THE URBAN SURFACE ENERGY BUDGET AND THE MIXING HEIGHT: SOME RESULTS OF RECENT EUROPEAN EXPERIMENTS STIMULATED BY THE COST – ACTION 715

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INTRODUCTION

During the last years, some major European campaigns for urban meteorology have been carried out and are partly still ongoing, which provide new data sets and thus new insight into urban modifications of meteorological fluxes and parameters. These campaigns have to a large extent been stimulated by the joint European project COST-715 (Meteorology Applied to Urban Air Pollution Problems), its Working Group 2 (WG2) addressing the specific problems of determining and simulating the surface energy balance and the mixing height which are critical components in many algorithms and/or numerical models.

The surface energy budget with the surface temperature and heat fluxes determine the hydrostatic stability conditions in the lower atmosphere, which regulate the mixing of pollutants. It is essential, both as input and boundary conditions, in advanced air pollution dispersion models. However, usually the surface energy balance or its components are not directly measured at meteorological stations.

Building and ground-covering materials have radiative properties, such as albedo (fraction reflected) and emissivity, different from natural grounds and vegetation while the vertical structure of spaces between buildings provides shade and radiation trapping. In addition, they have not only horizontal but also vertical and/or slanted orientations, which strongly alter the radiative transfers and energy budget. Heat flux to or from the ground changes with surface material: concrete, tarmac, soil etc. Anthropogenic energy use can be a noticeable fraction of annual solar input and thus influences the local stability of the atmosphere.

The atmospheric boundary layer (ABL) is the layer near the surface in which heat, momentum and moisture are exchanged between the Earth and the atmosphere. The turbulent properties of this layer (diffusivity, mixing, transport) will rule whether pollutants are dispersed and diluted or whether they build up and led to pollution episodes. Thus, the ABL height or the mixing height (MH) will determine the volume available for pollutant dispersion and depends on basic meteorological parameters, surface turbulent fluxes and physiographic parameters, and follows a diurnal cycle. MH cannot be observed directly by standard measurements, so that it must be parameterised or indirectly estimated from profile measurements or simulations.

During the last decades, several experimental studies of the ABL were realised for urban areas (Baklanov, 2002). COST-715 has analysed the specificities of the urban MH and verified different methods for estimating the MH against measurements (remote sensing devices such as wind profiler, sodar, aerosol backscatter lidar, or ceilometer and diagnostic evaluation methods to radiosonde temperature, humidity, and wind profiles) for several types of urban areas. Additionally, COST-715 performed some statistical surveys of the urban ABL as to its primary characteristics (e.g., height, inversion strength) and behaviour (e.g., growth and extent).

COST-715 (2002) summarised knowledge of the urban surface energy balance (SEB) available at mid-term of the COST-Action. A more complete review of the problem together with analyses of recent experimental data can be found in the report by Piringer et al. (2004). More extended discussions of COST-715 MH results can be found in Baklanov et al. (2004) and in Piringer et al. (2004). In the following, representative examples available from these COST-715 activities will be briefly shown, and finally recommendations for future activities will be given.

EXAMPLE 1: THE URBAN SURFACE ENERGY BALANCE

During the major Basel Urban Boundary Layer Experiment BUBBLE, three urban sites provided turbulent flux densities and radiation data over dense urban surfaces. Together with a suburban site and three rural reference sites, this network allows the simultaneous comparison of the urban, suburban, and rural energy balance partitioning in a Central European city during a summertime period of one month (Figure 1). The curves represent the average diurnal course including all weather conditions from clear-sky to completely overcast days. The increasing importance of the storage heat flux as one goes towards the city centre, well-known from North-American cities (Grimmond & Oke, 2002), is thus also a typical feature of a European city.

