DISPERSION METEOROLOGY OF THE PILBARA REGION

Bill Physick[1], Ken Rayner[2] and Peter Mountford[2]
[1] CSIRO Division of Atmospheric Research, PMB 1 Aspendale, Vic 3195, Australia
[2] Department of Environmental Protection, Perth, Western Australia.

Summary

Air quality data from Dampier and Port Hedland, surface winds at seven stations in the region, and upper-air data from radiosondes and an acoustic sounder, have been analysed. The model TAPM is used to expand the analysis to areas where there are no data. Winds are generally onshore all year round, and are characterised by a mixed layer capped by a very strong stable layer. With the exception of PM_{10}, 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 suggests the existence of recirculating flows with the potential to return pollutants to the sources and towns.

Keywords: Pilbara, sea breeze, air quality, TAPM, TIBL, Burrup Peninsula, Port Hedland, mesoscale model

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. This area is about 200 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 an environmental impact assessment, which includes an assessment of the impact of the industry on the air quality of the region. 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 Department of Environmental Protection (DEPWA) has initiated a Study to collect and analyse meteorological and air quality data in the region. This paper presents some early results of that Study. While it is not a modelling study *per se*, it is intended that its findings will help identify air quality models suitable for the evaluation of development in the region.

2. Data

2.1. Surface data

Monitoring stations for meteorology, including surface wind, temperature (at 2 and 10 m), relative humidity, shortwave and net radiation, pressure and rainfall were installed at Karratha and Dampier (see Figure 1) in the Burrup Peninsula area by DEPWA in 1998. The Dampier station also measures O_3, NO, NO_2, CO and PM_{10}. Meteorological data are also taken at Bureau of Meteorology (BoM) stations at Legendre Island and the airport, and at Maitland Estate by Woodward-Clyde. Beyond the Peninsula region, DEPWA surface data are collected at Wickham, 50 km east along the coast from Karratha, and at Radio Hill, 28 km south of Karratha.

At Port Hedland, 200 km east of the Burrup Peninsula, meteorological data are taken by BoM and BHP, with the latter's station at Boodarie also measuring O_3, NO, NO_2, SO_2, H_2S, PM_{10} and PM2.5.

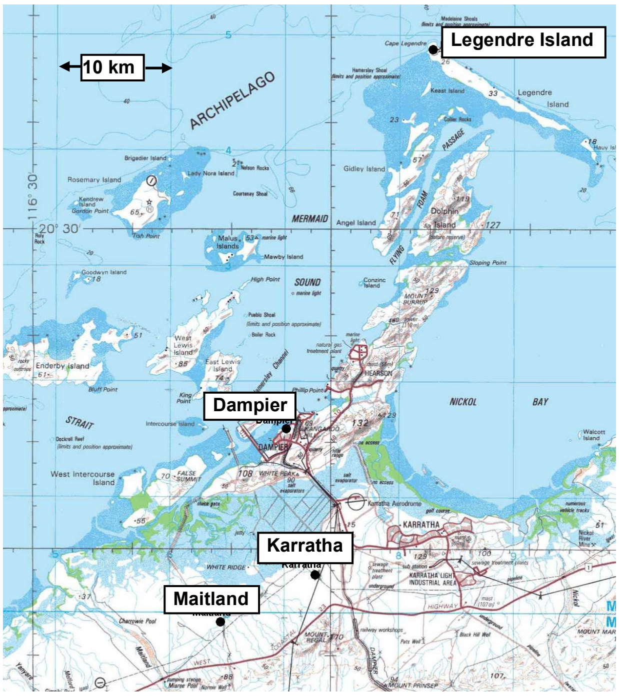


Figure 1. The Burrup Peninsula region, including the data sites Legendre Island, Dampier, Karratha and Maitland.

2.2. Upper-air data

A DEPWA sodar at Karratha measures 30-minute averaged winds at 25 m intervals from the ground to a height of about 800 m. Radiosonde flights have also been carried out at Dampier on selected days.

