INVESTIGATING THE SURFACE ENERGY BALANCE IN URBAN AREAS – RECENT ADVANCES AND FUTURE NEEDS

M. PIRINGER[1]*, C. S. B. GRIMMOND[2], S. M. JOFFRE[3], P. MESTAYER[4], D. R. MIDDLETON[5], M. W. ROTACH[6], A. BAKLANOV[7], K. DE RIDDER[8], J. FERREIRA[9], E. GUILLOTEAU[10], A. KARPPINEN[3], A. MARTILLI[11], V. MASSON[12] and M. TOMBROU[13]

[1] *Central Institute for Meteorology and Geodynamics, A-1190 Vienna, Austria;* [2] *Dept. of Geography, Indiana University, Bloomington, IN;* [3] *Finnish Meteorological Institute, FIN-00101 Helsinki, Finland;* [4] *LMF, CNRS – Ecole Centrale de Nantes, F-44321 Nantes, France;* [5] *Meteorological Office, Bracknell RG12 2SZ, United Kingdom;* [6] *Swiss Federal Institute of Technology, CH-8057 Zuerich, Switzerland;* [7] *Danish Meteorological Institute, DK-2100 Copenhagen, Denmark;* [8] *VITO-TAP, B-2400 Mol, Belgium;* [9] *Instituto de Meteorologia, P-1700 Lisbon, Portugal;* [10] *University Valenciennes, France;* [11] *Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland;* [12] *CNRM Meteo France, F-31057 Toulouse, France;* [13] *Dept. of Applied Physics, Univ. of Athens, GR-157 84, Athens, Greece*

(author for correspondence, e-mail: martin.piringer@zamg.ac.at, fax: +43 1 36026 74)*

Abstract. Recent advances in understanding of the surface energy balance of urban areas, based on both experimental investigations and numerical models, are reviewed. Particular attention is directed to the outcome of a COST-715 Expert Meeting held in April 2000, as well as experiments initiated by that action. In addition, recent complete parameterisations of urban effects in meso-scale models are reviewed. Given that neither the surface energy balance, nor its components, normally are directly measured at meteorological stations, nor are there guidelines for the set-up of representative meteorological stations in urban areas, this paper also provides recommendations to close these gaps.

Keywords: COST-715, meso-scale models, surface energy balance, surface flux modelling, urban boundary layer

1. Introduction

The requirements of the European Union Framework Directive on air quality assessment and management, adopted by the Council of Ministers of the European Union in September 1996, present new challenges for the meteorological community. Assessments of air quality will be required in urban areas with large populations for up to 13 air pollutants. The Directive requires remedial plans to be drawn for areas assessed to have poor air quality. Reliable air pollution models are needed to supplement measurements, for mapping, and to investigate future emission scenarios. The models are essential management tools. These models will need accurate and representative meteorological input variables consistently applied across EU Member States. Surface fluxes needed in urban air pollution

Water, Air, and Soil Pollution: Focus **2:** 1–16, 2002.

assessments are not routinely measured. Moreover, the number of meteorological stations in urban areas is commonly limited to a few sites, often just at airports.

The surface energy balance is the key component of any model aiming to simulate dynamical and thermodynamical patterns above the surface (e.g., Kallos, 1998; Mestayer, 1998). In its simplest one-dimensional form, it can be written as:

$$Q^* = H + LE + G \tag{1}$$

where H and LE denote turbulent sensible and latent heat fluxes, respectively, and G is the storage heat flux usually not measured but determined as a residual. In many cities, additional sources of energy due to human activities (Q_F, the anthropogenic heat flux) also have to be included. In urban areas, the terms of Equation 1 require special treatment, given the complexity of the materials and morphology of the urban surface. There are marked differences in energy partitioning compared to rural conditions, where most parameterisation schemes and measurements have been performed. There is still considerable uncertainty concerning the partitioning of the components of the surface energy balance in urban areas, and the role of surface cover (e.g. the fractions of built-up areas/greenspace), city surroundings, and prevailing meteorological conditions.

This paper addresses some of these issues. The focus in the experimental section 3.1 is on surface flux measurements conducted in North-American cities during the past 10 years and on ongoing recent European experiments. These latter studies were initiated in part by COST-715 (Co-operation in the Field of Scientific and Technical Research) on 'Meteorology Applied to Urban Air Pollution Problems'. The framework, objectives and work plan of this Action, which will end in September 2003, are discussed in Fisher *et al.* (2001). Working Group 2 of COST-715 conducted an Expert Meeting on the surface energy budget in urban areas, held in Antwerp, Belgium, on 12 April 2000 (COST-715, 2001). The findings were summarized by Piringer *et al.* (2001) at the 3rd International Air Quality Conference in March 2001 in Loutraki, Greece. The modelling section 3.2 mainly refers to recent full parameterisations of urban effects in meso-scale models. The paper ends by outlining future needs to further increase our knowledge of the urban surface energy balance. Assessing methods to determine or model the height of the urban boundary layer (UBL), which is itself strongly dependent on the surface heat fluxes, is the second task of WG2 of COST-715.

2. Siting Considerations

In contrast to rural areas, the UBL is more complex. A roughness sub-layer (RS) of much larger vertical extent than found in typical rural areas occupies the first tens of meters above the surface, with the remainder of the surface layer (i.e., the *inertial sublayer*) aloft. The RS includes the urban canopy layer, which is composed of individual street canyons and other roughness elements (Figure 1).

