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Performance of TAPM against MM5 at urban scale during GÖTE2001 campaign

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In this study, the performances of two widely-used models in air quality community, The Air Pollution Model (TAPM) and the PSU/NCAR fifth-generation Mesoscale Model (MM5), were evaluated and compared at an urban scale (a few kilometres) in the greater Gothenburg (Sweden) using the GÖTE2001 campaign data. Evaluation focused on simulated meteorological variables important to air quality applications: the near-surface air temperature and wind, vertical temperature gradient, low wind speed situation, diurnal cycle and diurnal heating. The results showed that (1) TAPM performs better than MM5 in simulating near-surface air temperature and wind in urban area, (2) both models are able to reproduce nighttime vertical temperature gradient reasonably well, but underestimate daytime temperature gradient, and (3) the two models significantly underestimate the occurrences of low wind speed situation at night. These results indicate that the performance of TAPM in simulating meteorological features over the urban area is generally comparable to that of MM5. TAPM can be used with some confidence to describe the local-scale meteorology needed for air quality applications.

Introduction

The Air Pollution Model (TAPM) is a three dimensional nestable, prognostic meteorological and air pollution model. Its meteorological component predicts the local-scale flow, such as sea breezes and terrain-induced circulations by given larger-scale synoptic meteorological fields (Hurley 2005). The PSU/NCAR fifth-generation Mesoscale Model (MM5) (Grell *et al*. 1995), as one of the most important mesoscale dynamical models, is designed to simulate or predict mesoscale atmospheric circulation and boundary layer processes. Both models are non-hydrostatic, terrain-following sigma-coordinate primitive equation models, allowing nesting techniques to predict higher-scale flows for the interest area. Detailed information on global radiation, surface air temperature, humidity, wind and atmospheric stability from the two models are frequently used to predict the dispersion of air pollutants combined with emissions. In TAPM, a specific component is packaged to predict air quality at regional and local scales. Also, it is a Windowsbased modelling system, which makes it easily accessible to many users in practical applications. MM5 is considered to be one of the most advanced mesoscale modelling systems and has been widely used by an air-quality community as a meteorological input into air quality models (Barna *et al*. 2000, Shafran *et al*. 2000, Hogrefe *et al*. 2001). It is a public-domain software for Unix environment, which means a variety of options available regarding parameterizations and modelling strategies. At the same time, a certain level of computing skills is needed, hence, as compared with TAPM, the use of the model may be limited.

Model performances in meteorological conditions directly influence the effects of air pollution prediction, in particular in an urban area with complex surface characteristics including the roughness length, building characteristics, thermal properties and anthropogenic heat flux. TAPM (ver. 3) provides four options for the urban land use, which makes the model widely adaptatable to different urban types. In a similar way, MM5 has some improvements in urbanization by introducing urban features both in thermal and dynamical parts (Dandou *et al*. 2005, Fan and Sailor 2005, Grossman-Clarke *et al*. 2005). The performances of TAPM and MM5 in particular in urban areas are interesting for a better understanding of the relevant physical processes behind the models. In terms of applications of the models, the comparison between their performances can help applicants to make their choice and to sensibly interpret the simulation results.

Previous evaluations of TAPM in Kwinana and Melbourne showed that TAPM performs well in coastal, inland and complex terrain areas in sub-tropical to mid-latitude conditions (Hurley and Luhar 2000, Hurley *et al*. 2003, Hurley *et al*. 2005). Moreover, an inter-comparison between TAPM and MM5 were carried out in Spain and New Zealand. Soriano *et al*. (2003) concluded that the differences between the two models for Catalunya, Spain, are not significant, and that TAPM has a satisfying prediction. Zawar-Reza *et al*. (2005) reported that TAPM is able to capture major meteorological features but MM5 performs better in the case of Christchurch, New Zealand.

Chen *et al*. (2002) evaluated the meteorological performance of TAPM over the greater Gothenburg, Sweden, for two years by comparing simulations and synoptic observations at five sites in the region. The results showed that the meteorological variables (near-surface air temperature and 10-m wind) from TAPM have fairly close agreement with the observations on both seasonal and daily time scales. However, since the observations were from the synoptic stations, performances of the model on an urban scale remained to be largely unknown. In order to obtain a detailed description of local meteorological and air pollutants features in the greater Gothenburg, an intensive field campaign GÖTE2001 was conducted (Borne *et al*. 2005). The data collected during the campaign was used by Miao *et al*. (2006, 2007, 2008) to evaluate the performance of MM5 in detail over the same area. These developments made it possible to compare MM5 and TAPM performances on an urban scale in this coastal environment.

The objectives of this study were (1) to evaluate the meteorological component of TAPM in an coastal urban environment in southwestern Sweden, and (2) to compare the performances of TAPM and MM5 in simulating local meteorological conditions over this urban area. The study focuses on evaluating the model variables important to air pollution studies.

Material and methods

GÖTE2001 field campaign

Gothenburg is the second largest city in Sweden with about 600 000 inhabitants. It is situated in a hilly landscape with steep sided joint aligned valleys over the Swedish southwestern coast. The campaign GÖTE2001 took place in and around Gothenburg during 7–20 May 2001. The measurements covered the Gothenburg city centre, suburban and rural areas, including the west coastal area. The meteorological variables available during this campaign were temperature, wind speed, wind direction and humidity at the near-surface level. Detailed information about the GÖTE2001 campaign can be found in Borne *et al*. (2005).

