PERFORMANCE OF A NEW URBAN LAND-SURFACE SCHEME IN AN OPERATIONAL MESOSCALE MODEL FOR FLOW AND DISPERSION

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Abstract: We evaluate a new urban surface scheme in an operational mesoscale model, TAPM, aimed at air pollution applications. The existing urban surface scheme in the model is based on a simple slab approach, with separate urban and vegetation-soil tiles, and a specified anthropogenic heat flux. Recently, a fast urban canyon scheme based on a building-averaged town energy balance approach has been coupled to TAPM. It simulates turbulent fluxes using a generic canyon geometry to resolve energy balances for walls, roads and roofs; includes air conditioning for energy conservation and in-canyon vegetation; and considers recirculation and venting of air within the canyon. TAPM is evaluated for these two schemes using the flow and dispersion data from the 2002 Basel UrBan Boundary Layer Experiment (BUBBLE) conducted in Basel, Switzerland. We find that the new scheme leads to an overall improvement in the prediction of surface fluxes, especially sensible heat flux, and better prediction of the observed concentrations fields.

Key words: *TAPM model; BUBBLE experiment; town energy balance approach; urban turbulence and dispersion*

INTRODUCTION

Urban surfaces need to be represented properly in meteorological models as they influence the mean meteorology, atmospheric stability and turbulence, and hence atmospheric dispersion. A surface scheme is used to parameterise the energy exchanges between the surface and the atmosphere. A simple scheme to represent urban surface in a mesoscale model is the slab approach (Oke, T. R., 1988), which describes the urban component as a concrete slab with modified roughness length and thermal properties. The operational mesoscale model TAPM (Hurley, P. J. et al., 2005) uses this approach. Recently, building-averaged urban canyon models have been developed that attempt to simulate the urban energy budget without the considerable computational requirements of a building-resolving urban simulation when coupled to a mesoscale model. Masson's (2000) town energy budget (TEB) scheme is based on such an approach. Thatcher, M. and P. Hurley (2012) modified the TEB scheme and coupled it to TAPM. We evaluate both urban schemes in TAPM using the flux and dispersion data from the 2002 Basel UrBan Boundary Layer Experiment (BUBBLE) conducted in Basel, Switzerland.

FIELD DATA

We use data from the Intensive Observation Period, 10 June – 10 July 2002, of the BUBBLE experiment. Basel is a mid-size town with a built-up area of about 130 km^2 (Rotach, M. W. et al., 2005). The main urban measurement tower, Basel-Sperrstrasse (or U1), was 32-m high and located inside a street canyon in an area with dense, fairly homogeneous, residential building blocks, and a mean building height of 14.6 m AGL (above ground level). In the vicinity of the tower, the building height was 14 m AGL and the street canyon aspect ratio (i.e. height-to-width ratio) was about unity. The surface roughness length was 2.1 m, and the zero-plane displacement height was 9.5 m. Sonic anemometers were installed at six levels, viz. 3.6, 11.3, 14.7, 17.9, 22.4 and 31.7 m AGL.

To study dispersion, sulfur hexafluoride (SF_6) tracer was released at near roof-level at two locations, namely R1 (18.6 m AGL) and R2 (21 m AGL), over four separate days (Rotach, M. W. et al., 2004; Gryning, S.-E. et al., 2005) (see Table 1 for release conditions). There were 19 SF_6 sampling locations, of which 13 were typically positioned 1.5 m above the roof level and 6 were street-level samplers.

Table 1. Details of the SF_6 release conditions and background concentrations

Date	Source	Release period (CET)	Release Rate ($g\ s^{-1}$)	Background concentration ($ng\ m^{-3}$)
26 June	R1	12:00-16:00	0.0503	33.6
4 July	R2	14:40-18:00	0.0499	32.2
7 July	R1	13:10-17:00	0.3008	34.0
8 July	R1	14:00-18:00	0.1319	53.2

Hourly-averaged data were used for model comparison. The BUBBLE data reveal the distinct influence of the urban surface on flow properties. Luhar, A. K. et al. (2006) previously used the BUBBLE flow data in conjunction with TAPM to evaluate relationships between urban and rural near-surface meteorology for diffusion applications.

