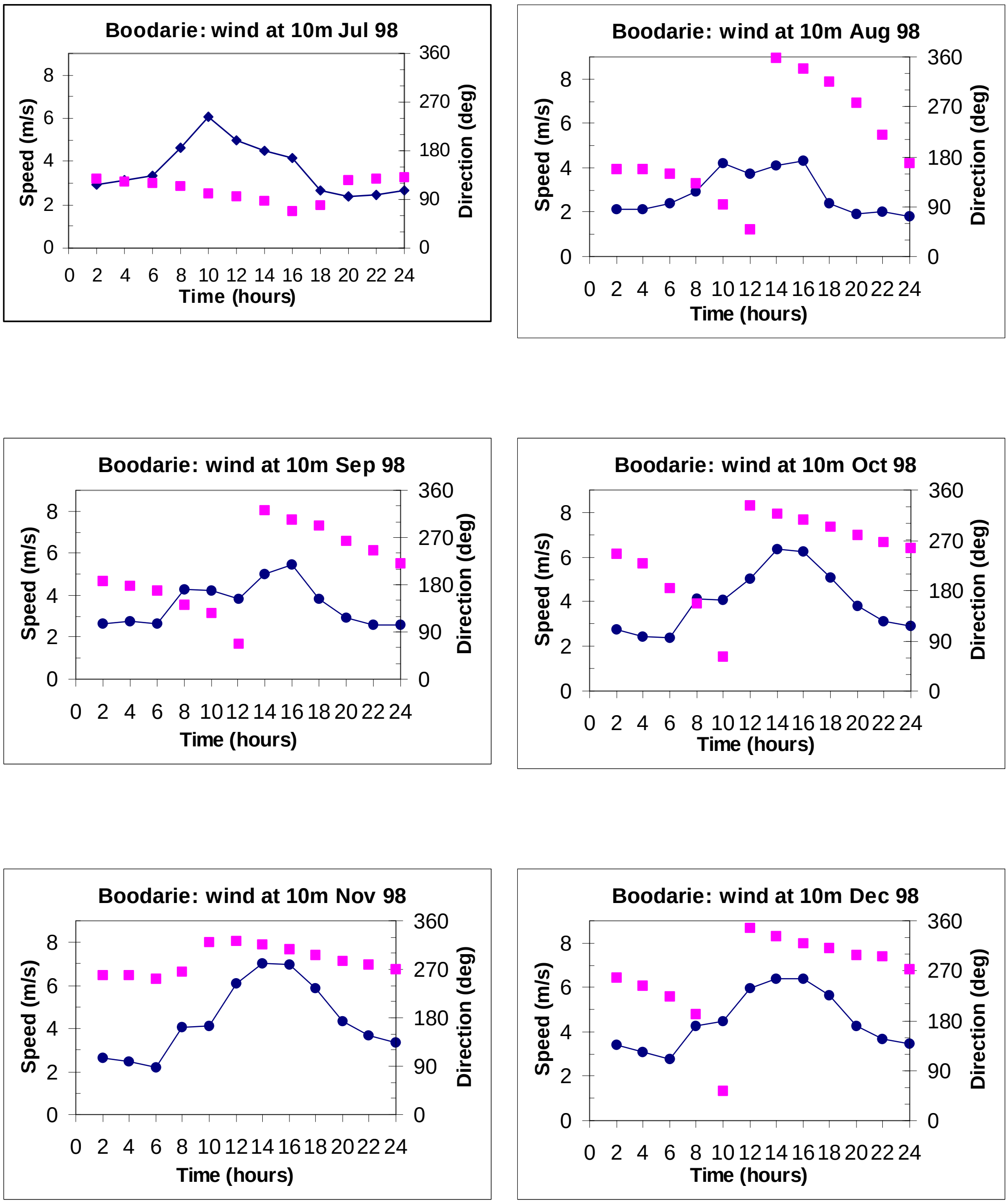
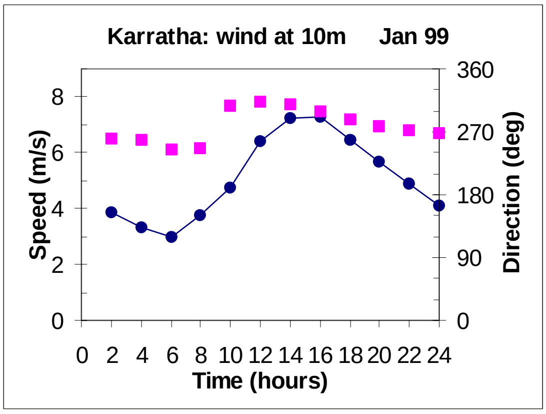
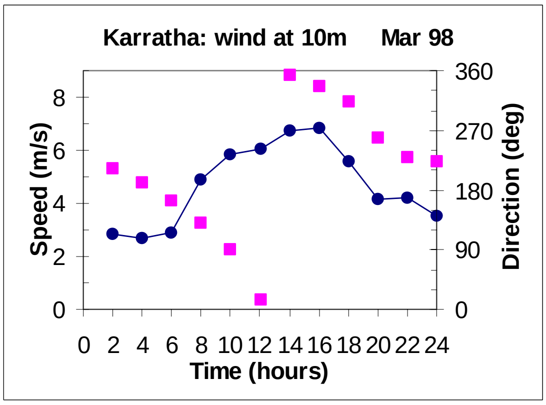
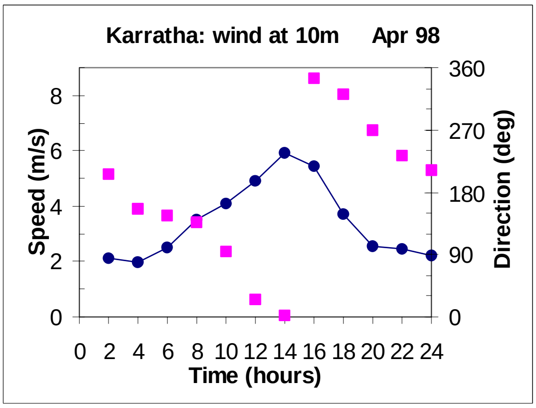