Routine radiosonde flights from the BoM station at Port Hedland (7 km inland) at 0700 and 1900 Western Standard Time (WST) furnish wind, temperature and relative humidity data at the fine vertical resolution of about 11 m. For 10 days in August 1999, additional sondes were released at 0100 and 1300 WST, with simultaneous afternoon flights from Dampier on five days. A field experiment involving frequent flights at the coast and the BoM station was carried out at Port Hedland for six days in March 2000. However data from August '99 and from the field trip are not discussed in this paper.

3. Analysis of Meteorological Data

3.1. Winds at 10 m

For each site, monthly averages of wind speed and direction at 1-hourly intervals were 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.

While the analysis 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, and is probably a consequence of the flat terrain and long relatively-straight coastline. Strongest winds occur in spring and early summer, with weaker winds in autumn and winter. Sea breezes occur on 50% of days in winter and on 80% in summer, where a sea breeze is defined here as an onshore wind.

The diurnal variation in the monthly-mean direction is most interesting, and is observed at all sites. There are three dominant wind regimes, illustrated for the Karratha site in Figure 2. 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 to 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. This type of day constitutes by far the majority of days in this period, but some days do exhibit the direction behaviour shown for April in Figure 2.

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).

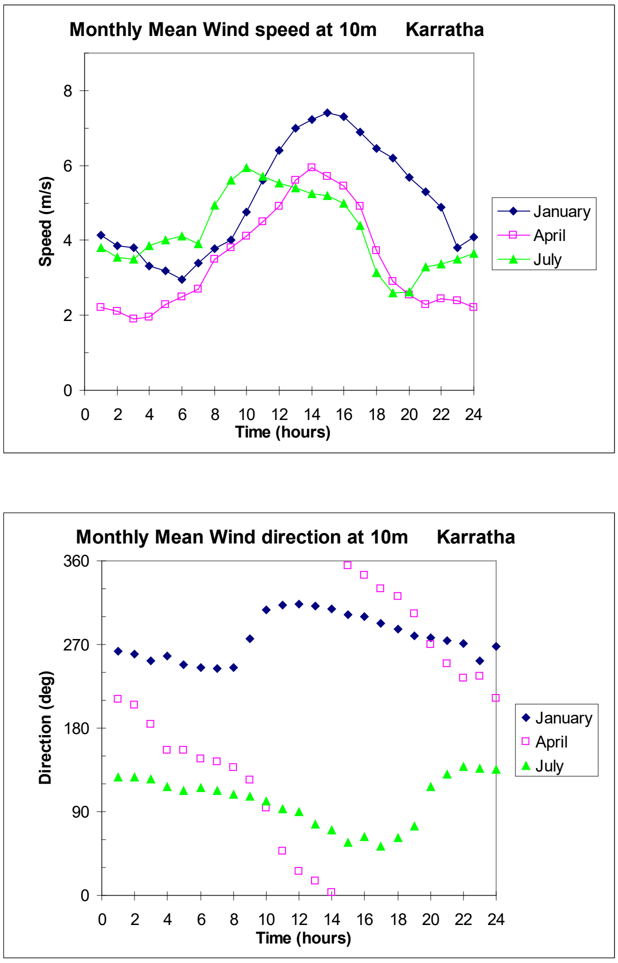


Figure 2. Monthly mean wind speed and direction at a height of 10 m at Karratha for January 1999, April 1998 and July 1998.

In the transition months March, April, August and September (and October at two sites), the behaviour of the mean 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. This type of day constitutes the majority of days in these months, but days with westerly and easterly regime winds are also found.

The finding that the vast majority of days exhibit daytime onshore winds, indicates that the thermal internal boundary layer (TIBL) in this region is likely to be an important factor in the dispersal of pollutants from near-shore sources. Also important are the days exhibiting 'around the clock' behaviour for the wind direction, as the recirculation of pollutants, already found in Australia's major coastal cities, is quite likely to occur.

