Representing urban areas in weather forecasting models

Martin Best*
Met Office, Joint Centre for Hydro-Meteorological Research, Wallingford, U.K.

1. INTRODUCTION

Urban weather forecasting within an operational model presents an interesting yet challenging problem. An increasing number of customers require accurate forecasts within these areas and many people are aware of how the cities can be warmer than the surrounding rural areas. However, within an operational weather prediction model, these urban areas are poorly resolved, so it is difficult to be able to model these urban-rural differences well.

We need to understand what limitations are presented by the relatively poor resolution of the operational models and what subsequent errors we may expect. One basic assessment that we can make of our numerical models is to see whether they can reproduce some of the well known urban phenomenon. Along with the urban heat island effects, these include a near neutral temperature profile during the night and a corresponding surface sensible heat flux which remains positive well into the evening (see, for instance, Oke 1995). In addition, the urban boundary layer remains more turbulent during the night, which has important impacts on the pollution within the city and its dispersion.

Little work has been done to date to include urban areas within an operational weather forecasting model. There are many reasons for this, including the fact the most urban areas are not resolved in these models and as such have been neglected. Other reasons include the computational constraints of an operational model, which require the representation of physical processes to be computationally efficient.

This paper will show how urban areas are represented within the Met Office operational Mesoscale model and how this has added little to the computational running cost of the model. The impact of such an urban scheme will be presented along with a two year validation of the operational results within the U.K.

2. SURFACE FORMULATION

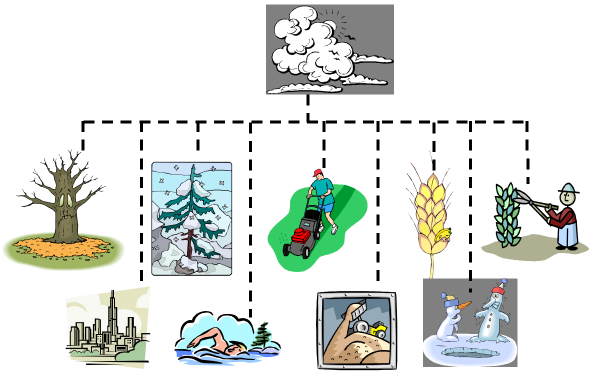
Although urban areas are typically poorly resolved in operational weather forecast models, the introduction of tile or MOSAIC surface exchange schemes into such models now allows the opportunity to explicitly model urban areas. Before tile schemes the traditional aggregate surface exchange schemes represented sub-gridscale heterogeneity by aggregate the parameters for each of the elements within a grid-box to derive average parameters. Hence it was difficult to represent urban areas in a different way to other types of surfaces.

Tile schemes represent sub-gridscale heterogeneity by calculating the surface energy balance for various elements within the grid-box and then use a weighted averaging to determine the resultant grid-box fluxes. Each surface element (or tile) sees the same atmospheric conditions which are assumed to be at the blending height. A schematic of the tile scheme used in MOSES, the Met Office Surface Exchange Scheme (Essery et al. 2003), is shown in figure 1. There are five different types of vegetation (broadleaf trees, needleleaf trees, C3 grasses, C4 grasses, and shrubs), open

* *Corresponding author address*: Martin Best, Met Office, Joint Centre for Hydro-Meteorological Research, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB. United Kingdom:
e-mail: martin.best@metoffice.gov.uk

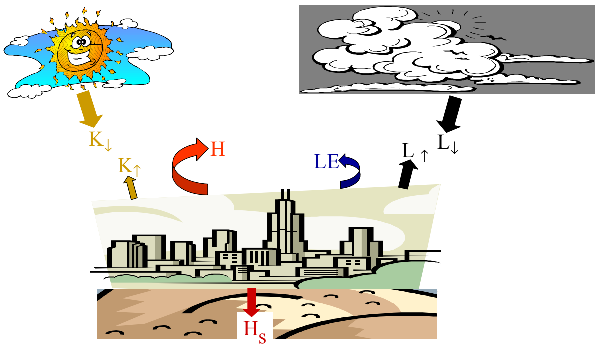
water, bare soil, permanent land ice and a tile for presenting urban areas.