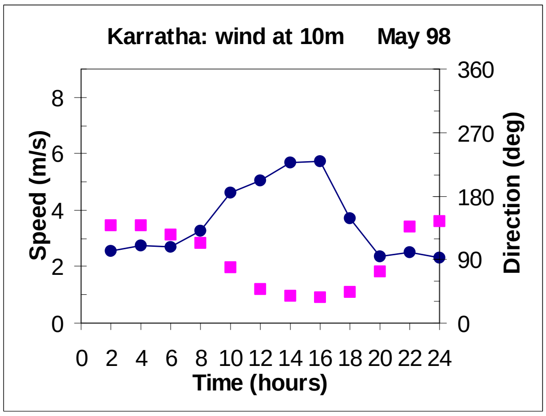
Figure A.2 (continued).



Feb 98 No Data







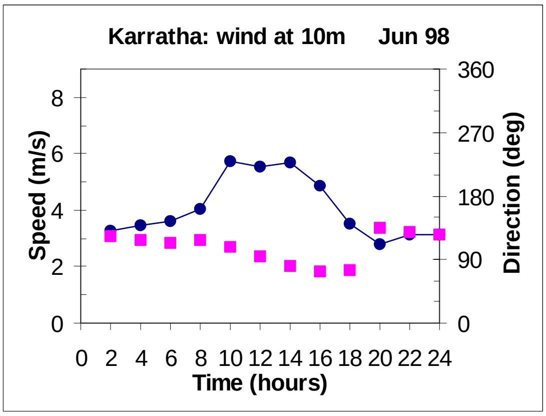


Figure A.3: Monthly-averaged surface wind speed (●) and direction (■) at Karratha for January 1999, and March through to December 1998.

