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Urban surface modeling and the meso-scale impact of cities

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With 2 Figures

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Summary

New developments of the international community in modeling the urban canopy surface energy balance are presented and classified into five main categories: (i) models statistically fit to observations, (ii) and (iii) modified vegetation schemes with or without drag terms in the canopy, and (iv) and (v), new urban canopy schemes, that present both horizontal and vertical surfaces, again with or without a drag approach. The advantages and disadvantages of each type of model are explained. In general, the more the physics are correctly simulated, the more complex are the urban phenomenon that can be addressed, on the other hand however, the more consuming of computer-time and difficult to couple with atmospheric models the scheme becomes.

Present use of these new models in meso-scale atmospheric models show their ability to reproduce the phenomenon of the urban heat island (UHI) and some of its consequences – urban breezes, storm initiation, interaction with sea-breeze. Their use opens up new perspectives, for example in the mitigation of the UHI, or assessment of the role of air-conditioning systems or the impact of urban dynamics on air pollution.

However, there is need to validate further the different urban models available. In particular it is necessary to compare model output with urban surface energy balance measurements. An intercomparison exercise involving these urban schemes is suggested as an efficient way to assess and improve these models.

1. Introduction: the urban surface

While cities occupy only 0.05% of the Earth's surface, more than half of the World's inhabitants now live in urban areas, and are therefore sensitive to their environmental conditions. Among them, the cities' climate is of importance, and differs from the climate of the adjacent countryside, due to the special nature of urban areas. The most well known atmospheric effect of towns on the atmosphere is the urban heat island (UHI): at night, city air is usually warmer by 3–10 K (Oke, 1987). This effect has economic consequences, but also an impact on human health, as has been shown by the excess mortality of 15,000 people in France during the heat wave of summer 2003, especially in the largest agglomerations (Hémon and Jougla, 2003).

Cities also generate other atmospheric changes, including effects due to the large roughness (e.g. Grimmond et al., 1998) such as changes to turbulence (for a review see Roth, 2000), enhancement of storms (Bornstein and Lin, 2000), altered urban hydrology (Grimmond et al., 1986; Grimmond and Oke, 1986), and impacts on pollutant dispersion from streets into the atmospheric boundary layer, and their chemical evolution or radiative impacts. In particular, the pollution issue has led to several major experimental campaigns, such as METROMEX over St-Louis (Changnon, 1978), MEDCAPHOT-TRACE over Athens (Klemm, 1995), ESQUIF and ESCOMPTE over Paris and Marseille (Menut et al., 2000; Cros et al., 2003). Modeling can be a useful tool to study these impacts on the atmosphere and thereby to reduce environmental risks.

The nature and objectives of urban models cover a wide range. The object of this paper is to focus only on those models which simulate the surface energy balance (SEB) of the urban canopy. It also focuses on the newest developments in this area, because urban schemes have evolved substantially from the time of the previous review by Brown (2000).

The coupling of such models to atmospheric models makes it possible to simulate and eventually to forecast city climates, in particular the UHI and city induced circulations in the Atmospheric Boundary Layer (ABL).

The surface energy balance can be written, following Oke (1982); LHS (resp. RHS) terms are positive (resp. negative) when they are an energy source for the surface:

$$Q^* + Qf = Qh + Qe + Qs + \Delta Qa \qquad (1)$$

The terms on the LHS are the energy inputs in the canopy system: net radiation Q^* is the radiative balance between solar irradiation and infrared exchanges. It is usually positive during the day and negative at night. In urban areas, an additional anthropogenic energy flux, Qf, comes from human activities, such as car traffic, heating, air conditioning or release of heat by industries. The storage term, Qs represents the storage of energy in the building materials or in the ground and roads. It is usually positive during the day.

