Observations and modelling of dispersion meteorology in the Pilbara region

W.L. Physick
CSIRO Atmospheric Research, Aspendale, Australia

K.N. Rayner and P. Mountford
Department of Environment, Water and Catchment Protection of Western Australia, Perth, Australia

and

M. Edwards
CSIRO Atmospheric Research, Aspendale, Australia

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Fuelled by offshore natural gas, industrial development is growing steadily in coastal parts of Western Australia's Pilbara region. In this paper, we present an analysis of meteorological data from the area, with an emphasis on those aspects that are important for the dispersion of pollutants. Three distinct wind patterns are identified, corresponding basically to the warmer, cooler and transitional months. The dominant pattern for the transitional months is particularly interesting, consisting of boundary-layer winds, up to a height of about 1000 m, rotating through 360 degrees over a 24-hour period. This can occur over several consecutive days and has implications for the recirculation of pollutants. Onshore winds occur on about 70 per cent of days, suggesting that fumigation of elevated plumes to the ground in thermal internal boundary layers (TIBLs) is also likely to be an important process for dispersion in the region. Data are presented that support the existence of these two processes.

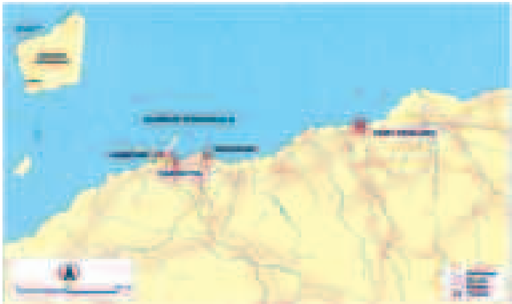
The Air Pollution Model (TAPM) is used to simulate the mesoscale meteorology of the region. It is able to reproduce the diurnal behaviour of the three wind regimes, as well as the vertical structure observed in early morning and evening wind profiles. A comparison with data shows good simulation of TIBL development in onshore flow and also recirculation of emissions back onshore in early evening, giving confidence in the application of TAPM as an air quality management tool in the Pilbara region.

Introduction

An abundant supply of offshore natural 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 (Figs 1 and 2). This area is about 200 km west of another industrial town, Port Hedland, a processing and shipping centre for ore from the Hamersley Range (Figs 1 and 3). 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

Corresponding author address: Dr W.L. Physick, CSIRO Atmospheric Research, PMB1, Aspendale, Vic. 3195, Australia.
Email: Bill.Physick@csiro.au

Fig. 1 A section of the Pilbara coastal region in north-western Australia, showing locations discussed in the study.



assessment of the impact of the industry on the local and regional air quality. As the meteorology at scales important for dispersion is virtually unknown in this region, the Department of Environmental Protection of WA (DEPWA) initiated a study to collect and analyse meteorological and air quality data. In this paper, we present an analysis of the meteorological data, with an emphasis on those aspects that are important for the dispersion of pollutants.

Future work in the DEPWA Study involves using the air quality monitoring data to evaluate the suitability of various pollutant dispersion models for the Pilbara region. One of these models, TAPM (Hurley 2000, 2002), predicts the meteorological and turbulence fields that are used to disperse emissions. For model validation purposes, we present here comparisons of TAPM simulations with surface and upper-air meteorological data.

Data

Surface data

Details of the meteorological data available in the Pilbara region, including the measurement period, are given in Table 1. Locations of the monitoring sites are

Table 1. Summary of the monitoring program.

Site	*Code*	*Start date*	*End date*	*WS*	*WD*	*AT10*	*AT02*	*RH/DP*	*SRad*	*NRad*	*Pres*	*Sodar*
Dampier[1]	DA	05/98	01/01	1	1	1		1	1		1	
King Bay[2]	KB	12/98	10/99	1	1							
Karratha townsite[2]	KT	11/99	10/00	1	1							
Karratha Station[1]	KA	02/98	04/01	1	1	1	1	1	1	1	1	1
Maitland[3]	MT	09/98	09/99	1	1	1		1				
Radio Hill[1]	RN	09/99	12/00	1	1	1		1				
Karratha Airport[4]	KP	01/96	Cont.	1	1		1	1			1	
Legendre Island[4]	LG	01/96	09/99	1	1		1				1	
Wickham[1]	WI	12/98	12/00	1	1	1		1				
Boodarie[5]	BD	06/97	Cont.	1	1	1		1	1		1	
Port Hedland Airport[4]	PA	09/98	Cont.	1	1		1	1			1	

1 – Department of Environmental Protection
2 – Woodside
3 – Department of Resources Development
4 – Bureau of Meteorology
5 – BHP

Key

WS	Wind speed at 10 metres
WD	Wind direction at 10 metres
AT10	Air temperature at 10 metres
AT02	Air temperature at 2 metres
RH/DP	Relative humidity or dew point temperature
Pres	Air pressure
SRad	Solar radiation
NRad	Net radiation
Sodar	Doppler acoustic sounder

shown in Figs 2 and 3. Monitoring equipment, measuring 10-minute averages of the variables listed in Table 1, were installed at Dampier and Karratha Station by DEPWA in the first half of 1998. Similar equipment was installed later at Wickham, 50 km east along the coast from Karratha, in December 1998, and at Radio Hill, 28 km south of Karratha, in September 1999. The Dampier station also measured ozone (O_3), nitrogen oxides (NO_x), carbon monoxide (CO) and particulate matter with aerodynamic diameter less than 10 mm (PM10).

Wind speed and direction (10-minute averages) were measured by Woodside Offshore Petroleum at King Bay from December 1998 to October 1999. Air quality data included 10-minute averages of O_3, NO_x and sulfur dioxide (SO_2). The equipment was moved to a site on the outskirts of the town of Karratha in November 1999 and measurements were continued there until the end of October 2000.

Meteorological data over the period were also gathered at Bureau of Meteorology (BoM) stations at Legendre Island and Karratha Airport, and at Maitland by the Western Australian Department of Resources Development.

At Port Hedland, meteorological data continue to be taken at the airport by BoM (half-hourly) and at the Boodarie site by BHP (10-minute), with the latter's station also measuring NO_x, SO_2, hydrogen sulphide, PM10 and PM2.5 (Fig. 3).