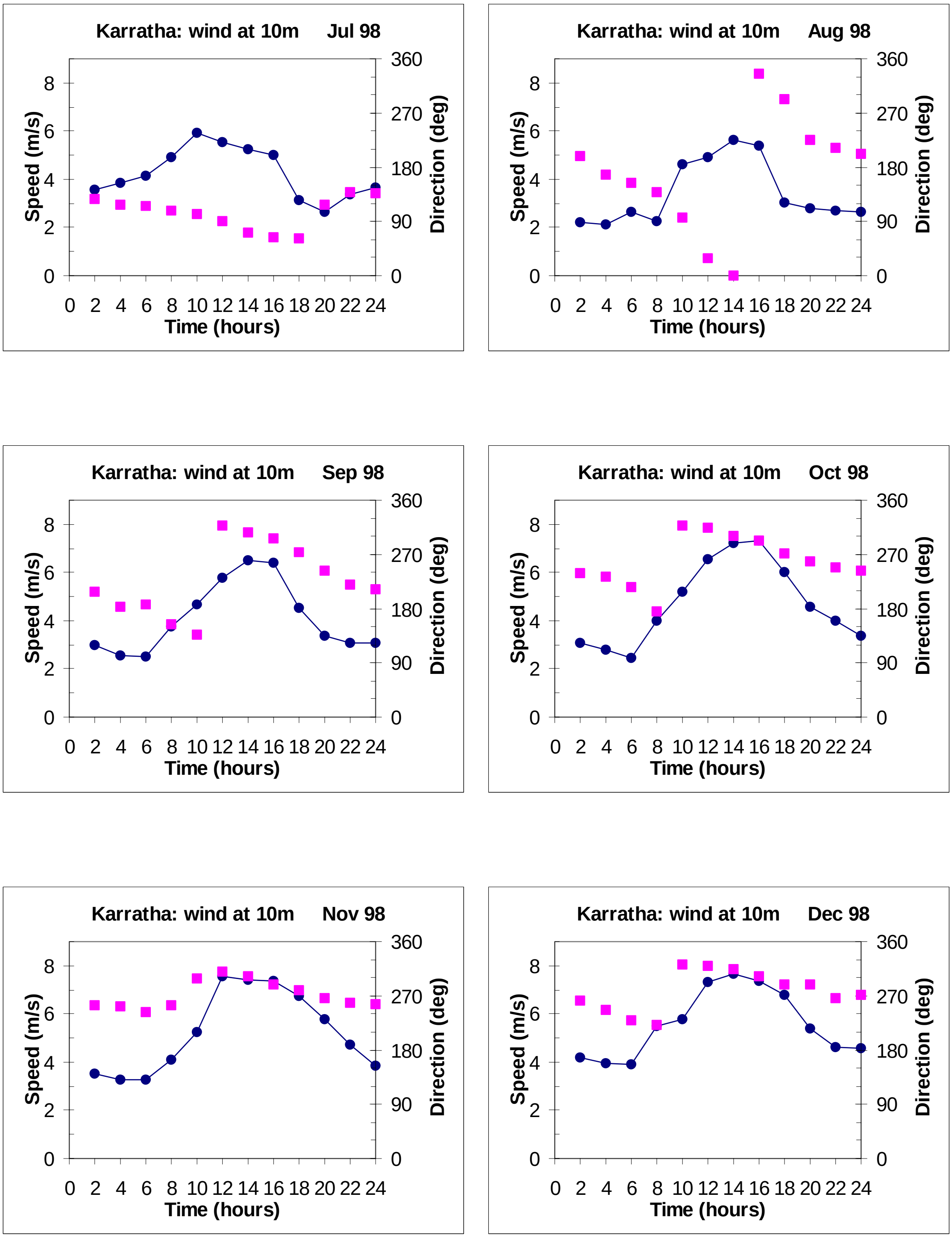
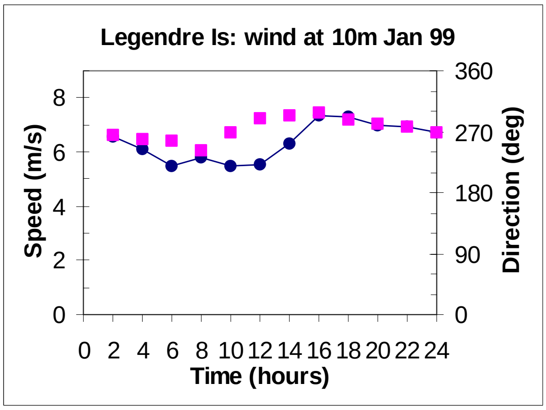
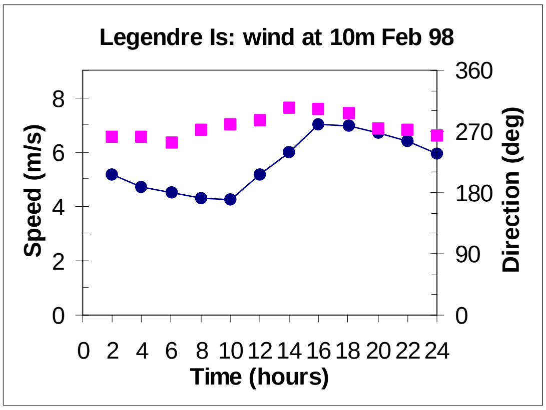
