Aust. Met. Mag. 53 (2004) 29-37

Verification of TAPM meteorological predictions using sodar data in the Kalgoorlie region

Mary Edwards, Peter Hurley and William Physick
CSIRO Atmospheric Research, Australia

(Manuscript received March 2003; revised December 2003)

The Air Pollution Model (TAPM) solves the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentration for a range of pollutants important for air pollution applications. The meteorological component of TAPM predicts the mesoscale flows important to local-scale air pollution, and in this paper has been evaluated in the Kalgoorlie region of Western Australia for the year 2000, using sodar data provided by Western Mining Corporation.

The results show that TAPM successfully predicted the annual, seasonal and diurnal variation of the winds at heights of available measurements (50–600 m). The mean and standard deviations were all within about 0.5 m s^{-1} for all heights, the root-mean-square errors increased from about 1.5 m s^{-1} for the 50 m level to about 3.0 m s^{-1} at the 600 m level. The average Index of Agreement was 0.92. The seasonal and diurnal variation of average winds were also shown to be predicted well, with no strong temporal bias indicated. The model also demonstrated good performance in predicting the passage of a cold front across the region.

The results show that TAPM has demonstrated good performance in predicting the temporal variation and vertical structure of the winds in the Kalgoorlie region, and these results, along with results from verification studies in other regions, indicate that TAPM can be used with confidence to describe the local-scale meteorology needed for meteorological and air pollution applications.

Introduction

Air pollution models that can be used to predict pollution concentrations for periods of up to a year are generally semi-empirical/analytic approaches based on Gaussian plumes or puffs. As input, these models typically use either a simple surface-based meteorological observations file or winds from a diagnostic wind-field model. The latter is basically a sophisticated interpolation model making use of conservation principles and available observations. The Air Pollution Model (TAPM V2) developed by CSIRO (Hurley 2002), is different to these approaches, in that it solves the fundamental fluid dynamics and scalar transport equations to predict mesoscale mete-

---

Corresponding author address: M. Edwards, CSIRO Atmospheric Research, PMB 1, Aspendale, Vic. 3195, Australia.

orology and pollutant concentrations for a range of pollutants important for air pollution applications, and so eliminates the need to have site specific meteorological observations to drive the model. Instead the model relies on large-scale synoptic fields of meteorological variables to provide the background meteorology, and it predicts the local-scale flows important to local air pollution, such as sea-breezes and terrain-induced flows.

TAPM has been used previously to evaluate various turbulence closures (Hurley 1997), to model winter and summer meteorology and photochemical smog in Melbourne (Hurley 2000a, 2000b), to model meteorological case studies in Kwinana (Hurley and Luhar 2000), to model events of transport of pollutants from Melbourne to Cape Grim (Cox et al. 2000), and to model year-long meteorology and air pollution for the industrial area of Kwinana (Hurley et al. 2001).

Examples of more recent TAPM verification studies are for year-long urban meteorology and photochemical smog and particles in Melbourne (Hurley et al. 2002b), for meteorology and air pollution in the Pilbara and Port Hedland regions (Physick et al. 2002a), for year-long urban meteorology and photochemical smog in Perth (Physick et al. 2002b), for a meteorological case study in Sydney (Azzi et al. 2002), for urban meteorology and air pollution on high ozone days in Brisbane (Ischtwan 2002), for air pollution modelling in the industrial region of Gladstone (Killip et al. 2002), and for meteorology and air pollution for several international tracer datasets (Luhar and Hurley 2002). A summary of some of these verification studies is contained in Hurley et al. (2002a).

In this paper, the meteorological component of TAPM V2 is used to predict meteorology at a site in Kalgoorlie where sonic detection and ranging (sodar) data are available. An overview of TAPM is presented, while further sections describe results and give conclusions.

Overview of TAPM V2

TAPM is a PC-based, nestable, prognostic meteorological and air pollution model driven by a user-friendly Graphical User Interface (GUI). The GUI allows the user to configure inputs, run the model, and analyse outputs generated by the model. The GUI is linked to databases of terrain height, land use, synoptic-scale meteorology and sea-surface temperature information. Analysis of outputs includes software for visualisation and extraction of time series and summary statistics for meteorology and ground-level pollution concentrations.

The following two subsections provide a brief overview of TAPM – more technical detail on TAPM including the numerical methods used to solve the model equations can be found in Hurley (2002).

Meteorological module

The mean horizontal wind components are determined from the momentum equations and the terrain-following vertical velocity from the continuity equation. Potential virtual temperature is determined from an equation combining the conservation of heat and water vapour. Pressure is determined from the sum of hydrostatic and non-hydrostatic components, with a Poisson equation optionally solved for the non-hydrostatic component. Conservation equations are solved for the specific humidity of water vapour, cloud water, and rain water.

Turbulence closure in the mean equations uses a gradient diffusion approach with diffusivity K, and includes a countergradient correction for temperature. An E - ε turbulence scheme is used to calculate K using prognostic equations for the turbulence kinetic energy (E) and its dissipation rate (ε).

Radiation at the surface is used for the computation of surface boundary conditions and for scaling variables, and includes the clear-sky short wave and long wave components with modifications for the effects of cloud liquid water.