Upper-air data

Winds (averaged over 30-minutes) at 25 m intervals from the ground to a height of about 800 m were obtained from a DEPWA sodar at the Karratha monitoring site from February 1998 to December 2000. Radiosonde flights were also carried out at Dampier on selected days.

Routine radiosonde flights from the BoM station at Port Hedland airport (7 km inland) at 0700 and 1900 Local Time (LT) produce wind, temperature and relative humidity data at the fine vertical resolution of about 11 m. For ten days in August 1999, additional sondes were released at 0100 and 1300 LT, with simultaneous afternoon flights from Dampier on five of those days.

The air pollution model (TAPM)

Details of the equations and parametrisations of the meteorological component of TAPM are given in Hurley (2000, 2002). In brief, the model is an incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations. It solves the momentum equations for horizontal wind components, the incompressible continuity equation for vertical velocity, and scalar equations for potential virtual temperature and the specific humidity of water vapour and cloud water (summed) and of rain water, and turbulence kinetic energy and eddy dissipation rate. Parametrisations include cloud microphysics, and a vegetative canopy and soil scheme at the surface.

Version 1 of TAPM, used in Hurley (1999), employed zero-gradient conditions at the lateral boundaries of the outermost grid and treated the mesoscale and large-scale components of the horizontal pressure-gradient term separately, the large-scale gradient being obtained from the synoptic-scale limited area prediction system (LAPS) analyses (Puri et al.

Fig. 2 The Burrup Peninsula area of the Pilbara coastline, showing data monitoring sites. The Karratha monitor is situated at the Karratha sodar site. Dampier and King Bay are situated on the Burrup Peninsula. Australian Map Grid (AMG) coordinates are in metres.

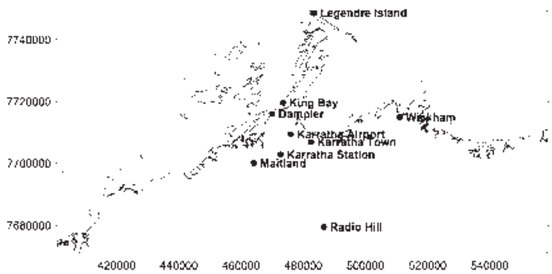


Fig. 3 The Port Hedland region, including the data sites Boodarie (BD) and Port Hedland airport (PA), and the coastal site for the field work.

1998) at a resolution of 0.75° . However in Version 2, used for the work described in this paper, there is no separation of the pressure gradient term and the boundary values for the outermost grid are obtained from the LAPS analyses. At all grid-points, the model is weakly nudged towards the synoptic analyses with an e-folding time of 24 hours.

The Burrup Peninsula simulations were carried out on three nests (each 40 x 40 x 20 grid-points) with grid spacings of 30 km, 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. Terrain elevation was obtained from Geoscience Australia's gridded 9-second DEM data (approximately 250 m). Simulations were done for months in the summer (January 1999), winter (July 1998) and the transition season (April 1998). Deep soil moisture content needs to be specified for each month, and test simulations showed that best agreement with wind data were obtained with 0.05 $m^3\ m^{-3}$ for January and April, and 0.15 $m^3\ m^{-3}$ for July.

Analysis of wind data

Winds at 10 m

For each site, monthly averages of wind speed and direction at one-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. 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, in mid-afternoon when the wind is onshore. The smallest monthly maximum, in July, occurs at 0900 LT, and probably arises from convective mixing of the nocturnal jet to the surface. Our analysis is also consistent with Tapp's conclusion that sea breezes occur on 50 per cent of days in winter and on 80 per cent in summer, where a sea breeze is defined by Tapp as an onshore wind. The coastline in this region can be considered to have an east-west orientation, so in the following discussion onshore winds are defined as those with a northerly component.

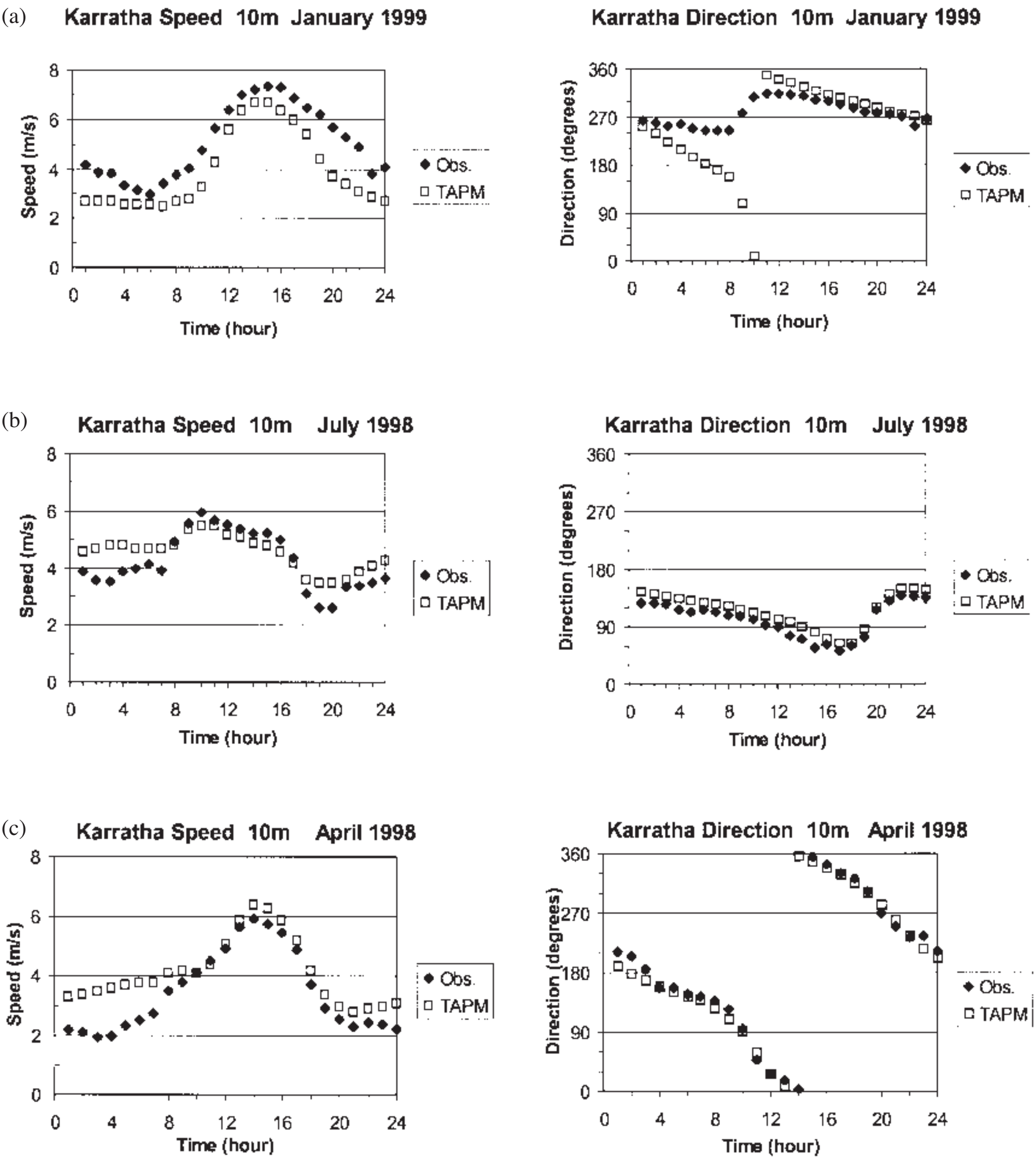
The seasonal variation in the diurnal pattern of monthly mean direction is most interesting, and is observed at all sites including Legendre Island. There are three dominant wind regimes, illustrated for January 1999, July 1998 and April 1998 at the Karratha site in Fig. 4. The wind behaviour in Fig. 4(a) is representative of any of the warmer months, October through to February, in which 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 Fig. 4(c).