By taking the data quality into account, four urban sites (Femmanhuset, Lejonet, GVC,

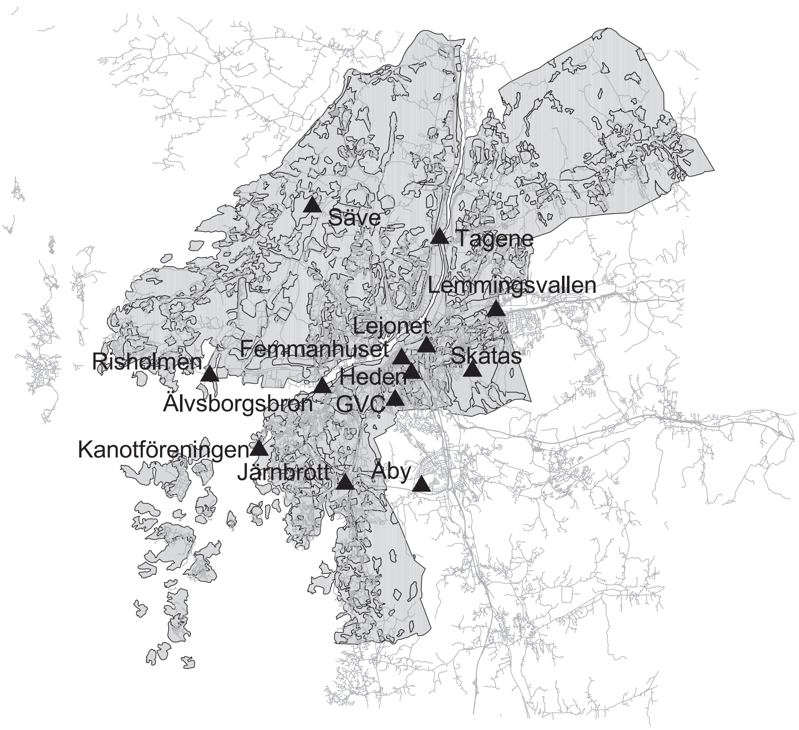


Fig. 1. Positions of the measurement sites used during the GÖTE2001 campaign: coastal sites (Risholmen, Älvsborgsbron), urban sites (Femmanhuset, Heden, GVC, Lejonet, Skåtas, Järnbrott, Åby, Tagene) and rural site (Säve).

Heden), three suburban sites (Åby, Järnbrott, Tagene), two coastal urban sites (Älvsborgsbron and Risholmen), one rural site (Säve with three-hourly time resolution) were selected for evaluating the 2-m temperature. Five urban sites (Femmanhuset, Lejonet, GVC, Heden, Skåtas), one suburban site (Lemmingsvallen), two coastal sites (Älvsborgsbron and Kanotföreningen) and one rural site (Säve with three-hourly time resolution) were used for the 10-m wind evaluation (Fig. 1).

Methods

In order to quantitatively measure the model performance, a set of statistical measures is needed to compare observations with model predictions, and to compare the statistics obtained from the other model (Hurley and Luhar 2000). According to Willmott (1981), the following measures were used in this study: mean (Mean), standard deviation (SD), mean bias error (MBE), root mean square error (RMSE), correlation coefficient (R), and one skill measure index of agreement (IOA). The definitions of these statistic measures are listed in the Appendix.

Model configurations

Miao *et al*. (2007, 2008) showed that MM5 with MRF PBL (Planetary Boundary Layer) scheme (Hong and Pan 1996) and Noah LSM (Land Surface Model) scheme (Chen and Dudhia 2001) has a better performance in reproducing the boundary layer structure and urban effects. Based on this MM5 configurations, TAPM was designed and set up accordingly for the inter-comparison purpose. In this study, TAPM had four nested domains with horizontal grid resolutions of 54, 18, 6 and 2 km, all centred at the location (57°42´N, 11°58´E). The innermost domain consisted of 40×46 horizontal grids (N–S direction by E–W direction) which covered the area of interest, including all the GÖTE2001 campaign sites. The lowest ten of the 40 vertical levels were 10, 25, 50, 75, 100, 150, 200, 250, 300, 350 m a.g.l (above ground level), with the highest model level at 8000 m a.g.l. Similar to MM5, the initial and boundary conditions in TAPM were extracted from the ECMWF (The European Centre for Medium-Range Weather Forecasts) operational analysis with the spatial resolution of 0.5° longitude by 0.5° latitude and the temporal resolution of six hours. In addition, the monthly sea-surface temperature (286.2 K), monthly deep-soil temperature (282.2 K) and monthly deep-soil volumetric moisture content (0.27 m^3 m^{-3}) were used in the model simulation according to the ECMWF analysis. Default surface information, such as the terrain height, vegetation and soil type datasets, were based on public-domain data available from the USGS (U.S. Geological Survey). The terrain height within the innermost model varied from 14 to 251 m a.s.l. The soil type of domain four in TAPM was sandy clay loam. In the innermost model domain, urban land use (catalogue 34) was dominant and surrounded by default land use pasture/herb-field-mid-dense (seasonal) and forest-low sparse (woodland). Different from TAPM, MM5 had an urban land use surrounded by crop and grassland instead.

Results and discussion

Surface temperature and wind field

An examination of the near-surface air temperature and wind is important for the model performance because these qualities reflect the nature of the local thermal circulation influenced by mesoscale forcing and govern contaminant distributions in air-quality models (Lee and Fernando 2004). The simulated results on the 2-m temperature, and U and V components of the 10-m wind at urban, suburban, rural and coastal sites are given in Tables 1 and 2.

The statistic measures showed a close agreement between the two models and observations (IOA > 0.84). This indicates that TAPM and MM5 have comparable results in simulating the near-surface air temperature. At urban sites (Femmanhuset, Lejonet, GVC and Heden) and two coastal urban sites (Risholmen and Älvsborgsbron), TAPM performed better in terms of a lower bias and RMSE and higher *R* and IOA, whereas MM5 underestimated the surface air temperature at the urban sites. When comprar-ing the major parameters related to the urban land use, two models that had similar levels of performance for albedo, roughness length and emissivity, but there were large differences in the minimum stomatal resistance (R_{smin}) and fraction of surface covered by vegetation (Table 3). The stomatal resistance reflects the ability of the stomates to impede the flow of water vapour from the interior of the leaf to the atmosphere and it governs the flow of water vapor through the stomates. By influencing the latent heat flux, a higher value of R_{smin} leads to a higher latent heat flux and lower air temperature under the same conditions. Therefore, the cold biases (MBE) at the most urban sites in MM5 are partly due to four times higher R_{smin} than that in TAPM. Moreover, the fraction of vegetation cover in MM5 tended to cool the urban air as well. At the

Table 1. Observed and modeled 2-m temperature statistics (°C) at urban, suburban and rural sites for GÖTE2001. The number of samples is 336, except for Säve with 112 samples due to the three-hour interval.