Surface temperature and moisture are calculated from a weighted average of soil and vegetation values. A force-restore approach is used for soil temperature and moisture, and a surface energy balance approach is used for the vegetation temperature. Boundary conditions for the turbulent fluxes are determined by Monin-Obukhov surface-layer scaling variables and parametrisations for stomatal resistance.

TAPM V2 enhancements (compared to V1) include the improved use of synoptic analyses, improved processes (radiation, surface, clouds, deposition) and optional wind data assimilation.

Air pollution module

The air pollution component of TAPM consists of an Eulerian grid-based set of prognostic equations for pollutant concentration, with optional pollutant cross-correlation equations to represent countergradient fluxes, and an optional Lagrangian particle mode for near-source concentrations. The model can be run in either a tracer mode, or in a chemistry mode that includes a semi-empirical photochemistry mechanism and wet- and dry-deposition processes for major species of interest including nitrogen oxides, sulphur dioxide, ozone, and particles. Plume buoyancy and momentum effects for point sources are also considered.

TAPM V2 enhancements (compared to V1) include the ability to deal with more pollutant species, optional building-wake effects and more emission source types (line, area/volume, grid-based).

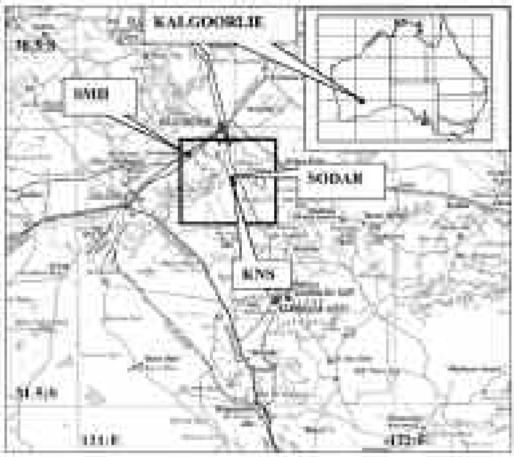
Predicting meteorology in Kalgoorlie

The Kalgoorlie region of southern Western Australia (see Fig. 1) is an inland industrial region with sparsely vegetated, relatively flat terrain. Western Mining Corporation (WMC) has some instrumented towers and a sodar system (see Fig. 1 for site locations) in the region, which are used as part of a reactive pollution control strategy to minimise the impact of industrial emissions on the local township. An important meteorological aspect of the reactive control strategy is the ability to deal with sharp changes in wind direction that potentially can sweep industrial plumes over the town (e.g. the passage of a cold front).

Model configuration

TAPM was used to model the hour-by-hour meteorology of the year 2000 in the Kalgoorlie region, using six-hourly analysis data at 1.0° grid resolution from the Bureau of Meteorology Global Assimilation and Prediction (GASP) system to provide the synoptic conditions (see Seaman et al. (1995); Bourke et al. (1995) for a description of GASP), Rand's global sea-surface temperatures from the US National Center for Atmospheric Research (NCAR), terrain height data from the Geoscience Australia (GEODATA) at nine-second grid resolution, and soil and vegetation classification data from CSIRO Wildlife and Ecology as model input. The model was run with a nested grid of 25 x 25 x 25 points at 30 km, 10 km and 3 km horizontal grid spacing, centred on longitude, latitude = (121°29′, -30°52.5′), with vertical levels: 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 750, 1000, 1250, 1500, 1750, 2000, 2500, 3000, 3500, 4000, 5000, 6000, 7000 and 8000 m above sea level. Model options used included time and space-varying synoptic conditions, vegetation, turbulence, and a dry deep-soil moisture content of 0.05 m^3 m^{-3} (m^3 water per m^3 soil). The model predictions on the 3000 m spaced grid were compared with measurements from the very closely located Kalgoorlie Nickel Smelter (KNS) tower and sodar (see Fig. 1 for site location). Model performance will not only be dependent on the model formulation, but also on the quality of the input data to the model, particularly the GASP analyses.

Fig. 1 **Locations of the SMH (Seven Mile Hill) tower (not used), the KNS tower and the sodar site. The WMC Kalgoorlie Nickel Smelter is located close to the tower and the sodar site. The geographical position of Kalgoorlie is also shown. The bold outline represents the innermost TAPM grid.**



Results

Model predictions of hourly averaged meteorology at model levels closest to the sodar levels, and to the KNS tower, were extracted at the nearest grid-point to each site for the 3000 m spaced inner grid. The corresponding sodar levels were at 50, 110, 140, 200, 260,

Table 1. **Wind (*ws, u* and *v*), temperature at 10 m (T10) and Total Solar Radiation (TSR) statistics for TAPM simulation of 2000 at the KNS tower site. (Note that the tower wind data are from a height of 60 m, while the model wind data are from 50 m.)**

	NUMBER	*MEAN_OBS*	*MEAN_MOD*	*STD_OBS*	*STD_MOD*	*CORR*	*RMSE*	*RMSE_S*	*RMSE_U*	*IOA*	*SKILL_E*	*SKILL_V*	*SKILL_R*
WS60	8584	6.3	5.6	2.3	2.1	0.70	1.90	1.17	1.49	0.81	0.64	0.89	0.81
U60	8584	-1.2	-0.9	5.1	4.6	0.91	2.10	0.88	1.91	0.95	0.38	0.92	0.42
V60	8584	0.6	0.4	4.3	3.6	0.86	2.19	1.18	1.84	0.92	0.43	0.85	0.51
T10	8580	19.5	17.4	6.4	7.7	0.92	3.82	2.22	3.11	0.93	0.48	1.20	0.59
TSR	8584	202	246	286	346	0.91	151	53.5	142	0.94	0.50	1.21	0.53