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, typified in Fig. 4(b). 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 anticlockwise direction while the sea-breeze pressure gradient acts normal to the coastline (from north to south in this case).

In the transition months of 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 anticlockwise direction with a 24-hour period. At midnight, the wind is typically from a south-southwest direction for each site. This behaviour is illustrated for April in Fig. 4(c).

Monthly means usually indicate the most common value (median) found during the month, and this is the situation here, as found from examining time series for each day of the three separate months of Fig. 4. For January, the mean value does reflect the direction on the vast majority of days, with westerly-component winds occurring all day on 23 occasions. Interestingly though, there are six days on which 'around the clock' behaviour is observed. Similarly in July, there are four occasions when the wind direction rotates anticlockwise over the 24-hour period, but once again most days reflect the monthly easterly component mean. On three days, winds have a westerly component all day.

Fig. 4 **Monthly mean observed wind speed and direction at a height of 10 m at Karratha for (a) January 1999, (b) July 1998 and (c) April 1998. Also shown are monthly mean winds from TAPM simulations.**



For April, 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 the warmer months and the transition months (illustrated by January and April in Fig. 4), the strongest winds are associated with the sea breeze and occur at 1400 LT, whereas in the cooler months (July in Fig. 4), the strongest winds occur at 0900 LT with the convective mixing to the ground of the nocturnal jet.

Also plotted in Fig. 4 are wind speed and direction at 10 m from the TAPM simulations on the 3 km spaced grid. The diurnal variation in wind speed is reproduced well for each month, as is the different pattern between months, e.g. the varying times at which the maximum wind speeds occur. Daytime speeds are within 10 per cent for all months, while nocturnal speeds are underestimated for January and overestimated for July and April.

Wind direction is also simulated well, apart from a backing (as opposed to the observed veering) of the morning wind in January as it shifts from offshore to onshore. Daily observations show that the wind can turn to offshore through either direction. The 'around the clock' behaviour of the wind direction in April was captured well by the model.

The finding that the vast majority of days exhibit daytime onshore winds, indicates that the 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 (Physick 1996), is quite likely to occur. In a separate study (Physick et al. 2002), TAPM was run for a 12-month period (1999) employing an additional inner grid with spacing of 1 km. Annual statistics for wind speed, east-west and north-south components of the wind, temperature and relative humidity, all at a height of 10 m above the ground, were extracted and are presented in Table 2 from the 1 km grid for the Dampier and Karratha sites. The values are very similar to those on the 3 km grid, reflecting the lack of very small-scale terrain features in the region. The statistical measures are defined in the caption for Table 2 and are discussed more fully in Hurley (2000). At both sites, the statistics are very encouraging as RMSEs are well below the standard deviation in the observations, the indices of agreement are especially high, and at Dampier the variance in observations and model are very similar. The modelled temperature at Karratha shows more variability than is observed, mainly due to lower temperatures at night on many occasions.

Upper-level winds at Karratha

Figure 5 shows the mean winds from the Karratha sodar for January, July and April at a height of 150 m above the ground. The diurnal speed patterns for each month at this height are quite different from those at 10 m, with a nocturnal jet most apparent in July. Modelled speed and direction from the 3 km grid are in good agreement with the observations, although a predicted speed maximum at 0700 LT in April is not observed. For this month at both the surface and 150 m, the model tends to over-predict wind speed at night when the wind direction is between south-southwest and south-southeast. This appears to be related to a general drainage flow from sloping ground to the south, rising to the Hamersley range, about 150 km south of Karratha.

