Meteorology applied to urban air pollution problems Draft Progress Report April 2002

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One of the meteorological projects under COST concerns “Meteorology applied to urban air pollution problems, COST 715”. COST "European Co-operation in the Field of Scientific and Technical Research" is a framework for international research and development co-operation, encouraging the co-ordination, but not the funding, of national research at a European level. COST includes member states countries from the European Union, and a number of other European countries.

The essential problem of COST 715 is the development of methodologies for dealing with widely varying scales and averaging over heterogeneous surfaces. It has been concerned with testing approaches, which may have more general application in meteorology and other branches of science.

The problem

Why is the urban meteorology problem so difficult? We discuss the dynamics of urban flow and the surface energy balance separately.

Urban dynamics

In contrast to rural areas, the urban boundary layer is more complex as a roughness sublayer of much larger vertical extension than found in typical rural areas occupies the first tens of metres above the surface, with the remainder of the surface layer (the inertial sublayer) aloft. The roughness sublayer includes the urban canopy layer, which is composed of individual street canyons and other roughness elements (see Fig. 1). The Monin-Obukhov similarity theory is not valid within the roughness sublayer and turbulent fluxes of momentum, energy, moisture and pollutants are height dependent. (One of the aims of COST 715 Working Group 1 is to try to improve on similarity theory.)

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. (This is one of the aims of Working Group 4.)

Only in the surface layer aloft, contributions from individual surface roughness elements are blended into possibly representative averages. In mesoscale models (which are the main tool by which episodes of high pollution in urban areas are predicted as shown by a review of European approaches conducted by Working Group 3) with scale of order 1km, the main influence is to increase the roughness described by a roughness length of 1m. This is defined by taking a logarithmic wind profile measured in the inertial sublayer, above the roughness sublayer. In an urban area the building density changes, and the urban boundary layer evolves (see Fig 2). It is not obvious that a local roughness length can be defined. In addition pollution transport within the roughness sublayer is complex, but needs to be described to assess human exposure.

Urban surface heat flux

The surface energy balance is the key component of any model aiming to simulate dynamical and thermodynamical patterns above the surface (Fig3). In its simplest one-dimensional form, it can be written as:

$$Q^* = H + LE + G$$

where Q* is the net all-wave radiation, 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. As with the urban roughness length, the variability in typical urban structure means that the terms on the right hand side of the heat balance equation vary within the urban area as the surface material varies.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 in this equation 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 and green space), city surroundings, and prevailing meteorological conditions.

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. The focus of Working Group 2 is on surface flux measurements in ongoing recent European experiments. This is explicitly concerned with testing practical schemes for estimating surface heat fluxes. Therefore, three new field campaigns, in Basle, Marseilles and Birmingham, have been initiated, to more explicitly study processes in European cities. Of particular difficulty is the heat storage term so that the main atmospheric components are not in equilibrium (Figure 3). Assessing methods to determine or model the height of the urban boundary layer, which is dependent on the surface heat fluxes, is the second task of Working Group 2.

In recent years, a number of boundary-layer parameterisation schemes have been developed to estimate net radiation, sensible heat flux and other urban boundary layer parameters from hourly standard meteorological data. An urban pre-processor 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. LUMPS has been shown to perform well when evaluated using data from North American cities. The scheme is now to be evaluated with data collected in European cities, notably Basle, Birmingham, Graz and Marseilles (funding constraints have slowed progress).

Working Group 4 has reviewed current methods of obtaining urban meteorological data in Europe for pollution applications, and has shown commonly applied methods not to be well justified.

Reduction in complexity

This project is an example of how to deal with complexity. Can one define characteristics of an urban area in terms of a few parameters? For example the basic premise of the LUMPS scheme is that heat fluxes can be modelled using net all-wave radiation, simple information on surface cover (area of vegetation, buildings and impervious materials), surface geometry (surface element roughness and density) and standard weather observations (air temperature, humidity, wind speed and pressure). The method has limited data requirements, yet is sophisticated enough to predict the spatial and temporal variability known to occur within urban areas. Empirical data to test the method in various urban areas is essential.

The aim of this and other methods is to reduce the complexity of the urban surface heat flux with a minimum increase in uncertainty. The general approach to reducing complexity is to divide systems into sub-systems and this has been applied to the treatment of urban meteorology.