KEY: OBS = Observations, MOD = Model Predictions, MEAN = Arithmetic mean, STD = Standard Deviation, CORR = Pearson Correlation Coefficient (0=no correlation,1=exact correlation), RMSE = Root Mean Square Error, RMSE_S = Systematic Root Mean Square Error, RMSE_U = Unsystematic Root Mean Square Error, IOA = Index of Agreement (0=no agreement, 1=perfect agreement), SKILL_E = (RMSE_U)/(STD_OBS) (<1 shows skill), SKILL_V = (STD_MOD)/(STD_OBS) (near to 1 shows skill), SKILL_R = (RMSE)/(STD_OBS) (<1 shows skill).

Table 2(a). Wind speed (m s^{-1}) statistics for TAPM simulation of 2000 at the sodar site.

HEIGHT	*NUMBER*	*MEAN_OBS*	*MEAN_MOD*	*STD_OBS*	*STD_MOD*	*CORR*	*RMSE*	*RMSE_S*	*RMSE_U*	*IOA*	*SKILL_E*	*SKILL_V*	*SKILL_R*
50 m	7846	5.6	5.5	2.1	2.0	0.73	1.52	0.62	1.39	0.85	0.66	0.95	0.72
100 m	7851	6.7	6.8	2.6	2.4	0.75	1.79	0.77	1.62	0.86	0.62	0.93	0.69
150 m	7713	7.1	7.7	2.9	3.0	0.76	2.07	0.81	1.90	0.86	0.66	1.03	0.72
200 m	7263	7.8	8.0	3.3	3.1	0.77	2.24	0.88	2.06	0.87	0.63	0.96	0.68
250 m	6762	8.3	8.8	3.7	3.7	0.79	2.49	0.83	2.35	0.88	0.64	1.02	0.68
300 m	6486	8.5	9.2	3.8	4.1	0.79	2.68	0.87	2.53	0.88	0.66	1.08	0.70
400 m	5514	9.1	9.6	4.2	4.5	0.79	2.84	0.77	2.73	0.89	0.65	1.06	0.67
500 m	4935	9.6	9.7	4.4	4.6	0.80	2.87	0.75	2.77	0.89	0.62	1.04	0.65
600 m	4483	10.2	9.8	4.6	4.7	0.80	2.98	0.93	2.83	0.89	0.62	1.02	0.65

KEY: Same as for Table 1.

Table 2(b). West-east (*u*) component of the wind (m s^{-1}) statistics for TAPM simulation of 2000 at the sodar site.

HEIGHT	*NUMBER*	*MEAN_OBS*	*MEAN_MOD*	*STD_OBS*	*STD_MOD*	*CORR*	*RMSE*	*RMSE_S*	*RMSE_U*	*IOA*	*SKILL_E*	*SKILL_V*	*SKILL_R*
50 m	7846	-1.1	-0.9	4.6	4.6	0.93	1.79	0.50	1.72	0.96	0.37	0.99	0.39
100 m	7851	-1.3	-1.3	5.5	5.5	0.93	2.11	0.37	2.08	0.96	0.38	1.01	0.39
150 m	7713	-1.4	-1.4	5.8	6.3	0.93	2.35	0.06	2.35	0.96	0.40	1.09	0.40
200 m	7263	-1.1	-1.6	6.4	6.6	0.93	2.48	0.36	2.46	0.96	0.39	1.03	0.39
250 m	6762	-1.5	-1.8	6.9	7.4	0.93	2.67	0.22	2.66	0.96	0.39	1.07	0.39
300 m	6486	-1.5	-1.7	7.1	7.8	0.94	2.78	0.30	2.77	0.96	0.39	1.10	0.39
400 m	5514	-1.5	-1.6	7.8	8.3	0.94	2.95	0.14	2.95	0.97	0.38	1.07	0.38
500 m	4935	-1.4	-1.3	8.3	8.6	0.94	3.00	0.25	2.99	0.97	0.36	1.04	0.36
600 m	4483	-1.2	-1.0	8.8	8.7	0.94	3.10	0.66	3.03	0.97	0.34	0.99	0.35

KEY: Same as for Table 1.

Table 2(c). South-north (*v*) component of the wind (m s^{-1}) statistics for TAPM simulation of 2000 at the sodar site.

HEIGHT	*NUMBER*	*MEAN_OBS*	*MEAN_MOD*	*STD_OBS*	*STD_MOD*	*CORR*	*RMSE*	*RMSE_S*	*RMSE_U*	*IOA*	*SKILL_E*	*SKILL_V*	*SKILL_R*
50 m	7846	0.6	0.4	3.6	3.6	0.87	1.87	0.57	1.78	0.93	0.49	0.99	0.51
100 m	7851	0.7	0.5	4.4	4.4	0.87	2.27	0.68	2.16	0.93	0.49	0.99	0.51
150 m	7713	0.7	0.3	4.8	5.1	0.87	2.53	0.58	2.46	0.93	0.51	1.05	0.53
200 m	7263	0.9	0.2	5.3	5.3	0.87	2.79	0.98	2.61	0.93	0.49	0.99	0.52
250 m	6762	0.5	0.2	5.8	5.8	0.89	2.75	0.64	2.68	0.94	0.47	1.01	0.48
300 m	6486	0.5	0.1	5.9	6.1	0.89	2.82	0.62	2.75	0.94	0.47	1.04	0.48
400 m	5514	0.6	0.1	6.2	6.3	0.89	2.93	0.77	2.83	0.94	0.46	1.02	0.47
500 m	4935	0.7	0.0	6.5	6.4	0.89	3.06	1.01	2.89	0.94	0.45	0.99	0.47
600 m	4483	0.7	0.0	6.7	6.4	0.88	3.29	1.28	3.03	0.93	0.45	0.96	0.49

KEY: Same as for Table 1.

