Exascale Simulations of the Urban Atmospheric Boundary Layer for Understanding Urban Climate Change

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Improved turbulent flow simulations provided by Exascale systems can provide dramatic improvement to climate models, particularly in their treatment of energy/mass fluxes through the turbulent boundary layer. The DOE Office of Science has a long-standing interest in climate change as it relates to energy production and, through the Office of Biological and Environmental Research, has developed global climate models and deployed large-scale measurement systems to better understand the climate system and climate change. Recently, the BER climate modeling division launched the Accelerated Climate Modeling for Energy (ACME) program with climate model development focused on specific science questions, mission needs including climate impacts on energy infrastructure and performance on current and future Leadership Computing Facilities (ACME Program Plan, 2014).

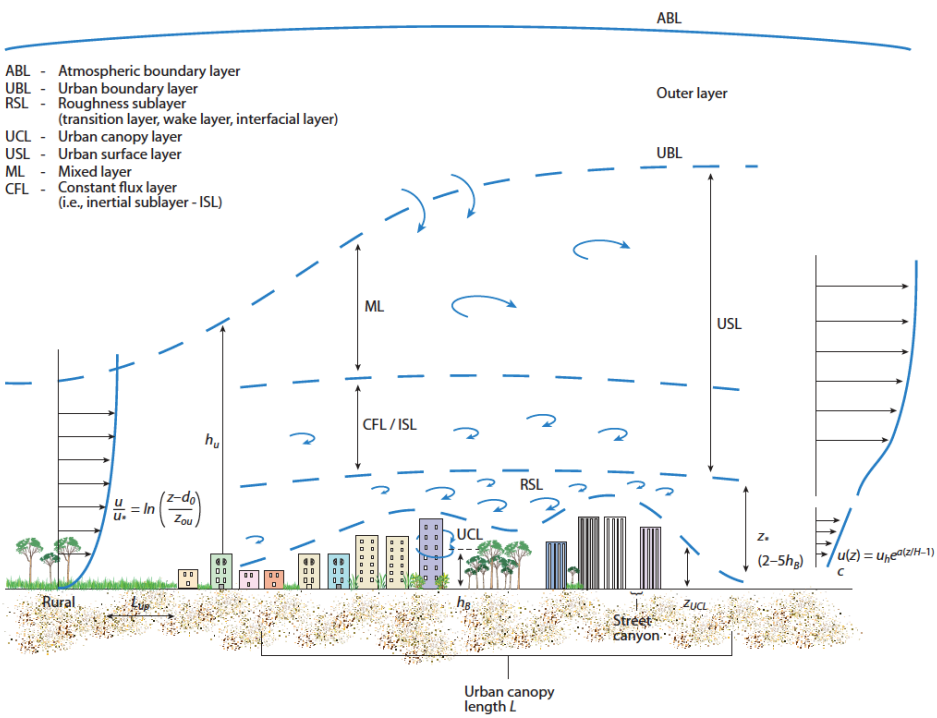

Figure 1. Illustration of elements of the Urban Boundary Layer. Taken from Fernando, 2010.

The global atmosphere and ocean both contain highly turbulent boundary layers that are important to overall flow of energy and constituents through the system. In today's state-of-the-art global and regional climate models, with horizontal resolutions of 50km-3km, boundary layers are highly parameterized. The arrival of Exascale computing will make it possible to begin simulating important regions of these boundary layers over complex geometries through Large Eddy Simulations[1]. BER has started a program to do LES of highly instrumented sites of the Atmospheric Radiation Measurement Program Climate Research Facility for improving the interplay between modeling and observations (ARM-ASR High Res. Modeling Report, 2014). But probably the region of the global boundary layer where Exascale can provide the most improvement is simulation of the urban atmospheric boundary layer (Figure 1).

[1] Direct Numerical Simulation of the atmospheric boundary layer is well beyond the reach of Exascale, requiring 10^{20} points by one estimate (Sorbjan, 2004).

With more and more people living in cities, understanding the controls and time varying behavior of the turbulent urban boundary layer (UBL) where they live becomes crucial to understanding the energy demands (and health and welfare) of most of the majority of the world's population. Better modeling of the UBL is also needed to provide climate change projections relevant to where people live. Because of their materials and geometry, cities do not have the same climate as the surrounding region (and micro-climates within cities can vary). The urban climate is not a simple linear addition to climate of the surrounding region but the result of a complex interaction between the regional climate and the urban boundary layer, which is itself made up of many sub-layers (See Figure 1). This difference is most famously seen in the Urban Heat Island, the tendency for cities to be warmer then their surroundings especially at night and in winter. Cities also impact precipitation and pollutants both within their borders and far outside. While more homogeneous regions of the atmospheric boundary layer can learn much from 100m-200m "Giga-LES" simulations (Moeng, 2009), the highly heterogeneous urban surface, containing parks, buildings, roads, canyons, and waterways, requires LES simulations over complex terrain with resolutions of 10m - 1m. Petascale is enough to perform 10m resolution simulations over a 10 km^2 domain with simple physics (Urban Large Eddy Simulation, 2014). Increasing to 1m resolution over 100 km^2 will require Exascale systems as well as highly scalable Large Eddy Simulation codes that allow for multiphysics (radiation and surface fluxes) and "backscatter" of energy. Exascale UBL simulations will be used to construct better low-order models for exascale weather and climate models. If the simulation speed of the LES model is high enough, operational urban weather forecasting would be possible but less ad-hoc and more mathematically sound coupling schemes will be required between the UBL LES and mesoscale model.

Exascale computing will provide the opportunity to model this important turbulent boundary layer with better established physics and with realistic geometry over large domains and possibly couple it to the larger mesoscale atmosphere, through a limited-area weather model or a regionally-refined global model like ACME. Such applications will provide new insights in how cities establish and maintain their internal climate and interact with the regional climate. These insights can be used in planning mitigation and adaptation strategies for the homes of billions of people.

References:

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