COMPARISON OF METEOROLOGICAL AND DISPERSION PREDICTIONS OBTAINED USING TAPM WITH THE KINCAID (RURAL), INDIANAPOLIS (URBAN) AND KWINANA (COASTAL) FIELD DATA SETS

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INTRODUCTION

The Air Pollution Model (TAPM) developed by CSIRO is a PC-based, three-dimensional (3-d), nestable, prognostic meteorological and air pollution model, driven by a graphical user interface (*Hurley,* 2002). It uses global input databases of terrain height, land use, sea-surface temperature, and synoptic meteorological analyses. The meteorological component of TAPM predicts the local-scale flow, such as sea breezes and terrain induced circulations, given the larger scale synoptic meteorological fields. Its air pollution component uses the predicted meteorology and turbulence, and consists of an Eulerian grid-based approach for concentration, with an optional Lagrangian mode for capturing the near-source dispersion. TAPM (version 2.0) is evaluated using three field data sets on point-source dispersion: the 1980–81 Kincaid (USA) dataset, the 1985 Indianapolis (USA) data set, and the 1995 Kwinana (Australia) data set. The first two are part of the Model Validation Kit (*Olesen,* 1995) and were taken in relatively simple orography. The third set is for dispersion under sea-breeze conditions, which are not represented by the Kit. Since the dates of the three data sets precede the input synoptic meteorological data supplied with TAPM, which are given from 1997, we used the National Centers for Environmental Prediction (NCEP) data (*Kalnay*, 1996). TAPM was run in Lagrangian mode with and without wind data assimilation. The model evaluation results are compared with (published) results from the ADMS3 (UK), AERMOD (USA) and ISCST3 (USA) models for Kincaid and Indianapolis, and with results from the DISPMOD (Australia) model for Kwinana.

DATA SETS AND MODEL APPLICATION

The Kincaid field study involved sulfur hexafluoride (SF_6) tracer releases from the 187-m stack at the Kincaid power plant in Illinois (relatively flat farmland with a roughness length ≈ 0.1 m). Most meteorological measurements were taken from 10-m and 100-m towers located near the plant. Ground-level concentrations of SF_6 were measured on a maximum of 12 arcs at distances from 0.5 to 50 km from the stack, representing mostly convective cases. Out of a total of 1284 hours of data on arc-wise maxima, 585 are Quality 2 (maxima identified) and 338 are Quality 3 (maxima well defined). TAPM was run for the three data periods: 20 April–9 May 1980, 10–25 July 1980, and 16 May–1 June 1981. Three nested domains of 31 × 31 horizontal grid points at 16-, 4-, and 1-km spacing for the meteorology, and 61 × 61 points at 8-, 2-, and 0.5-km spacing for the pollution were used. The lowest five of the 25 vertical levels were 10, 25, 50, 100 and 150 m. A deep soil moisture content value of 0.15 kg kg^{-1} (the model default value) was used to match the recommended value of 0.5 for the moisture availability factor (α). The data assimilation runs involved the use of the observed wind speed and direction at 10, 30, 50 and 100 m AGL. The hourly average pollution predictions on the 0.5-km spaced grid were processed to obtain maxima at the 0.5-, 1-, 2-, 3-, 5-, 7-, 10- and 15-km arcs while those on the 2-km spaced grid (corresponding to the 4-km spaced meteorological grid) were processed to obtain the maxima at the 20-, 30-, 40- and 50-km arcs.

The Indianapolis study, conducted during 16 September–12 October 1985, involved SF_6 tracer releases from the 83.8-m stack at the Perry K power plant in Indianapolis (typical industrial/commercial/urban complex (roughness length ≈ 1 m) with relatively flat local terrain).

Meteorological observations were taken at a height of 94 m at the top of a bank building in the urban area, from two 10-m towers in suburban and rural areas, and an 11-m tower at an urban location. Concentrations were observed on up to 160 ground-level monitors on 12 arcs at distances from 0.25 to 12 km from the stack, representing all stability classes and most wind speed ranges. Out of a total of 1511 hours of arc-wise maxima, 747 are Quality 2 and 469 are Quality 3. TAPM was run for the above period with four nested domains of 30 × 30 grid points at 30-, 10-, 3- and 1-km spacing for the meteorology, and 101 × 101 points at 7.5-, 2.5-, 0.75- and 0.25-km spacing for the pollution. Other model settings were the same as in the Kincaid case. The data assimilation runs used winds observed at the urban tower and the Bank building. A deep soil moisture content value of 0.3 kg kg^{-1} was used for this soil and surface type. The hourly average pollution predictions on the 0.25-km spaced grid were processed to obtain ground-level maxima.