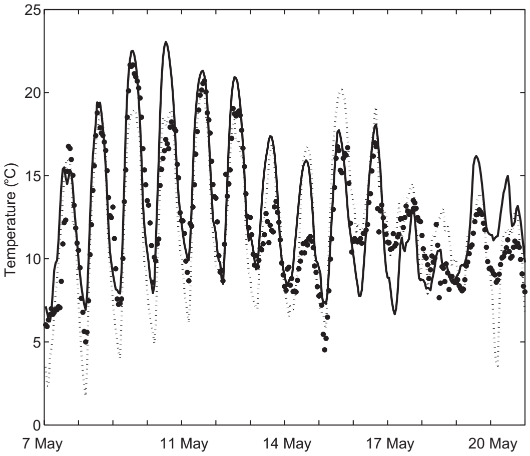
	Järnbrott	Åby	Femmanhuset	Lejonet	Tagene	Risholmen	Älvsborgsbron	GVC	Heden	Säve*
Mean_OBS	12.7	11.8	12.8	13.1	12.8	12.0	12.6	13.3	12.1	11.6
Mean_MM5	11.9	12.0	12.1	12.1	11.5	11.8	12.0	12.0	12.1	11.7
Mean_TAPM	12.6	12.6	12.9	13.1	12.7	12.5	12.3	12.7	12.9	11.9
MBE_MM5	–0.8	0.2	–0.8	–1.1	–1.2	–0.1	–0.6	–1.4	–0.1	0.1
MBE_TAPM	–0.1	0.8	0.0	–0.1	0.0	0.6	–0.3	–0.6	0.8	0.3
SD_OBS	3.9	4.0	3.6	4.3	4.0	2.9	2.9	4.7	3.6	4.3
SD_MM5	3.8	4.0	4.2	4.3	4.2	2.6	3.7	4.1	4.2	4.1
SD_TAPM	3.6	4.2	3.9	4.0	4.0	2.7	2.4	4.0	4.1	4.4
RMSE_MM5	2.37	2.40	2.84	3.11	3.00	1.86	2.54	3.02	2.38	1.92
RMSE_TAPM	2.37	2.77	2.53	2.80	2.68	1.79	1.58	2.44	2.35	2.51
R_MM5	0.83	0.82	0.76	0.77	0.78	0.77	0.75	0.82	0.82	0.90
R_TAPM	0.80	0.79	0.78	0.77	0.78	0.81	0.85	0.86	0.84	0.84
IOA_MM5	0.90	0.90	0.86	0.86	0.86	0.87	0.84	0.88	0.90	0.95
IOA_TAPM	0.89	0.88	0.88	0.87	0.88	0.89	0.91	0.92	0.90	0.91

only rural site (Säve) the two models performed similarly well.

By taking the statistic measures into account, TAPM performed much better than MM5 at the 10-m wind simulation at both urban and rural sites. TAPM could predict the temporal variation of winds with IOA values ranging from 0.80 to 0.94 for U and V components. This conclusion is

Table 2. Observed and modeled U and V components of 10-m wind statistics (m s^{-1}) at urban, suburban and rural sites for GÖTE2001. The number of samples is 336, except for Säve with 112 samples due to the three-hour interval.

	Järnbrott	Åby	Femmanhuset	Lejonet	Tagene	GVC	Heden	Skåtas	Lemmingsvalen	Älvsborgsbron	Kanotföreningen	Säve
Mean_OBS												
U	0.7	0.9	1.0	0.8	0.6	1.0	0.8	0.5	0.5	1.3	1.1	1.3
V	0.1	0.1	–0.1	–0.1	–0.1	–0.2	0.1	–0.1	–0.1	–0.1	0.4	–0.1
Mean_MM5												
U	0.9	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.7	1.1	1.9	–0.2
V	0.5	0.5	0.5	0.4	0.3	0.5	0.5	0.5	0.3	0.4	0.7	–2.8
Mean_TAPM												
U	0.9	0.6	0.7	0.6	0.5	0.7	0.5	0.4	0.4	1.1	1.5	0.7
V	0.4	0.4	0.4	0.4	0.2	0.2	0.4	0.4	0.2	0.4	0.5	0.4
MBE_MM5												
U	0.2	–0.1	–0.2	–0.1	0.2	–0.2	0.0	0.2	0.2	–0.1	0.8	–1.5
V	0.3	0.4	0.6	0.5	0.4	0.7	0.3	0.6	0.4	0.5	0.2	–2.7
MBE_TAPM												
U	0.2	–0.3	–0.3	–0.2	–0.1	–0.4	–0.3	–0.1	–0.2	–0.1	0.4	–0.6
V	0.2	0.3	0.5	0.5	0.3	0.4	0.2	0.4	0.3	0.4	0.0	0.5
SD_OBS												
U	2.0	2.8	3.0	2.1	1.9	2.6	1.9	2.5	2.5	4.4	3.3	3.3
V	2.1	1.8	2.5	1.6	2.2	1.8	1.5	1.3	1.3	3.5	2.2	2.5
SD_MM5												
U	2.3	2.4	2.2	2.3	2.5	2.2	2.2	2.3	2.4	2.6	3.7	0.2
V	2.2	2.1	2.0	2.0	2.2	2.1	2.0	2.1	2.0	2.4	3.7	1.7
SD_TAPM												
U	2.7	2.2	2.3	2.3	2.4	2.1	2.2	2.2	2.1	3.0	3.9	2.2
V	2.1	1.8	1.9	1.9	2.1	1.8	1.8	1.8	1.7	2.5	3.1	2.0
RMSE_MM5												
U	1.69	1.85	2.09	1.54	1.72	1.64	1.56	1.69	1.70	2.78	2.82	3.67
V	1.90	1.44	1.88	1.49	1.68	1.57	1.53	1.63	1.49	2.53	3.08	4.22
RMSE_TAPM												
U	1.43	1.58	1.78	1.20	1.58	1.30	1.10	1.53	1.44	1.93	1.80	1.91
V	1.64	1.12	1.79	1.19	1.26	1.05	1.30	1.21	1.08	1.97	2.26	1.55
R_MM5												
U	0.70	0.75	0.72	0.76	0.73	0.78	0.72	0.76	0.76	0.80	0.71	0.50
V	0.62	0.76	0.71	0.71	0.72	0.74	0.66	0.70	0.69	0.71	0.57	0.14
R_TAPM												
U	0.85	0.82	0.81	0.86	0.76	0.88	0.87	0.80	0.82	0.93	0.90	0.85
V	0.71	0.82	0.74	0.81	0.83	0.86	0.71	0.79	0.79	0.85	0.69	0.81
IOA_MM5												
U	0.83	0.86	0.82	0.87	0.83	0.88	0.84	0.87	0.87	0.83	0.83	0.35
V	0.77	0.86	0.81	0.81	0.84	0.83	0.79	0.75	0.77	0.80	0.70	0.36
IOA_TAPM												
U	0.90	0.89	0.88	0.92	0.85	0.92	0.92	0.89	0.90	0.93	0.94	0.87
V	0.83	0.90	0.83	0.88	0.91	0.91	0.83	0.84	0.86	0.89	0.80	0.87