290, 410, 500 and 590 m, and were all within 10 m of the nearest model level. Note that the number of data points was reduced by about a factor of two by the 590 m height level, and by even more above this level where the data were thought to be outside the valid range of the instrument, and so were not used. Typically, this instrument is less reliable at heights above 400 m.

The predictions and observations were used to produce statistics based on the recommendations of Willmott (1981). As well as the usual mean and standard deviations, the statistics include a breakdown of root mean square errors (RMSE) into systematic (RMSE_S) and unsystematic (RMSE_U) components, the Index Of Agreement (IOA) which provides a more consistent measure of performance than the

Fig. 2 **Annual-averaged scalar wind speed and wind components varying with height at the sodar site.**

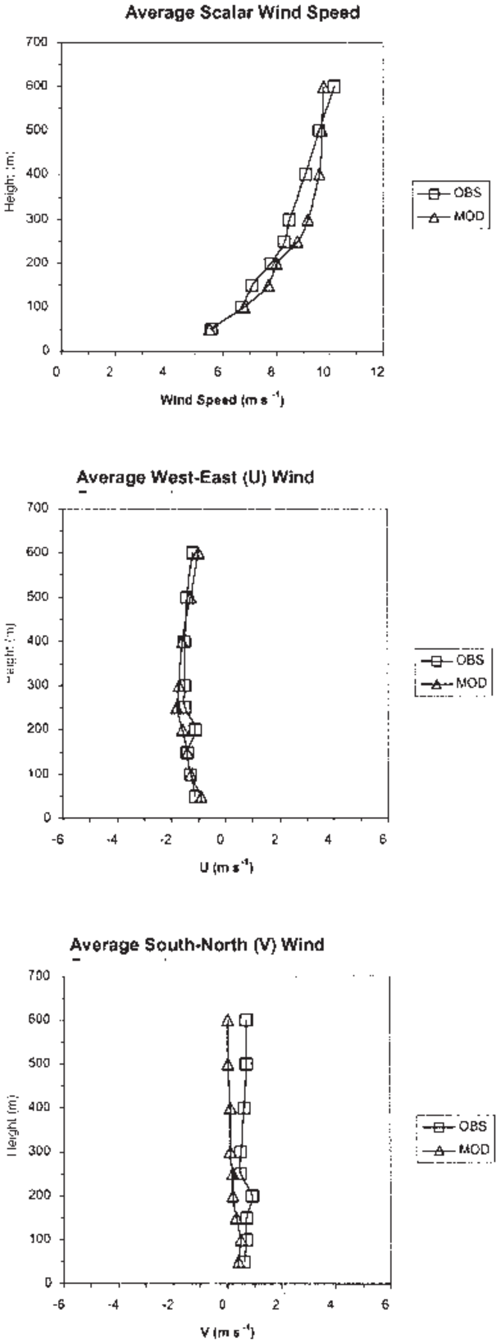
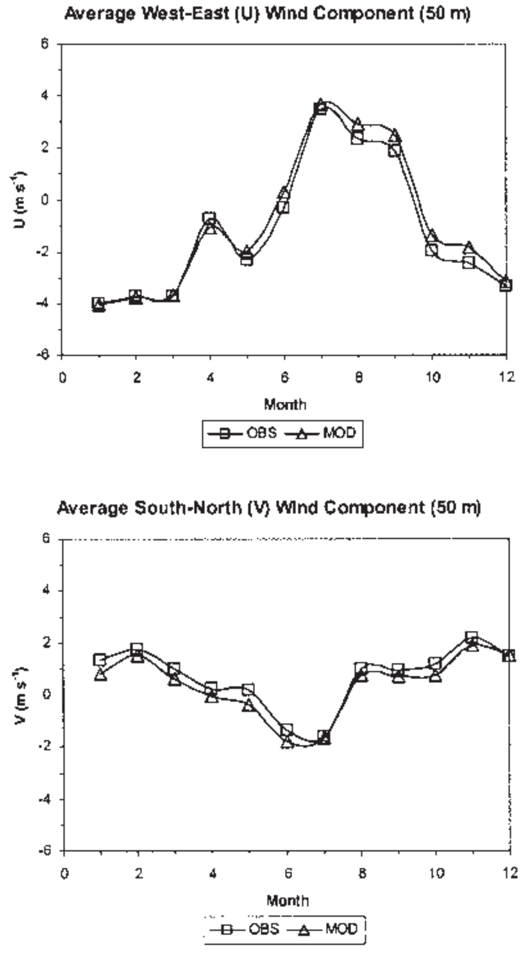