Fumigation under sea-breeze conditions is a common occurrence in the coastal region of Kwinana in Western Australia. As part of the 1995 Kwinana Coastal Fumigation Study, plumes from two stacks, Stage A and Stage C (heights 114 m and 189 m, respectively), of the Kwinana Power Station located on the coastline were scanned using a lidar (see *Luhar and Young*, 2002). These scans were then used to derive hourly average dispersion moments at several downwind distances, both before and after fumigation. An existing network of air quality stations measured surface sulfur dioxide (SO_2) concentrations and meteorology (see *Luhar*, 2002). To simulate the SO_2 data, TAPM was run for the period 26 January−6 February, 1995, with four nested domains of 30 × 30 horizontal grid points at 30-, 10-, 3- and 1-km spacing for the meteorology, and 81 × 81 points at 7.5-, 2.5-, 0.75- and 0.25-km spacing for the pollution. The vertical levels were the same as above. A total of 20 significant point sources of SO_2 were included in the model. The winds observed at 10 m and 27 m AGL at the Hope Valley monitoring station (about 2.5 km inland from the coast) were assimilated. A very dry (summertime) deep soil moisture content of 0.05 kg kg^{-1} was used based on past experience. The hourly average model meteorological and pollution predictions on the smallest respective grids were extracted at the nearest grid point to each of the five monitoring sites in the area. To simulate the lidar moments, TAPM was run with data assimilation with a finer resolution of 161 × 121 grid points at 3-, 1-, 0.3- and 0.1-km spacing for pollution. The 3-d concentration field predicted for each stack plume was processed by converting the model grid coordinates into locations in the wind coordinate system.

MODEL COMPARISON RESULTS

Figure 1 compares the time series of the hourly-average winds observed at 100 m AGL at Kincaid for 16 May−1 June 1981 with that predicted by TAPM at the same level. It can be seen that overall the model without data assimilation (TAPM) simulates the observed trend quite well, but there are some localised discrepancies, especially in wind speed during 48−96 h and 312−336 h when the model underpredicts significantly and in wind direction during 240−264 when the model points to a more easterly flow. As expected, the model results with data assimilation (TAPM-A) follow the observations very closely. Table 1 gives the model performance statistics for SF_6, together with those presented in *McHugh et al.* (1999), for ISCST3, AERMOD and ADMS3. It is clear that overall model statistics are the best for ADMS3 followed by TAPM-A and TAPM. The ratio of the predicted to observed robust highest concentration (RHC_R) (*Cox and Tikvart*, 1990) shows that TAPM-A performs the best for extreme values with an over-prediction of only about 20%. The fact that TAPM performs satisfactorily without data assimilation, here as well as in the other regions given below, is of great use because, unlike the other models, in this case the model does not require any direct meteorological observations. TAPM does well for the Quality 3 data as well.

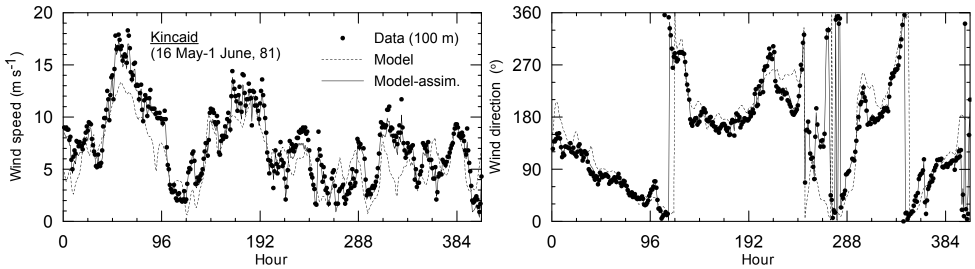

Figure 1. Time series of the hourly-average wind speed and direction at 100 m for Kincaid.

Table 1. Model performance statistics for Kincaid (Quality 2 and 3)

Model	Mean ng/m^3/g/s	Sigma ng/m^3/g/s	Bias ng/m^3/g/s	NMSE	Cor	Fa2	Fb	Fs	RHC_R
C_OBS	41.0	39.3	0.0	0.00	1.00	1.00	0.00	0.00	1.00
ISCST3	23.1	53.3	17.9	3.8	0.26	0.26	0.56	-0.30	0.61
AERMOD	20.3	24.1	20.7	2.3	0.35	0.33	0.68	0.48	0.52
ADMS3	43.2	33.5	-2.2	0.8	0.49	0.58	-0.05	0.16	0.70
TAPM	68.9	64.5	-27.9	1.5	0.44	0.44	-0.51	-0.49	1.48
TAPM-A	60.4	58.6	-19.4	1.3	0.44	0.50	-0.38	-0.40	1.18

NMSE: normalised mean square error, Cor: correlation, Fa2: fraction within a factor of 2, Fb: fractional bias, Fs: fractional variance, RHC_R ratio of the predicted to observed robust highest concentration based on top 10 values.