Figure 1. Schematic of the nine surface types in the MOSES tile scheme



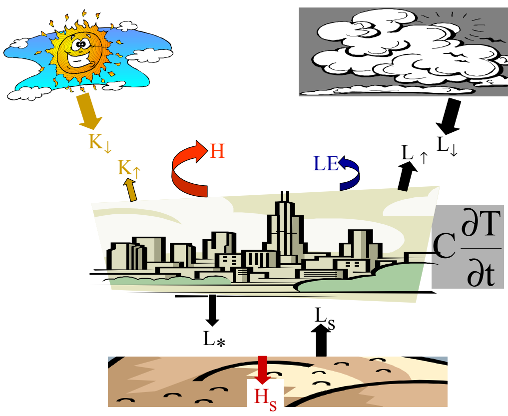
For models that have included urban areas in the surface representation, the traditional way is to present the urban surface in the same way as a bare soil surface is represented, but with the parameters set to be appropriate for a city. Figure 2 shows the typical surface energy balance for this approach for representing urban areas.

Figure 2. Surface energy balance for standard urban representation



An alternative approach is to represent the surface as a simple canopy which is radiatively coupled to the underlying soil instead of conductively coupled. This approach has been used for vegetation, but is adapted here by including a thermal capacity for the canopy that is appropriate for an urban area. Figure 3 shows this alternative surface energy balance for urban areas. Since this representation is similar to the standard approach, it is easy in implements and does not add any additional computational cost to the model.

Figure 3. Surface energy balance for canopy urban representation

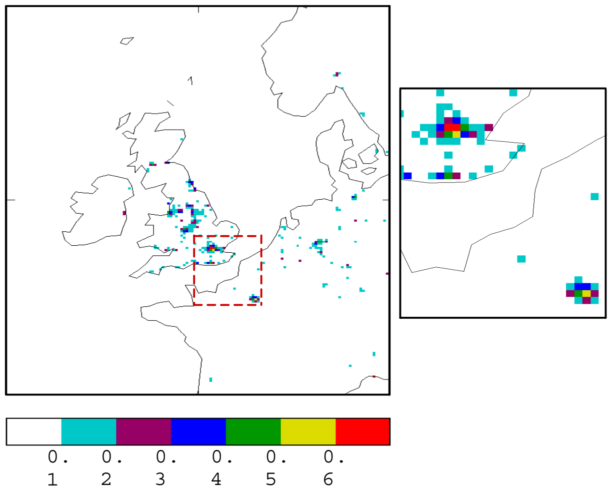


3. CASE STUDY RESULTS

The standard and canopy representations for urban areas were implemented within the Met Office Mesoscale model and used to simulate the weather for a clear skies summer period of 24 hours in the U.K. This period corresponded to anticyclonic conditions leading to a light Easterly wind.

Figure 4 shows the domain of the Met Office Mesoscale model along with the fraction of urban landuse within each grid-box. In addition, the area surrounding London and Paris (shown by the dashed red line) has been enlarged to show that there are some grid-boxes with an urban fraction of over 60%. This figure shows that although the urban areas are nor well resolved (even for a Mesoscale model) the main cities within the domain can be identified.

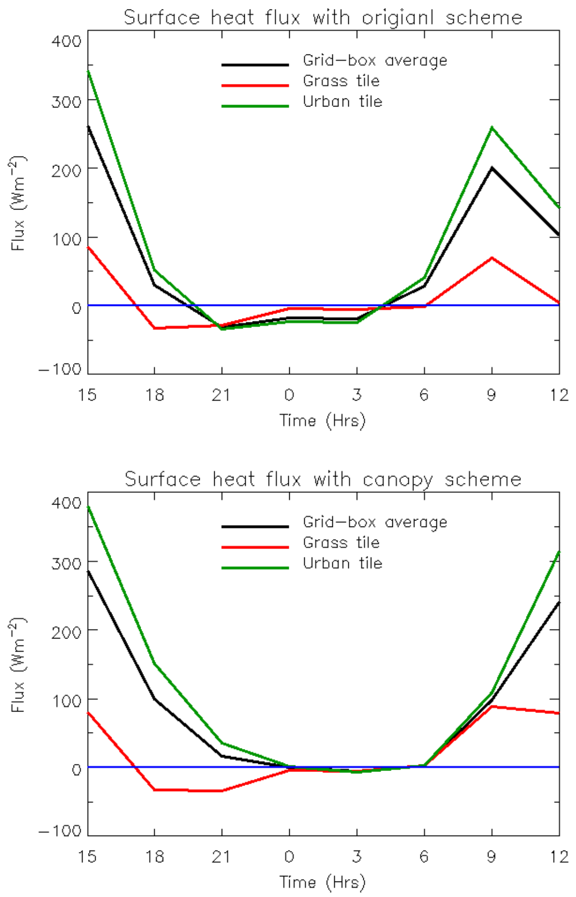
Figure 4. Urban fractions within the Met Office Mesoscale model domain.