3.2. Upper-level winds at Karratha

For the recirculation of pollutants, it is important to know the variation of the offshore/onshore wind pattern with height. Monthly mean sodar winds to a height of 750 m are shown in Figure 3 for April 1998. 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. Similar behaviour is found for the March, August and September mean fields. 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.

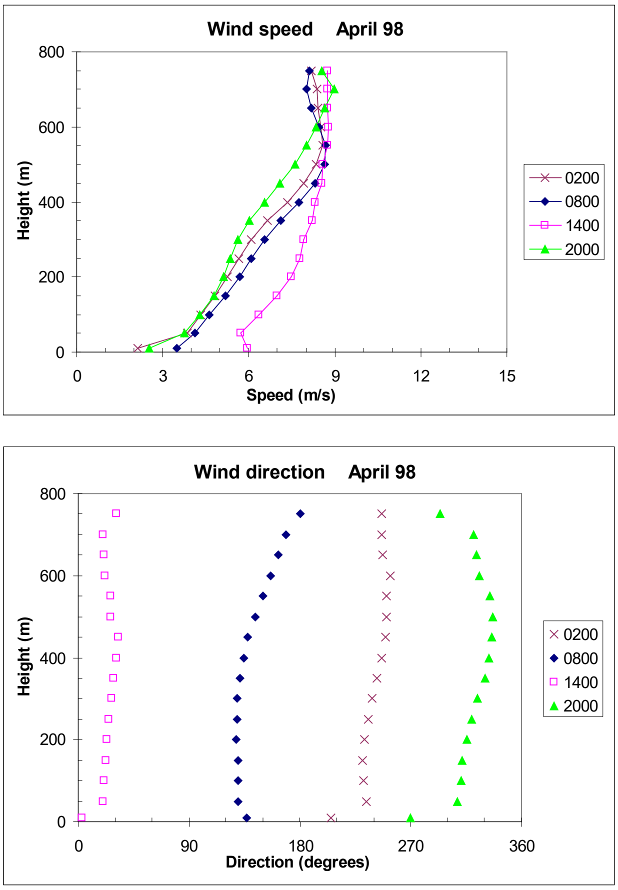


Figure 3. Mean wind profiles at 0200, 0800, 1400 and 2000 WST for April 1998 at Karratha.

3.3. Port Hedland radiosonde data

For most months of the year, the winds at the BoM's Port Hedland radiosonde station (7 km inland) are from an offshore direction at 0700 and 1900 WST. However, for the 25 days in January 1999 for which there were sonde data, surface winds at 0700 WST were onshore on 10 occasions. At 1900 WST, every day exhibited onshore winds. This allowed us to examine the important dispersion characteristics of the flow for this month, such as the mixed-layer depth and the strength of the capping stable layer.

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 4, 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.