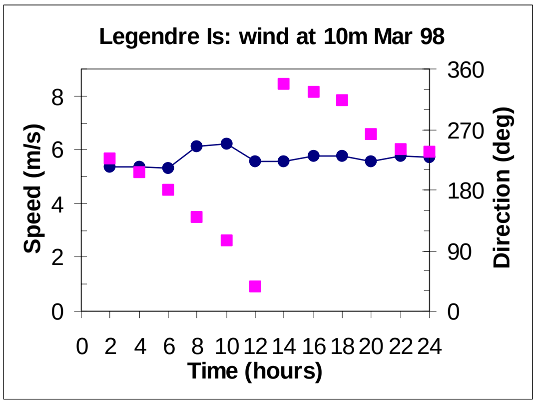
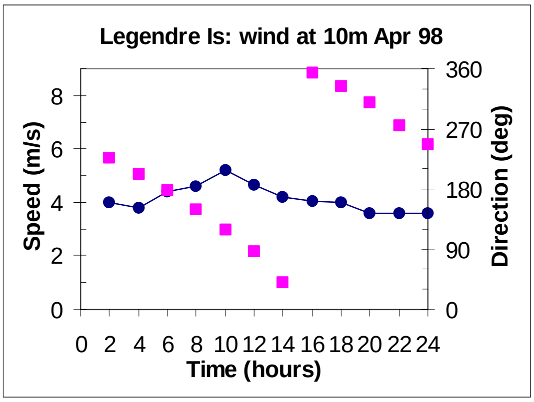