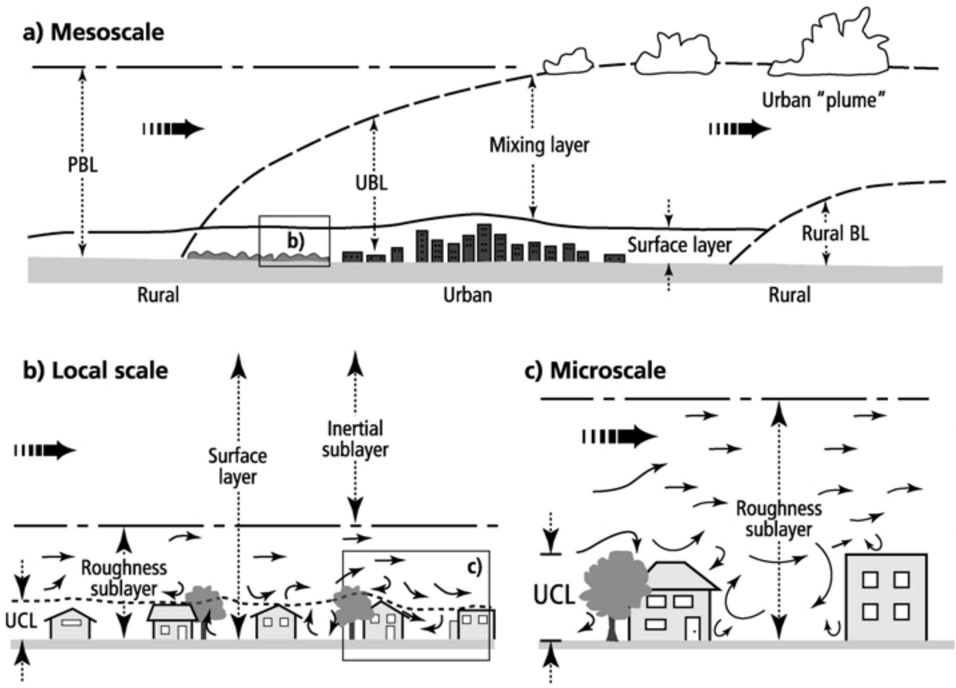

Figure 1. Schematic of the urban boundary layer including its vertical layers and scales. 'UBL' stands for Urban Boundary Layer, and 'UCL' for Urban Canopy Layer (revised by Oke and Rotach after a figure in Oke, 1997).

The Monin-Obukhov similarity theory is not valid within the RS and turbulent fluxes of momentum, energy, moisture and pollutants are height dependent (e.g. Rotach, 2001). Only in the surface layer aloft, contributions from individual surface roughness elements are blended into possibly representative averages (Taha and Bornstein, 2000).

The WMO-guideline for rural stations declares wind measurements as representative if placed 10 m above ground without close obstacles; temperature and humidity measurements have to be conducted at 2 m. For urban areas, no guidelines for proper siting exist, although this issue is presently under review by WMO (Oke, *pers. comm.*, 2000).

Monitoring stations in urban areas should be sited so that their data reflect the characteristic meteorological state of the urban terrain zone (quarter) under consideration, excluding local influences. For surface energy balance observations, instruments must be placed above the RS. This height, z^*, is usually expressed as a function of the roughness element separation and/or the mean building height h_r. When described by the latter, z^*, as a rule-of-thumb, is somewhere between 2–5 h_r (see Figure 1 b-c). With instruments mounted at such heights, the area for which the measurements are representative (the flux footprint), typically is of the order of 10^2–10^4 m^2. The exact dimensions and area of influence will vary with the exact height of measurements and roughness of the surface, as well as with wind speed, direction and atmospheric stability. The area of influence is much greater at night, a factor that must be considered when interpreting surface controls on urban energy balance fluxes through time. If large observational heights are necessary, the fetch of the observation may become very large and the surface cover inhomogeneous. Achieving uniform upwind fetch may be difficult to meet in parts of typical European cities.

3. The Urban Surface Energy Balance

3.1. Experimental Investigations

Knowledge of surface heat fluxes as well as atmospheric stability and surface roughness is essential, both as input and boundary conditions, in advanced air pollution dispersion models. Normally, however, the surface energy balance or its components are not directly measured at meteorological stations. In the last decade, a series of local-scale energy balance observations have been conducted at a restricted number of sites, largely, though not exclusively, residential areas in North America (see, for example, Grimmond and Oke, 1995, 1999, 2000; Grimmond *et al*., 1996; Oke *et al*., 1998, 1999; Spronken-Smith, 1998; Feigenwinter *et al*., 1999).

A **M**ulti-city **U**rban **H**ydrometeorological **D**atabase (MUHD) has been generated to document local-scale surface heat flux variability in several North-American cities (Grimmond and Oke, in COST-715, 2001). MUHD integrates surface energy balance observations, each 1 to 8 weeks in duration, conducted over a ten-year period. These surface energy balance data were collected primarily in summertime, with the exception of Mexico City (dry winter season). The urban land uses represented include central city, light industrial, and low or medium density residential. Sites were selected to represent different building densities (sometimes in the same city) and climates. Grimmond and Souch (1994) outlined the methods used to develop the surface cover information for the MUHD sites. For all sites, areas of similar surface cover and morphometry in a 2–5 km radius around each measurement site are mapped from aerial photographs, and detailed attributes such as building height and type, density, vegetation amount and type are documented. These databases are then coupled to the Flux Source Area model of Schmid (1994, 1997) to quantify the surface cover influencing local-scale surface energy balance observations taken using instruments mounted on tall towers ($> 2h_r$, the mean height of the surrounding roughness elements).