Of course there are situations where it does not apply. Since the method is a one-dimensional energy balance, it is unlikely to perform well in areas where there is significant spatial variability in land cover or surface geometry e.g. at the urban-rural edge. As with other boundary layer schemes it needs to be tested over the full range of atmospheric conditions to which it will be applied e.g. tests at moderate latitudes do not apply to extreme weather conditions.

Other simplifications

Simplification methods have also been applied to the aerodynamic properties of urban areas. The roughness length and zero plane displacement are the two main properties influencing the flow. Two broad methods have been proposed: the geometric method that uses parameters which broadly describe the geometric form, or micrometeorological methods that use observations of wind and turbulence to derive parameters from the logarithmic wind profile. The later method requires tall towers and instrumentation. Within COST 715, data from the 300m Hamburg radio tower and the 327m Helsinki (Kivenlahti) radio tower have been considered. Sodar and meteorological masts have been used to derive the roughness length and displacement length for Lille (Wrobleski, Coppalle and Dupont, 2001). The former method require knowledge of certain average geometric factors describing urban roughness elements, such as the average height of roughness elements (buildings or trees), fractional plan area, fractional frontal area etc. Relationships can be derived from idealised flows over simplified arrays in wind tunnels, but need to be tested in real situations. One choice of relationship may not apply universally (Grimmond and Oke, 1999), but they would be of use in characterising urban areas for the urban pollution calculations routinely needed by air quality management planners, when the uncertainty in other factors may be greater. A classification of effective terrain roughness is often valuable in working situations (Davenport, Grimmond, Oke and Wieringa, 2000). It should be possible to associate aerodynamic parameters with each of the urban meteorological sites identified in the COST 715 inventory of urban meteorological stations.

The air quality modeller or planner needs to know a number of key parameters. Some are familiar, such as roughness length, zero plane displacement, surface heat flux, boundary layer height. Some may be derived from routine measurements, some from improved routine urban measurements and some from formulae based on idealised conditions (usually some scaling rule). There are other parameters, such as the velocity in the street (within the urban canopy u_C), the exchange velocity w_E between the street and the flow above, the canopy length Lc, proportional to distance required for the flow to adjust to a step change in roughness and inversely proportional to the canopy drag (Figure 2). Britter (private communication) has suggested that $u_C/u_* = \sqrt{2/C_D\lambda_f}$ where C_D is the drag coefficient and λ_f is the fractional frontal area of roughness elements, and $w_E/u_* = u_*/(u_{ref} - u_C)$. u_{ref} is the wind speed 2.5 (?) times the height of buildings. This is at the blending height between the roughness sublayer and the inertial sublayer according to some definitions (Grimmond and Oke, 1999). It should represent the minimum height at which the observations are representative of the integrated surface rather than individual roughness elements. It should also depend on the horizontal separation of roughness elements.

The blending height is another useful simplification above which the effective friction velocity and roughness lengths for a surface with inhomogeneous surface characteristics (spatially varying roughness or surface heat flux) can be defined. Associated with the blending height are aggregation formulae, or weighted averages, of the surface characteristics. For the regional heat flux a simple weighted average over the subareas of patches with different characteristics is used (Gryning and Batchvarova, 2001). For the effective roughness height a more complex averaging is needed. Such methods need to be tested, but are clearly essential for numerical models, in which surface characteristics are averaged over some grid square within which some effective exchange of heat or momentum is visualised to take place. Typically the blending height is of the order of 1/100 of the horizontal scale of the meso-scale model. For a 1000m grid length, the blending height is of the order of 10 m. In some cases the blending height is taken to be the lowest model level. Issues regarding blending height and aggregation, or the use of the tile approach, are important for hydrological models and climate models, or any model which averages values over a discrete grid.

Evaluation of approaches

In weak wind conditions, the influence of strong variations of surface characteristics may not be confined to a shallow fraction of the boundary layer, limiting the value of the blending height approach. When applicable, the blended surface heat flux is the appropriate quantity to use in estimating the height of the urban boundary (Baklanov, 2001a). The literature is full of formulae (e.g. Baklanov (2001b) for mixing height under stable conditions). The air pollution modeller needs advice on which, if any, to use based on operational reasons and this is part of COST 715's role.

There are other features of urban areas for which there are at present no suggested practical formulae, for example on the relationship between the wind speed at a standard 10m height outside a city to the wind speed on a mast within the city. Experimental results have been reported e.g.