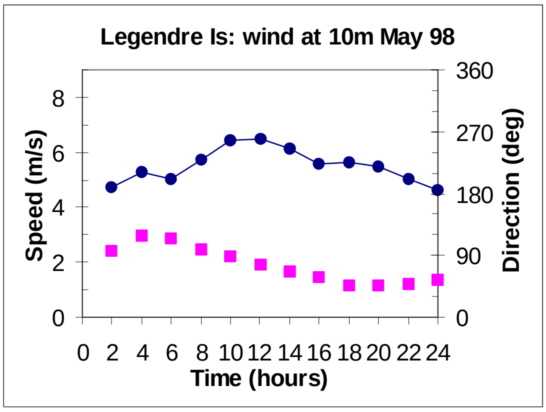
Figure A.3 (continued).









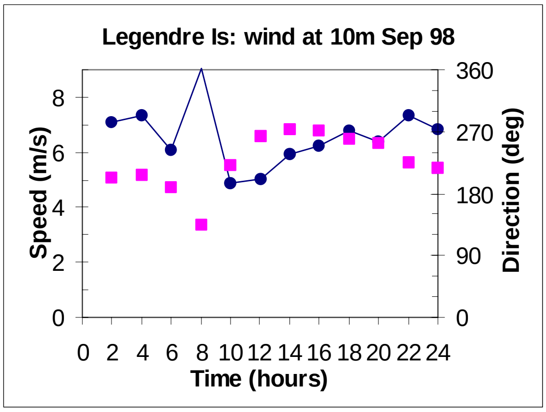


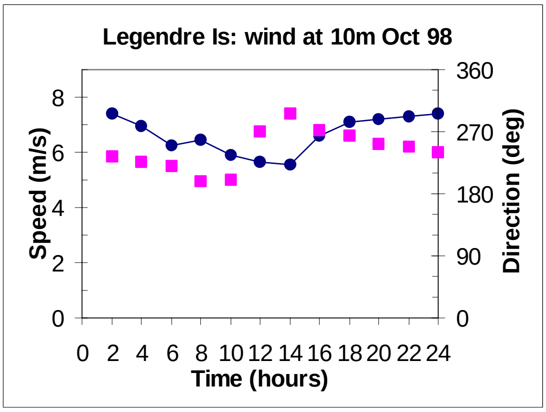
Jun 98 Missing Data

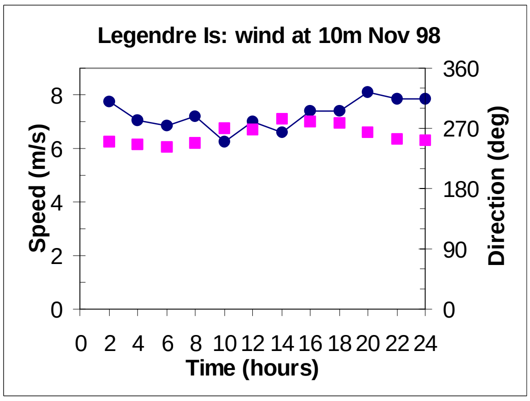
Figure A.4: Monthly-averaged surface wind speed (●) and direction (■) at Legendre Island for January 1999, February through to May 1998, and September through to December 1998.

Jul 98 Missing data

Aug 98 Missing data







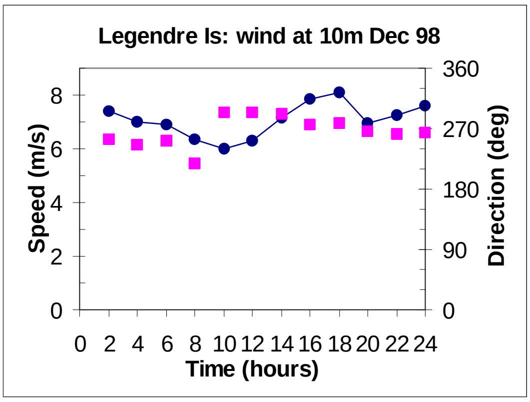
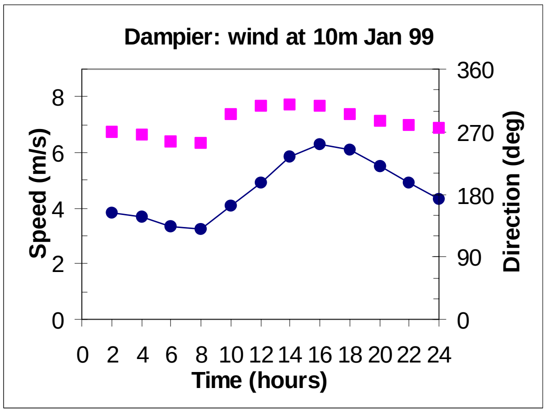


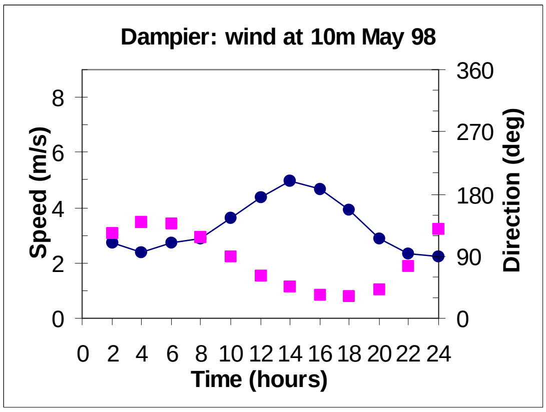
Figure A.4 (continued).



Feb 98 Missing Data

Mar 98 Missing Data

Apr 98 Missing Data



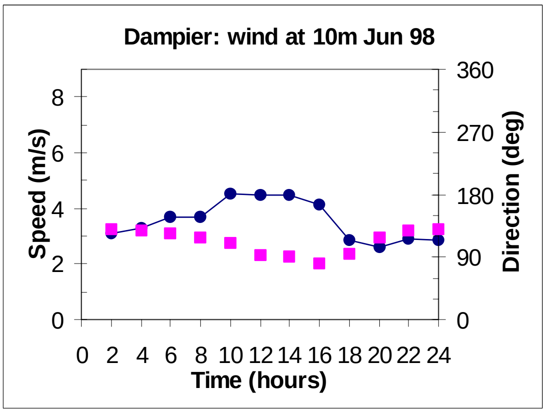


Figure A.5: Monthly-averaged surface wind speed (●) and direction (■) at Dampier for January 1999, and May through to December 1998.