Some key characteristics of surface energy balance partitioning, derived from MUHD, are summarised in Table I. In general, the radiation fluxes of cities show magnitudes and diurnal behaviour similar to those of rural surfaces (Oke *et al*., 1998). As expected, areas with little vegetation have extremely small latent heat

TABLE I

Ranges of average daily maximum values of net radiation and fluxes at the MUHD sites (after Grimmond and Oke, in COST-715, 2001)

Parameter	Range (W m^{-2})
Net all-wave radiation Q*	<400–650
Latent heat flux LE	10–235
Sensible heat flux H	120–310
Storage heat flux G	150–280
Average daytime Bowen ratios H/LE:	(Dimensionless)
Residential sites	1.2–2
During irrigation ban Vancouver	~ 2.8
Light industrial site	~ 4.4
Downtown	~ 9.8

flux values. Of the residential sites, the neighbourhood in Vancouver had the lowest measured rates, due to an effective garden irrigation ban that was in force in 1992, an abnormally dry year (Oke *et al.*, 1998). The remaining residential areas have daytime peaks in evaporation ranging from 125 to 235 W m^{-2}; these are significant fluxes, sustained by garden irrigation and/or frequent rainfall (at least 20 to 40% of daytime Q*). At all sites, more energy leaves the surface as sensible rather than latent heat flux; consequently the Bowen ratio values are greater than unity (Table 1). Storage heat flux was determined as a residual (Equation 1; Grimmond and Oke, 1999). This is always a significant term in the surface energy balance in urban areas (Table I), and is considerably larger than for most natural systems, except water. In general, the storage sensible heat flux is most important at central city and light industrial sites (at least 50% of daytime Q*), whereas turbulent sensible heat flux is most important at residential sites (40 to 60% of daytime Q*).

An investigation of urban-rural energy balance differences for three North-American cities with different rural environments revealed contrasting heat and water balance regimes, some even being capable of completely inverting expected urban-rural difference (Oke and Grimmond, in COST-715, 2001). The cities studied were Tucson, Arizona, with surrounding desert, Sacramento, California, with semi-arid grassland and irrigated farmland, and Vancouver, British Columbia, with surrounding moist farmland. Whereas urban-rural differences in net radiation are mostly less than ± 50 W m^{-2}, the Tucson results are distinctly different. Daytime urban Q* in Tucson is as much as 125 W m^{-2} greater than in the surrounding rural desert suggesting the city is a better absorber than the desert by day. This might be interpreted to be due to the lower albedo and/or lower surface temperature of the city, which in turn is related to greater abundance of urban vegetation and irrigation. For all the cities, the storage heat flux is, as expected, greater than the rural values; the urban fabric sequesters more heat by day than the surrounding countryside. At night, the cities release greater amounts of heat from storage. For the turbulent sensible and latent heat fluxes, the station pairs with moist and wet rural sites (Vancouver and Sacramento) confirm conventional expectations, i.e. cities evaporate less and generate a greater sensible heat flux to the air than their rural surroundings. On the other hand, the semi-arid and desert pairs show the reverse. The source of urban moisture here is garden irrigation.

While offering much new insight into surface energy exchanges in urban environments, more data need to be collected to represent cities with different building materials and architectural styles, and for conditions where direct release of energy from human activities (the anthropogenic heat flux, Q_F) is more significant. Moreover, the above results cannot be directly extrapolated to European cities due to land use, climatological and urban metabolism differences. There are several experimental studies of the urban surface energy budget for European cities (e.g. Klysik, 1996; Dupont *et al.*, 1999; Holmer and Eliasson, 1999), but they do not specifically analyse the different components of the surface energy budget in cities. Therefore, three new field campaigns, in Basle, Marseilles and Birmingham, have been initiated, to more explicitly study processes in European cities.

BUBBLE, the **B**asle **U**r**b**an **B**oundary **L**ayer **E**xperiment, is an initiative of six Swiss research institutes (Rotach *et al.*, 2001) financed in the framework of COST 715. It is supported by a large number of groups from all over the world. The objective of BUBBLE is to study the UBL in the city of Basle for a one-year period, monitoring near-surface turbulence characteristics as well as the vertical structure of the entire UBL. Near-surface observations are undertaken at two urban, one suburban and a rural reference sites up to a height greater than twice the mean roughness element height; these comprise conventional meteorological observations, turbulence measurements by sonic anemometers, full radiation balance, and, at the urban sites, detailed measurements of the canyon thermal and radiative properties. A 1290 MHz wind profiler is operated at one urban site. The aerosol distribution within the urban boundary layer and aloft is determined with an aerosol backscatter Lidar. The data set will be used to evaluate and improve the surface exchange parameterisation of Martilli (2001) as described in section 3.2.

Another experiment on the urban boundary layer was undertaken during the large French photochemistry experimental campaign ESCOMPTE in Provence, June-July 2001. The urban meteorological (UBL/CLU-Escompte) campaign took advantage of the project's dense network of meteorological and remote sensing observations both on the ground and from airplanes. Surface energy balance fluxes were measured at five stations within Marseilles, with three above the urban canopy of different parts of the city. A central site, located in the densely built 19^{th} Century city centre, was also equipped with an array of infrared thermoradiometers with a thermal scanner monitoring street sections and individual building elements. These data are to be integrated with those from a small aircraft equipped with a scanning thermal infrared camera, NOAA/AVHRR satellite observations, and a network of 20 T-RH sensors 6 m above ground. The 4D structure of the UBL was documented with two mini-Sodars, one RASS sounder, one UHF radar, and two 3D-scanning O_3 and Doppler Lidars. The data are to be used to test urban energy budget models, improve remote sensing methods to determine the effective urban surface temperature to predict heat fluxes, and to test high resolution meteorological and chemistry-transport models.

A field program to measure surface fluxes at an industrial site at Birmingham, UK, has been set up to better forecast urban air quality and understand past pollution episodes (Ellis and Middleton, 2000). Three data sets (1998, 1999 and 2000) each of about four weeks collected data from ultrasonic anemometers and resistance thermometers on masts at 15, 30 and 45 m as well as radiation, humidity and pressure sensors.