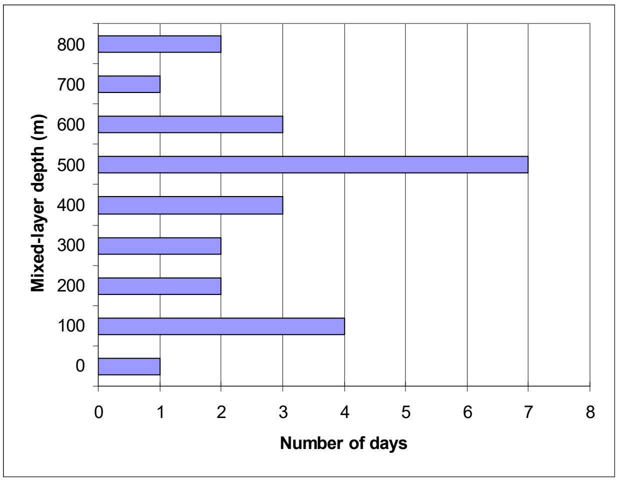
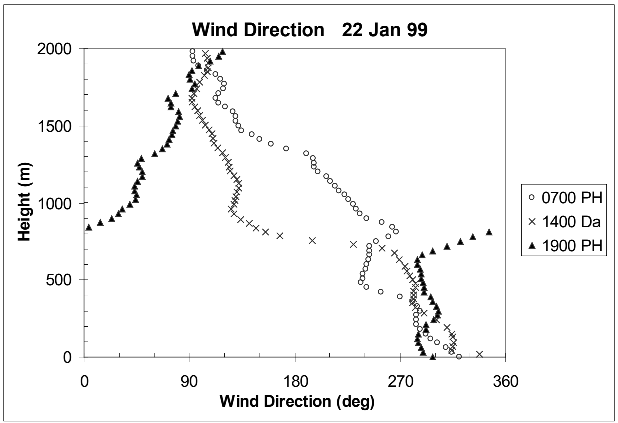


Figure 4. Frequency distribution of mixed-layer depths at 0700 WST at Port Hedland (7 km inland) for January 1999.

The appearance of such deep mixed layers so early in the morning (1.5 hours after sunrise) is a little surprising. It may be that the near-surface stability induced by radiative cooling overnight is shallow and has already been dissipated by surface heating since sunrise. This must be the situation on those mornings when the wind is from an inland direction (the southwest quadrant). However, as all mixed layers deeper than 500 m occur when the low-level winds are onshore from the northwest quadrant, and no layers shallower than 400 m are found under this wind direction, the static stability of these airmasses on crossing the coastline (7 km distant) is likely to be relatively weak. Hourly surface data on such occasions shows that winds are also onshore during the night, suggesting that the air has a sea trajectory.

The 1900 WST profiles all show a mixed layer below a 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 wind direction and potential temperature profiles is shown in Figure 5. As well as being representative, 22 January 1999 was chosen because a radiosonde was also released at Dampier on this day at 1400 WST. The 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 at Port Hedland 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. The mixed layer at Dampier is shallower because the site is at the coastline, compared to the Port Hedland station which is 7 km inland. However, the strong stable layer beginning at about 400 m is present at both locations.



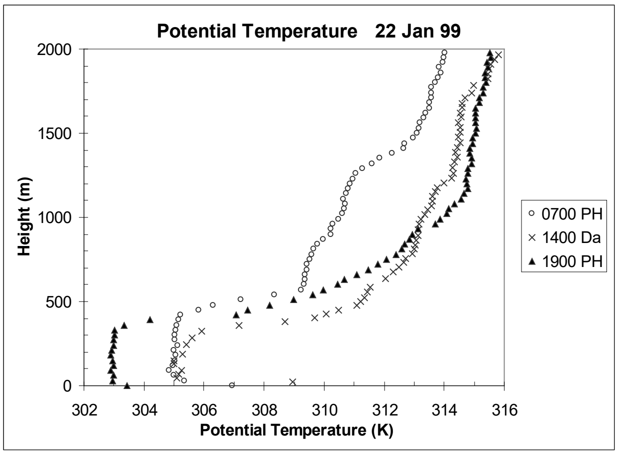


Figure 5. Wind direction and potential temperature profiles on 22/1/99 at Port Hedland (0700 WST and 1900 WST) and Dampier (1400 WST).

4. Modelling with TAPM

Simulations were carried out with the mesoscale model TAPM (Hurley 2000) to complement the data analysis of the previous section. TAPM is also being evaluated for its suitability as an air quality assessment model for the Pilbara region.

TAPM was run for four months which are representative of the different weather patterns which occur throughout the year. A comparison of surface and upper-wind predictions at Karratha with observations showed that the model is able to reproduce the dominant wind characteristics, such as those shown in Figures 2 and 3 (Physick 1999). The simulations captured 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 was simulated, not only in the monthly means, but also for individual days of the month.