MESOSCALE MODEL

TAPM (v4.0) is a three-dimensional, coupled prognostic meteorological and air pollution model, and is widely used in Australia for air quality management and research applications (Hurley, P. J. et al., 2005; http://www.cmar.csiro.au/research/tapm). The model employs an E-ε turbulence closure, where the turbulent kinetic energy (E) and its dissipation rate (ε) are determined using prognostic equations. A vegetative canopy, soil scheme, and urban scheme are used at the surface. The model uses large-scale synoptic analyses, typically obtained from the Australian Bureau of Meteorology's GASP (Global AnalySis and Prediction) system (used here) at a horizontal grid spacing of 1° × 1° at 6-hourly intervals, as input boundary conditions for the outermost nest. Other inputs to the model include global databases of terrain height, land use and soil type, leaf area index and sea-surface temperature. The air pollution component uses the predicted meteorology and turbulence, and consists of an Eulerian grid-based set of prognostic equations for pollutant concentration, and an optional particle-puff Lagrangian mode (used here); the latter to allow a more detailed accounting of dispersion within the innermost nest. Four horizontal nests were used with resolutions 20 km, 7.5 km, 2 km and 0.5 km (35 × 35 grid points) for meteorology and 2 km, 750 m, 200 m and 50 m (41 × 41 grid points) for pollution. The hourly-averaged predictions on the innermost meteorological and pollution nests are used for analysis. For dispersion, we also ran TAPM with assimilation of wind speed and direction measured at the urban tower into the model's momentum equations as nudging terms.

Current urban scheme

As stated earlier, TAPM's current surface scheme is based on a simple slab approach. It calculates surface moisture, surface temperature and surface fluxes for bare soil, vegetation cover, and urban cover separately, and then uses a weighting scheme according to the fraction of the area covered by the three surfaces in order to derive the effective surface values of these parameters. The default urban category for the urban area under study is Category 31, which assumes that the fraction of the urban cover is 0.5, albedo is 0.15, the urban anthropogenic heat flux is 30 W m^{-2} in the surface heat flux term, and the overall urban roughness length is 1.0 m.

New urban scheme

An example of a building-averaged urban canyon models is the TEB scheme of Masson, V. (2000), which separates the urban energy budget into roofs, roads and walls and also includes shadowing effects due to the canyon geometry and parameterises the in-canyon exchange of turbulent heat fluxes. All canyons (in a given model grid cell) have the same height and width and are located along identical roads. The two facing walls are not treated separately, as they are identical for all processes, except for the direct solar radiation. The canyon orientation effects, with respect to the sun or the wind direction, are averaged over 360° for roads and walls. This allows the computation of averaged forcing for road and wall surfaces. The parameters of the scheme depend directly on building shapes and construction materials. Anthropogenic heat fluxes due to domestic heating and combustion are included. When a mesoscale model is coupled to such a scheme, the surface level in the model approximately corresponds to the roof level and the model only sees a constant flux layer as its lower boundary.

Thatcher, M. and P. Hurley (2012) modified the above TEB approach and coupled it to TAPM. The modifications include an efficient big-leaf model to represent in-canyon vegetation and a parameterisation for air-conditioners for energy conservation. Additionally, canyon turbulent heat fluxes between walls, roads and in-canyon vegetation are parameterised according to a modified version of Harman, I. N. et al.'s (2004) resistance network, which considers recirculation and venting of air within the canyon. This approach requires separation of the energy budgets of the two walls into an easterly facing component and a westerly facing component (whereas the original TEB model employs a single wall energy budget after averaging the canyon fluxes over 360° of possible canyon orientations). The two wall energy budgets are derived by averaging the canyon fluxes over 180° of possible canyon orientations. Since walls with an easterly facing component have a different temperature diurnal cycle compared to westerly walls, there is an aggregate representation of a temperature differential across the canyon when considering the recirculation of air in the canyon. These modifications allow a more realistic representation of turbulent heat transfer within the canyon than the original TEB model. Where available, the surface parameter values were chosen to be consistent with those reported by Christen, A. and R. Vogt (2004) for the urban area. Following are the parameter values required and used in the new scheme: in-canyon vegetation fraction = 0.16, area fraction occupied by buildings = 0.54, mean building height = 14.6 m, building height to canyon width ratio = 1.0, ratio of roughness length to building height = 0.05, roughness length of in-canyon surfaces = 0.1 m, industrial sensible heat flux = 0 W m^{-2} (default), and daily averaged traffic sensible heat flux = 1.5 W m^{-2} (default).

MODEL RESULTS

Below, we present the fluxes and dispersion results obtained using the two urban schemes in TAPM.