Satellite remote sensing has the potential to provide estimates of urban surface energy balance fluxes (Zhang *et al.*, 1998; De Ridder, in COST-715, 2001). The two most common methods to derive information about surface energy balance fluxes across cities are either the difference between the surface radiation temperature measured by the satellite and the local air temperature, or based on estimating surface parameters from satellite remote sensing and land-use maps and computing the surface energy balance via a SVAT (Soil Vegetation Atmosphere Transfer) module. The use of thermal remote sensing to infer the surface heat flux is potentially prone to large errors, which become even more pronounced in the case of urban environments. This is due to uncertainties in the determination of the surface radiant temperature itself, particularly in the case of large roughness elements, as well as ancillary parameters such as the roughness length and the wind speed, if they are extrapolated from routine meteorological observations (e.g., the discussion in Voogt and Grimmond, 2000). Given these uncertainties accumulate in the determination of the sensible heat flux, the second method may be preferred compared to the first. However, more complete evaluations of the predicted fluxes for urban environments, based on carefully conducted field studies, is urgently needed.

3.2. Model Results

Air quality management is mainly concerned to identify pollution 'hot-spots' or areas of exceedence; the modelling of concentration maxima in these is strongly sensitive to the diagnosing of stable conditions. Modelling of the urban energy balance and stability is largely absent from current dispersion models. Across Europe, different cities can be expected to influence local stability to differing extents, but little is known about this. Another possibility to obtain the surface fluxes, needed in urban air pollution assessments, is the use of nested numerical weather prediction and meso-meteorological models. Such models will approach the necessary resolution for the urban scale, but parameterisations of urban effects in most of the existing operational models are absent or greatly simplified for this purpose (Baklanov *et al.*, 2001). More research, such as the work in Basle, Birmingham, and Marseilles, is needed to identify sensible constraints on stability diagnosis, and to improve parameterisations (as discussed above).

3.2.1. *Detailed Surface Exchange Parameterisations*

The most detailed parameterisations of urban effects within current numerical models are the Town Energy Balance (TEB) scheme of Masson (2000) and the surface exchange parameterisation in the Finite Volume Model (FVM) of Martilli *et al.* (in COST- 715, 2001). Both explicitly consider the effects of buildings, roads, and other anthropogenic building materials on the urban surface energy budget.

The meso-scale atmospheric model MESO-NH in combination with the TEB scheme has been used to compute urban surface fluxes to investigate the influence of Paris on the atmospheric boundary layer for an anticyclonic summer day (Lemonsu and Masson, 2001). The TEB model parameterises both the urban surface layer and the roughness sublayer, so that the atmospheric model only 'sees' a constant flux layer as its lower boundary. All the turbulent fluxes and the upward radiation flux are computed for each land cover type (e.g. sea, lake, natural and cultivated terrestrial surfaces, urban) by the appropriate scheme (TEB/ISBA) and then averaged in the atmospheric model grid mesh, in proportion to the area covered by each land cover type. The city is represented by generic buildings which have the same height and width, with the roof level at the surface level of the atmospheric model. Buildings are located along identical roads; any road orientation is possible, but all exist with the same probability. A detailed scheme parameterising multiple reflection of radiation is available in TEB.

Surface cover information comes from the Corine Land Cover database with a horizontal resolution of 250 m. Atmospheric data come from ECMWF analyses updated every 6 h. When the simulation output is compared to observations from 30 meteorological stations in and around Paris, and with atmospheric profiles from radiosondes, the urban heat island is simulated fairly well, though temperature is over-predicted, especially during the night (Figure 2). Simulated surface energy balance fluxes are shown in Figure 3. The enhanced storage heat flux documented in urban areas and the distinct diurnal hysteresis pattern (Grimmond *et al.*, 1991) both are reproduced well. During the night, storage heat release is enough to maintain a small positive turbulent sensible heat flux (also observed by Grimmond and Oke in COST-715, 2001).

Urban effects are parameterised in the meso-scale FVM model by considering roofs, walls, and the canyon floor as active surfaces (Martilli *et al.*, 2002). For the exchange of momentum, two different roughness lengths are defined for the roof and canyon floors, respectively, while the contribution of the walls is parameterised with a drag force approach. The sensible heat fluxes are determined as a function of the difference between the air temperature and the corresponding surface temperat-

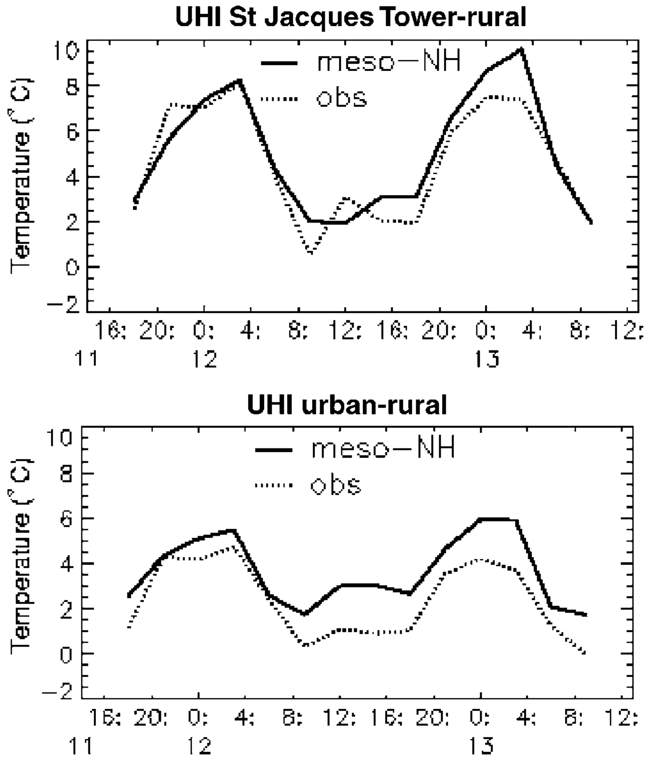

Figure 2. Observed and simulated urban heat island on 11–13 July, 1994. Top: between the center of Paris and the surrounding countryside; bottom: between all dense urban area and countryside (from Masson *et al.*, in COST-715, 2001).

ure. The short and long wave radiative fluxes are computed by taking into account the shadows and multiple reflection effects of the street canyon element.