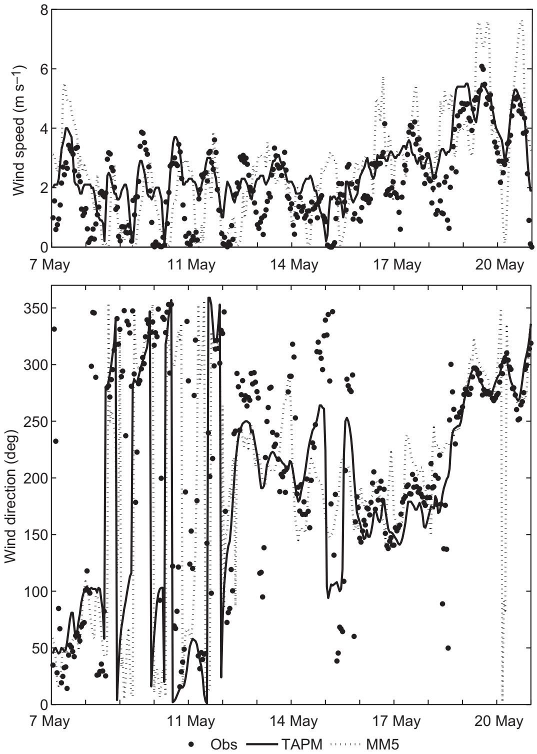


Fig. 2. Time series of the modelled and observed hourly near-surface air temperature (2-m), wind speed and wind direction (10 m) at the closest grid point to Heden (Urban) from the domain four with a 2-km grid resolution during the period from 00:00 UTC on 7 May to 23:00 UTC on 20 May 2001.

also in agreement with an earlier study (Edwards *et al*. 2004).

TAPM simulations of the hourly 2-m temperature, 10-m wind speed and wind direction during GÖTE2001 agreed well with the observations at these sites for either near-surface air temperature or wind speed and wind direction. However, MM5 tended to have larger amplification than TAPM in simulating the surface temperature and wind speed (Figs. 2–4).

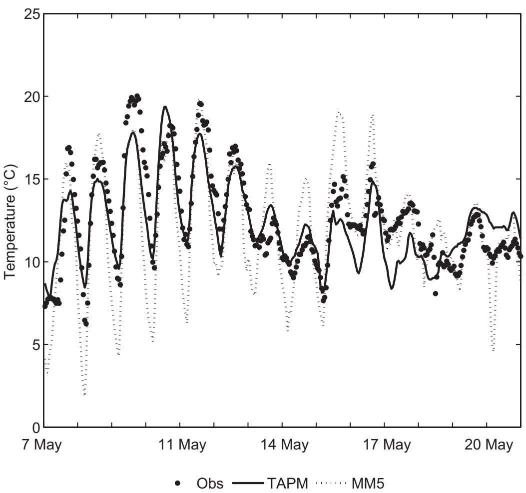
In order to check how much TAPM and MM5 modify the background meteorological field, 2-m temperature and 10-m wind components at nearest grid to urban site Heden were extracted from the ECMWF analysis with the six-hour time resolution and 0.5° × 0.5° spatial resolution (Fig. 5). Compared with the ECMWF analysis, TAPM and MM5 showed improvement in the surface field simulation, which demonstrates better performance and added-value of the fine-grid models. Beyond that, the improvement of TAPM and MM5 are characterised by the same direction and level.

Table 3. Parameters associated with urban land use in MM5 and TAPM.

	MM5	TAPM
Albedo (%)	15	13
Roughness length (cm)	80	80
Emissivity (%)	88	95
Rs_{min} (minimum stomatal resistance) (m s^{-1})	400	100
Fraction of surface covered by vegetation (%)	95	75

Boundary-layer structure

The most important local-scale meteorological conditions leading to an air pollution episode for PM10 are temperature inversions, atmospheric stability, and in some cases, wind speed (Kukkonen *et al*. 2005). Examination of the boundary-layer structure simulation in the two models was focused on vertical temperature gradient during daytime and nighttime, as well as the low wind speed situations.