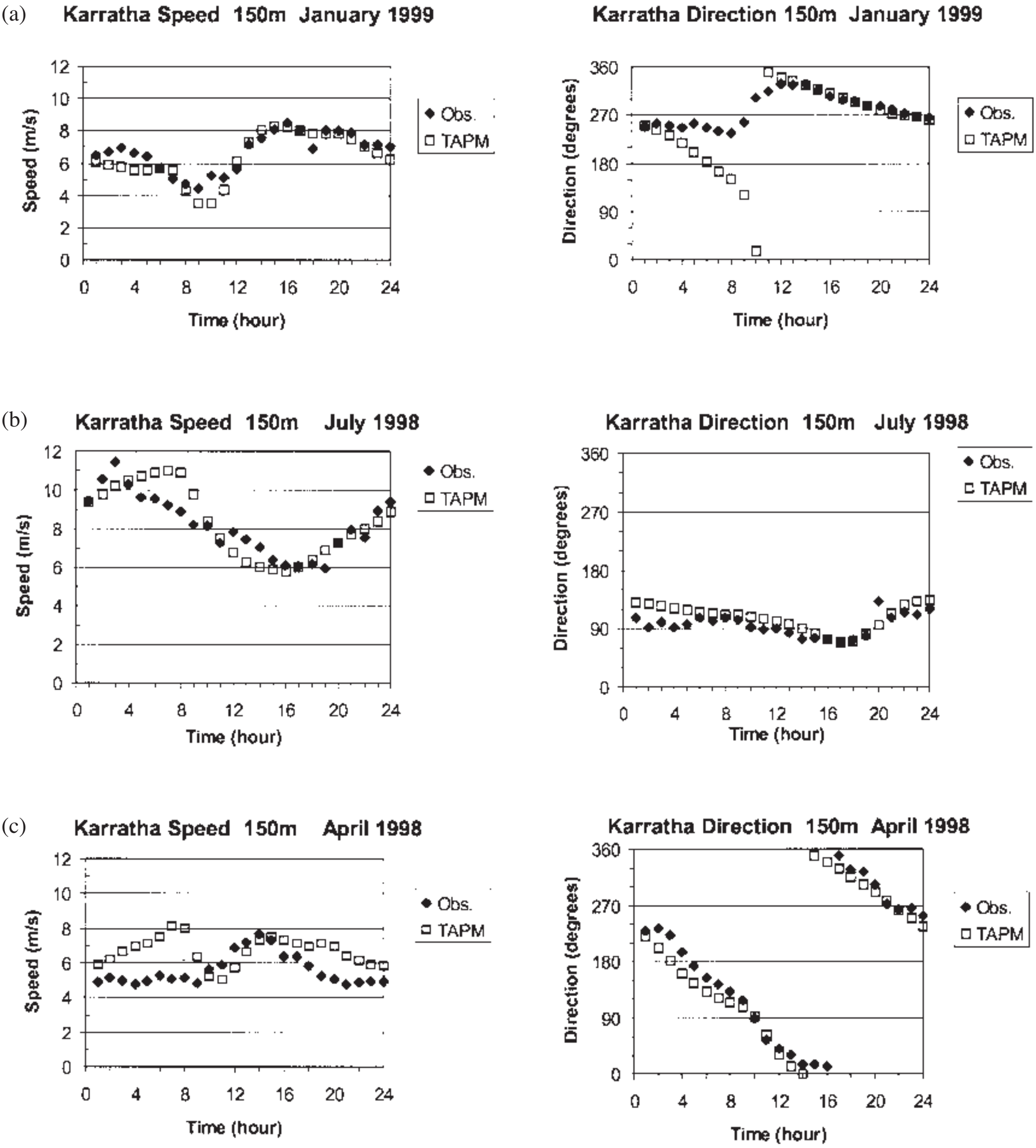
For the recirculation of pollutants, it is important to know the variation of the offshore/onshore wind pattern with height. Monthly mean wind profiles to a height of 750 m from the acoustic sodar at Karratha

Table 2. Annual statistics at Dampier and Karratha for TAPM simulation of 1999 for the following surface variables (10 m above the ground): wind speed (WS10), the west-east component of the wind (U10), the south-north component of the wind (V10), temperature (Temp), and relative humidity (Rel. h).

Variable	*Number*	*Mean_obs*	*Mean_mod*	*STD_obs*	*STD_mod*	*Corr*	*RMSE*	*IOA*	*Skill_V*	*Skill_R*
Dampier										
WS10	8405	3.8	4.0	1.7	1.6	0.47	1.72	0.68	0.89	0.99
U10	8405	0.3	-0.3	3.3	3.5	0.83	2.09	0.90	1.04	0.63
V10	8405	0.0	0.2	2.5	2.5	0.74	1.87	0.85	1.00	0.74
Temp	8668	25.8	25.6	3.9	4.3	0.90	1.88	0.94	1.12	0.49
Rel. h	8633	60.9	60.6	18.2	18.1	0.74	12.99	0.86	1.00	0.71
Karratha										
WS10	8737	4.4	4.4	2.3	1.8	0.65	1.78	0.79	0.76	0.77
U10	8737	0.2	-0.4	4.1	3.6	0.86	2.17	0.92	0.86	0.53
V10	8737	-0.3	0.2	2.8	3.1	0.77	2.11	0.86	1.10	0.74
Temp	8737	25.6	25.2	5.0	7.5	0.88	3.89	0.90	1.50	0.78
Rel. h	8736	60.3	56.6	21.9	25.1	0.78	16.46	0.87	1.14	0.75

KEY: Obs = Observations, Mod = Model Predictions, Number = Number of hourly-averaged values used for the statistics, Mean = Arithmetic mean, STD = Standard Deviation, Corr = Pearson Correlation Coefficient (0=no correlation,1=exact correlation), RMSE = Root Mean Square Error, IOA = Index of Agreement (0=no agreement, 1=perfect agreement), Skill_V = (Std_mod)/(Std_obs) (near to 1 shows skill), Skill_R = (RMSE)/(Std_obs) (<1 shows skill).

Fig. 5 **Monthly mean observed wind speed and direction at a height of 150 m at Karratha for (a) January 1999, (b) July 1998 and (c) April 1998. Also shown are monthly mean winds from TAPM simulations.**



reveal that in the cooler months of May, June and 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. In January, the monthly-mean wind direction to 750 m varies between south-west and north-west over the diurnal period and is constant with height at any particular time.

The observed mean wind profiles for April 1998 are shown in Fig. 6. 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

Fig. 6 **Mean wind profiles at 0200, 0800, 1400 and 2000 Local Time for April 1998 at Karratha.**