Days typical of the easterly, westerly, and rotation wind patterns identified in section 3 were simulated. For the first two patterns, results indicate that recirculation of pollutants back to the Burrup Peninsula region does not appear to be a possibility. However for the rotation regime, observed primarily in March, April, August and September, the results indicate the potential for morning emissions from Peninsula sources to move back onshore and combine with recently-emitted pollutants. The complex surface flow fields predicted at 1100 Local Time for a day from this regime are shown in Figure 6.

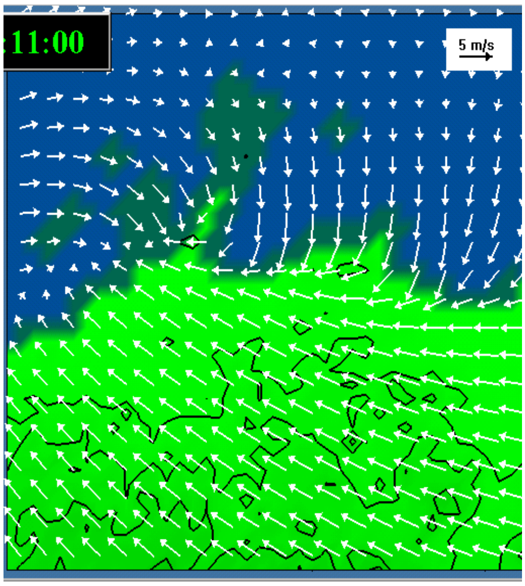


Figure 6. TAPM modelled winds at a height of 10 m for 12/10/98 at 1100 Local Time. The contours denote terrain height at 50 m, 100 m and then at a contour interval of 100 m. The domain size is 117 x 117 km^2.

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 over a three-day period in September 1996.

Figure 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.

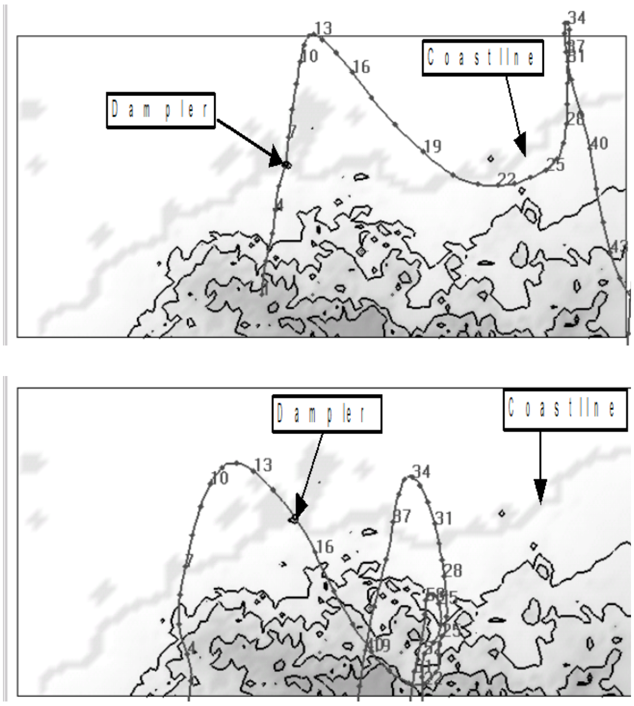


Figure 7. Trajectory of a marked particle released at a height of 10 m from Dampier at 0600 LT (top) and 1500 LT (bottom) on day 1 of a 3-day simulation. Numbers on the trajectory denote hours from 0000 LT on day 1.

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.

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 PM_{10} at Dampier are shown in Table 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 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.

Table 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. For each pollutant, the last row contains the NEPM standard, except for CO which is EPA Victoria.