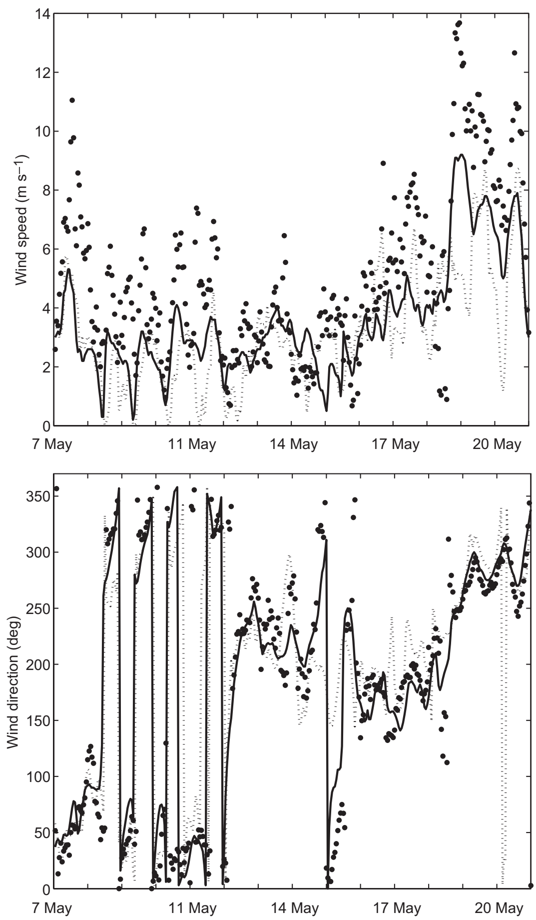


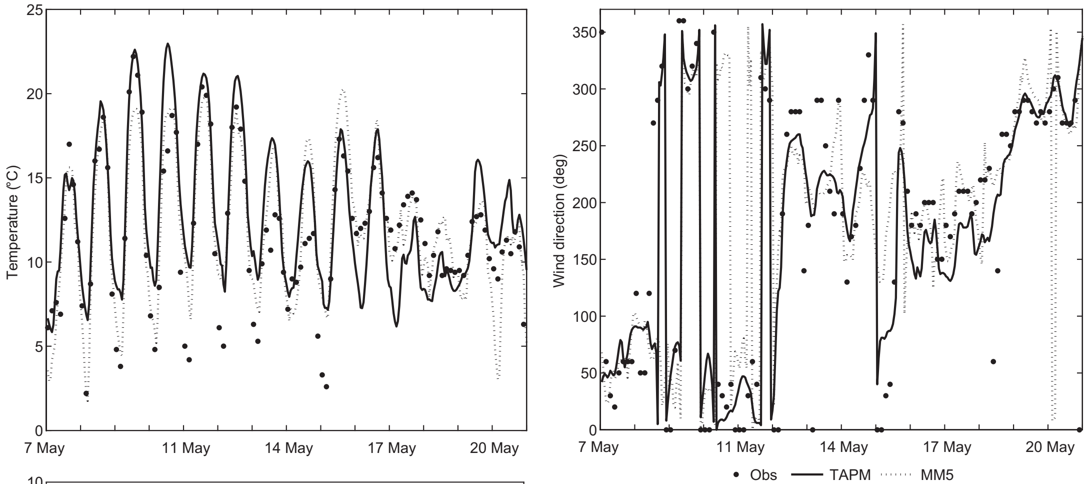
Fig. 3. Time series of the modelled and observed hourly near-surface air temperature (2 m), wind speed and wind direction (10 m) at the closest grid point to Älvsborgsbron (Coast) from the domain four with a 2-km grid resolution during the period from 00:00 UTC on 7 May to 23:00 UTC on 20 May 2001.

Vertical temperature gradient

Stability of the lower atmosphere is characterized by the vertical temperature gradient, which is often measured from an instrumental mast. In this study, the vertical temperature gradient was calculated by using hourly 3-m and 105-m measurement at the Järnbrott mast site during 7–19 May 2001. The comparisons of modelled vertical temperature gradient were carried out separately for daytime and nighttime (Fig. 6). The nighttime temperature gradient was well predicted by the two models (IOA_TAPM = 0.85; IOA_MM5 = 0.83). However, both models failed to simulate the daytime temperature gradient. TAPM greatly underestimated the daytime temperature gradient due to the overestimation of the surface temperature and underestimation of the daytime temperature at the high altitude (105 m). The MBE for the daytime temperature at 2-m was 0.10 °C for TAPM and –0.12 °C for MM5, while that at 105 m was –0.89 °C for TAPM and –0.43 °C for MM5. It might be due to the local urban effects are not properly accounted for by the generic single-layer canopy scheme used, which indicates the necessary improvement in land-surface scheme in TAPM (Luhar and Hurley 2003, Luhar *et al*. 2006).

Low wind speed stable conditions

In an urban boundary layer, many studies have highlighted the importance of the roughness sublayer (RSL) and its determination to the dispersion of ground-level concentrations in an urban area (Venkatram *et al*. 2005, Fisher *et al*. 2006). MOST (Monin-Obukhov Similarity Theory) is not valid within the urban RSL because the turbulent flux of momentum decreases to zero due



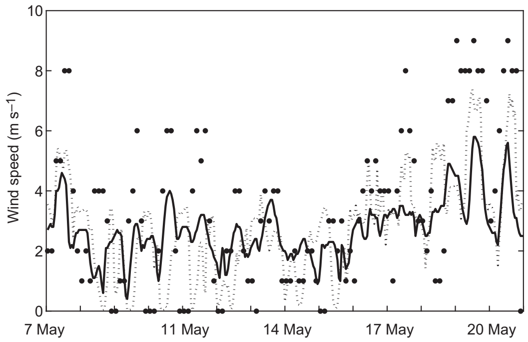


Fig. 4. Time series of the modelled and observed hourly near-surface air temperature (2 m), wind speed and wind direction (10 m) at the closest grid point to Säve (three-hourly data) (Rural) from the domain four with a 2-km grid resolution during the period from 00:00 UTC on 7 May to 23:00 UTC on 20 May 2001.

to the drag on the flow caused by the buildings (Rotach 2001, Fisher *et al*. 2006). However, many dispersion models still use MOST in an urban area by adjusting the roughness length or M–O length under very stable conditions (Craig and Bornstein 2001). In order to examine how well this adjusting is working, we compared the frequencies of different wind levels during daytime and nighttime at urban, coastal and rural sites (Table 4).

As one character of stable or very stable atmospheric conditions — low wind speed — is of interest, partly because the simulation of airborne pollutant dispersion is rather difficult in such situations, when turbulent motions may be of the same order as the wind speed (Seaman 2000, Anfossi *et al*. 2005). At low wind speeds (< 2 m s^{-1}), the highest ground-level concentrations of air pollutants are often encountered (Luhar *et al*. 2007). The results of this study showed that the two models severely underestimate the nocturnal low wind situation (< 2 m s^{-1}) at all three sites. This indicates that the weakness

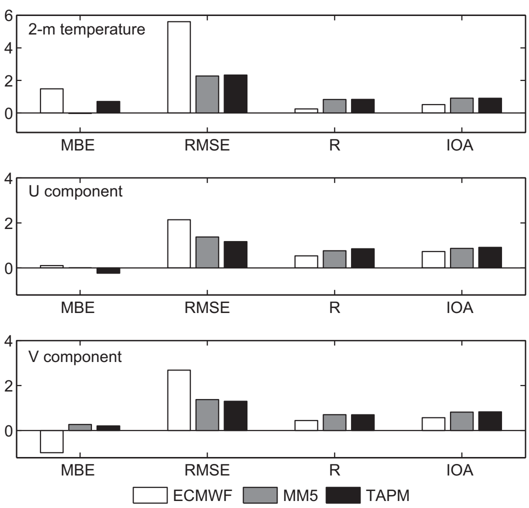


Fig. 5. Comparison 2-m temperature, U and V components of the 10-m wind for ECMWF analysis, MM5 and TAPM at the urban site Heden. The unit of MBE and RMSE for the 2-m temperature is °C, while that for the 10-m wind components is m s^{-1}.

