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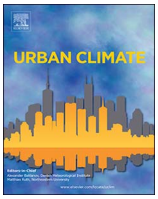

Urban surface effects on current and future climate

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ABSTRACT

This study aims to improve the representation of urban surfaces by implementing the Town Energy Balance (TEB) model for urban surface simulation, and the Canadian Land Surface Scheme (CLASS) for the simulation of natural surfaces. The study is conducted over eastern North American continent selected for its higher urban fractions. Seven sets of simulations with different initial and boundary conditions were conducted, and comparisons were made between urban and non-urban fractions using selected meteorological and energy variables such as temperature, surface albedo, and the turbulent latent and sensible heat fluxes. Results indicated that the realistic representation of urban surfaces by TEB resolved urban radiation and turbulent energy partitioning better than the bare soil formulation representation of urban regions by CLASS - an overall improvement of the mean land surface temperature by about 2 °C. The model also produced an annual mean surface temperature of up to a maximum of 4 °C higher over urban than non-urban regions in the current climate. Diurnal cycle of the urban heat island intensity is higher in the second half of the day than early mornings, and seasonally, the urban heat island intensity is higher in summer than in winter pertaining to maximum solar radiation during the day and in summer. Most of the incident solar radiation on urban surfaces are stored during the day and released at night causing thermal discomfort to urban residents. The urban canopy model TEB also simulated the strong correlation between the urban heat island effect and the turbulent energy fluxes relatively well. Furthermore, projections were made in to the future because the urban canopy model TEB has demonstrated sufficient performance over urban regions for the current climate. Projections show that urban land surfaces will get warmer by up to a maximum of 6 °C in the mid-century (1941–1970) and by up to a maximum of 13 °C at the end of 2100 under RCP8.5 emissions scenario. However, the projection of urban-rural heat island contrast is very low, but significant enough to warm urban regions to cause urban thermal discomfort. The differences in temperature and energy partitions between urban and rural regions show that the realistic representation of urban surfaces in climate models would improve the performance of NWP models. Therefore, climate models should take into account the effects of urban surfaces to appropriately investigate the impact of built-in urban environments on weather and climate, and in turn the effect of these weather and climate changes on urban community.

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1. Introduction

Land surface types, including urban regions, play an important role in the energy and water partitioning at the lower boundary of climate models. Unlike non-urban surfaces, urban land features have reduced vegetation and permeability that limit evapotranspiration and infiltration. Urban surfaces consist of asphalt road, concrete pavements and buildings which have lower albedo and higher absorptivity than rural regions. These urban surface properties modify the urban surface energy and water balance different from the natural surfaces. Urban geometry could also affect wind speed and direction creating urban canyons where air is confined in small compartments surrounded by building walls. This restricted air in between buildings reduces mixing of air creating favorable condition for pollutants to concentrate in small areas, which have an impact on health and infrastructure. The confined air would also reduce ventilation creating warmer spots within the urban canyon, which results in urban thermal discomfort. Not only the built surfaces, but also heat-generating fuel combustion machines (e.g., cars), heating, ventilation and air conditioning (HVAC) systems, and other anthropogenic processes affect local and large scale weather and climate processes (Landsberg, 1981).

Generally, the well known urban surface effects include, (1) higher temperature over urban regions compared to the adjoining non-urban regions - which is generally referred to as the Urban Heat Island (UHI) effect (Oke, 1982; Taha, 1997; Arnfield, 2003; Oleson et al., 2011; Huang et al., 2013; Ren et al., 2007; Huszar et al., 2014; Li et al., 2016b, 2017), (2) warm season thunderstorms causing flash flooding (Ntelekos et al., 2008; Bornstein and Lin, 2000), (3) enhancement of precipitation in the downwind part of the urban regions (Dixon and Mote, 2003; Mölders and Olson, 2004; Shepherd et al., 2002; Shepherd and Burian, 2003; Shepherd, 2005 and Shepherd, 2006), and (4) increase in the length of growing seasons (Shochat et al., 2006).