To maximise the effect of the urban scheme, the analysis of this case study has concentrated on a grid-box within London that contains the maximum urban fraction within the domain of the model. The remaining landuse within the grid-box consists of C3 grass, with a very small fraction of bare soil.

Figure 5 shows the sensible heat flux from the C3 grass tile and the urban tile along with the grid-box average flux. It is clear from the figure that the sensible heat flux from the grass tile in similar in both of the simulations. However, the sensible heat flux for the urban tile has a different behaviour. With the standard scheme, the sensible heat flux goes negative during the early part of the evening, resulting in the grid-box average flux also becoming negative around this time. This does not agree with observations that suggest that the sensible heat flux within an urban area remains positive during the night (e.g. Oke 1995). The sensible heat flux from the urban tile with the canopy scheme has a behaviour that is more like we would expect from observations. The flux remains positive until around midnight and then even after this time, the flux stay close to zero. This is also reflected in the grid-box average heat flux.

Figure 5. Sensible heat flux for the C3 grass tile, the urban tile and the grid-box average from simulations with the standard and canopy urban schemes.



The temperature profile throughout the model boundary layer at various times during the night are shown in figure 6 for simulations with both the standard urban scheme and the canopy scheme. This figure shows that with the standard urban scheme, the temperature profile has stabilised by early evening, and this stable profile persists throughout the night. With the canopy scheme however, there is a near neutral boundary layer during the night. This neutral layer corresponds to a height of approximately 100 m., although it does decrease slightly during the night. Again, the canopy scheme is in better agreement with observations which suggest that not only is there a near neutral temperature profile during the night, but it can extend up to heights of the order of a 100 m. (e.g. Oke 1995).

Figure 6. Potential temperature profiles during the night for both the standard and canopy urban schemes.

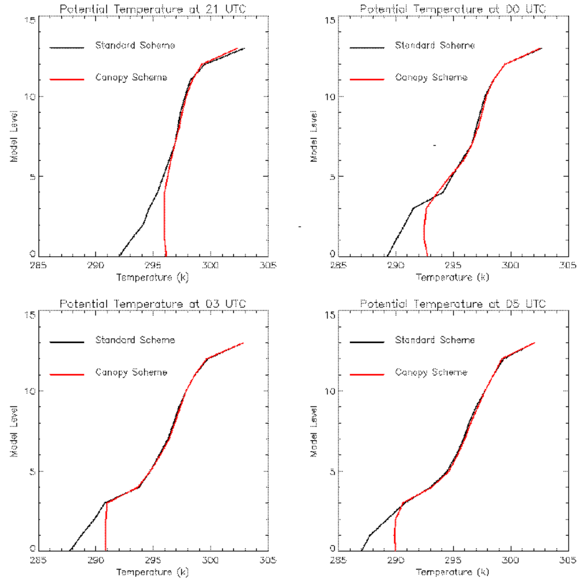
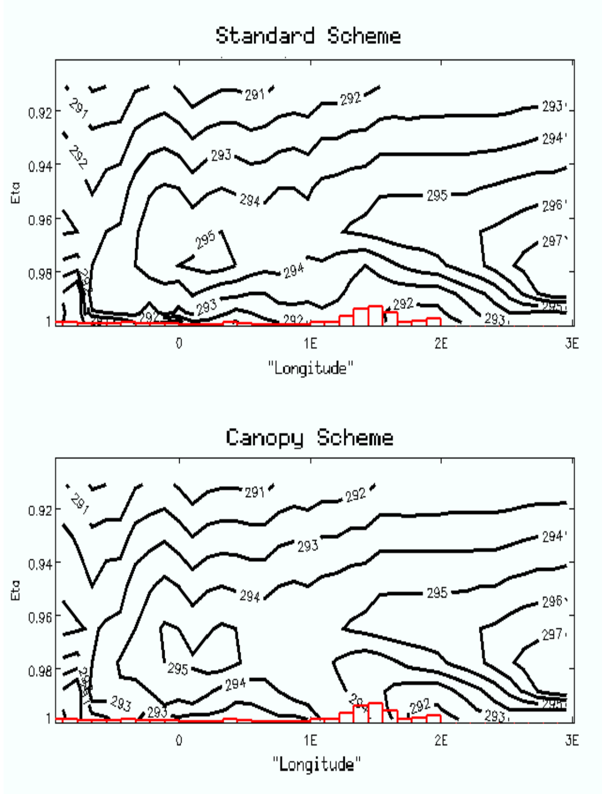