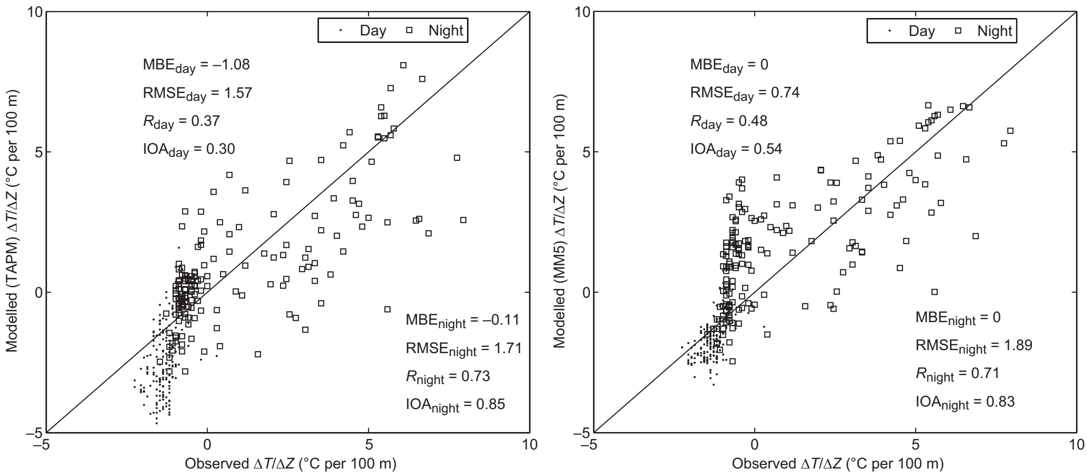


Fig. 6. Observed and modelled vertical temperature gradients at the Järnbrott mast site from TAPM and MM5. The results are based on hourly data of the near-surface and 105-m measurements/simulations during the period 7–19 May 2001. The temperature gradient during night hours (20:00–07:00 UTC) is denoted by squares to show nocturnal temperature inversion for clarity. Statistical parameters at day and night are presented within the plot.

of MOST under strongly stable conditions is still evident in the two models. However, the two models perform better during the daytime at all wind levels. Compared with MM5, the advantage of TAPM is the simulation at an urban site, giving progressively better simulation results for higher wind speeds.

Diurnal temperature variation in an urban area

The urban features simulated by the two models need to be checked and compared, since the interesting area is dominated by an urban land use. Diurnal temperature variations, including

Table 4. Observed and modelled frequencies (%) of the hourly-averaged wind speed at 10-m AGL during daytime (08:00–19:00 UTC) and nighttime (20:00–07:00 UTC) at Kanotföreningen, Säve and Heden from 7 to 20 May 2001.

			0–2 m s^{-1}	2–4 m s^{-1}	4–6 m s^{-1}	6–8 m s^{-1}	> 8 m s^{-1}
Kanotföreningen (coast)		OBS	17.9	41.1	26.2	9.5	5.4
	Day	TAPM	8.9	40.5	31.0	4.2	15.5
		MM5	7.1	22.0	38.1	12.5	20.2
		OBS	57.1	23.2	6.0	7.7	6.0
	Night	TAPM	10.7	51.2	22.0	3.6	12.5
		MM5	9.5	36.9	34.5	8.9	10.1
Säve (rural)		OBS	21.4	35.7	21.4	17.9	3.6
	Day	TAPM	19.6	66.1	14.3	0.0	0.0
		MM5	37.5	33.9	19.6	8.9	0.0
		OBS	64.3	23.2	3.6	7.1	1.8
	Night	TAPM	23.2	73.2	3.6	0.0	0.0
		MM5	23.2	69.6	7.1	0.0	0.0
Heden (urban)		OBS	26.8	58.3	14.3	0.6	0.0
	Day	TAPM	22.6	61.9	15.5	0.0	0.0
		MM5	39.3	29.2	22.0	9.5	0.0
		OBS	74.4	17.9	7.7	0.0	0.0
	Night	TAPM	40.5	50.6	8.9	0.0	0.0
		MM5	33.9	64.3	1.8	0.0	0.0

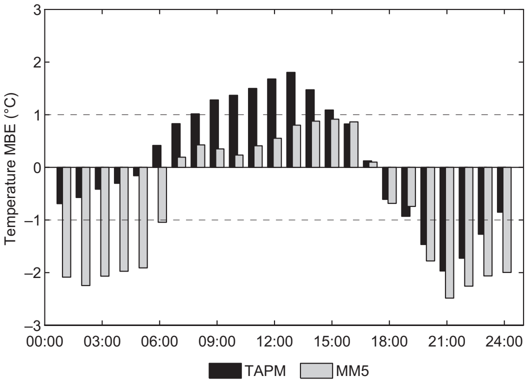


Fig. 7. Comparison of the diurnal cycles for the near-surface air temperature mean bias error (MBE) at the urban sites between the two models.

