Urban roughness sublayers

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Interest in the meteorology of urban areas is being driven by diverse applications such as downscaling weather forecasts to urban areas, forecasting urban air quality, assessing the impact of buildings and design on the external microclimate and emergency response to hazardous releases. These diverse applications make great demands since the flows in urban areas are turbulent, the geometry complex and the thermodynamic forcing strong. This complexity is vividly summarised by the New Yorker's complaint that 'in New York the wind is always in your face'.

The aim of this talk is to give an outline of these problems, to suggest where progress is being made and finally to suggest some similarities and differences to other roughness sublayers.

The roughness elements in urban areas are largely composed of a 'canopy' of buildings separated by a network of streets, although most urban areas also have significant fractions of vegetated surface. The buildings are typically cuboidal in shape, so that the roughness elements are compact bluff bodies, of dimension d of the same order as the canopy height h. The large roughness elements distort the flow substantially, driving motions that are coherent across the depth of the urban canopy, with rapid lateral and vertical mixing across the depth of streets (e.g. Coceal et al 2006; Kanda 2004). In this way the urban canopy represents a very different parameter regime of canopies, with $d/h = 1$, when compared with vegetation canopies, composed of randomly distributed small scale roughness elements, with d/h very small.

Nevertheless a canopy model for urban areas can be formulated following the procedures developed for vegetation canopies: the differences identified above being absorbed into the momentum transfer by turbulent and dispersive motions. Such a model works well compared with wind tunnel measurements and observations of the flow through arrays of cubes (Coceal & Belcher 2005). Typically h is smaller than L_c, the length scale that characterises the distance required for the canopy drag to reduce the wind speed to zero. In contrast vegetation canopies typically have h and L_c of similar magnitude. This explains why the urban environment is on average windier than forests.

Urban areas typically have very heterogeneous distributions of building shapes and layout: suburban areas are typically less densely packed than central areas. For this reason an important process is the adjustment of the wind profile to changes in canopy density and height. A canopy approach has been shown to model well the mean winds in such an adjustment, and that winds within the canopy adjust within a distance of 3 L_c (Belcher et al 2003; Coceal & Belcher 2005) Whether patches of land use in urban areas are bigger or smaller than $3L_c$ therefore determines whether or not the urban winds can be thought of as adjusted or continually adjusting.

The open structure of the urban canopy, with cuboidal roughness elements, has important implications for the surface energy balance. Downwelling radiation penetrates to the ground and building surfaces, with well defined shadowed regions. The large-scale coherent motions forced by the roughness elements also mediate transport of heat from the urban surface into the boundary layer aloft (e.g. Masson 2006; Harman & Belcher 2006).

Finally the large scale motions associated with the roughness elements are also the key to understanding dispersion in urban areas. In the near field the local motions forced by the local geometry control the dispersion. Despite this complexity there is evidence gathered from a range of field experiments that the concentration on the centreline of the plume decays as an inverse square of the distance from the source (Belcher 2005). Finally, the implications of this result for distributed sources are beginning to be assessed.

The talk will conclude with an attempt(!) to identify the parameters that measure the differences between urban and vegetation canopies. Such a step is important as it can suggest ways of organising simulations and experiments of difference canopies.

References

Belcher S.E. 2005 Mixing and transport in urban areas. *Phil. Trans. Roy. Soc.* **363** 2947-2968

Belcher, S.E., Jerram, N. & Hunt, J.C.R. 2003 Adjustment of a turbulent boundary layer to a canopy of roughness elements. *J. Fluid Mech*., **488**, 369-398.

Coceal, O., Thomas, T.G., Castro, I.P. & Belcher, S.E. 2006 Numerical simulation of turbulent flow over cubic roughness arrays. To appear in *Boundary-Layer Met*

Coceal, O. & Belcher, S.E. 2005 Mean winds through an inhomogeneous urban canopy. *Boundary-Layer Met.* **115** 47-68

Harman, I.N. & Belcher, S.E. 2006 Interactions between the energy balance and boundary layer over urban areas. To appear in *Q. J. R. Meteorol. Soc*

Kanda M 2004 Large-eddy simulation of turbulent organized structures within and above explicitly resolved cube arrays *Boundary Layer Met* **112** 343

Masson V Urban surface modeling and the meso-scale impact of cities. *Theoretical Applied Climatol.* **84** 35-45