At night, Qs becomes negative, i.e. it is a source of energy, as heat stored in the fabric by day is released. The available energy $(Q^* + Qf - Qs)$ goes to the atmosphere, either through vertical turbulent exchanges of sensible heat (Qh) or of latent heat, by evaporation, (Qe). Note that a horizontal flux of heat (ΔQa), called the advective flux, also exists (if the complete budget of the urban canopy – i.e. buildings, roads and canyon air – is considered), but it is usually small if the site is horizontally extensive. While the surface energy budget of vegetated areas and of water bodies have been extensively observed and modeled for several decades, very few observational studies in urban or suburban areas were conducted before 1990. Since then, observations have increased substantially (for a review, see Arnfield, 2003). They show that the strongly heterogeneous 3D form of the urban canopy strongly modifies the behaviour of the different terms of the SEB: (i) trapping of radiation in the canopy (Q^*), (ii) high storage uptake during the day, due to the thermal properties of the building materials and the 3D form of the surface (Qs) – it can be as large as 60% of Q^* (in winter in Mexico City, Oke et al., 1999)-, (iii) generating a positive turbulent heat flux to the atmosphere at night (Qh), (iv) generally favouring sensible heat over latent heat sharing because of reduced evaporation (Qe and Qh), and (v) sometimes large anthropogenic fluxes (Qf).

From the modeling point of view, these aspects ideally need to be parameterized in urban schemes. This complexity and particularity of processes may explain why it is only very recently that parameterization and models dedicated to the representation of the urban SEB have been developed. The different approaches taken to modeling are presented here and recommendations are made regarding how to improve the models.

Finally, examples are given of the way such models can illustrate impacts of cities.

Numerous models of urban SEB exist in the literature, however, they can be classified in five main categories, each having their own advantages and weaknesses: (i) empirical models, (ii and iii) vegetation models, with or without drag terms, adapted and modified to fit the urban canopy physics; most operational mesoscale atmospheric models use such vegetation schemes, where urban effects are only represented by changes of landuse and hence of surface properties, (iv and v) the recent group of urban canopy models themselves, that can be classified into single layer and multilayer models.

2. Empirical models

These models are primarily based on observations of the SEB. The objective is to reproduce the energetics of the canopy using statistical relations derived from observations.

Such empirical models use very little forcing (e.g. type of surface, incoming solar radiation), and do not require the solution of many equations. The approach is based on the assumption that the physical behaviour is already contained in the observed data. In order to build such a statistical scheme, it is necessary to develop relations using data from many measurement sites.

One of the more accurate and complete of these schemes for the urban canopy is the NARP-LUMPS model. It is based on three components.

- Firstly, the net radiation is estimated, according to Offerle and Grimmond (2003) using incoming solar forcing, K↓, some atmospheric forcing (air temperature, Ta, relative humidity, RH), and surface radiative properties (albedo, α; emissivity, ε): $Q^* = f(K\downarrow, Ta, RH, \alpha, \text{and } \varepsilon)$.
- Secondly, once the net radiation is known, the heat storage flux is estimated with the Objective Hysteresis model (OHM, Grimmond et al., 1991), as $Qs = f(Q^*, a1, a2, a3)$ where the three coefficients depend on the land cover (possibly coming from an urban GIS, as in Grimmond and Souch, 1994). These three coefficients were initially statistically calibrated by Grimmond and Oke (1999a) using data from different urban land use zones (dense urban, suburban, industrial).
- Finally, the turbulent fluxes, Qe and Qh are computed using the LUMPS scheme (Grimmond and Oke, 2002), following the Penman-Monteith (Monteith, 1965) approach: $Qh, Qe = f(Q^* - Qs, \alpha, \beta)$, where α and β are two empirical parameters.

This type of approach makes it possible to use extremely simple schemes. Their main weakness, however, is that the statistics are based on field data, therefore they are limited to the range of conditions (land cover, climate, season, etc...) encountered in the original studies.

3. Vegetation schemes adapted to include an urban canopy

The most common way to simulate the urban SEB is to adapt an existing Soil Vegetation Transfer Scheme (SVAT). The advantage is that SVATs have been developed for several decades, and therefore a large background literature is available (see e.g. Brown, 2000).

