Flow, Turbulence and Transport in Complex Terrain Airsheds: From Meso to Street Canyon Scales

By

H.J.S. Fernando
Mechanical & Aerospace Engineering, Environmental Fluid Dynamics Program, Arizona State University

Recently the world's population demographics crossed an important threshold: more people now live in urban than in rural areas (UN 2006). Projections show that the urbanization continues at a significant rate of ~ 1.5% per year, presenting difficult challenges of providing basic needs such as clean air, water and security for urban dwellers while managing available resources efficiently. In this context, planners need to take into account the symbiotic workings of several urban systems -- for example, environmental, ecological, transportation, energy, material, social and political -- and their complex interplay. This paper concerns one of the relevant aspects, namely, the meteorology and turbulence in urban airsheds, which has important implications in air quality, energy usage and human comfort. Noting that more than ~ 70% of the world topography is in areas replete with mountains, valleys and escarpments, of particular interest will be the transport and dispersion of contaminants in urban areas located in complex terrain, which have profound implications in determining the quality of air and pathways of contaminant releases (and hence emergency response). Although it is generally sufficient to make air quality calculations on scales on the order of neighborhood scales (~ a few hundreds of meters to km scales), calculations of contaminant dispersion in downtown areas (e.g. Central Business Districts - CBDs) for emergency response need to be on a much smaller scale, paying attention to the details of the building clusters and roadway canyons within. Therefore, a successful modeling system ought to cascade from synoptic (~ 1000 km) to personnel (1 m) scales, incorporating the effects of terrain, vegetation and building canopies (Figure 1). One of the ways of parsing such continuum is to develop a nested modeling system, starting from a large scale model (say NCEP eta model) to a personal scale model. In the modeling system to be discussed, the CFD code developed by Baik et al. (2003) is used for small scales with the intermediate scales calculated using a mesoscale model (MM5).

Also of concern are physical processes of the atmospheric boundary layer in complex terrain, especially on how they can be parameterized as sub-grid scale processes in 'coarser' models. The challenges posed include parameterization of turbulence under stable periods, wherein turbulence is intermittent and strongly anisotropic and the near surface flow is disconnected from the layers aloft due to suppression of vertical diffusion. Some new features of the stable boundary layer in complex terrain have been identified using data from the VTMX program conducted in October 2000 in Salt Lake City, TRANSFLEX experiment in Phoenix as well as using laboratory and numerical experiments. The katabatic wind velocities along the slopes appear to be dominated by a balance between the buoyancy and (entrainment) shear stress gradients at low stabilities (expressed using a suitable Richardson number Ri) and inertia effects at high stabilities. Unlike stable boundary layer in flat terrain, the complex terrain boundary layer maintains weak but continuous turbulence, with turbulence levels oscillating out of phase with the local Richardson number. The mean flow also can show oscillations with a frequency close to the critical internal waves on a slope, thus facilitating production of turbulence over the slope. Direct measurements of eddy diffusivities and flux Richardson number show a strong dependence on Ri. The eddy diffusivities so derived are incorporated into the MM5 mesoscale model (both the 3.7.3 and Urban Canopy versions), and improvements are noted with regard to nocturnal predictions (Lee et al. 2006). The transitions between nocturnal katabatic flow and daytime anabatic flows are also studied and interesting flow reversal mechanisms are noted during morning and evening transitions.

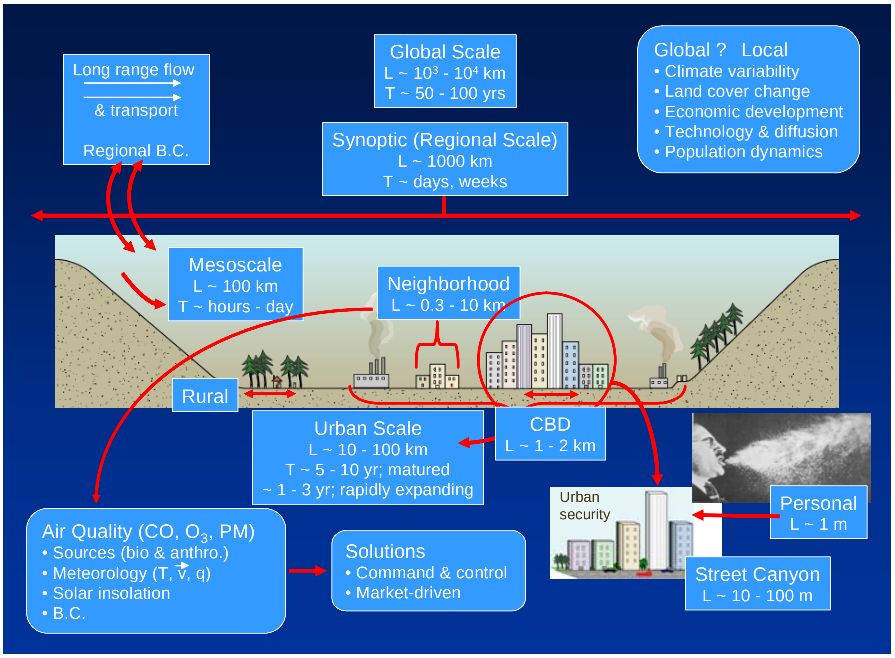

Figure 1: The different scales involved in a multi-scale urban modeling system. The goal is to predict small-scale motions, starting with regional (synoptic scale) flows. Synoptic flow provides boundary conditions for mesoscale flow models. Mesoscale flow is modified by large urban features to produce urban scale flow, which is again perturbed by land use inhomogeneities to produce neighborhood scale flow patterns; it is in this scale that typical meteorological and air quality predictions are made. Mesoscale models can be used down to the large-scale end of neighborhood scales. Computational fluid dynamics models can be nested with mesoscale models to predict the smaller central business district (CBD) scale and personal scale flows.

How mesoscale flows interact with a central business district or urban canyons therein have also been studied using idealized (Mock Urban Setting Test – MUST) and real (Joint-Urban 2003) building configurations. On the theoretical front, using a control volume approach, a new building canopy velocity scale has been derived, which depends on the friction velocity and roughness height of the approach flow and morphological parameters of the canopy. The efficacy of this scaling is corroborated by the measurements. The new scaling appears to be robust and has general applicability to any canopy (after making certain adjustments). For example, in the context of complex canopies, turbulence and velocity profiles within the canopy are spatially changing, but once these profiles are determined through experimentation, they are valid for any flow velocity from a given direction. As such, the scale derived has direct applications for developing fast response dispersion models for cities. The new scale also offers the advantage of not requiring measurements within or above the canopy to educe the velocity scale, which is a drawback of available velocity parameterizations. In idealized experiments, the linear distortion model advanced by Belcher et al. (2003) was found to predict the streamwise spatial variation of the mean velocity well. The steepest flow variation was found to occur at the leading and trailing edges over a distance $2L_c$, where L_c is the adjustment length scale.

References:

Baik, J.J., Kim, J.J. and Fernando, H.J.S., *J. Applied Meteor.*, **42(11)**, 1636-1648, 2003.

Belcher, S. E., Jerram, N. & Hunt, J. C. R., *J. Fluid Mech.*, **488**, 369-398, 2003

Lee, S.M., Giori, W., Princevac, M. and Fernando, H.J.S., *Boun. Layer Meteor.*, DOI: 10.1007/s10546-005-9018-4, 2006.

United Nations Secretariat (Population Division of the Department of Economic and Social Affairs). *World Population Prospectus*, Revision, 2006.