For Indianapolis, the agreement between the time series of the hourly-average wind speed and wind direction observed at 94 m AGL and those predicted by TAPM at the 100-m level both with and without wind data assimilation is excellent (Figure 2). The performance statistics

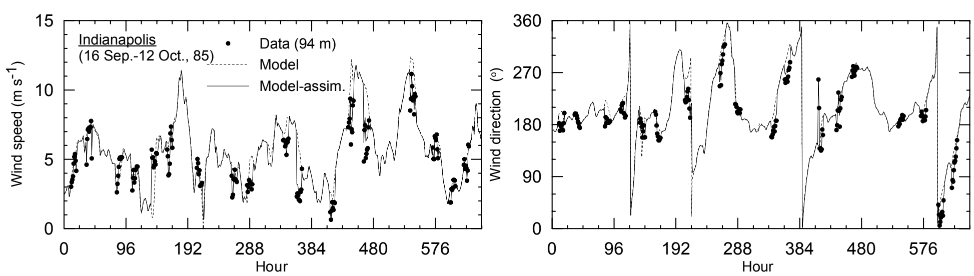

Figure 2. Time series of the hourly-average wind speed and direction observed at 94 m AGL and that predicted by TAPM at the 100-m level for Indianapolis.

given in Table 2 suggest that overall the three top performing models are TAPM-A, TAPM and ADMS3. The correlation coefficient is the highest for TAPM-A followed by TAPM and ADMS3. The Fa2 (fraction within a factor of two) values are somewhat lower for the present model, largely because in TAPM occasionally the plume does not reach the ground under night-time stable conditions. In all other models, the *observed* meteorological data are used as input with the assumption that the minimum value of the Obukhov length is 50 m in stable conditions, which moderates the stability and causes the plume to diffuse more. All models perform well for the prediction of extreme concentrations.

Table 2. Model performance statistics for Indianapolis (Quality 2 and 3)

Model	Mean ng/m³/g/s	Sigma ng/m³/g/s	Bias ng/m³/g/s	NMSE	Cor	Fa2	Fb	Fs	RHC_R
C_OBS	258	222	0.0	0.0	1.00	1.00	0.00	0.00	1.00
ISCST3	404	321	-146	1.4	0.16	0.45	-0.44	-0.37	1.14
AERMOD	225	196	33	1.3	0.17	0.41	0.14	0.13	0.86
ADMS3	265	255	-8	1.3	0.26	0.42	-0.03	-0.14	1.03
TAPM	261	335	-2.8	1.4	0.46	0.32	-0.01	-0.41	1.21
TAPM-A	248	284	10	1.0	0.51	0.36	0.04	-0.25	0.92

In Figure 3 for Kwinana, there is good agreement between the time series of the hourly-average winds observed at 10 m AGL at the Hope Valley station and the corresponding TAPM predictions, including the change in wind direction to the west/south-west during the day on most days, which corresponds to the onset of sea breeze that turns more southerly with time. There are some differences between the two model curves close to the start and end times of the simulated period. Table 3 indicates a reasonable performance by TAPM in predicting concentrations at the five monitoring stations in Kwinana, especially as they are paired in both space and time. Data assimilation leads to better results. The performance of DISPMOD, a plume model incorporating shoreline fumigation, wind shear, and skewed convective mixing algorithms (see *Luhar*, 2002), is very similar to TAPM-A.

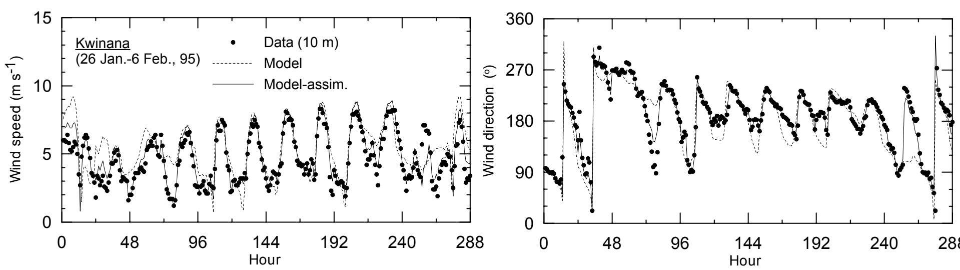

Figure 3. Time series of the hourly-average wind speed and wind direction observed at 10 m AGL at the Hope Valley station and that predicted by TAPM at the same level.