Urban areas however, behave very differently from natural environments, so modifications are necessary in order to mimic at least part of the specificities of the urban SEB.

3.1 Dynamical effects

To reproduce the impact of the high density of obstacles on the mean airflow one of two approaches are usually adopted (Brown, 2000). The first is the roughness length approach, based on the observation that roughness length (and displacement heights) are large over cities (Grimmond et al., 1998; Grimmond and Oke, 1999b). Some refinement, depending how the buildings are spatially organized, can be used to model the roughness length (Bottema, 1997). When coupled to an atmospheric model, the first atmospheric level is above the surface scheme, with all the friction located at this level.

The second approach is the so-called drag approach. It is derived from forest canopy parameterizations, as used in the models of Dupont et al. (2004), Brown (2000) or Urano et al. (1999). A drag force is directly added in the equations of motions of the atmospheric model, up to the height of the highest buildings. This allows representation of the effect of the canopy down to the surface, as is done for forests. Additional terms in the turbulence equation also can be taken into account. The main disadvantage of drag based schemes is that they imply directly modifying the equations of the atmospheric models to which they are coupled.

3.2 Radiative effects

Radiation trapping in the urban canopy prevents some of the reflected solar radiation from exiting to the sky, via interception by vertical (wall) surfaces. Hence, the urban albedo is lower than the average of the albedo of its individual surfaces (e.g. roads, walls, parks, roofs).

In fact, it is usually darker than the albedo of the countryside (Arnfield, 1982; Oke, 1982, 1987). A common way to represent this shortwave radiation trapping in urban models is to specify a relatively low surface albedo, of the order of 0.15 (e.g. Arnfield and Grimmond, 1998; Taha, 1999; LEAF2 scheme in Rozoff et al., 2003; Kondo, 1990, 1995; Atkinson, 2003, among others). Note here that only the modifications of albedo due to the surface itself must be considered, and not the additional attenuation of solar radiation due to aerosols and pollution (Arnfield, 2003).

Parameterization of the attenuation of solar radiation with depth in the canopy can be incorporated into drag approach models (e.g. Brown, 2000; Dupont et al., 2004). The most original way to represent the radiative interactions between the canopy and the soil surface is the model of Best (1998). In this model, the canopy (either a forest canopy or for cities a concrete canopy), does not touch the surface, but interacts radiatively (in the infrared) with the soil. This means a building SEB and a soil/road SEB are modeled separately.

3.3 Energy balance: evaporation

There is little disagreement when the question is how to model the evaporation in dense urban areas using vegetation models: the water is removed and evaporation is very small.

Depending on the exact formulation of the model, this can be achieved by setting the water availability coefficient to zero, or the Bowen ratio is given a large value, or the soil water reservoirs are given low values. When suburban areas are modelled, an intermediate position between the vegetated and dense urban cases is generally chosen. However, if the focus of the study is on the urban surface hydrology, coupling the SEB and water budgets brings attention to the evaporation regime (e.g. Grimmond and Oke, 1991).

3.4 Energy balance: storage

The usual method to represent heat storage in the modified vegetation schemes is to use concrete surfaces/canopy instead of vegetated ones (e.g. Atkinson, 2003). However, this is not suffcient to produce large storage, because the increased roughness length (for dynamical effects) favours the turbulent sensible heat flux (Best, personal communication 2004).

It can help if the roughness length for heat is set to a much smaller value than that for momentum (as in Voogt and Grimmond, 2000). However, a more accurate method in vegetation schemes seems to be use of the Grimmond and Oke (1991a) urban parameterization scheme OHM (Arnfield and Grimmond, 1998; Taha, 1999).