Fig. 3 **Monthly-averaged scalar wind speed and wind components for each month of the year (month 1 is January, month 2 is February, etc.) at the sodar site.**



correlation coefficient (also shown for comparison), and measures of variational skill as recommended by Pielke (1984). Low RMSE values in a model indicate that the model explains most of the variation in the observations, while in a model lacking bias, RMSE_S should approach zero, and consequently RMSE_U should be close to RMSE. According to Pielke (1984), a model predicts with skill if two conditions are satisfied: (a) the standard deviations of the predictions and observations are approximately the same; and (b) RMSE is less than the standard deviation of the observations. The Index of Agreement is a measure of how well the predictions' departures from the

Table 3(a). Wind speed (*ws*), west-east (*u*) wind component and south-north (*v*) wind component (m s^{-1}) statistics for TAPM simulation of January 2000 at the sodar site, at model levels 50 and 500 m.

HEIGHT	NUMBER	MEAN_OBS	MEAN_MOD	STD_OBS	STD_MOD	CORR	RMSE	RMSE_S	RMSE_U	IOA	SKILL_E	SKILL_V	SKILL_R
WS50	671	6.0	5.8	2.1	2.1	0.76	1.47	0.50	1.39	0.87	0.66	1.00	0.70
WS500	518	9.3	10.0	4.0	4.6	0.81	2.82	0.72	2.73	0.89	0.68	1.15	0.70
U50	671	-4.0	-3.5	3.7	4.1	0.86	1.91	0.57	1.82	0.93	0.49	1.11	0.52
U500	518	-6.9	-7.6	5.9	6.3	0.87	3.20	0.78	3.10	0.93	0.52	1.07	0.54
V50	671	1.3	0.8	3.0	2.9	0.81	1.92	0.82	1.73	0.89	0.57	0.96	0.63
V500	518	0.3	-0.4	4.5	4.8	0.84	2.75	0.81	2.63	0.91	0.59	1.08	0.61

KEY: Same as Table 1.

Table 3(b). Wind speed (*ws*), west-east (*u*) wind component and south-north (*v*) wind component (m s^{-1}) statistics for TAPM simulation of July 2000 at the sodar site, at model levels 50 and 500 m.

HEIGHT	NUMBER	MEAN_OBS	MEAN_MOD	STD_OBS	STD_MOD	CORR	RMSE	RMSE_S	RMSE_U	IOA	SKILL_E	SKILL_V	SKILL_R
WS50	742	6.4	6.3	2.1	2.1	0.79	1.39	0.43	1.32	0.88	0.62	1.02	0.66
WS500	466	12.6	12.4	4.3	3.8	0.83	2.41	1.17	2.11	0.90	0.49	0.88	0.56
U50	742	3.5	3.7	4.0	3.8	0.93	1.44	0.43	1.38	0.96	0.35	0.97	0.36
U500	466	8.7	9.2	6.8	5.9	0.91	2.93	1.52	2.51	0.95	0.37	0.87	0.43
V50	742	-1.6	-1.7	3.9	3.6	0.92	1.56	0.57	1.45	0.95	0.38	0.93	0.40
V500	466	-2.2	-2.9	7.1	6.4	0.94	2.53	1.29	2.18	0.96	0.31	0.90	0.36

KEY: Same as Table 1.

observed mean match the observations' departures from the observed mean, and in particular how well is the match in the sign of the departures. Hurley (2000a) summarises the formulae for the various statistical measures, lists some previous studies with other models that have used these measures to evaluate model performance – these studies imply that an IOA of 0.5 or greater represents a good result – and uses these statistics to evaluate TAPM performance for the Melbourne region. Hurley et al. (2002a) summarises TAPM performance statistics for a number of studies, achieving an IOA for winds and temperature of greater than 0.8.

Annual results

Table 1 shows statistics for the KNS tower for wind observed at 60 m and predicted at 50 m, temperature at 10 m, and for total solar radiation (TSR). There is some systematic bias in the results, of about 1 m s^{-1} in wind speed (due mainly to the 10 m height difference in the observations compared to predictions) and of about 2°C in the temperature (due to an underprediction of night-time temperature on some occasions, possibly caused by inaccurate surface parametrisation and/or underprediction of the occurrence of cloud). There is also a small bias in the TSR, tending toward an overprediction. Average RMSE and IOA are 2.1 m s^{-1} and 0.89 for winds, 3.8 °C and 0.93 for temperature, and 151 W m^{-2} and 0.94 for TSR. The results also indicate that the model shows skill for each of these variables, as in all cases the standard deviations of the predicted and observed variables are within about 20 per cent, the RMSE are much less than the observed standard deviations, and the IOA are all well above 0.5.

Tables 2(a)–(c) show statistics for observed (OBS) versus model predicted (MOD) winds for various model levels, compared to the sodar data. The results show that the sodar winds are modelled very well at all heights, and suggest that the small bias in wind speed in the tower comparisons of Table 1 are indeed mostly due to the 10 m height difference that is more critical for heights near the ground. The mean and standard deviations are all within about 0.5 m s^{-1} for all heights (also see Fig. 2), the RMSE increases from about 1.5 m s^{-1} for the 50 m level to about 3.0 m s^{-1} at the 600 m level for wind speed (slightly higher for the wind components), and the average IOA are 0.87 for wind speed, 0.96 for the west-east (*u*) component and 0.93 for the south-north (*v*) component (an average of 0.92 for winds). The level of skill shown at all levels indicates that the standard deviations of the predicted and observed variables are within about 10 per cent, the RMSE are much less than the observed standard deviations, and the IOA are all well above 0.5 – in fact they are all 0.85 or higher.