	O_3 (ppb)	*NO_2 (ppb)*	*CO (ppb)*	*PM_{10} ($\mu g\ m^{-3}$)*
May	27	-	167	36
Jun.	30	13	233	22
Jul.	30	14	617	40
Aug.	34	15	250	27
Sep.	32	17	233	36
Oct.	35	15	667	39
Nov.	34	9	200	36
Dec.	37	14	370	44
Jan.	41	16	183	40
NEPM	**100**	**120**	**30000**	**50**

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 8 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.

Carbon monoxide maxima occur for all wind directions, but they are very low compared to the NEPM standard. 24-hour mean PM_{10} concentrations in Table 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 certain that dust is the dominant source of PM_{10}. Other sources of particulates are currently being quantified, but are believed to be quite small. The clustering of hourly-averaged PM_{10} maxima around the northeast and west directions corresponds to the direction of the two ore-loading facilities.

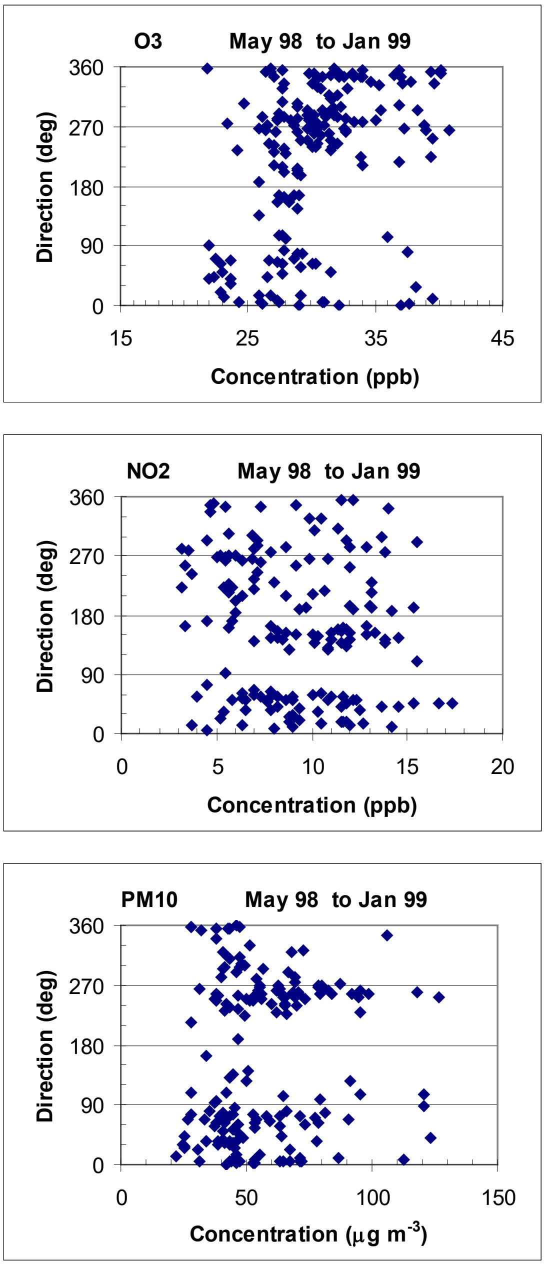


Figure 8. Twenty highest concentrations each month at Dampier from May 1998 to January 1999.

6. Summary and Discussion

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. Work is currently being done to compare results from annual runs of TAPM, AUSPLUME and DISPMOD using meteorological files that are combinations of observations and predictions from TAPM and a 1D boundary layer model (to predict mixed-layer heights). This will provide some insight into the use of TAPM in data-sparse areas to produce meteorological files for the simpler models.

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. Models such as DISPMOD, and AUSPLUME cannot model these recirculation situations, and nor are they, along with AUSPUFF/CALPUFF, suitable when photochemistry is important. Under these conditions, it is necessary to use an air chemistry model coupled to a prognostic mesoscale model.

Acknowledgments

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