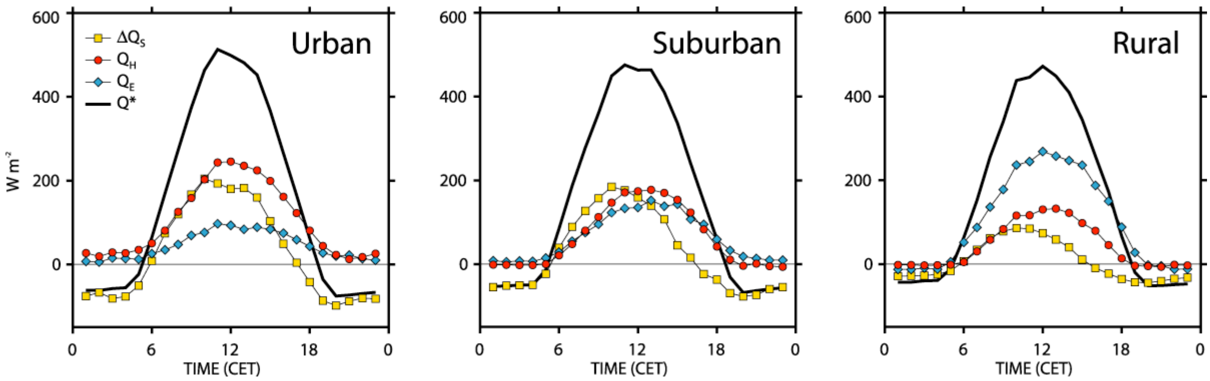

Figure 1: Ensemble diurnal courses of the energy balance at three sites during BUBBLE: average days for the IOP from June 10 to July 10, 2002 (including all sky conditions) of an urban site (Basel-Sperstrasse), a suburban site (Allschwil), and a rural site (Village-Neuf) (modified after Christen et al., 2003).

In contrast to rural surfaces, where the nocturnal sensible heat flux Q_H is directed towards the surface over urban areas both turbulent flux densities transport energy away from the surface in the city centre of Basel. Long-term measurements between 1994 and 2002 at the tower "Basel-Spalenring" show the observed nocturnal turbulent fluxes to be directed upwards throughout the year (Christen and Vogt, 2004).

EXAMPLE 2: THE URBAN MIXING HEIGHT

The MH is often higher in urban areas than in the rural case. This is illustrated for Athens (Fig. 2), using two versions of the Penn State/NCAR Mesoscale Model MM5 (Anthes et al., 1978). The MM5 model was applied (1) in its original version with the high resolution non-local NCEP MRF (National Center for Environmental Prediction Medium Range Forecast Model) ABL scheme. This scheme is based on the Troen and Mahrt (1986) representation for countergradients and K-profile in the well-mixed CBL (Hong et al., 1996). Urban areas are represented as a bare soil formulation with different classification of surface characteristics and physical parameters, such as roughness length, albedo etc. The second version (2) uses a modified ("urbanized") version of MM5 whereby urban features were introduced both in the thermal and the dynamical part (Dandou et al., 2004). In the MM5 model, during convective conditions the MH is equated to the level acting as a lid to rising thermals (parcel method approach), while for stable and neutral conditions, it is assumed to coincide with the maximum wind speed. In particular, the urban heat storage according to the Objective Hysterisis Model (OHM) of Grimmond et al. (1991) was incorporated into the model. Also, the anthropogenic heat effects for Athens were considered following Taha (1998).

Figure 2 demonstrates the diurnal variation of the MH at the National Observatory of Athens (NOA) station in the city center (left) and for the rural station Spata (right), produced by the original MM5/MRF model (dark blue line), the urban area replaced by a dry cropland and pasture area (orange line) and the modified MM5/MRF model (green line) on 14.09.1994. The modified version of MM5, which includes some urban effects, increases the MH for the nocturnal conditions (due to the additional heat flux) and changes the time dynamics of the day-time MH (due to the storage flux) for the urban area, but does not considerably affect the values of the MH for the non-urban site.