3.5 Energy balance: anthropogenic heat fluxes

The role of anthropogenic fluxes is relatively simple to model; they are usually prescribed as an additional source of energy. These fluxes are typically of the order of $10\,\mathrm{W\,m^{-2}}$, for car traffic, but can become much larger in dense cities in winter (because of space heating) or in summer (because of air conditioning). For central Tokyo, Ichinose et al. (1999) estimated anthropogenic fluxes as large as $200\,\mathrm{W\,m^{-2}}$ in summer and $400\,\mathrm{W\,m^{-2}}$ in winter, using databases of energy consumption. These values were just added as an extra turbulent heat flux at the base of the atmosphere. Baik et al. (2001) and Urano et al. (1999) preferred to include the anthropogenic heating term directly in the thermodynamic equation of the atmospheric model in the boundary layer above the city.

4. Urban canopy models

In order to more accurately model the physics of the urban canopy, new concepts in surface modeling have been developed. These models aim to solve the SEB for a realistic 3D urban canopy. They share in common the following three parameterizations in their construction:

- Buildings have a 3D shape.
- The schemes possess separate energy budgets for roof(s), road(s), wall(s).
- Radiative interactions between road(s) and wall(s) are explicitly treated.

These models are based on a geometry which, even if it is simplified, is reasonably close to the reality that they aim to represent. Since they are composed of both horizontal and vertical surfaces, they are more able to capture the special energetic behaviour of the urban canopy.

The use of distinct surface types gives the advantage that their properties (e.g. wall heat capacity, wall temperature) are more easily interpreted than the corresponding averaged quantities found in modified vegetation schemes (e.g. heat capacity or surface temperature of the whole system). These new models use a relatively simple and robust methodology to compute the complex radiative exchanges in the manner of Oke and Nunez (1976) and Noilhan (1981), based on view factors between the different surfaces or facets comprising the surface. Solar reflections and shadows are also explicitly resolved. Storage of energy in the materials is easily modeled, either by the force-restore method or the more accurate heat conduction equation. The latter allows simulation of different layers in roads, roofs or walls, including insulation layers.

These models can be separated into two main categories, as for SVATs: those where the canopy air is parameterized, as in TEB (Masson, 2000), and those using a drag approach, as for forests, but here with buildings (as in Martilli et al., 2002). Here the first ones are referred to as single-layer models, because there is direct interaction with only one atmospheric layer, above the uppermost roof level. The second category are called multi-layer models, because several air layers are explicitly influenced by the buildings (down to the road surface, because the air layers extend down into the canopy).

4.1 Single-layer models

In these schemes, the exchanges between the surface and the atmosphere occur only at the top of the canyons and roofs (Fig. 1). This means that, when coupled with an atmospheric model, the base of the atmospheric model is located at roof level. This has the advantage of simplicity and transferability, but means that the characteristics of the air in the canyon space must be specified. In general, the logarithmic law for wind is assumed to apply down to just under the top of the canyon, and an exponential law is used below. Air temperature and humidity are assumed to be uniform in the canyon. The simplest of these models is the Town Energy Balance (TEB) scheme of Masson (2000). Its simplicity derives from the use of only one roof, one generic wall and one generic road. This does not mean that road orientations are not considered, because averaging is performed over all directions in order to keep only these generic surfaces. The advantage to the generic facet scheme is that relatively few individual SEBs need to be resolved, radiation interactions are simplified, and therefore computation time is kept low, despite the (simplified) 3D geometry. Interception of water and snow, and the associated latent heat fluxes, are also included. Despite the simplification hypotheses, TEB has been shown to accurately reproduce the SEB, canyon air temperature and surface temperatures observed in dense urban areas (Masson et al., 2002; Lemonsu et al., 2004).