Fig. 4 **Annual-averaged scalar wind speed and wind components varying with time of day at 50 m above ground level at the sodar site. GASP results are for 90 m above ground level.**

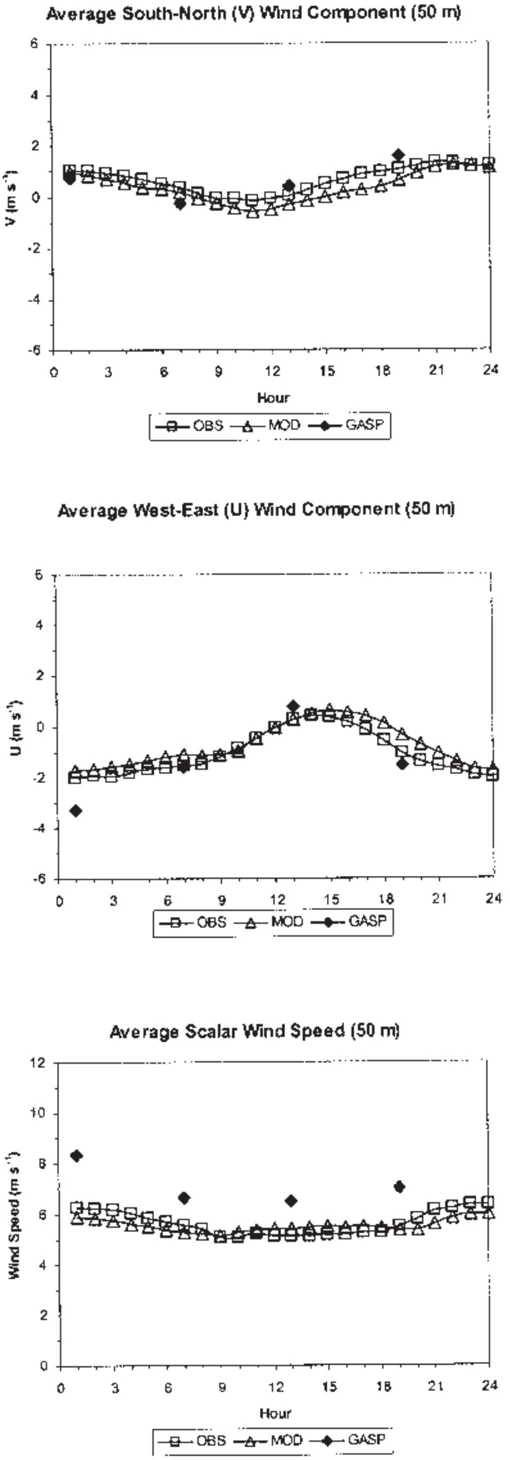
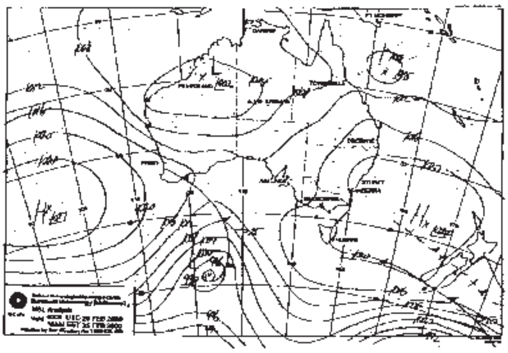


Fig. 5 **Mean sea level pressure chart at 0000 UTC (0800 hours local time) on 25 February 2000 (courtesy of the Australian Bureau of Meteorology). The geographical position of Kalgoorlie is shown on Fig. 1.**