Meteorology and fluxes

For comparison, we use the data from the 17.9-m level, which is the first level clearly above the roof-top level and where the sensible heat and momentum fluxes were observed to be at maximum. Figure 1a shows a scatter plot of the observed and predicted sensible heat flux (H_s) computed using the current urban scheme (sample size = 723). The agreement is reasonably good, but it is apparent that the model yields too many occurrences of negative H_s between 0 and –50 W m^{-2} when the observations suggest values between 0 and 100 W m^{-2}. This issue is virtually not present in Figure 1b when the new urban scheme is used. A weak stability (i.e. near-neutral conditions) at night is a feature of urban meteorology, which the new scheme is able to reproduce. The index of agreement (d) is the same for both the schemes at 0.85 (d = 0 means no agreement, d = 1 means perfect agreement). The percentage of data within a factor of two (FAC2) and the normalised mean square error (NMSE) are 37% and 0.73, respectively, for the current scheme, and 62% and 0.45, respectively, for the new scheme. Figure 1c shows that the new scheme describes the observed probability (or frequency) distribution of H_s very well, whereas the current scheme does comparatively well only for heat fluxes higher than 200 W m^{-2}.

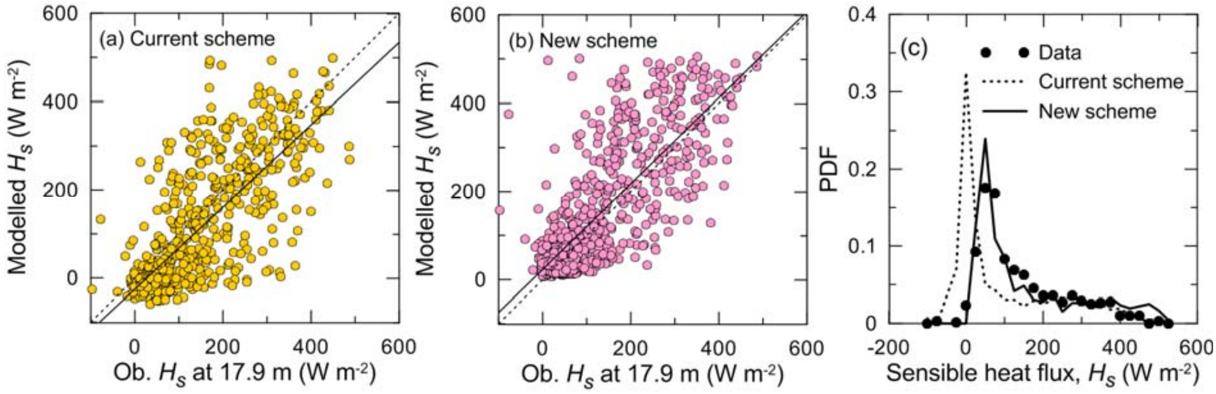

Figure 1. Scatter plot of the observed vs. predicted sensible heat flux (H_s): (a) when the current urban scheme is used and (b) when the new urban scheme is used; and (c) probability density function (PDF) of H_s for the data and the two schemes.

There are no latent heat flux (Q_E) data at the 17.9-m level, but they are available at 31.7 m. This level is probably a little too high for comparison with the modelled values, but a tentative comparison can still be made. The scatter plots in Figure 2 suggest that overall there is an overprediction of Q_E by the current scheme and an underestimation by the new scheme. The PDFs in Figure 2c indicate mixed results, with the new scheme performing better for Q_E > 125 W m^{-2} whereas the current scheme yielding better results for $Q_E \approx$ 25 W m^{-2}. Figure 3 shows diurnal patterns of Q_E in which an overestimation of the observed peak values by the current scheme and an underestimation (but to a lesser degree) by the new scheme are evident.