The two other such schemes retain a higher level of detail, because the differently orientated roads (and hence their walls) are simulated separately. Mills (1997) chose a geometry kernel based on building blocks, with roads at right angles. Kusaka et al. (2001) is very similar to

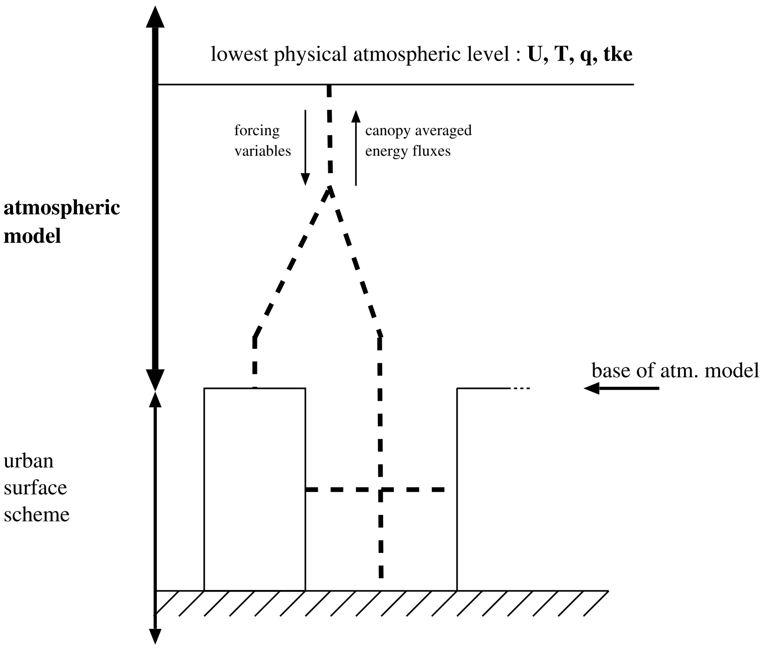

Fig. 1. Schematic view of single-layer urban surface schemes: all surfaces interact with the same atmospheric level (thick dashed lines)

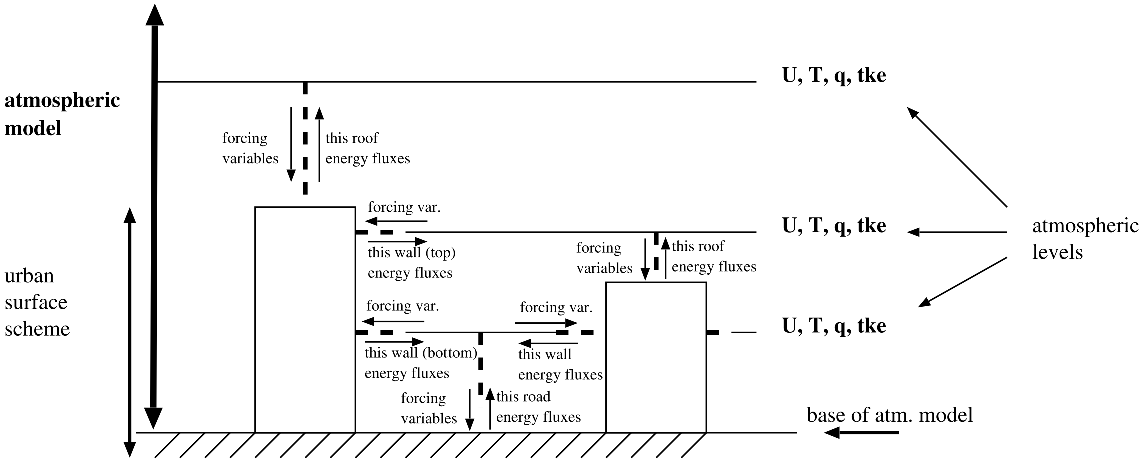

Fig. 2. Schematic view of multi-layer urban surface schemes: the interactions between the surface scheme and the atmosphere are drawn in thick dashed lines. Roads interact with the first atmospheric level. Each building wall interacts with the levels that intersecting with it. Each roof interacts with the first atmospheric level above it. Each forcing variable is chosen at the corresponding atmospheric level

TEB, using canyon geometry, but with several canyons treated independently.