Seasonal and diurnal results

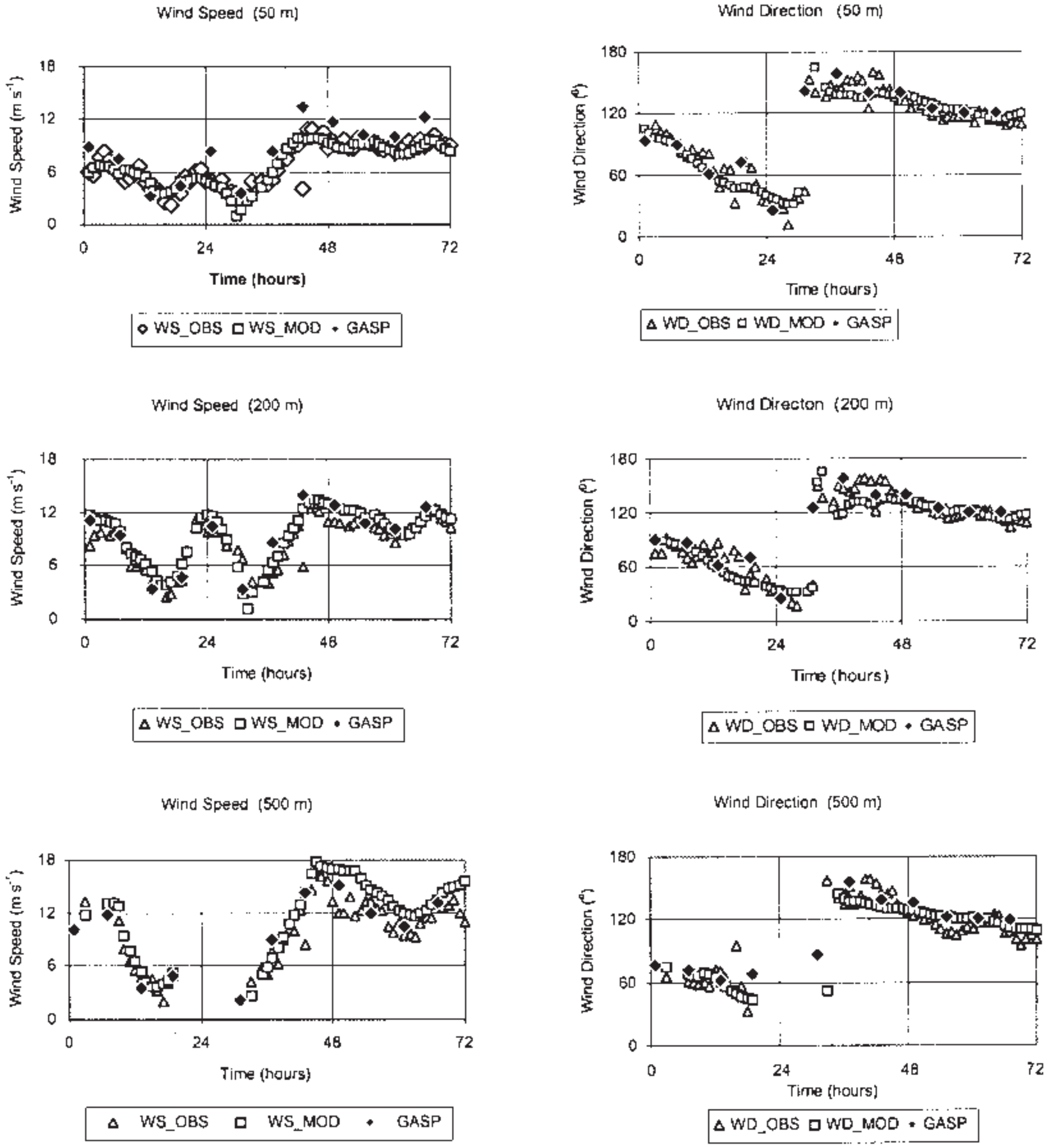
Tables 3(a)–(b) show statistics for observed (OBS) versus model predicted (MOD) winds for a summer (January) and winter (July) month, for various model levels. These results show similar monthly performance to the statistics for the whole year, but also indicate the seasonal variability in the observations, which is well predicted by the model. This is also apparent from Fig. 3, which presents the monthly-averaged observed versus predicted wind speed and wind components. In particular, the monthly-averaged wind components vary by a large amount over the year, due mainly to synoptic-scale seasonal effects that are controlled to some extent by the six-hourly GASP analyses. Figure 4 shows the average wind speed and wind components for each hour of the day, and the results indicate that the model performs well (on average) at all times of the day, as do the six-hourly GASP analyses (approximately 90 m above the ground), although there is some overprediction of wind speed in the GASP results probably due to the increased height (90 m as opposed to 50 m for TAPM).

Example results for the passage of a cold front

As mentioned earlier, the passage of cold fronts across the Kalgoorlie region is important for air pollution applications, and so here we present an example of model performance for 25 February 2000 when such an event occurred, (see the synoptic chart in Fig. 5).

Figure 6 shows the observed and predicted time-series of hourly average wind speed and direction at heights of 50, 200 and 500 m, for the period 24–26 February 2000. The model successfully predicts the

Fig. 6 **Time-series of observed and predicted wind speed and direction at 50, 200, and 500 m for 24–26 February 2000. GASP results are for 90, 230 and 460 m.**



change in wind direction from north-northeast to south-southeast and the corresponding increase in wind speed at all levels up to and including 500 m, on the morning of 25 February 2000. The model not only reproduces the strength and timing of the cold front, but also predicts the observed nocturnal jet at the 200 m level shown in the plots during the night of 24–25 February 2000. The overlaid six-hourly GASP results (at heights of 90 m, 230 m and 460 m above ground level) also do well against the data for this case.

Conclusions

The Air Pollution Model (TAPM) was used to model the meteorology of the Kalgoorlie region of southern Western Australia for the year 2000. Model predictions of hourly averaged meteorology were compared to data from both a tower and a sodar owned and operated by Western Mining Corporation.

The results show that TAPM is able to capture well the meteorology of the region, and in particular, successfully predict the annual, seasonal and diurnal variation of the winds at heights of available measurements (50–600 m). The mean and standard deviations are all within about 0.5 m s^{-1} for all heights, the RMSE increases from about 1.5 m s^{-1} for the 50 m level to about 3.0 m s^{-1} at the 600 m level for wind speed (slightly higher for the wind components), and the average IOA are 0.87 for wind speed, 0.96 for the west-east (u) component and 0.93 for the south-north (v) component (an average of 0.92 for winds). The level of skill shown at all heights indicates that the standard deviations of the predicted and observed variables are within about 10 per cent, the RMSE are much less than the observed standard deviations, and the IOA are all 0.85 or higher.