The model has been run for an idealised 2-D case of an UBL with flat terrain and an idealised city of 10 km, building height 25 m, street width 25 m, surrounded by a rural area. The computations show that walls are the most active surfaces for momentum and turbulent kinetic energy, during day and night. For heat, on the other hand, street and roofs are more active during daytime and walls during night-time.

Determining the impact of vertical and horizontal surfaces on the energy balance is very important in order to estimate the storage heat flux term correctly. To investigate this, Martilli et al (2002) have compared their new surface exchange scheme (‘urb’ in Figure 4) to the ‘traditional’ approach (‘trad’), in which the roughness length and the soil thermal properties are modified in order to simulate urban influences (Figure 4). Considering only the ground as an active surface with an increase in the roughness length and the soil thermal characteristics of the concrete (‘Trad’ in Figure 4), there is a tendency to underestimate the magnitude of the storage heat flux during day- and night-time. On the other hand, there is

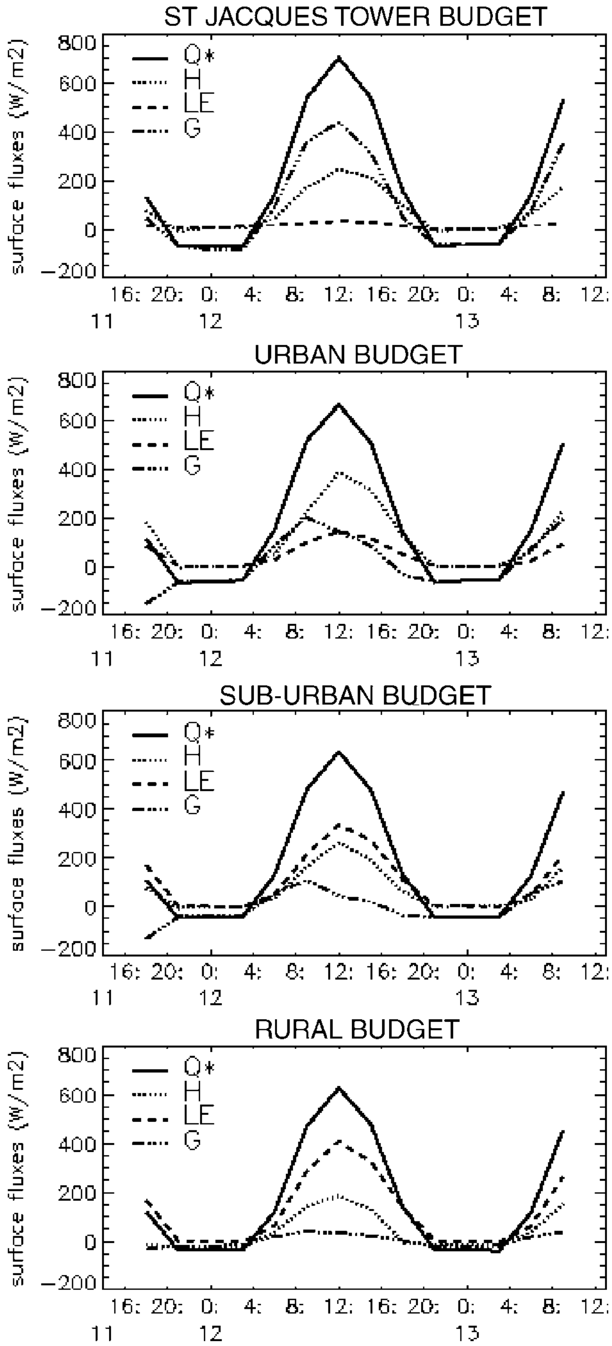

Figure 3. Comparison of surface fluxes at various sites in the City of Paris as calculated by MesoNH using the TEB scheme. The four panels refer to specific sites of areas as indicated (from Masson *et al.*, in COST-715, 2001).

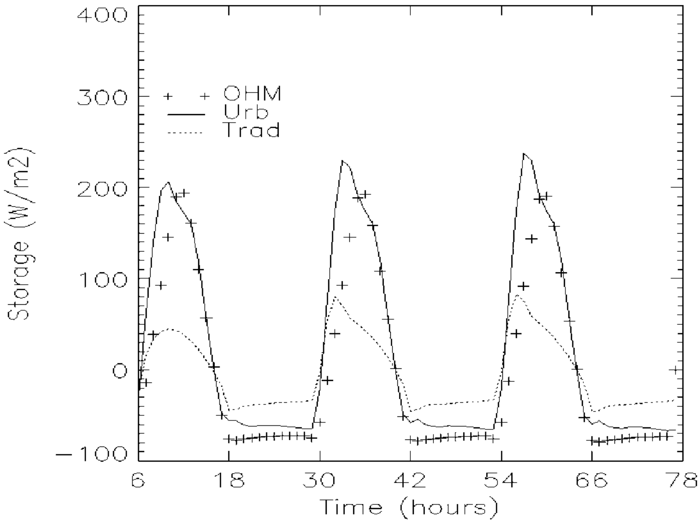

Figure 4. Comparison of different methods to estimate heat storage (from Martilli *et al.*, in COST-715, 2001). OHM refers to the Objective Hysteresis Model (Grimmond *et al.*, 1991), 'trad' and 'urb' are defined in the text.

quite a good agreement in the three-day simulation between the results obtained with the new parameterisation used in FVM and the Objective Hysteresis Model OHM (Grimmond *et al.*, 1991; Arnfield and Grimmond, 1998; Grimmond and Oke, 1999), an empirical formulation for the storage term based on the total radiation of the canyon and its material properties.