Table 3. Model performance statistics for Kwinana (N_{obs} = 498)

Model	Mean μg/m³	Sigma μg/m³	Bias μg/m³	NMSE	Cor	Fa2	Fb	Fs	RHC_R
C_OBS	15.3	19.1	0.0	0.0	1.00	1.00	0.00	0.00	1.00
DISPMOD	17.7	25.6	-2.4	1.8	0.55	0.26	-0.14	-0.29	1.05
TAPM	14.7	28.8	0.6	3.3	0.42	0.20	0.04	-0.41	1.52
TAPM-A	15.8	27.9	-0.5	2.4	0.54	0.26	0.03	-0.38	1.32

Figure 4 shows the TAPM and lidar variations of the scaled vertical plume spread (σ_z/z_e) and vertical skewness as a function of the scaled downwind distance X (= $(x/u_o)(w_*/z_e)$). The same values of z_e (thermal internal boundary layer (TIBL) height in the fumigation zone), w_* (convective velocity) and u_o (mean wind speed) as used by *Luhar and Young* (2002) for the scaling of the lidar data and model results were used. There are seven hours of fumigation data, mostly involving releases from the small stack into neutral onshore flows. The model and lidar vertical spreads display similar behaviours, both showing an initial increase ($X \leq 1.3$) due to plume buoyancy and then to the plume spreading out within the TIBL under fumigation. σ_z/z_e eventually reaches a near-constant value as the bulk of the plume material becomes trapped within the slow-growing TIBL. At larger distances, the model spreads are slightly larger than the data. The observed vertical skewness reaches a peak magnitude of −1 at about X = 1 (the distance at which the plume is fumigating) and then gradually approaches zero. A negative Sk_z implies that the concentration distribution has a peak near the top of the boundary layer with a tail towards the ground, which is consistent with the classic fumigation distribution. The model describes the skewness data well for the overall range of distances.

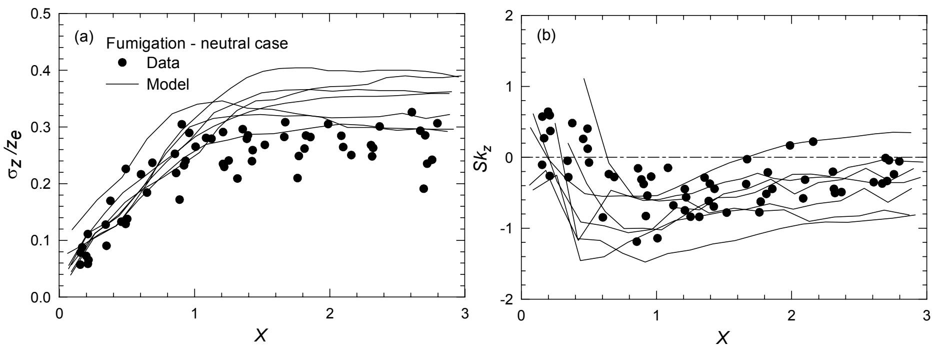

Figure 4. The lidar and model variations of the (a) normalised vertical spreads and (b) vertical skewness. The model curves correspond to seven separate hourly periods.

CONCLUSIONS

Evaluation of The Air Pollution Model (TAPM) using the Kincaid, Indianapolis and Kwinana field data sets provided an independent test of the model under a variety of conditions. Comparison with (published) results obtained using ADMS3, AERMOD and ISCST3 for Kincaid and Indianapolis indicates that TAPM generally performs as well as the best of these models. As expected, TAPM performed better when the meteorological data assimilation option was used, but the results without data assimilation were also good. The latter is extremely important because, unlike the other models, in this case the model does not require any direct local meteorological observations. The Kwinana results show that TAPM also can simulate coastal effects, such as sea-breeze onset and fumigation cases, well.

REFERENCES

Cox, W. and J. Tikvart, 1990: A statistical procedure for determining the best performing air quality simulation. *Atmos. Environ.,* **24A**, 2387−2395.

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

Kalnay, E. and co-authors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteorol. Soc*., **77**, 437−471.

Luhar, A.K., 2002: The influence of vertical wind direction shear on dispersion in the convective boundary layer, and its incorporation in coastal fumigation models. *Bound.-Layer Meteorol.,* **102**, 1−38.

Luhar, A.K. and S.A. Young, 2002: Dispersion moments of fumigating plumes—lidar estimates and PDF model simulations. *Bound.-Layer Meteorol.*, **104**, No. 3.

McHugh, C.A. and co-authors, 1999: Comparison of model evaluation methodologies with application to ADMS3 and US models. *6th Int. Conf. on Harmonisation within Atmos. Dispersion Modelling for Regulatory Purposes,* Rouen, France, 11−14 October.

Olesen, H.R., 1995: The Model validation exercise at Mol: Overview of results. *Int. J. Environ. Pollut.,* **5**, 761−784.