Roof-top wind (Leek U.K.) =0.63 (airport wind at 10m)
Urban wind at 32m (Lisbon)=0.65 (rural wind at 10m) + 1.24
Urban wind at 30m (Copenhagen)=0.51 (airport wind at 10m)

Even in the absence of a simplifying (scaling?) formula the allocation of cases to categories and developing a European data set would be valuable. Developing a methodology for this falls within COST 715's remit.

It should be obvious that the methods developed by Working Groups 1 and 2 have application in the practical methods considered by Working Groups 3 and 4. However it is recognised that in some cases no advice is currently available. It may be possible to point to alternative approaches. For example McNaughton and Brunet (2000) have questioned the validity of Monim-Obukhov similarity in the atmospheric boundary layer, and have surmised that coherent ejection/sweep structures can transport a large amount of heat and momentum. Belcher and Coceal (2002) introduce an additional spatial averaging term into the momentum equations within the inertial and roughness sublayers. Carissimo and Macdonald (2001) introduce effective drag, and turbulence terms to describe the averaged conservation equations within the urban canopy. Other methods have been reported by members of Working Groups and will be tested on the data sets available.

The existence of active Working Groups enables this to happen in an effective way. The final report will refer to published papers at various COST 715 Workshops. It will not reproduce these, but will attempt to evaluate the usefulness and range of applicability of the methods. Figure 4 shows that the activities of the Working Groups are closely interlinked.

Conclusions and Future Work

The key to success in this Action will be field measurements, taken during and continuing after the Action. However simplified methods will be an essential part in unravelling the uncertainty caused by urban complexity. Although research will continue, the success of the Action has been in identifying urban meteorological issues relating to urban pollution assessments. In addition for practical use, advice needs to be given on urban correction factors. It is the intention of COST 715 to provide such advice as the main outcome of its Action.

There is a need for the Working Groups representing the various areas of meteorology, which affect urban air quality, to be more closely integrated. Table 1 lists some of the parameters, or concepts, ideas on which need to be transferred between Working Groups. It is suggested that the following key questions need to be addressed by the Working Groups:

(1) What should there be interactions between the topics covered by the Working Groups?

(2) For each interaction what are the concepts, or parameters, which are common to both areas?

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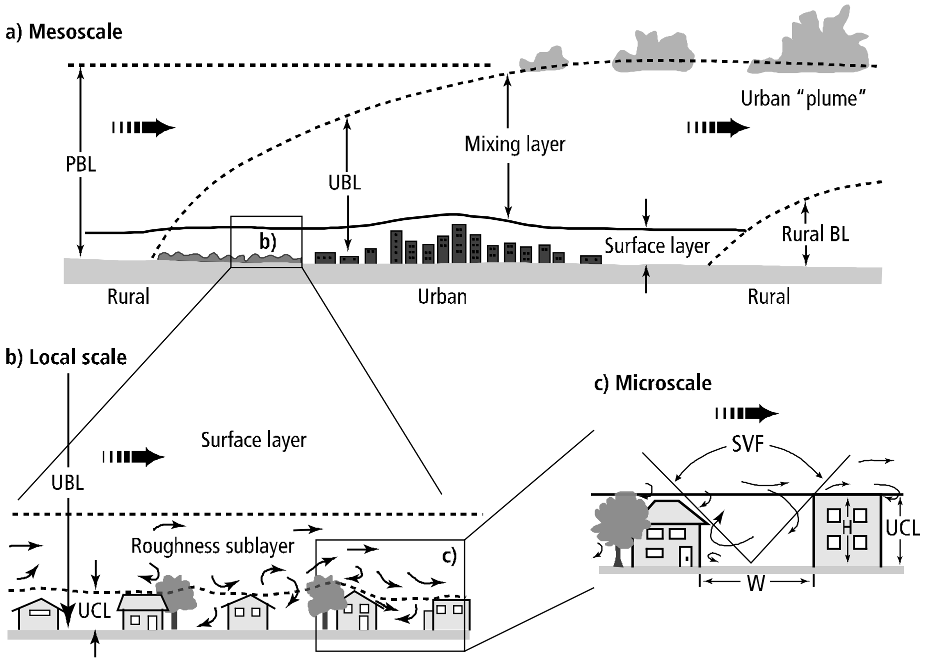
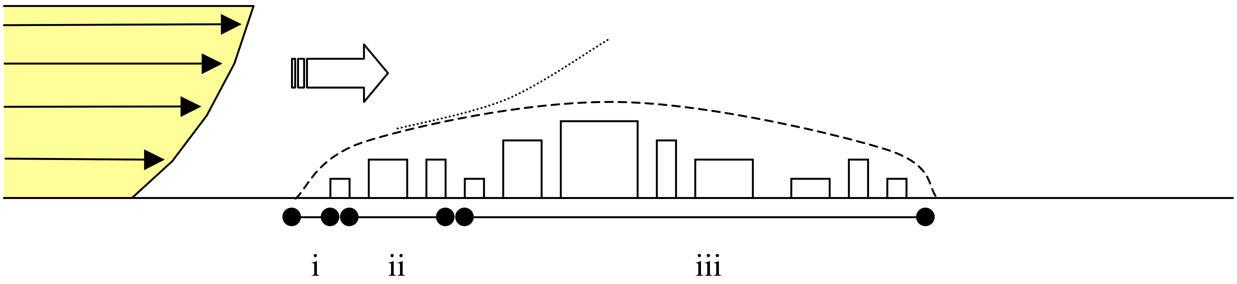
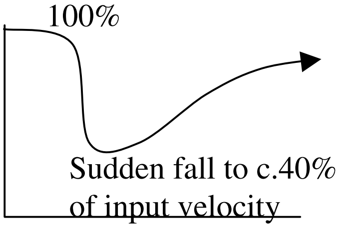