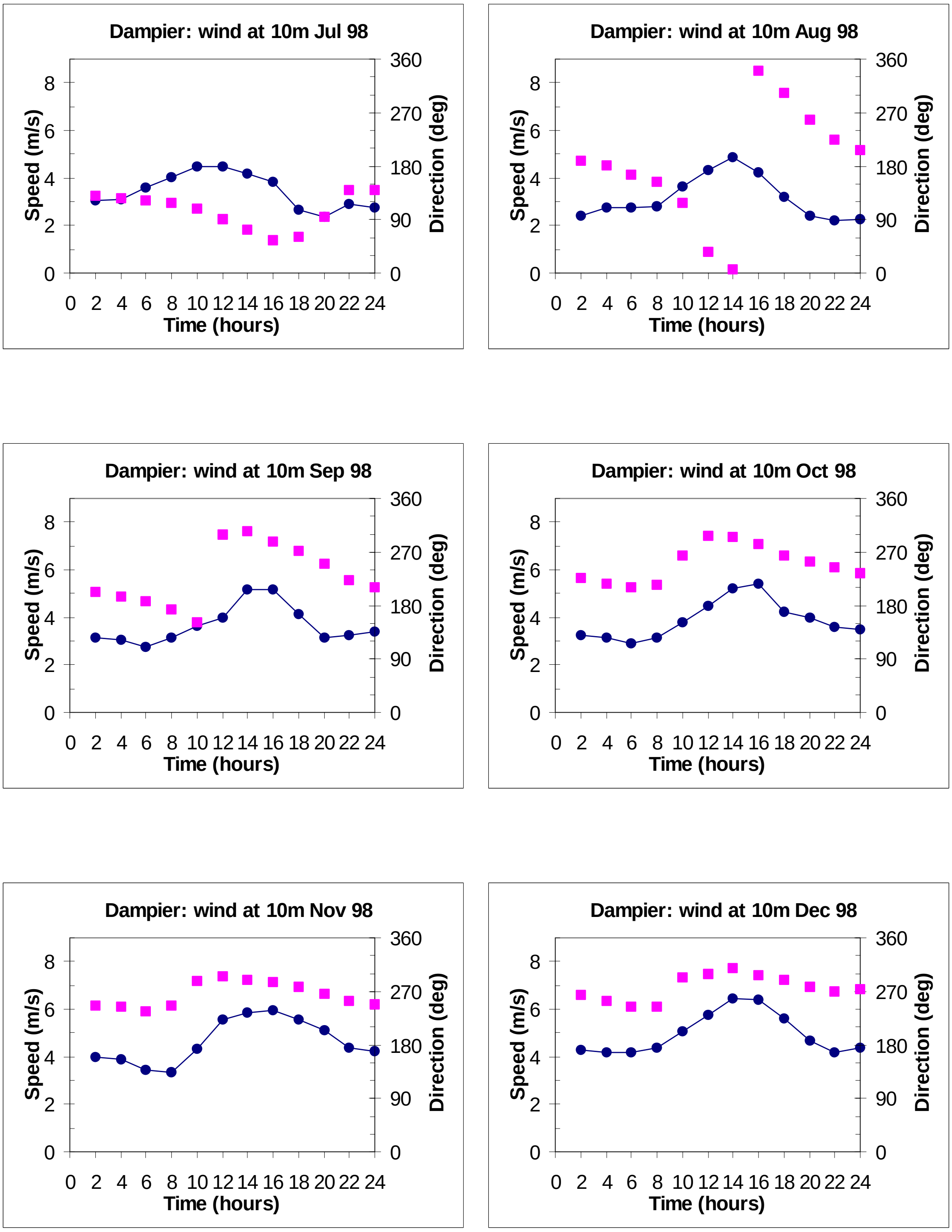


Figure A.5 (continued).