Figure 7 shows an East-West cross-section through the model at midnight, for both the standard and canopy urban schemes. Since there is an Easterly wind during this case study, the wind is blowing from right to left in this cross-section. In additional to the contours of potential temperature in this figure, the urban fraction within the grid-box is shown in red at the bottom of the plots. It is clear from this where London is within the cross-section.

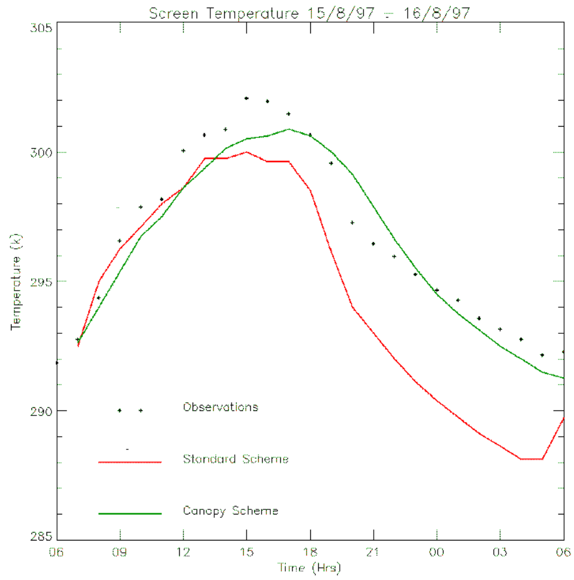
With the standard urban scheme there is a slight warming over the London area of around 1 ^{o}C, but this does not extend far into the boundary layer. In addition, the effect of the urban scheme is isolated to the immediate area above the urban area. The urban canopy scheme has a much bigger influence however. The increase in temperature near the surface over London around 2 ^{o}C and this extends into the boundary layer for around 100 m. or so. In addition to this, the impact of the urban area is not isolated, but is advected downstream where a neutral layer remains lofted above a new stabilising surface layer as the landuse becomes more rural again. This is another example of where the canopy scheme has a more realistic behaviour than the standard scheme. Also, the impact of the scheme on the boundary layer is of critical importance for pollution and dispersion models that rely upon an accurate simulation of the stability of the atmosphere for the mixing of the particles.

Figure 7. East-West cross-section of potential temperature for both the standard and canopy schemes.



To assess the accuracy of the two schemes against some actual observations, the screen level temperatures from the urban tile within the grid-box containing London Weather Centre have been compared to the synoptic observations. The results for both the standard urban scheme and the canopy scheme are shown in figure 8. It is clear from this figure that the standard scheme cools too quickly during the evening compared to the observations, whilst the canopy scheme is in good agreement with the observations for this period. Neither scheme captures the warming at dawn, or the peak temperatures during the day. However, the canopy scheme shows a significant improvement compared to the standard scheme.

Figure 8. Screen level temperature from the urban tile for both the standard and canopy schemes compared to the synoptic observations at London Weather Centre.