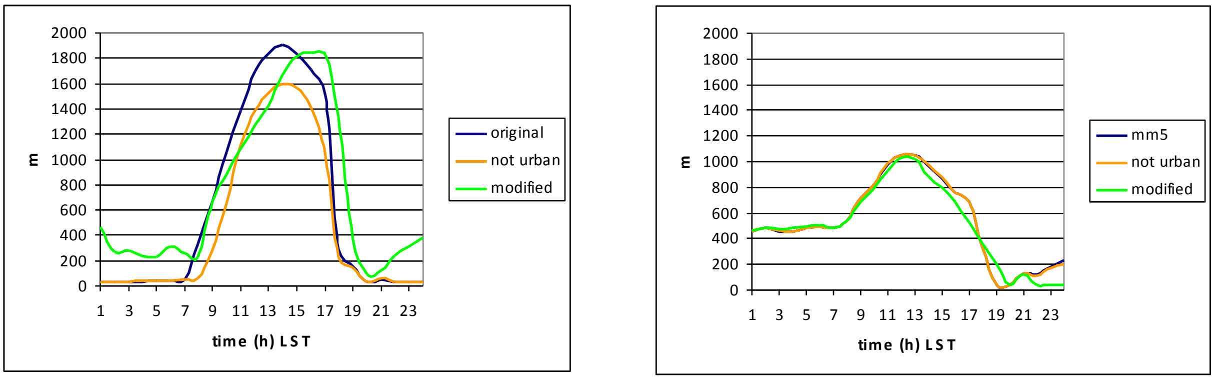

Figure 2: The diurnal variation of the mixing height (m) at the NOA station in the city center (left) and the rural station Spata (right), produced by the original MM5/MRF model (dark blue line), the urban area replaced by a dry cropland and pasture area (orange line) and the modified MM5/MRF model (green line) on 14.9.1994.

RECOMMENDATIONS AND CONCLUSIONS

The main recommendations and conclusions from experimental and numerical studies concerning the urban surface energy balance undertaken by WG 2 members are:

1. 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.

2. Available observations of urban heat fluxes demonstrate significant perturbation of surface energy balance partitioning compared to the rural surroundings. In particular, the convective sensible heat flux remains positive throughout the night, sustained by large releases of heat stored in the urban fabric from the previous day. As expected, given the lack of vegetation cover at most urban sites, the latent heat fluxes are small, and the Bowen ratios therefore larger than 1.
3. 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 very 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.
4. For applications in connection with dispersion modelling, generally, no detailed surface exchange parameterisation can (computationally) be afforded. As an alternative, meteorological pre-processors that have been modified for urban surfaces are increasingly available. Turbulent fluxes (and hence stability) obtained from these schemes apply to heights sufficiently far from the urban fabric. Further detailed validations, especially using data from European cities, would complement already existing North American studies and are much encouraged.

With respect to MH estimation, the following is recommended for urban areas:

1. For estimation of the daytime MH, applying standard rural methods is more acceptable than for the nocturnal MH, provided they allow for the urban heat storage as well as changed surface characteristics.
2. For the convective UBL the simple *slab models* (e.g., Gryning and Batchvarova, 2001) were found to perform quite well.
3. The formation of the nocturnal UBL occurs in a counteraction with the negative 'non-urban' surface heat fluxes and positive anthropogenic/urban heat fluxes, so the applicability of standard methods for the stably-stratified UBL estimation is less promising.
4. The determination of the stable UBL height needs further developments and verifications versus urban data. As a variant of the methods for stable MH estimation, the new Zilitinkevich *et al*. (2001) parameterisation can be suggested in combination with a prognostic equation for the horizontal advection and diffusion terms (Zilitinkevich and Baklanov, 2001).
5. Meso-meteorological and NWP models with modern high-order non-local turbulence closures give promising results (especially for the convective UBL), however currently the urban effects in such models are not included or included with great simplifications (Baklanov *et al.*, 2002).

More specific definitions of the MH for urban areas and adapted for various empirical devices is needed. Though useful background information was provided by the COST-710 Action, however, also the horizontal inhomogeneity and the vertical structure of the ABL over the urban area have to be taken into consideration. It is recommended that the MH is a useful concept in the context of simpler regulatory dispersion models, although not a very accurate one. Concerning numerical weather prediction (NWP) models, it is not so clear whether the MH is sufficiently accurate to be useful at the present stage of development of knowledge.

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