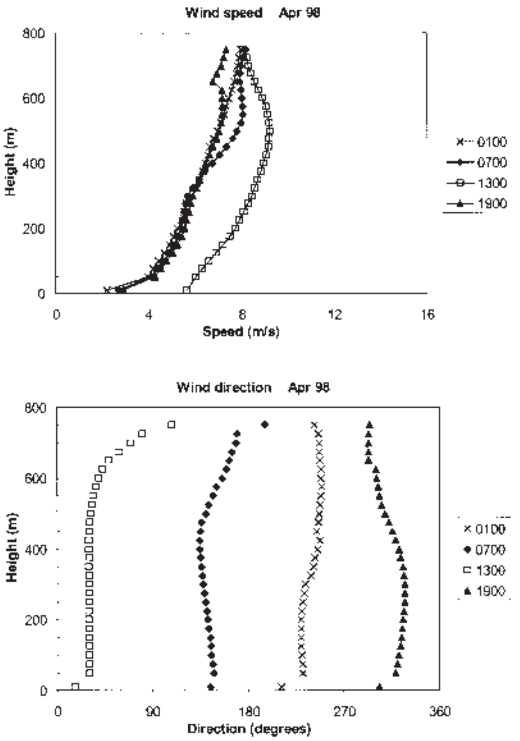
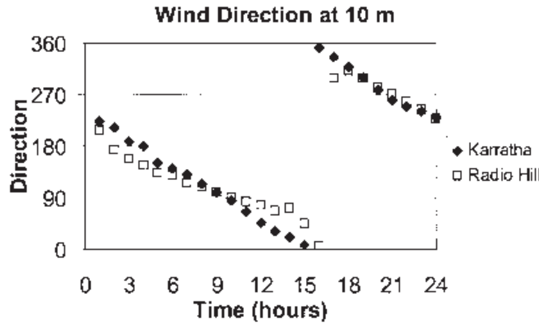


Fig. 7 **Observed wind direction at Karratha and Radio Hill averaged over 52 days on which there was diurnal rotation at Karratha.**



consecutive days of the year there is a mass of air at least 750 m deep rotating with the diurnal period. Data from twice-daily radiosonde flights at Port Hedland and a few flights at Dampier show that it is rare for this diurnal wind rotation to extend beyond a height of 1000 m.

Some idea of the extent to which the diurnal rotation extends inland can be gauged from the surface wind data at Radio Hill, south of Karratha and 30 km from the coastline (Fig. 2). This station operated from mid-August 1999 to mid-April 2000 and in this period there were 52 days when the wind direction at Karratha rotated through 360 degrees over 24 hours. The diurnal variation of the wind direction averaged over these 52 days at Karratha and at Radio Hill, shown in Fig. 7, indicates that the same rotation of the wind occurs at 30 km inland. The wind direction just prior to sunrise reflects the synoptic surface-pressure gradient on such days, generally east-south-east, and as the convective boundary layer grows through the morning, more-easterly winds are mixed down to the surface at both sites. At Karratha the winds become more northerly as the sea breeze develops and continue to rotate anti-clockwise with the Coriolis effect, with the sea breeze acquiring a westerly component by the time it reaches Radio Hill in mid-afternoon. As the surface cools in the early evening, the frictional and land-sea mesoscale pressure gradient forces diminish and the winds execute an inertial oscillation as they return through south to the synoptic pressure gradient direction. Drainage flow from gradually sloping terrain further inland may also contribute to the southerly component of the wind overnight.

Upper-level winds at Port Hedland

Monthly TAPM simulations have also been done for the Port Hedland region, 200 km east of Karratha. Port Hedland (20°18'S, 118°35'E) is primarily a shipping port for ore from mines in the inland Hamersley Range. At this location, the coastline runs approximately east-west, with the sea to the north. TAPM modelling results were compared to observed upper-air winds from the twice-daily radiosonde flights at 0700 and 1900 LT at the Bureau of Meteorology's station, 7 km from the coastline. The same months were simulated as for Karratha, except that April 1999 was substituted for April 1998 as the finer vertical-resolution flights did not commence at Port Hedland until July 1998. Monthly mean winds up to a height of 1000 m were used in the comparison. Results were also compared to winds from BoM's LAPS analyses, at the coarser grid spacing of 0.75° (about 75 km). Boundary conditions for the outer nest of a TAPM simulation are obtained from the six-hourly LAPS analyses.

Simulations for the Port Hedland region were carried out on three nests centred on the BoM station. Each nest consisted of 41 x 41 x 20 grid-points with grid spacings of 30, 10 and 3 km. Vertical grid levels were at the same heights above the ground as those for the Karratha simulation. Deep soil moisture content was specified as 0.05 m^3 m^{-3} for January, and 0.15 m^3 m^{-3} for April and July.

Fig. 8 Diurnal variation of observed (diamonds) and TAPM modelled (squares) monthly mean wind speed and direction profiles at 0700 Local Time at Port Hedland for January 1999, April 1999 and July 1998. Modelled LAPS profiles (triangles) are also shown.