Another approach to modelling urban surface energy balance fluxes is to adapt current modules for rural conditions by introducing urban features. The French SUBMESO model, which has a force-restore model for rural soil (derived from Noilhan and Planton, 1989) was used to introduce new parameterisations for urban soil-atmosphere interactions (Guilloteau and Dupont, in COST-715, 2001). Five soil cover types are considered: water, natural soil, vegetation, impervious surface materials (asphalt, concrete), and buildings. The processes considered are evaporation or dewfall, transpiration by the vegetation, interception of water by the vegetation and buildings run-off towards the natural soil and impervious ground materials as well as infiltration of water through the surface to the underlying soil. Return toward equilibrium state is considered for the temperature of the natural and artificial materials and for the humidity of the natural soil. Drainage of the water intercepted by the buildings and the impervious surface to the drainage and sewerage network are also included. Additional heat input from vehicles is considered.

One-dimensional simulations with imposed meteorological data (rural soil of Caumont during the Hapex-Mobilhy experiment) were carried out over typical urban terrain types (Table II) for one year to assess model behaviour. As seen from the example shown in Figure 5, the model simulates the low latent heat flux values expected for a city centre, but transforms most of the net radiation into turbulent

TABLE II

Surface cover characteristics of five typical urban terrain zones (from Guilloteau and Dupont, in COST-715, 2001)

% grid surface	soil	veg.	water	paved	build.
City centre	0	10	0	40	50
Residential	20	30	0	30	20
Green quarter	10	60	15	10	5
Industrial and commercial	10	0	0	50	40
Tall apartments	5	25	0	40	30

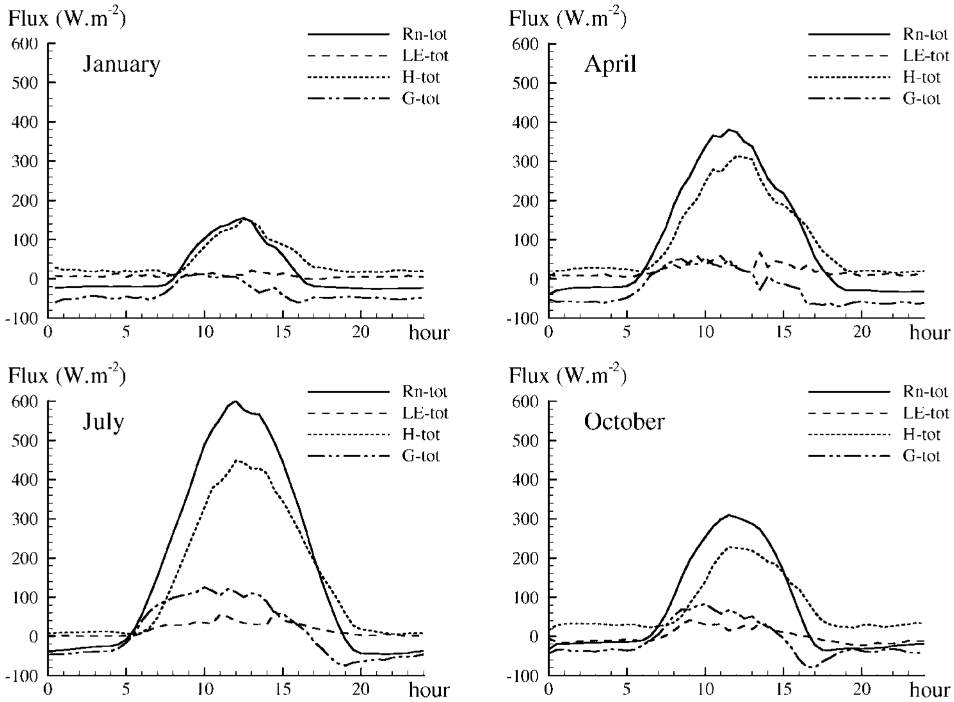

Figure 5. Energy balance over 'City centre' for the average day of four typical months (from Guilloteau and Dupont, in COST-715, 2001). Note: symbols are different to that used in text (Rn is equivalent to Q*).

sensible heat; as a consequence, the heat storage in the fabric is too small. The same model behaviour is found for 'industrial and commercial' and 'tall apartment' districts. For residential areas, the partitioning of fluxes is reasonable. For vegetated zones the calculated latent heat flux is lower than expected. The shortcomings of these simulations were due to the model considering only the horizontal surfaces of the city (grounds, roofs, vegetation cover), demonstrating the importance of the 3-D structure of the urban canopy. The SM2-U version (Dupont *et al.*, 2000) now includes efficient parameterisations for the heat storage by building walls and for an effective albedo depending on building shape and sky view factor, deduced from the work of Masson (2000). The SM2-U model has the advantage of universality for all urban areas, from the rural soils to the dense city centre. Though similar to the TEB scheme, it does not however offer the possibility to explicitly simulate the 3D canopy exchange due to the employed force-restore approach.

3.2.2. *Meteorological Preprocessors*

In recent years, a number of boundary-layer parameterisation schemes have been developed to estimate net radiation, sensible heat flux and other UBL parameters from hourly standard meteorological data. COST-710 (1998) conducted an extensive comparison of these methods and presented various validations against observational data. Most of these models were developed and validated using data from flat, grass-covered environments. These approaches are therefore limited to horizontally homogeneous conditions. Grimmond and Oke (2000, 2002) developed a linked set of equations to calculate heat fluxes, and in turn atmospheric stability, specifically designed for the urban environment. The scheme is basically an urban-specific modification of the approach of Holtslag and van Ulden (1983). This preprocessor scheme (LUMPS -**L**ocal-scale **U**rban **M**eteorological **P**re-processing **S**cheme) makes use of parameterisations that require standard meteorological observations, supplemented by basic knowledge of the surface character of the target urban area. Ideally LUMPS is forced by observed short- or net radiation data, but these fluxes also can be modelled. Heat storage in the urban fabric, including hysteresis, is parameterised from the radiation and surface cover information using the objective hysteresis model (Grimmond *et al.*, 1991; Grimmond and Oke, 1999). The turbulent sensible and latent heat fluxes are calculated using the available energy and a simplified Penman-Monteith/Priestley-Taylor type of equation using a measure of the surface moisture status, given by the fraction of the surface covered by vegetation, and temperature. LUMPS has been shown to perform well when evaluated using data from North American cities. The scheme is tried to be evaluated with data collected in European cities, notably Basle, Graz and Marseilles.