4.2 Multi-layer models: the drag approach

When the drag approach is applied, exchanges with the atmosphere occur at ground level and at several atmospheric levels in contact with the buildings (Fig. 2). The SEB is still computed for each surface or part of the surface, but atmospheric properties such as the wind and temperature are not assumed, they depend more closely on the interaction between the canopy and the air. In particular, such models are able to represent profiles of the turbulent statistics of the canyon air and in the roughness sub-layer. However, such a refinement is made at the cost of direct interaction with the atmospheric model because their equations are modified:

$$\frac{\mathrm{dU}}{\mathrm{dt}} = \cdots + \text{Drag term}$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \cdots + \text{Heating term}$$

$$\frac{\mathrm{dtke}}{\mathrm{dt}} = \cdots + \text{Production term}$$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{dt}} = \cdots + \text{Production term}$$

where U is a wind variable, T the temperature, tke the turbulent kinetic energy, usually present in the atmospheric model when such surface schemes are coupled, and ε, if present, is the dissipation of tke. This makes these urban schemes complicated to couple with atmospheric models, the coupling being dependent on the equations and their discretization.

Among these models, Martilli's et al. (2002) presents a high level of detail of the SEB, since any number of road (and wall) orientations are available, different building heights can be present together, and at each level of the wall intersecting an air level, there is a separate energy budget. This feature means this model is able to represent the differential heating of the wall when the Sun is close to the horizon. This model has been tested against wind turbulence data from Rotach (2001) and Roth (2000).

Two other models of this type have been developed, one by Vu et al. (1999, 2002) the other by Kondo and Liu (1998). They exhibit workings similar to that of Martilli, except that only one SEB per wall is possible (no vertical description). However, in Vu et al. (1999), the volume occupied by the buildings is more accurately taken into account. In Martilli's model, additional terms influence the air at each level, but the volume of air remains the same as when there are no buildings. In the Vu et al. model the volume of the buildings is removed from the volume of air, however, this requires strong modification to the atmospheric model equations.

4.3 Modeling air conditioning

These new urban schemes, both the single layer and multi-layer ones, permit the modeling of air conditioning systems in the buildings. This is possible because:

- the outside canyon air temperature, wind and humidity is known (more accurately in multi-layer models),
- the inside air can be modeled, e.g. with an energy balance for each storey, because solar radiation interactions and reflections are explicitly simulated, as well as heat conduction through walls and roofs.

An air-conditioning model must also be coupled to the building model. This has been done by Vu et al. (1999), using the air-conditioning model of Ashie et al. (1999). Their simulation indicates that during the daytime, the energy used for cooling reaches $150\,\mathrm{W\,m^{-2}}$, a value which is coherent with the energy consumption estimates for Tokyo. Similar coupling has also been performed by Kondo and Kikegawa (2003), with the canopy model of Kondo and Liu (1998).

5. Summary of urban canopy modeling

A summary of the advantages and disadvantages of each modeling approach for the urban SEB is presented in Table 1. In general, the more the physics are reproduced, the more complex and difficult it is to couple the canopy model with an atmospheric model and the more computational time is required. Note however that the time required for the urban scheme generally stays negligible compared to the total run time of an atmospheric model.

Note that new generation urban models are easier to initialize than SVATs for urban areas, because they can directly use material characteristics (e.g. heat capacity, albedo) derived from field surveys or GIS databases, while SVATs need city averaged quantities, that are not always easy to define, for example they may need the thermal characteristics of the whole canopy.

6. How to improve urban schemes

Once a surface scheme for the urban SEB has been developed, it may be used alone or coupled to an atmospheric model for scientific studies. However, it needs to be validated first. If this is not done one cannot rely on the ability of the scheme to reproduce correctly the physical phenomena under study. Unfortunately, this validation phase is often neglected or not complete enough in the field of urban SEB modeling. Authors tend to validate their models after they are already coupled to an atmospheric model, using observations of the UHI intensity, mean air temperature above or in canyon (e.g. Vu et al., 1999; Kondo and Kikegawa, 2003) or against dynamical statistics of the flow in the canopy