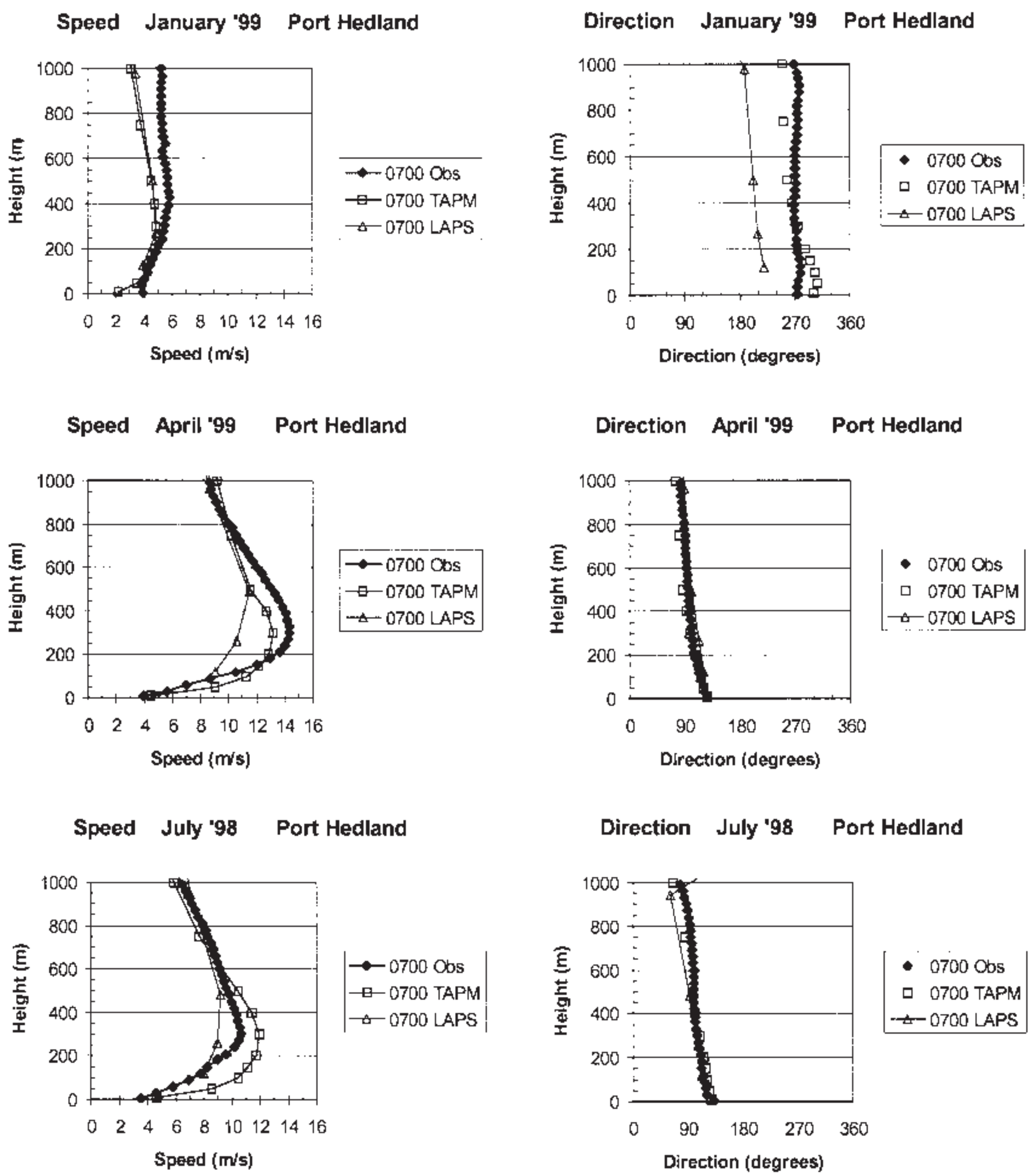


Figure 8 shows the profile comparisons for the three months at 0700 LT. Agreement with observations is good at all times of the year. For April and July, it is evident that the finer-scale model TAPM is able to capture the low-level jet at about 300 m, whereas the coarse vertical resolution in LAPS produces a weaker and more elevated jet. Both models agree well with observed wind direction profiles, except in January when the mean LAPS direction is too southerly.

The predicted and observed wind profiles at 1900 LT are shown in Fig. 9. The January speeds have increased from 0700 LT, due to a daytime sea-breeze effect. It is likely that the coarse horizontal resolution

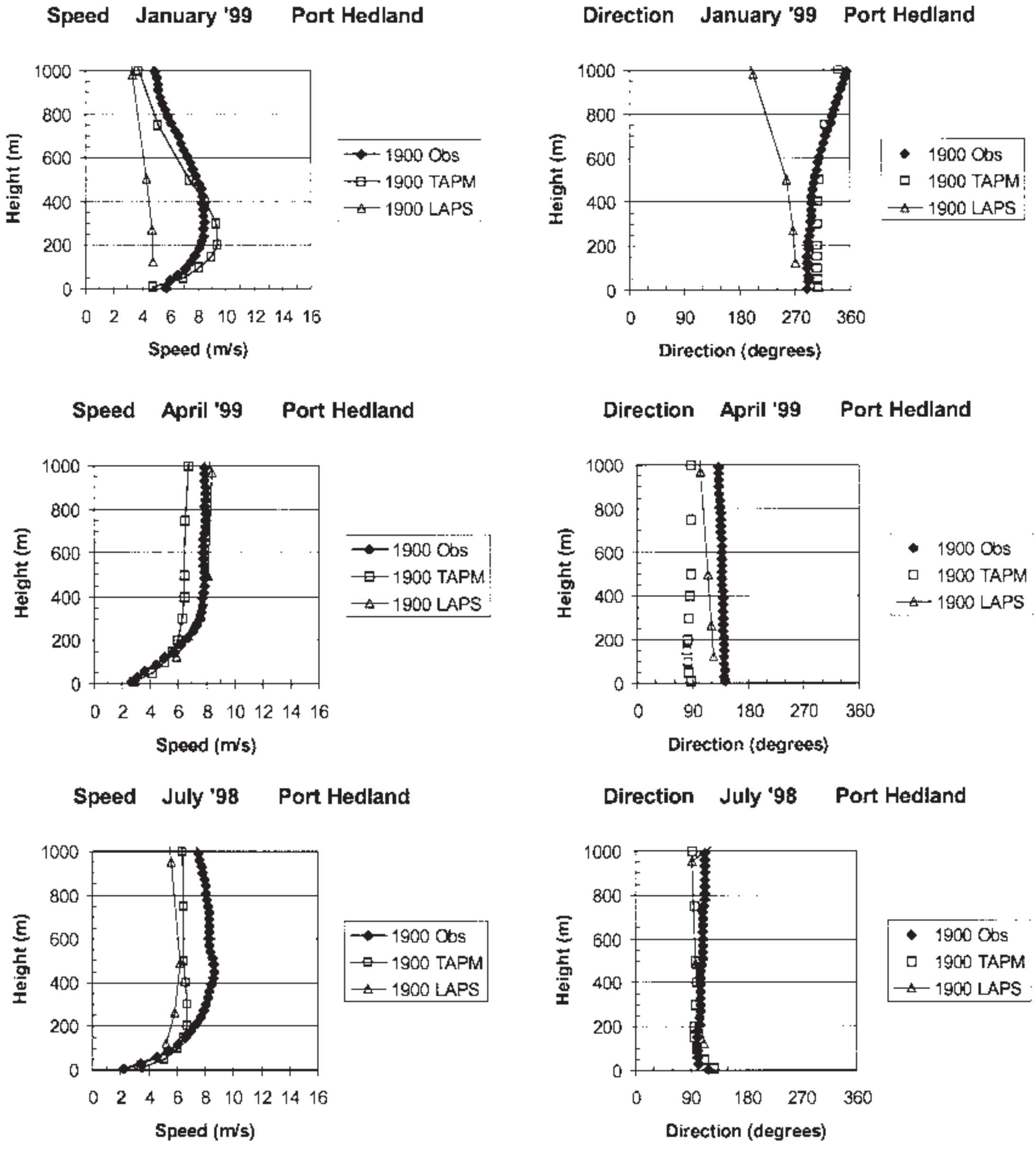


Fig. 9 Diurnal variation of observed (diamonds) and TAPM modelled (squares) monthly mean wind speed and direction profiles at 1900 Local Time at Port Hedland for January 1999, April 1999 and July 1998. Modelled LAPS profiles (triangles) are also shown.

of LAPS limits its ability to produce sea breezes of the observed strengths. The low-level wind maxima observed in January have been reproduced, as have the well-mixed profiles in April and July, although wind speeds in the latter months are underpredicted by 1-2 m s^{-1} above 200 m. In April, wind direction is too easterly by about 40 degrees, but agreement is very good for the other two months.