4. Findings and Recommendations

1. Siting criteria for urban stations are urgently needed. Sites should be characterised with the help of aerial photos, local surveys, maps, building dimensions, GIS, and urban databases.
2. Measurement of surface fluxes at meteorological stations is desirable, but so far such measurements have only been realised in research programs of limited

duration. Urban meteorological masts should extend above the roughness sub-layer into the inertial sub-layer and above. The heights of these layers vary with conditions and fetch (2 to 5 times the building height). For central urban areas with relatively tall buildings, the above requirements may be unrealistic for practical purposes. Therefore, the urban roughness sublayer should be investigated in more detail, specifically with regard to defining appropriate and practical guidelines for the siting of meteorological instruments in urban areas.

3. Available observations of urban heat fluxes demonstrate significant perturbation of surface energy balance partitioning compared to the rural surroundings.
4. The behaviour of turbulent flux profiles in the roughness sub-layer, due to high roughness elements requires more study, both in the field and with models.
5. The state of rural soil moisture, and therefore soil thermal admittance is a very important determinant of city heat island effects; the state of the surrounding countryside therefore must be considered in any such studies.
6. Horizontal inhomogeneity of the canopy means that the diffusivities for heat and water vapour differ, (i.e., $K_E \neq K_H$). This is because while all surfaces are sources of sensible heat, not all urban surfaces are sources of water vapour (Roth and Oke, 1995).
7. A number of European groups run meso-scale models with sub-models of fluxes for urban areas. These models are not operational yet, but advances are encouraging. Preliminary simulations indicate that the influence of the urban canopy, building energy flows and thermal properties, along with effective albedo reduction by radiative trapping between canyon walls is important and need to be explicitly modelled.
8. For applications in connection with dispersion modeling, often no detailed surface exchange parameterisation can (computationally) be afforded. As an alternative, a meteorological pre-processor that has been modified for urban surfaces (LUMPS) is available. Turbulent fluxes (and hence stability) obtained from this scheme apply to heights sufficiently far from the urban fabric. A detailed validation, especially using data from European cities, would complement already existing North American studies and is much encouraged.
9. Satellites can in principle be used to measure the urban surface energy balance, but there are significant issues concerning the ability to estimate the appropriate interface temperature.

References

Arnfield, A. J. and Grimmond, C. S.: 1998, 'An urban canyon energy budget model and its application to urban storage heat flux modelling', *Ener. Build.* **27**, 61–68.

Baklanov, A., Rasmussen, A., Fay, B., Berge, E. and Finardi, S.: 2001, 'Potential and shortcomings of NWP models in providing meteorological data for UAP forecasting', *Ext. abstract to the Third Urban Air Quality Conference*, Loutraki, Greece. CD-ROM, paper PL.4.1. (*Int. J. Water, Air and Soil Poll.*, accepted).

COST-710: 1998, 'Harmonisation of Pre-Processing of Meteorological Data for Atmospheric Dispersion Models, Final Report', European Commission, Report EUR 18195 EN.

COST-715: 2001, 'Surface Energy Balance in Urban Areas', *Extended Abstracts of an Expert Meeting. WG-2 COST Action 715*, Antwerp, Belgium, 12 April 2000. European Commission. Report EUR 19447.

Dupont, S., Guilloteau, E. and Mestayer, P. G.: 2000, 'Energy Balance and Surface Temperatures of Urban Quarters', *Proc. 3rd AMS Symposium on Urban Environment*, Davis, California, 14–18 August 2000, pp. 149–150.

Dupont, E., Menut, L., Carissimo, B., Pelon, J. and Flamant, P.: 1999, 'Comparison between the atmospheric boundary layer in Paris and its rural suburbs during the ECLAP experiment', *Atmos. Env.* **33**, 979–994.

Ellis, N. L. and Middleton, D. R.: 2000, 'Field Measurements and Modelling of Urban Meteorology in Birmingham, UK', *Proc. 3rd AMS Symposium on Urban Environment*, Davis, CA, American Meteorological Society, Boston, MA, 108–109.

Feigenwinter, C., Vogt, R. and Parlow, E.: 1999, 'Vertical structure of selected turbulence characteristics above an urban canopy', *Theoret. Appl. Climatol.* **62**, 51–63.

Fisher, B. E. A., Kukkonen, J., Schatzmann, M.: 2002, 'Meteorology applied to urban air pollution problems COST 715', *Sixth Int. Conf. On Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, October 11–14, 1999, Rouen, France, 10 p. *Int. J. Environment and Pollution* **16**, 560–569.

Grimmond, C. S. B. and Oke, T.R .: 1995, 'Comparison of heat fluxes from summertime observations in the suburbs of four North American cities', *J. Appl. Meteor.* **34**, 873–889.

Grimmond, C. S. B. and Oke, T. R.: 1999, 'Heat storage in urban areas: Local-scale observations and evaluation of a simple model', *J. Appl. Meteor.* **38**, 922–940.

Grimmond, C. S. B. and Oke, T. R.: 2000, 'A Local-Scale Urban Meteorological Pre-Processing Scheme (LUMPS)', *Proceedings of the COST 715 Workshop 'Preparation of Meteorological Input Data for Urban Site Studies'* (ed.: M. Schatzmann, J. Brechler, B. Fisher), Prague, Czech Republic, June 15, 2000, 73–83.