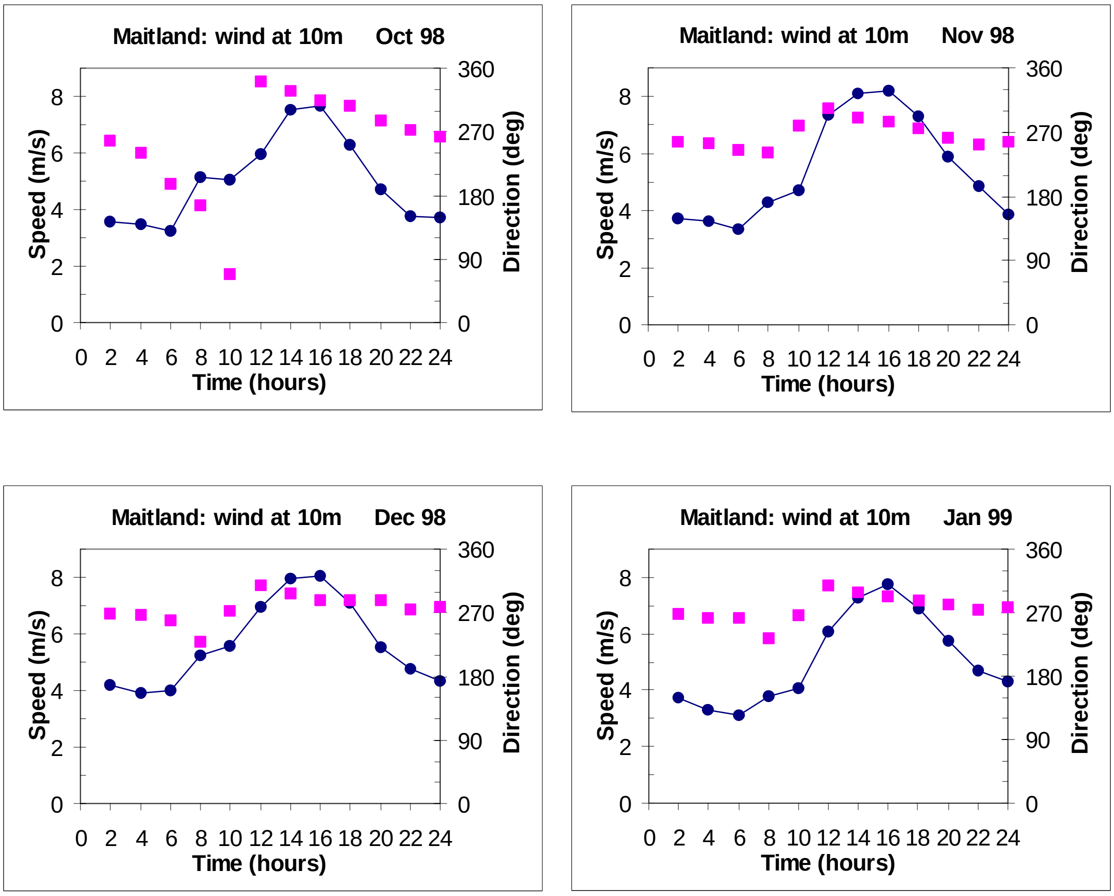


Figure A.6: Monthly-averaged surface wind speed (●) and direction (■) at Maitland Estate for October 1998 through to January 1999.

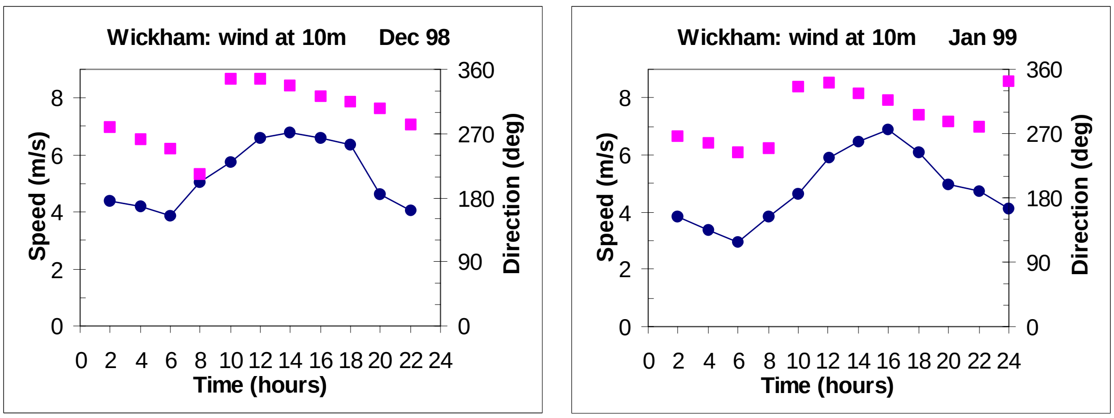


Figure A.7: Monthly-averaged surface wind speed (●) and direction (■) at Wickham for December 1998 and January 1999.