Figure 1 Schematic of the urban boundary layer including its vertical layers and scales. [Oke, 1997]

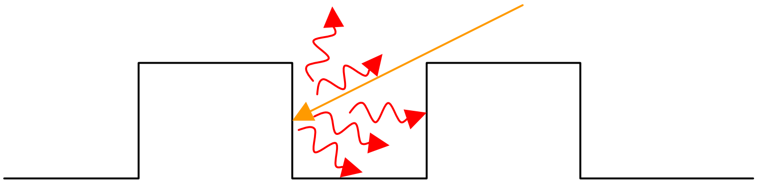
Figure 2 Interaction of the rural boundary layer as it impacts on to the urban area.





i - Impact region – sudden deceleration with shear forces and deflection
ii – Canopy adjustment region – flow adjusts through and over canopy
iii – Roughness change region

Figure 3 Energy balance within street canyons and its implications on the heat island effect, and exchange between air in streets and the air above roof tops



Rate of ventilation or exchange w_E from the street canyon to urban air above roofs

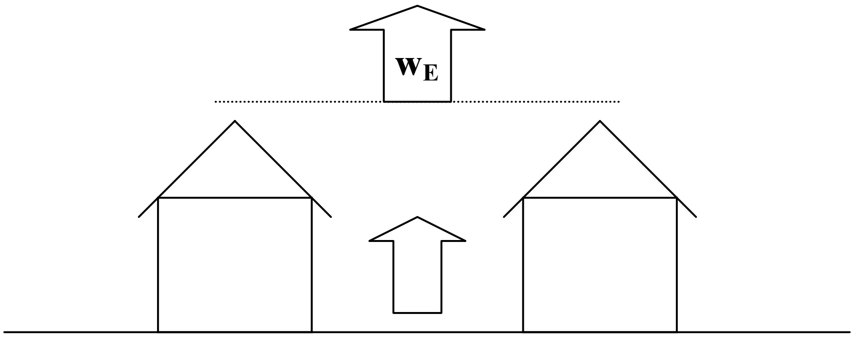


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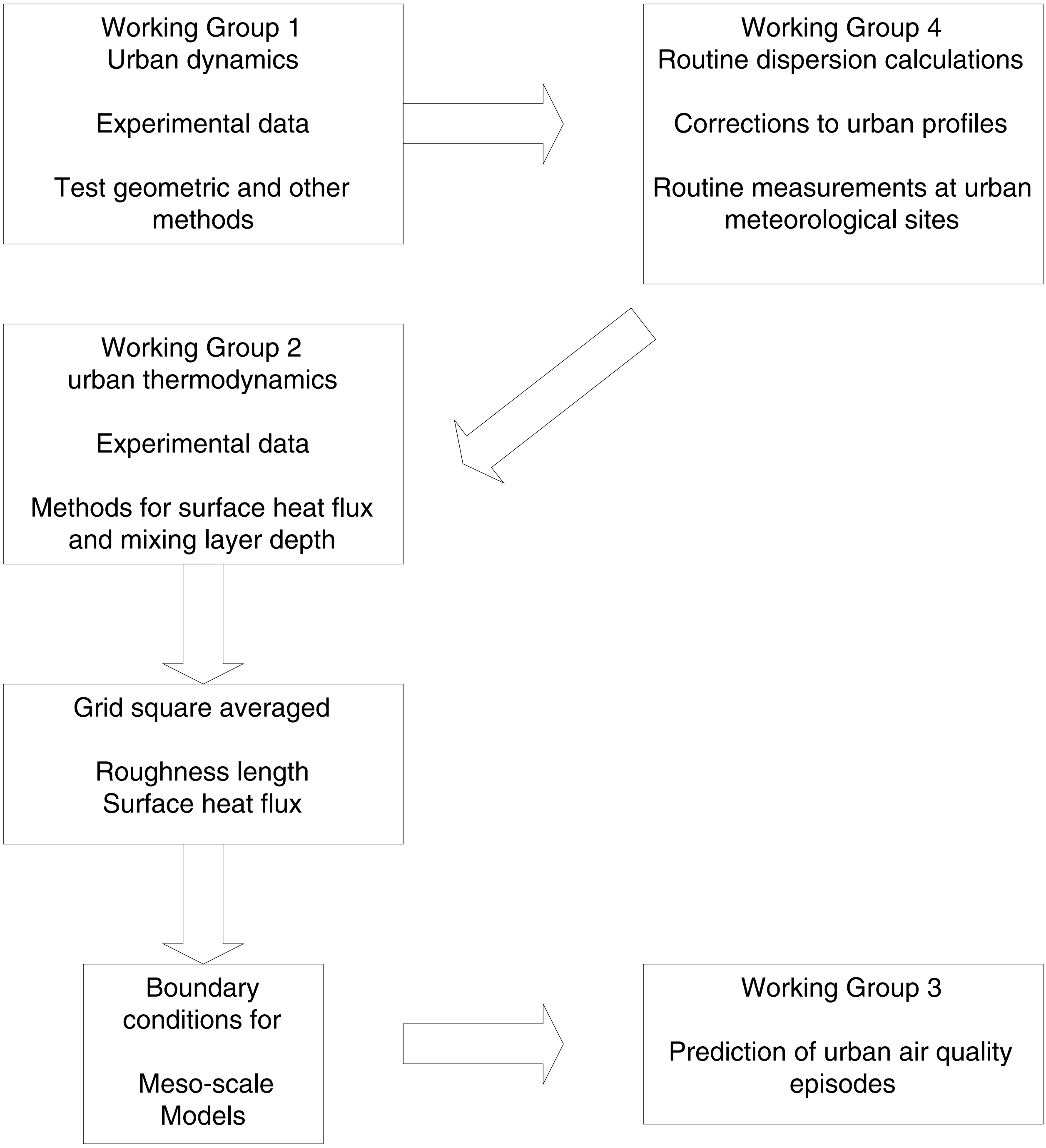
Figure 4 Relationships between Working Groups in COST 715



Appendix 1 Assessment of progress made towards completing the aims of COST 715.

Some of the key parameters which need to be explored in order to improve our understanding of urban meteorology are:

Parameter		Typical dependencies
u_c	Wind in urban canopy	λ_f fractional frontal area of roughness elements
L_c	Canopy length scale	
w_E	Exchange velocity	
u_{ref}	Wind at reference height	λ_f fractional frontal area of roughness elements
h_{ref}	Blending height	Aggregation method
$u_{rural} \rightarrow u_{urban}$	Transfer function	
h_{urban}	Height of urban boundary layer	
z_0	Roughness length	Average height of buildings

Appendix 1 The following table is a basis for assessing progress.

Table A1 Progress made towards achieving the aims of COST 715

Activity	Measure of progress
Working Group 1 Urban dynamics Experiments Theoretical advances	
Working Group 2 Urban dynamics Experiments Advances in prediction of surface heat flux, Mixing height	
Working Group 3 Episodes Quality of prediction methods Use of COST 715 results	
Working Group 4 Applications Use of routine met data Recommendations on siting	