UHI is higher in city centers than in parks or lakes (Oke, 1987; Wang et al., 2015) and thermal energy may advect to rural areas towards the leeward side of the cities creating thermal inconvenience for urban and surrounding rural residents. It can also modify local weather and climate, affects air visibility, increases local air pollution, disturbs agriculture, increases water and energy usage, and impacts health (Hunt and Watkiss, 2011). It should also be noted that more than 54% of the world's population live in urban regions and projections indicate that this number will increase to 66% by 2050 (UN, 2014) and hence the majority of the world population experiences urban weather/climate. It is, therefore, important to have realistic representations of urban regions that would improve the prediction of urban weather and climate. On the other hand, the resolution of climate and weather models are increasing which is an advantage to include urban surface characteristics into climate models. Previous studies, such as ISBA (Interaction Soil-Biosphere-Atmosphere) with Town Energy Balance (TEB) model (Lemonsu and Masson, 2002; Lemonsu et al., 2006, Lemonsu et al., 2010) for cities of Paris, Marseille and Montreal, documented improvements in the prediction of temperature and snow compared to ISBA alone. The other examples are the application of Urban Canopy Parameterization (UCP) into MM5 climate model (Otte et al., 2004) for Philadelphia, Pennsylvania urban region, and the application of a Single Layer Urban Canopy Model (SLUCM) into the WRF model (Kusaka et al., 2009; Chen et al., 2011; Miao et al., 2009 and Lin et al., 2008) for Tokyo, Houston, Beijing and Taiwan, have shown significant differences between urban and rural weather and climate because of inclusion of the urban surfaces into the climate models. On a global scale, urban canopy models have demonstrated the impact of urban surfaces on exacerbating global warming (Oleson et al., 2011). Similarly, regional scale urban surface impact studies on surface thermal and hydrology: Li et al. (2016b) for continental United States and Huszar et al. (2014) for Europe obtained significant change in urban weather and climate due to urbanization. Simultaneously, counter to these urban impacts, adaptation studies using cool, vegetated and solar-panel roofs (e.g., Georgescu et al., 2014; Masson et al., 2014) demonstrated our capacity to adapt or mitigate these urban effects. Some cities have already started to implement these adaptation strategies and some are following steps.

Urban models generally follow four approaches to represent urban regions into climate models (Garuma, 2017): (a) by implementing building resolving models in which individual buildings and shapes are considered, which allows detailed examination of specific processes (radiative, or wind channeling effects for example) (e.g., Fernando et al., 2001), (b) representing urban surfaces based on the modified soil-vegetation transfer scheme often called the slab model (for example Dupont and Mestayer, 2006), (c) the Single Layer Urban Canopy Model (SLUCM) (e.g., Kusaka et al., 2001; Masson, 2000; Huszar et al., 2014 and Li et al., 2016a), and (d) the Multi Layer Urban Canopy Model (MLUCM)(e.g., Martilli et al., 2002 and Chen et al., 2010). The first method called building resolving Computational Fluid Dynamics (CFD) models are limited to local urbanization related channeling and comfort studies due to high computational cost and huge input data requirement. In the second approach called the modified soil/vegetation models or slab models, modifications are made to the heat capacities, thermal conductivities, surface albedo, roughness length, and moisture availability in soil-vegetation-transfer schemes to capture the urban land surface features relatively very well. This method treats urban geometry as a flat surface or similar to vegetation canopy with a large roughness length and/or small albedo (Brown, 2000; Wiernga, 1993; and Petersen, 1990). Hence, the assumption is that buildings and roads have the same temperature, and treats the building height and coverage ratio implicitly in the surface layer. Similar to the forest canopy schemes which divide the land surface fraction into forest and soil, the slab scheme divides the land surface into urban and non-urban fractions of which the former is treated as bare ground with modifications to the variables mentioned above. Such models were used during the early days when vegetation models were incorporated into the regional climate models as part of the land systems models. Further modifications to capture the heat storage by urban surfaces were made by using semi-empirical formulation for the heat storage flux - the Objective Hysteresis Model (HM) (Taha, 1999; Arnfield and Grimmond, 1998). However, most of the field observations indicated that the slab model approaches were unable to reproduce vertical turbulent fluxes in the urban roughness sublayer (Rotach, 1993). Furthermore, it does not take into account for the shadowing and radiation trapping effects of buildings in the energy balance computations. Therefore, such representation of urban surfaces is not sufficient to reproduce the large heat storage that is characteristic of urban surfaces because of the increased roughness length which favors the sensible heat flux than heat storage. The other problem is urban areas have different characteristics from soil/vegetation, hence an independent and detailed parameterization for urban surfaces is