Table 1. Advantages and disadvantages of the different types of urban models. The first column expresses the ability to reproduce urban SEB and roughness. The second shows the ability to simulate the canopy air characteristics directly. The fourth column includes coupling and portability aspects of the schemes

	Urban SEB + roughness	Canopy air profiles	Computer time	Coupling to atmospheric models	Remarks
Empirical models	Yes	–	Fastest	Very easy	
SVATs, (modified, no drag)	Approx.	–	Fast	Easy/average	Large background, needs averaged parameters
SVATs (modified, drag)	Approx.	Yes	Average	Average	Large background, needs averaged parameters
Single-layer urban models	Yes	–	Fast/expensive	Average	Initialization from a GIS & material properties
Multi-layer urban models	Yes	Yes	Expensive	Difficult	Initialization from a GIS & material properties

(momentum flux profile, turbulent kinetic energy,. . ., see e.g. Martilli et al., 2002; Vu et al., 2002). However, such validation alone is not sufficient, and has the significant disadvantage that imperfections of both the surface scheme and the atmospheric model are involved in the evaluation.

It is curious to note that in the literature, at present, schemes which aim to reproduce the SEB of the urban canopy have not yet been validated against in-situ measurements of the SEB components. Exceptions are the empirical models, that are statistically built from these SEB measurements and so reproduce them correctly (Grimmond and Oke, 2002), and the TEB scheme, that was validated for dry conditions over industrial and dense urban areas in Masson et al. (2002) and Lemonsu et al. (2004). Note that during the validation exercises of TEB, it became necessary to modify the turbulent exchanges between the surfaces, the canyon air and the atmosphere above, but now the robustness of the scheme has been proven.

Laboratory experiments in a wind tunnel or water plume, can be a complementary tool. Such experiments permit direct measurement of some processes that may not be available from field measurements. This has been done by Barlow and Belcher (2002) using the napthalene sublimation technique. Their experiments suggest that the mixing of quantities between canyon air and the atmosphere above is much more efficient than the release of the same quantity from the surfaces to the canyon air. An improvement of TEB in Lemonsu et al. (2004) was effected based on this laboratory finding, and applied to the turbulent mixing of temperature.

Urban surface schemes are emerging, but they still need to be validated against SEB data. An efficient and cooperative way to achieve such validation by a whole community of modelers has already been undertaken several times with success for SVATs. Intercomparison exercises are organized among the interested laboratories, and all models are tested against the same data. Further the discrepancies of each model are analysed and discussed in common, in order to help design the improvements needed. It is recommended that such an intercomparison exercise be organized in the urban modeling community.

7. Recent numerical studies of the urban boundary layer

The significance of modeling the urban canopy SEB is particularly clear when the urban effects are simulated by an atmospheric model. Such studies are presently in the realm of research, but in the next few years will be applied in operational forecast models, as the increasing resolution of these atmospheric models allows the explicit representation of urban areas. A few examples of possible applications are given below.

7.1 The Urban Heat Island and its induced effects

Atmospheric mesoscale models are able to simulate not only the intensity of the UHI, but also its spatial structure and temporal dynamics. Taha (1999) simulated the UHI in Atlanta after incorporating the OHM scheme in his surface scheme. Vu et al. (1999) validated their mesoscale simulations over Tokyo against measured temperatures. Lemonsu and Masson (2002) show for Paris, that the modified SEB is the key to explain the 8 K intensity of the nocturnal UHI and the reproduction of a near-neutral boundary layer at night. Furthermore, they show that during the daytime, an urban breeze develops over the city, which eventually is slightly shifted downwind due to light synoptic winds. Martilli (2002b) found similar results in 2D idealized cases. He shows that, during the day, the thermal factors are very important to the evolution of the ABL over the city.