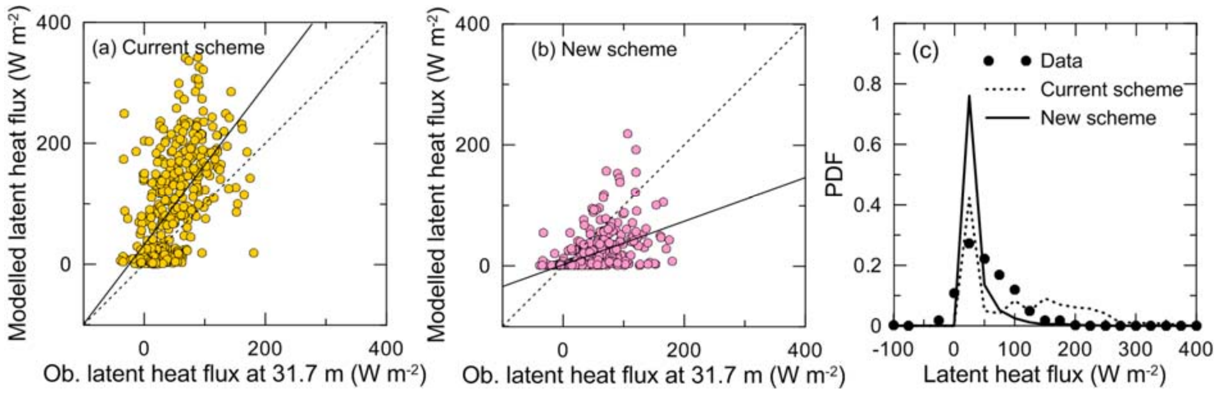

Figure 2. Scatter plot of the observed vs. predicted latent heat flux (Q_E): (a) when the current urban scheme is used and (b) when the new urban scheme is used; and (c) probability density function (PDF) of Q_E for the data and the two schemes.

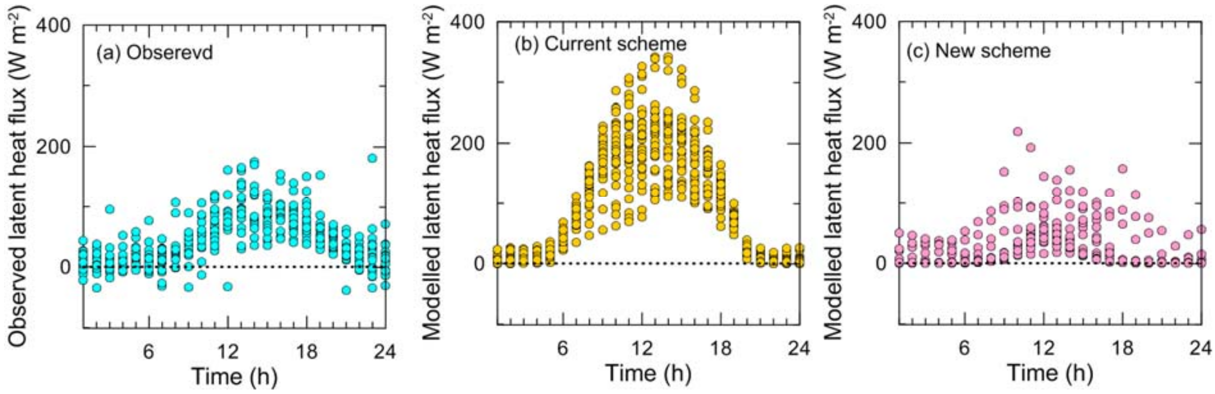

Figure 3. Diurnal variations of latent heat flux over the experimental period: (a) data, (b) modelled with the current urban scheme, and (c) modelled with the new urban scheme, in TAPM.

Figure 4 is the same as Figure 1, except for friction velocity (u_*), a measure of momentum flux. There is not a great deal of difference between the scatter plots for the current and new scheme, but the PDF plots in Figure 4c suggest that the new scheme performs noticeably better for $u_* < 0.2$ m s^{-1} and the current scheme for $u_* >$ 0.6 m s^{-1}. The value of d is the same for both schemes at 0.75. The FAC2 and NMSE are 72% and 0.30, respectively, for the current scheme, and 80% and 0.24, respectively, for the new scheme, which suggest slightly better performance by the new scheme.

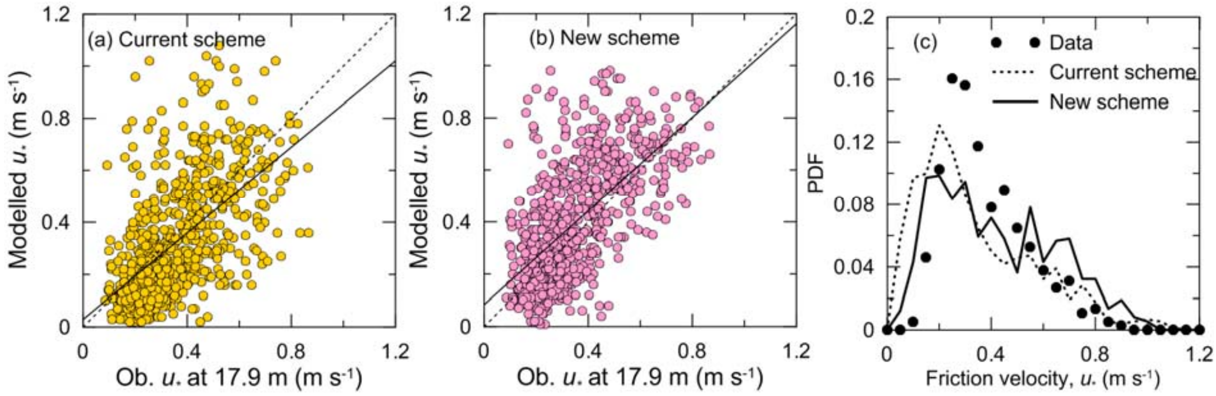

Figure 4. Scatter plot of the observed vs. predicted friction velocity (u_*): (a) when the current urban scheme is used and (b) when the new urban scheme is used; and (c) probability density function (PDF) of u_* for the data and the two schemes.