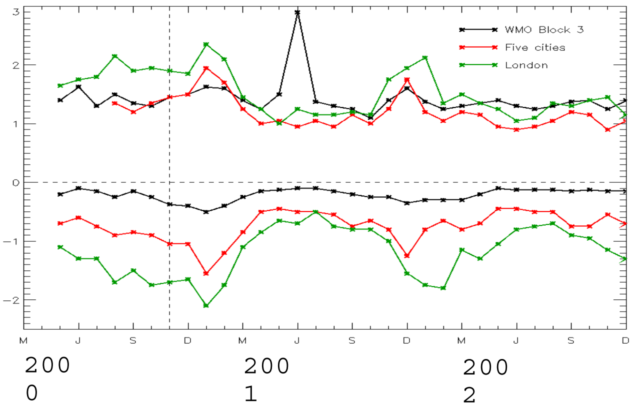
4. OPERATIONAL VERIFICATION

The urban canopy scheme was implemented within the Met Office operational Mesoscale model in November 2000. To asses the impact that this urban scheme has had within the operational model performance, the bias and root mean square errors for a period from May 2000 to December 2002 are shown in figure 9. This covers a period of 6 months before the urban canopy scheme implementation and 2 years after the implementation. The vertical dashed line in the figure shows the time at which the scheme was implemented.

There is a constant cold bias in the results of the model throughout the period, so the bias errors are all below the zero line (shown as a dashed line) and the root mean square errors are all above the zero line. There are three sets of results shown in this figure. In green are the errors compared to the synoptic observations at London Weather Centre. Shown in red are the combined errors for five cities around the U.K. (London, Manchester, Glasgow, Cardiff and Belfast). Finally the results in black are for all synoptic reporting stations within the U.K. (WMO block 3 stations). Urban areas have little impact on the results for all WMO block 3 stations, so the black results shows how the model performance has altered due to other changes that have been made to the model.

It is clear from these results that the overall performance of the model (the black results) has not changed significantly during the period. This implies that any changes seen in the other results are associated directly to the implementation of the urban canopy scheme.

Figure 9. Bias and root mean square temperature errors for the Met Office Mesoscale model from May 2000 to December 2002



Looking at the results for London shows that both the bias and the root mean square errors have been significantly reduced since the implementation of the urban canopy scheme. The bias and root mean square errors are now about half what they were before the implementation. In addition, the root mean square error for London is now comparable to the errors for the whole of the model domain.

The results for the 5 cities show similar trends to those for London, except that the magnitude of the improvements are smaller. This is to be expected, since London has the highest fraction of urban and therefore is likely to see the biggest impact from the urban canopy scheme.

It is clear from figure 9 that there is still a strong seasonal cycle in both the bias and root mean square errors for London, and to a lesser extent the other 5 cities. It should be noted at this point that the urban canopy scheme does not include any anthropogenic heat source, which is known to play an important role in the urban heat island. It is also likely that the anthropogenic heat source will be larger and more significant in winter than it is in summer. This is consistent with the model results that have an increased cold bias during the winter months. Therefore it is possible that the seasonal cycle of the model errors for the urban areas could be improved by including an anthropogenic heat source into the urban canopy scheme.

5. CONCLUSIONS

Since the majority of the World's population live in cities, it is important to explicitly represent urban areas in operational weather forecasting model in order to improve the accuracy of the forecasts within these environments.

The results presented in this paper have shown that the traditional approach to representing urban areas, i.e. in the same way as a bare soil surface, does not give physically realistic behaviour. However, the simple urban canopy scheme described here does give a physically realistic behaviour and can significantly improve the simulation for urban areas.

The canopy scheme has been implemented within the Met Office operational Meoscale model. Results have been presented to shown that the errors for London and other cities within the domain have been reduced significantly since the scheme was introduced.

There is still a seasonal cycle to the errors for urban areas within the operational model with the peak errors occuring during the winter months. It has been suggessted that these additional errors may be caused by the fact that anthropogenic heat sources, which are greatest and most influential during these period, are not represented in the model. This suggests possible future improvements to the urban canopy scheme.

In summary, a simple and computationally cheap scheme for representing urban areas can have a significantly positive impact within an operational weather forecasting model.

6. REFERENCES

Oke, T. R., 1995: The heat island of the urban boundary layer: characteristics, causes and effects. *Wind climate in cities. Proceedings of the NATO Advanced Study Institute, Waldbrom, Germany. July 15-16, 1993.* Kluwer Academic Publishers

Essery, R.H.L., Best, M.J., Betts, R.A., Cox, P.M. and Taylor, C.M., 2003: Explicit representation of subgrid heterogeneity in a GCM land surface scheme. *J. Hydrometeorol.*, **4**, 530-543.