Grimmond, C. S. B. and Oke, T. R.: 2002, 'Turbulent heat fluxes in urban areas: Observations and local-scale urban meteorological parameterization scheme (LUMPS)', *J. Appl. Meteor.* **41**, 792–810.

Grimmond, C. S. B. and Souch, C.: 1994, 'Surface description for urban climate studies: a GIS based methodology', *Geocarto Int.* **9**, 47–59.

Grimmond, C. S. B., Cleugh, H. A. and Oke, T. R.: 1991, 'An objective urban heat storage model and its comparison with other schemes', *Atmos. Env.* **25B**, 311–326.

Grimmond, C. S. B., Souch, C. and Hubble, M.: 1996, 'The influence of tree cover on summertime energy balance fluxes, San Gabriel Valley, Los Angeles', *Clim. Res.* **6**, 45–57.

Holmer, B. and Eliasson, I.: 1999, 'Urban-rural vapour pressure differences and their role in the development of urban heat islands', *Int. J. Climatol.* **19**: 989–1009.

Holtslag, A. A. M. and Van Ulden, A. P.: 1983, 'A simple scheme for daytime estimates of the surface fluxes from routine weather data', *J. Appl. Meteor.* **22**, 517–529.

Kallos, G.: 1998, 'Regional/Mesoscale Models', *Urban Air Pollution – European Aspects* (Part. IV., Chap. 11.), Kluwer Acad. Publ., Dordrecht, Boston, London, pp. 177–196.

Klysik, K.: 1996, 'Spatial and seasonal distribution of anthropogenic heat emissions in Lodz, Poland', *Atmos. Env.* **30**, 3397–3404.

Lemonsu, A. and Masson, V.: 2001, 'Simulation of a summer urban breeze over Paris', *Boundary-Layer Meteorol.* **104**, 463–490.

Martilli, A.: 2001, 'Development of an Urban Turbulence Parameterisation for Mesoscale Atmospheric Models', *Swiss Federal Institute of Technology Lausanne (EPFL)*, Dissertation 2445, 176 pp.

Martilli, A., Clappier, A. and Rotach, M. W.: 2002, 'An urban surface exchange parameterisation for mesoscale models', *Boundary-Layer Meteorol.* **104**, 261–304.

Masson, V.: 2000, 'A physically-based scheme for the urban energy budget in atmospheric models', *Boundary-Layer Meteorol.* **94**, 357–397.

Mestayer, P. G.: 1998, 'Urban Scale Models', *Urban Air Pollution – European Aspects* (Part. IV., Chap. 11.), Kluwer Acad. Public., Dordrecht, Boston, London, pp. 197–222.

Noilhan, J. and Planton, S.: 1989, 'A simple parameterization of the land surface processes for meteorological models', *Mon. Wea. Rev.* **117**, 536–549.

Oke, T. R.: 1997, 'Urban environments', in W. G. Bailey, T. R. Oke and W. R. Rouse (eds), *The Surface Climates of Canada*, McGill-Queen's University Press, Montréal, 303–327.

Oke, T. R., Grimmond, C. S. B. and Spronken-Smith, R.: 1998, 'On the confounding role of rural wetness in assessing urban effects on climate', *Preprints of the AMS Second Urban Environment Symposium*, 59–62.

Oke, T. R., Spronken-Smith, R., Jauregui, E. and Grimmond, C. S. B.: 1999, 'Recent energy balance observations in Mexico City', *Atmos. Env.* **33**, 3919–3930.

Piringer, M., Baklanov, A., De Ridder, K., Ferreira, J., Joffre, S., Karppinen, A., Mestayer, P., Middleton, D., Tombrou, M., Vogt, R.: 2001, 'The Surface Energy Budget and the Mixing Height in Urban Areas: Status Report of Working Group 2 of COST-Action 715', *Ext. abstract to the Third Urban Air Quality Conference*, Loutraki, Greece. CD-ROM, paper Pl 1.3.

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

Rotach, M. W., Mitev, V., Vogt, R., Clappier, A., Richner, H., Ruffieux, D.: 2001, 'BUBBLE – Current Status of the Experiment and Planned Investigation/Evaluation of the Urban Mixing Height', *Proc. COST-Action 715 Workshop on the Mixing Height and Inversions in Urban Areas*, Toulouse, 3–4 Oct. 2001 (submitted).

Roth, M. and Oke, T. R.: 1995, 'Relative efficiencies of turbulent transfer of heat, mass and momentum over a patchy urban surface', *J. Atmos. Sci.* **52**, 1864–1874

Schmid, H. P.: 1994, 'Source areas for scalars and scalar fluxes', *Boundary-Layer Meteorol.* **67**, 293–318.

Schmid, H. P.: 1997, 'Experimental design for flux measurements: matching scales of observations and fluxes', *Agr. Forest Meteorol.* **87**, 179–200.

Spronken-Smith, R. A.: 1998, 'Comparison of Summer and Wintertime Energy Fluxes over a Suburban Neighborhood', *Preprints of the Second Urban Environment Symposium*, Christchurch, New Zealand, American Meteorological Society, pp. 243–246.

Taha, H. and Bornstein, R.: 2000, 'Urbanization of meteorological models and implications on simulated heat islands and air quality', in R. J. de Dear, J. D. Kalma, T. R. Oke and A. Auliciems (eds), *Biometeorology and Urban Climatology at the Turn of the Millenium*. Selected Papers from the Conference ICB-ICUC '99, Sydney, Australia, 8–12 Nov. 1999, pp. 431–435.

Voogt, J. A. and Grimmond, C. S. B.: 2000, 'Modeling surface sensible heat flux using surface radiative temperatures in a simple urban area', *J. Appl. Meteor.* **39**, 1679–1699.

Zhang, X., Aono, Y., Monji, N.: 1998, 'Spatial variability of urban surface heat fluxes estimated from LANDSAT TM data under summer and winter conditions', *J. Agric. Meteor.* **54**, 1–11.