Seasonal and diurnal variation of winds were also shown to be predicted well, with no bias shown towards better performance at particular times of the year or day. This was also illustrated by the good performance of the model in predicting the passage of a cold front across the region, and in reproducing the diurnal variation of winds – particularly an elevated nocturnal jet. At least for the gentle terrain of Kalgoorlie, the six-hourly 1° grid resolution of the GASP analyses is also able to well describe the observations; the analyses are therefore an excellent source of forcing for TAPM.

The good performance of TAPM in predicting the vertical structure of the winds in the Kalgoorlie region, together with the good performance demonstrated by other studies at other sites throughout Australia, gives increasing confidence in the use of the model for meteorological and air pollution applications.

Acknowledgments

Thanks to Bryn McDougall of Western Mining Corporation for providing the Kalgoorlie tower and sodar data, and to Owen Pitts of Sinclair Knight Merz for suggesting that these data may make a good upper-level verification dataset for TAPM.

References

Azzi, M., Hyde, R. and Duc, H. 2002. Comparison of predicted and observed temperature and wind profiles on a high ozone event in Sydney. *Proceedings of the 16th International Clean Air and Environment Conference of CASANZ*, Christchurch, New Zealand, 19–22 August 2002.

Bourke, W., Hart, T., Steinle, P., Seaman, R., Embery, G., Naughton, M. and Rikus, L. 1995. Evolution of the Bureau of Meteorology Global Assimilation and Prediction system. Part2: Resolution enhancements and case studies. *Aust. Met. Mag., 44,* 19-40.

Cox, M., Hurley, P., Fraser, P. and Physick, W. 2000. Investigation of Melbourne region pollution events using Cape Grim data, a regional transport model (TAPM) and the EPA Victoria carbon monoxide inventory. *Clean Air, 33*, 35–40.

Hurley, P.J. 1997. An evaluation of several turbulence schemes for the prediction of mean and turbulent fields in complex terrain. *Bound. Lay. Met., 83,* 43–73.

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

Hurley, P. 2000b. The Air Pollution Model (TAPM): summary of some recent verification work in Australia. *Proceedings of the 15th International Clean Air Conference of CASANZ,* Sydney, 26-30 November 2000, 98–103. Available at http://www.dar.csiro.au/publications/hurley_2000a.pdf.

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

Hurley, P., Blockley, A. and Rayner, K. 2001. Verification of a prognostic meteorological and air pollution model for year-long predictions in the Kwinana region of Western Australia. *Atmos. Environ., 35,* 1871–1880.

Hurley, P.J. and Luhar, A.K. 2000. The Kwinana Coastal Fumigation Study: III. Meteorological and turbulence modelling on selected days. *Bound. Lay. Met., 94*, 115–38.

Hurley, P., Physick, W. and Luhar, A. 2002a. The Air Pollution Model (TAPM) Version 2. Part 2: Summary of some verification studies. *CSIRO Atmospheric Research Technical Paper, No. 57*. Available at http://www.dar.csiro.au/TAPM.

Hurley, P., Manins, P., Lee, S., Boyle, R., Ng, Y. and Dewundege, P. 2002b. Year-long urban airshed modelling in Melbourne: verification of TAPM for photochemical smog and particles. *Proceedings of the 16th International Clean Air and Environment Conference of CASANZ*, Christchurch, New Zealand, 19-22 August 2002, 347–353. Available at http://www.dar.csiro.au/publications/hurley_2002d.pdf.

Ischtwan, J. 2002. Prognostic modelling of a period of summer photochemical smog in south-east Queensland. *Proceedings of the 16th International Clean Air and Environment Conference of CASANZ,* Christchurch, New Zealand, 19–22 August 2002.

Killip, C., Brooke, A., Jackson, L., Best, P., Verrall, K. and Wainwright, D. 2002. Advanced modelling tools for air quality management – Gladstone 10 years on. *Proceedings of the 16th International Clean Air and Environment Conference of CASANZ*, Christchurch, New Zealand, 19–22 August 2002.

Luhar, A. and Hurley, P. 2002. Evaluation of TAPM using the Indianapolis (urban) and Kwinana (coastal) field datasets. *Proceedings of the 16th International Clean Air and Environment Conference,* Christchurch, New Zealand, 18-22 August 2002, 518–525. Available at http://www.dar.csiro.au/publications/hurley_2002a.pdf.

Physick, W., Blockley, A., Farrar, D., Rayner, K. and Mountford, P. 2002a. 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, 629–634. Available at http://www.dar.csiro.au/publications/physick_2002a.pdf

Physick, W., Cope, M. and Stuart, A. 2002b. Evaluation of a population-surrogate emissions inventory for Perth using TAPM. *Proceedings of the 16th International Clean Air and Environment Conference,* Christchurch, New Zealand, 18–22 August 2002, 625–640. Available at http://www.dar.csiro.au/publications/physick_2002b.pdf

Pielke, R.A. 1984. *Mesoscale Meteorological Modelling*. Academic Press, Orlando, 612pp.

Seaman, R., Bourke, W., Steinle, P., Hart, T., Embery, G., Naughton, M. and Rikus, L. 1995. Evolution of the Bureau of Meteorology Global Assimilation and Prediction system. Part1: Analysis and initialisation. *Aust. Met. Mag., 44,* 1-18.

Willmott, C.J. 1981. On the validation of models. *Phys. Geography, 2*, 184-194.