Concentrations

In the quantile-quantile (q-q) plots in Figure 5, the sorted predicted concentrations are plotted against the sorted observed values for cases without and with wind data assimilation in TAPM. In Figure 5a, the current urban scheme overpredicts for observed concentrations above 70 ng m^{-3}, whereas the new urban scheme performs noticeably better. There are no significant differences between the two schemes for the observed concentrations below 70 ng m^{-3}, with both schemes underestimating for concentrations below 30 ng m^{-3}. Prediction of concentrations due to point sources is generally very sensitive to wind direction. In order to reduce the influence of any predicted inaccuracy in wind direction, we assimilated the observed winds in TAPM, and the results are shown in Figure 5b. It is clear that the previous model underestimation for the lower-end concentrations has improved for both schemes, but the current scheme overpredicts mid- and higher-end concentrations even more. The index of agreement, d, calculated using concentrations paired in space and time is 0.73 and 0.79 for the current and new scheme, respectively, without wind assimilation. It is 0.78 and 0.82 for the current and new scheme, respectively, with wind assimilation. Note that the concentration measurements were done in daytime when the differences between the predicted sensible heat fluxes from the two schemes are not as great as at night. Therefore, we anticipate that concentration differences between the two schemes would be greater at night.

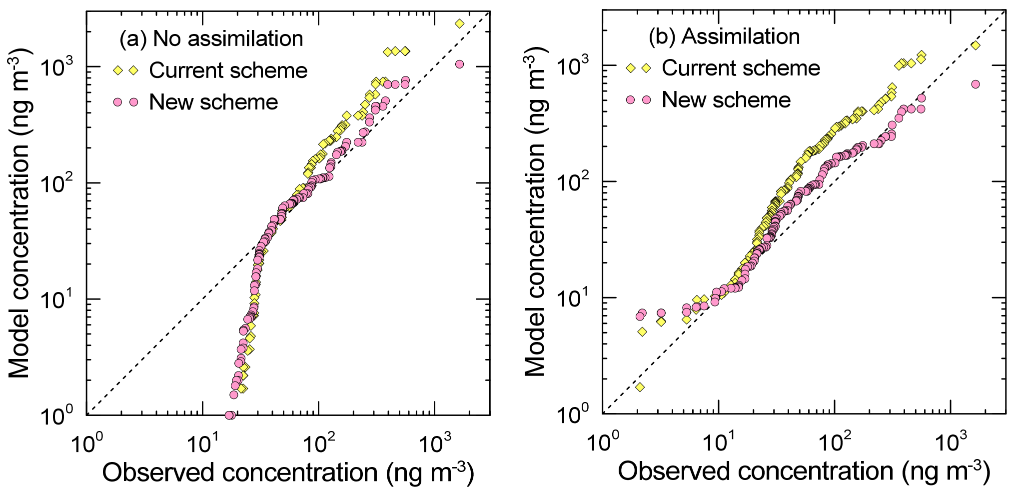

Figure 5. Quantile-quantile plot of the modelled versus observed concentration: (a) without and (b) with wind data assimilation in TAPM.

CONCLUSIONS

We tested a new urban surface scheme in the mesoscale model TAPM using data from the BUBBLE experiment. This scheme is based on a building-averaged town energy balance (TEB) approach with a generic canyon geometry, and improves upon the current scheme based on a simple slab approach. It is observed that the new scheme leads to an overall improvement in the prediction of surface fluxes, especially the sensible heat flux. This will influence turbulence and atmospheric stability predictions that directly affect dispersion, especially at night. The observed concentration fields are better predicted using the new urban scheme, but because there were no nighttime observations, the full capability of the new scheme under such conditions could not be demonstrated. Coupling surface fluxes to the atmosphere via surface similarity requires more work since the roughness sublayer is not explicitly included.

ACKNOWLEDGEMENTS

We are grateful to the BUBBLE Program, in particular Dr Roland Vogt of University of Basel (Switzerland), for the data used in this work.

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