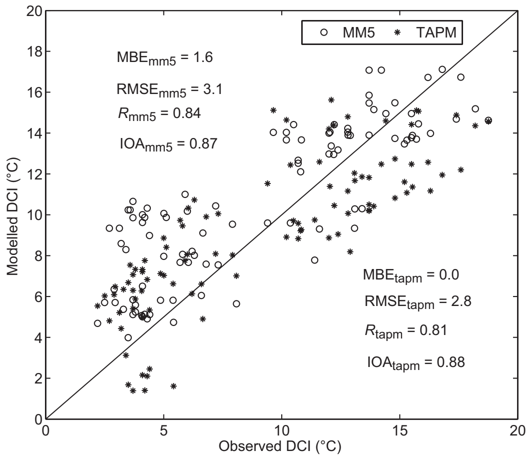


Fig. 8. Scatter plot of observed *vs*. modelled diurnal cycle intensities (DCI) at urban sites.

the diurnal cycle and diurnal heating of the surface temperature, are two major characters to the evaluate model performance. In this study, the near-surface air temperature data at seven urban sites (Femmmanhuset, Heden, Lejonet, GVC, Järnbrott, Åby and Tagene) were used to calculate the urban-averaged diurnal cycle and diurnal heat indexes (Figs. 7–8). TAPM and MM5 had similar timing at three phases of the diurnal cycle. Compared with MM5, TAPM evidently overestimated the daytime temperature. In this study, the diurnal heat index was expressed as the diurnal cycle intensity (DCI), defined as the difference between the daily maximum and minimum near-surface air temperatures (Miao *et al*. 2008). Since local-scale circulations are driven by the heating contrast across the coastline or land use boundaries, and the strength of the circulation depends on the diurnal heating, i.e. the diurnal amplitude of the temperature difference from day to night (Borne *et al*. 1998, Zhang and Zheng 2004). As can be seen from Figs. 7 and 8, TAPM and MM5 could similarly well simulate diurnal heating.

Summary and conclusions

This study evaluated the performance of TAPM during GÖTE2001 campaign by comparing it with the performance of MM5. The comparison focused on the application of the models in southwestern coastal urban area at high latitudes, and on those urban-scale meteorological features that are important to the dispersion of air pollutants. The meteorological features included the near-surface air temperature and wind, vertical temperature gradient, low wind speed conditions, as well as the diurnal cycle and diurnal heating in an urban area.

The major findings were as follows:

- Overall, the results from TAPM are comparable with those from MM5 at an urban scale.
- TAPM scored higher than MM5 in simulating the near-surface air temperature in both urban and coastal areas, and the two models had a similarly good performance in a rural area. For the 10-m wind simulation, TAPM had obviously better performance in all the areas.
- The two models were able to predict the vertical temperature gradient during nighttime acceptably but failed to predict it correctly during the daytime. The underestimation of the daytime temperature gradient by TAPM is due to overestimation of the surface temperature and underestimation of the high-altitude temperature. This indicates that the sensible heat flux parameterization needs to be improved.
- Both TAPM and MM5 had difficulties in correctly predicting the near-surface wind under the nocturnal stagnant wind situations (< 2 m s^{-1}), which confirms the limitation of

applying MOST under strongly stable conditions.
- Considering urban sites, TAPM and MM5 had similar comparable skills in simulating the diurnal cycle and diurnal heating. However, TAPM evidently overestimated the daytime near-surface air temperature.

This study supports the previous findings that TAPM is reliable and further concludes that its meteorological predictions in an urban area are comparable with those of the more advanced model MM5. Simulations of the near-surface air temperature and wind, nighttime temperature gradient and diurnal heating from TAPM can thus be used with confidence to describe the local-scale meteorological conditions needed for air quality applications. However, TAPM needs to be improved with regard of the used PBL and LSM schemes because of its relatively poor performance in the vertical temperature gradient during daytime. As a common difficulty for most existing meteorological models, under strongly stable conditions MOST needs to be better parameterized in an urban area.

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References

Anfossi D., Oettl D., Degrazia G.A. & Goulart A. 2005. An analysis of sonic anemometer observations in low wind speed conditions. *Bound.-Layer Meteor.* 114: 179–203.

Barna M., Lamb B., O'Neill S., Westberg H., Figueroa-Kaminsky C., Otterson S., bowman C. & DeMay J. 2000. Modeling ozone formation and transport in the Casadia region of the Pacific Northwest. *J. Appl. Meteor.* 39: 349–366.

Borne K., Chen D. & Nunez M. 1998. A method for finding sea breeze days under stable synoptic conditions and its application to the Swedish wets coast. *Int. J. Climatology* 18: 901–914.

Borne K., Chen D., Miao J.-F., Achberger C., Lindgren J., Hallquist M., Pettersson J., Haeger-Eugensson M., Wyser K., Eliasson I. & Langner J. 2005. Data report on measurements of meteorological and air pollution variables during the campaign GÖTE-2001. *Research Report* C67, Earth Sciences Centre, Göteborg University, Göteborg, Sweden.

Chen D., Wang T., Haeger-Eugensson M., Aschberger C. & Borne K. 2002. Application of TAPM in Swedish west coast: validation during 1999–2000. *IVL report:* L02/51.

Chen F. & Dudhia J. 2001. Coupling an advance land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part II: Preliminary model validation. *Mon. Wea. Rev.* 129: 587–604.

Craig K.J. & Belcher S.E. 2001. Urbanisation of numerical meso-scale models. In: Rotach M.W., Fisher B. & Piringer M. (eds.), *Workshop on urban boundary layer parameterisations, Zürich, Switzerland, 24–25 May 2001*, European Commission, Eur no. 20355, pp. 17–30.

Dandou A., Tombrou M., Akylas E., Soulakellis N. & Bossioli E. 2005. Development and evaluation of an urban parameterization sheme in the Penn State/NCAR Mesoscale Model (MM5). *J. Geophys. Res.* 110: D10102, doi: 10.1029/2004JD005192.

Edwards M., Hurley P.J. & Physick W.L. 2004. Verification of TAPM meteorological predictions using sodar data in the Kalgoorlie region. *Australian Meteorological Magazine* 53: 29–37.

Fan H.-L. & Sailor D.J. 2005. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. *Atmos. Environ.* 39: 73–84.

Fisher B., Kukkonen J., Piringer M., Botach M.W. & Schatzmann M. 2006. Meteorology applied to urban air pollution problems: concepts from COST 715. *Atmos. Chem. Phys.* 6: 555–564.

Grell G.A., Dudhia J. & Stauffer D.R. 1995. A description of the fifth-generation Penne State/NCAR Mesoscale Model (MM5). *NCAR Technical Note*, NCAR/TN-398+STR, National Centre for Atmospheric Research, Boulder, CO.

Grossman-Clarke S., Zehnder J.A., Stefanov W.L., Liu Y. & Zoldak M.A. 2005. Urban modifications in a mesoscale meteorological model and the effects on near-surface variables in an arid metropolitan region. *J. Appl. Meteor.* 44: 1281–1297.