7.2 The impact of anthropogenic fluxes

Meso-scale studies on the role of anthropogenic fluxes have been conducted in large Japanese cities. They are a good target because the density of population, height of buildings and energy consumption are all very large. Ichinose et al. (1999) conclude that anthropogenic fluxes explain the areas of maximum UHI in Tokyo. Urano et al. (1999) evaluate the impact of the anthropogenic heat release height, and conclude that by concentrating all people in taller buildings would reduce the UHI near the surface, because less heat is accumulated there. However, they only considered the effect due to anthropogenic heat input, the radiative and energetic impact accompanying taller buildings also needs to be evaluated.

7.3 The enhancement of storms

Experimental campaigns over St Louis (METROMEX) and Atlanta suggest that large cities may play a role in initiating storms in the downwind region. This is usually modeled with idealized 2D or 3D simulations using a simple parameterization of the urban influence (as in Baik et al., 2001). However, the use of more realistic urban schemes in 3D atmospheric models now allows the separation of the respective roles of the different urban effects on the atmosphere. Rozoff et al. (2003) show, with TEB coupled in the RAMS atmospheric model, that in fact it is not the high roughness that causes the appearance of such a storm downwind, but the heat fluxes due to the distinctive urban SEB.

7.4 Interaction with the sea breeze

Martilli et al. (2003) studied the role of the urban area on the land-sea breeze circulation and the pollution in Athens, using the TAPOM atmospheric model with the Martilli et al. (2002) scheme. The city weakens the nocturnal land breeze, both because of friction and because of the UHI, which produces a smaller horizontal pressure gradient. The effect on pollution however is not clear. In the daytime, the impact of the city is to reduce penetration of the sea breeze front inland due to greater roughness and the urban induced thermal circulation. This has been confirmed by Martilli (2003) using idealized 2D simulations, with the same model. However, when the sea breeze is of large extent compared to the city, the city no longer influences the sea breeze front (Lemonsu et al., 2005, 2006), the urban effects are limited to local perturbations of the near surface air temperature, the SEB and an increase of turbulence in the urban boundary layer.

7.5 The role of urban energetics on pollution chemistry

Cities obviously produce air pollution, due to the release of chemical species by vehicle traffic or industries. What is less studied is the impact of the boundary layer dynamics produced by the urban SEB on this pollution. Sarrat (2003) using the MESONH atmospheric model (Lafore et al., 1998) coupled with TEB, shows that during nighttime, the surface NOx and ozone concentrations over Paris are lower and higher respectively, and are better reproduced when a realistic urban scheme is used. This is because the boundary layer stays near neutral over the city, and has a relatively large depth of about two hundred meters.

8. Conclusions

Recent developments in the modeling of the urban SEB have been presented and classified, and the advantages and weaknesses of each approach have been highlighted. If the objective is to study cases about which there is good observational understanding, empirical models may be sufficient. For large scale studies, such as in global climate simulations, the role of the cities is small, mixed in with the countryside, and hence modified vegetation schemes are probably appropriate. But if one wants to focus on the influence of cities, from regional climate studies to mesoscale and urban scales, single-layer urban schemes are recommended for the SEB. Because they solve physical equations, they can be used with relative confidence even where no SEB data are available, for any forcing condition. For more specific objectives, such as the impact and feedback between canyon air and air-conditioning, multi-layer models are probably necessary. Note also that empirical models are always useful to interpret the results of more complex schemes, because they are themselves an interpretation of observations.

The reasons why there is interest in coupling these urban schemes with mesoscale models has been demonstrated. Future studies are likely to add to the range of topics of interest. For example, they may investigate how to mitigate the UHI by modifying the properties of construction materials or the road albedo, or how to reduce the energy consumption for heating or space cooling and hence improve the urban climate for human comfort, or quantify precisely the role of the city induced dynamics and thermodynamics on air pollution.

Attention is also focused on the necessity to validate these different schemes. This should include not only comparison with observed air temperatures and turbulent profiles in the canyon, but also against observed components of the SEB, where all terms (incoming and outgoing radiation, turbulent fluxes, storage, anthropogenic fluxes) are involved. This must be done over the widest range of atmospheric conditions and cities. An international intercomparison exercise might be the best way to perform such validations with integrity and efficiency.

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