Dispersion processes

Analysis of the wind data has identified two processes that may be important in the dispersion of pollutants in the coastal Pilbara region. Firstly, the strong solar insolation and the predominance of days with onshore winds suggests that fumigation of elevated emissions may regularly lead to relatively high ground-level concentrations. Secondly, the morning offshore winds followed by onshore winds in the afternoon, especially when the wind direction rotates through 360 degrees over the diurnal period, may bring about the recirculation of emissions back to the source region. Examples of these two processes follow.

Fumigation of elevated plumes

Industrial emissions in the Dampier and Port Hedland areas are from elevated sources (stacks) and are buoyant, regularly reaching a final rise height between one and two hundred metres above the stack. A common dispersion process in coastal regions, known as fumigation and illustrated in Fig. 10, can occur during onshore flow when emissions from an elevated coastal source are released into a stable atmosphere (hence with little dispersion), then travel inland and intersect a growing TIBL. The emissions are then mixed quickly to the ground, usually resulting in higher concentrations than occur when emissions are released within a convectively mixed boundary layer. An example of the inland growth of a TIBL at Port Hedland is shown in Fig. 11. The data are from a six-day field study from 28 March to 2 April 2000 in which wind, temperature and humidity profiles were obtained at regular intervals throughout the daytime (Physick and Blockley 2001). Sondes were released at the coastline, and 7 km inland at the BoM's Port Hedland station (see Fig. 3 for locations). At the coast, Fig. 11 shows that the temperature profile in the afternoon sea breeze is stable, apart from the lowest 50 m where the superadiabatic lapse rate probably arises from the cool air being heated as it passes over warmer shallow water near the shore. By 7 km inland, it can be seen that the TIBL has grown to a depth of about 350 m, confirming that fumigation of plumes from near-coastal sources is a process that is likely to be important along the Pilbara coastline. Profiles from a TAPM simulation (1 km spaced grid) are also plotted in Fig. 11 and it can be seen that the model is able

Fig. 10 Schematic diagram of the coastal fumigation process showing a plume intersecting the thermal internal boundary layer (TIBL) and mixing to the ground.

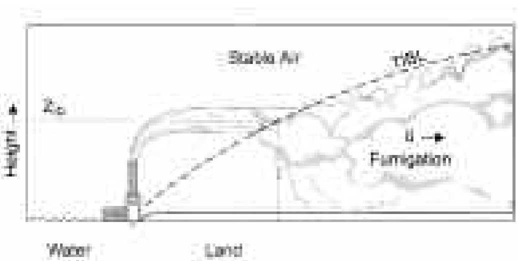
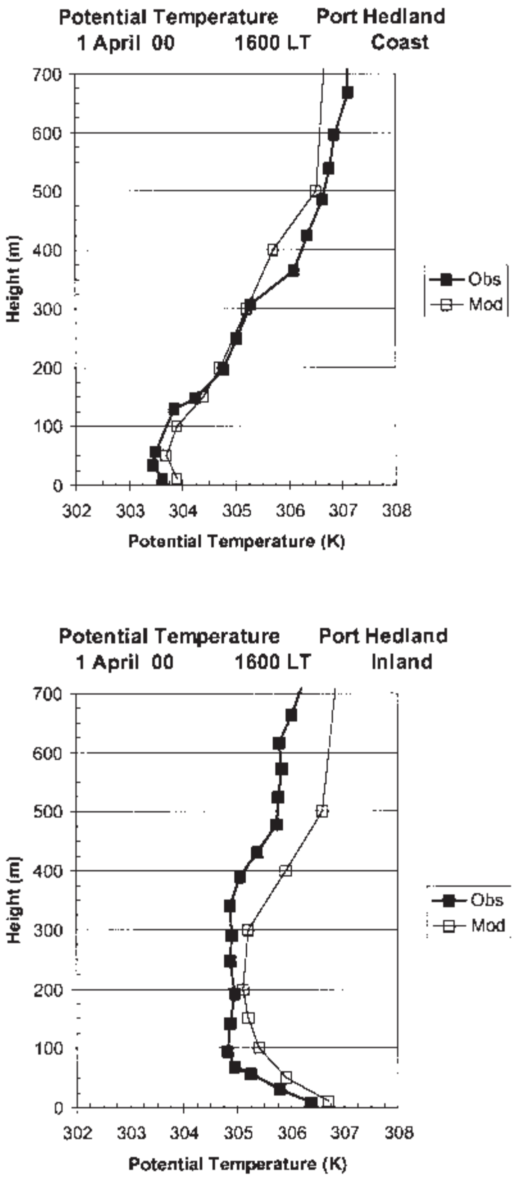


Fig. 11 Observed (solid squares) and TAPM modelled (outline squares) potential temperature profiles at 1600 LT on 1 April 2000 from two sites at Port Hedland, at the coast (above) and 7 km inland (below).

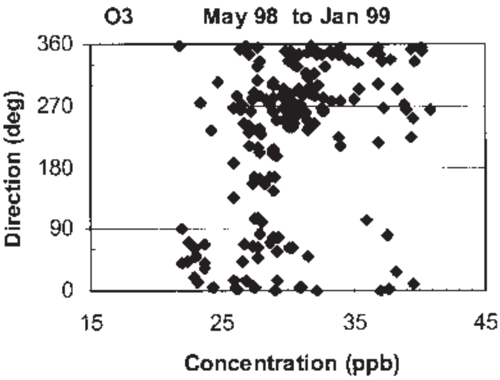


to simulate well both the stability profile in the onshore sea-breeze flow and the growth rate of the TIBL with distance inland.