Hogrefe C., Rao S.T., Kasibhatla P., Kallos G., Tremback C.J., Hao W., Olerud D., Xiu A., MeHenry J. & Alapaty K. 2001. Evaluating the performance of regional scale photochemical modelling systems: Part I — meteorological predictions. *Atmos. Environ.* 35: 4159–4174.

Hong S.Y. & Pan H.L. 1996. Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.* 124: 2322–2339.

Hurley P.J. & Luhar A.K. 2000. The Kwinana coastal fumigation study: III — meteorological and turbulence modelling on selected days. *Bound.-Layer Meteor.* 94: 114–138.

Hurley P.J., Blockley A. & Rayner K. 2003. Verification of a prognostic meteorological and air pollution model for year-long predictions in the Kwinana industrial region of Western Australia. *Atmos. Environ.* 35: 1871–1880.

Hurley P.J. 2005. The air pollution model (TAPM) ver. 3. Part 1, *Technical description*. CSIRO. Australia.

Hurley P.J., Physick W.L. & Luhar A.K. 2005. TAPM: a practical approach to prognostic meteorological and air pollution modelling. *Environ. Modell. Softw.* 20:

737–752.

Kukkonen J., Pohjola M., Sokhi R.S., Luhana L., Kitwiroon N., Fragkou L., Rantamäki M., Berge E., Ødegaard V., Slørdal L.H., Denby B. and Finardi S. 2005. Analysis and evaluation of selected local-scale PM10 air pollution episodes in four European cities: Helsinki, London, Milan and Oslo. *Atmos. Environ.* 39: 2759–2773.

Lee S.-M. & Fernando H.J.S. 2004. Evaluation of meteorological models MM5 and HOTMAC using PAFEX-I data. *J. Appl. Meteor.* 43: 1133–1148.

Luhar A.K. & Hurley P.J. 2003. Evaluation of TAPM, a prognostic meteorological and air pollution model, using urban and rural point-source data. *Atmos. Environ.* 37: 2795–2810.

Luhar A.K., Venkatram A. & Lee S.-M. 2006. On relationships between urban and rural near-surface meteorology for diffusion applications. *Atmos. Environ.* 40: 6541–6553.

Luhar A.K., Hurley P.J. & Rayner K.N. 2007. Modelling low wind-speed stable conditions in a prognostic meteorological model and comparison with field data. In: Carruthers D.J. & McHugh C.A. (eds.), *Proceedings of the 11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Cambridge, United Kingdom, 2–5 July 2007*, Cambridge Environmental Research Consultants, Cambridge, UK, pp. 251–255.

Miao J.-F., Chen D. & Wyser K. 2006. Modelling subgrid scale dry deposition velocity of O_3 over the Swedish west coast with MM5-PX model. *Atmos. Environ.* 40: 415–429.

Miao J.-F., Chen D. & Borne K. 2007. Evaluation and comparison of Noah and Pleim-Xiu land surface models in MM5 using GÖTE2001 data: Spatial and temporal variations in near-surface air temperature. *J. Appl. Meteor. Climatol.* 46: 1587–1605.

Miao J.-F., Chen D., Wyser K., Borne K., Lindgren J., Svensson M.K., Thorsson S., Achberger C. & Almkvist E. 2008. Evaluation of MM5 mesoscale model at local scale for air quality applications over the Swedish west coast: Influence of PBL and LSM parameterizations. *Meteorol. Atmos. Phys.* 99: 77–103.

Rotach, M.W. 2001. Simulation of urban-scale dispersion using a Lagrangian stochastic dispersion model. *Bound.-Layer Meteor.* 99: 379–410.

Seaman N.L. 2000. Meteorological modelling for air-quality assessments. *Atmos. Environ.* 34: 2231–2259.

Shafran P.C., Seaman N.L. & Gsyno G.A. 2000. Evaluation of numerical predictions of boundary layer structure during the Lake Michigan ozone study. *J. Appl. Meteor.* 39: 412–426.

Soriano C., Soler R.M., Pino D., Alarco'n M., Physick B. & Hurley P. 2003. Modelling different meteorological situations in Catalunya, Spain, with MM5 and TAPM mesoscale models: a comparative study. *Int. J. Environ. Pollut.* 20: 256–268.

Venkatram A., Isakov V., Pankratz D. & Yuan J. 2005. Relating plume spread to meteorology in urban areas. *Atmos. Environ.* 39: 371–380.

Willmott C.J. 1981. On the validation of Models. *Physical Geography* 2: 184–194.

Zawar-Reza P., Sturman A. & Hurley P. 2005. Prognostic urban-scale air pollution modeling in Australia and New Zealand — a review. *Clean Air and Environmental Quality* 39: 41–45.

Zhang D.L. & Zheng W.Z. 2004. Diurnal cycles of surface winds and temperatures as simulated by five boundary layer parameterizations. *J. Appl. Meteor.* 43: 157–169.

Appendix

Mean observation (M_o) and mean model estimate (M_e) are given by

$$M_o = \frac{1}{N}\sum_{i=1}^{N}\Phi_{oi};\ M_e = \frac{1}{N}\sum_{i=1}^{N}\Phi_{ei}$$

where N is the product of the number of simulation hours and the number of ground-level monitoring locations providing hourly-averaged observational data. Φ_{ei} represents the model estimate at hour i and Φ_{oi} represents the observations at hour i.

Standard deviation of observation (SD_o) and standard deviation of estimation (SD_e) are given by

$$SD_o = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left|\Phi_{oi} - M_o\right|^2};\ SD_e = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left|\Phi_{ei} - M_e\right|^2}$$

Mean bias error (MBE) is given by

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(\Phi_{ei} - \Phi_{oi}\right)$$

Root mean square error (RMSE) is given by

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left|\Phi_{ei} - \Phi_{oi}\right|^2}$$

Correlation coefficient (R) is given by

$$R = \frac{\mathrm{cov}\left(\Phi_{oi}, \Phi_{ei}\right)}{SD_o \times SD_e}$$

Index of agreement is given by

$$IOA = 1 - \left[\frac{N\left(RMSE\right)^2}{\sum_{i=1}^{N}\left(\left|\Phi_{ei} - M_o\right| + \left|\Phi_{oi} - M_o\right|\right)^2}\right]$$