Recirculation of emissions

The twenty highest concentrations each month of ozone, a secondary pollutant that forms over a few hours from nitrogen oxides and volatile organic com-

Fig. 12 **Twenty highest concentrations of ozone (ppb) each month at Dampier from May 1998 to January 1999, plotted against Dampier wind direction at time of measurement.**

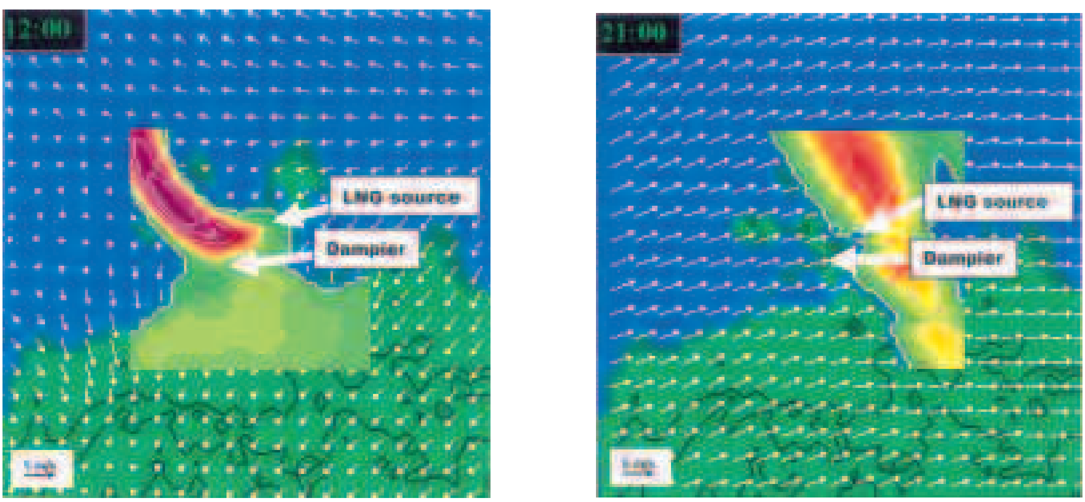


pounds in the presence of sunlight, are plotted in Fig. 12 against the corresponding wind direction at the Dampier monitor. The dominant directions for ozone maxima are north and west, both off the sea, and occur from about midday to early evening. Ozone maxima associated with winds from the south-west sector arrive between 1900 and 2400 LT. TAPM was run for days when relatively high concentrations were observed with south-westerly winds at Dampier in the evening, the simulations showing that the ozone maxima are due to recirculated emissions from the LNG (liquefied natural gas) plant on the Burrup Peninsula, 9 km to the north-east of Dampier. On such days, the diurnal heating of the land causes early-morning south-easterly winds to back through north to the south-west by late afternoon. Figure 13 shows TAPM-predicted surface winds at 1200 and 2100 LT, with hourly-averaged ozone concentration contours also shown. A comparison of TAPM air quality modelling results with ozone observations can be found in Physick et al. (2002).

Summary

Analysis of surface wind data in the Pilbara coastal region has identified three distinct wind regimes. In the warmer months (September to April), winds predominantly have a westerly component, being north-west during the daytime (onshore) and from the south-west quadrant at night (offshore). Conversely in the cooler months of May through August, winds are mainly easterly, also with an onshore-offshore pattern related to diurnal heating of the land. Additionally, for all months of the year a third regime was found, comprising of days, and series of days, on which the wind direction rotates steadily through 360 degrees over 24 hours, as a result of sea breezes and an inertial oscillation. These days occur throughout the year, but are especially frequent in March, April, August and September. The same behaviour was also found at a

Fig. 13 **TAPM-predicted surface winds at 1200 and 2100 Local Time. Also shown are hourly averaged ozone concentration contours (equally spaced), on a smaller grid domain than for the wind. The locations of the major emissions source LNG (liquefied natural gas) and the Dampier monitor are indicated.**



site 30 km from the coastline. Examination of upper-air data showed that the diurnal wind rotation was a boundary-layer phenomenon, rarely extending beyond a height of 1000 m.

Two aspects of the meteorology were identified as being important for the dispersion of pollutants. Firstly, vertical temperature profiles from coastal and inland sites illustrated the presence of a growing thermal internal boundary layer within onshore flow, confirming that fumigation of elevated plumes from coastal sources is likely to be a dominant dispersion process in the region. Secondly, the 360 degrees rotation of wind direction over the diurnal period suggests that recirculation of coastal emissions could occur on a regular basis. This hypothesis was supported by data showing that the highest concentrations of ozone occur at Dampier in the evening hours when the wind has a westerly (onshore) component.

The mesoscale dispersion model TAPM was used to simulate the meteorology of the region. It was able to reproduce the diurnal behaviour of the three wind regimes at the surface and 150 m, as well as the vertical structure observed in early morning and evening wind profiles. A comparison with data showed good simulation of thermal internal boundary layer development in onshore flow and the reproduction of evening ozone concentrations at Dampier, giving confidence in the application of TAPM as an air quality management tool in the Pilbara region.

References

Hurley, P. 1999. The Air Pollution Model (TAPM) Version 1: Technical description and examples. *CSIRO Atmospheric Research Technical Paper No. 43*. Available at www.dar.csiro.au/TAPM.

Hurley, P.J. 2000. Verification of TAPM meteorological predictions in the Melbourne region for a winter and summer month. *Aust. Met. Mag., 49*, 97–107.

Hurley P. 2002. The Air Pollution Model (TAPM) Version 2. Part 1: Technical Description. *CSIRO Atmospheric Research Technical Paper No. 55*. Available at www.dar.csiro.au/TAPM.

Physick, W.L. 1996. *Photochemical smog studies in Australian cities, Urban Air Pollution, Vol.2*. H. Power and N. Moussiopoulos, Eds., Computational Mechanics Publications, Southampton, Boston, 141-84.

Physick, W.L. and Blockley, A. 2001. *An evaluation of air quality models for the Pilbara region*. CSIRO Division of Atmospheric Research. A Report to the Department of Environmental Protection, Western Australia, 98 pp., June 2001.

Physick, W.L., Blockley, A., Farrar D., Rayner, K. and Mountford, P. 2002. Application of three air quality models to the Pilbara region. *Proceedings of the 16th International Clean Air and Environment Conference*, Christchurch, New Zealand, 18-22 August 2002.

Puri, K., Dietachmayer, G., Mills, G., Davidson, N., Bowen, R. and Logan, L. 1998. The BMRC Limited Area Prediction System, LAPS. *Aust. Met. Mag., 47*, 203-23.

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.