GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L24401, doi:10.1029/2009GL041082, 2009

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Upstream urbanization exacerbates urban heat island effects

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Received 22 September 2009; revised 11 November 2009; accepted 17 November 2009; published 19 December 2009.

[1] Urban Heat Island (UHI) effects adversely impact weather, air quality, and climate. Previous studies have attributed UHI effects to localized, surface processes. Based on an observational and modeling study of an extreme UHI (heat wave) episode in the Baltimore metropolitan region, we find that upstream urbanization exacerbates UHI effects and that meteorological consequences of extra-urban development can cascade well downwind. Under southwesterly wind, Baltimore, MD, experienced higher peak surface temperatures and higher pollution concentrations than did the larger urban area of Washington, DC. Ultra-high resolution numerical simulations with National Land Cover Data (NLCD) of 2001 show a nonlocal, dynamical contribution to UHI effects; when the upstream urban area is replaced by natural vegetation (in the model) the UHI effects could be reduced by more than 25%. These findings suggest that judicious land-use and urban planning, especially in rapidly developing countries, could help alleviate UHI consequences including heat stress and smog. **Citation:** Zhang, D.-L., Y.-X. Shou, and R. R. Dickerson (2009), Upstream urbanization exacerbates urban heat island effects, *Geophys. Res. Lett.*, *36*, L24401, doi:10.1029/2009GL041082.

1. Introduction

[2] There is considerable evidence that changes in land use, especially urbanization, can change local climate [e.g., *Oke and Cleugh*, 1987; *Bornstein and Lin*, 2000; *Kalnay and Cai*, 2003; *Rotach et al.*, 2005; *Intergovernmental Panel on Climate Change*, 2007; *Grossman-Clarke et al.*, 2008]. Artificial surfaces increase runoff, inhibit evapotranspiration, and increase absorption of solar radiation, in addition to the heat directly emitted by fuel combustion and air conditioning. These urban heat island (UHI) effects lead to heat stress in the summer and increased concentrations of the air pollutants ozone [e.g., *Banta et al.*, 1998; *Cheng and Byun*, 2008; *Jacob and Winner*, 2009; *Bloomer et al.*, 2009] and fine particulate matter (PM2.5) or haze (see Figure S1).[3] The heat wave of 2003 is blamed for hundreds of excess deaths in England and thousands in other European countries [e.g., *Fischer et al.*, 2004; *Stedman*, 2004]. Herein we show that some heat wave events may be exacerbated by a nonlocal dynamical impact that cascades from upwind urbanization. This will be achieved by numerically simulating the extreme UHI (heat wave) episode of 7–10 July 2007 in the Mid-Atlantic region of the eastern United States. This UHI episode exhibited a peak (2-m) surface temperature (T_{sfc}) of 37.5°C with a maximum 8-h average ozone concentration of 125 ppb and a maximum 24-h average particulate matter concentration of 40 μg m^{-3} in Baltimore (the current standards are 75 ppb and 35 μg m^{-3}), but concentrations were 85 ppb and 29 μg m^{-3} in Washington where the peak T_{sfc} was 36.5°C. The contrast in UHI intensity with respect to the similar rural surroundings and synoptic conditions can not be explained by the city size and population [*Oke*, 1973], since the Baltimore metropolitan has a smaller urban area (and population) than that of Washington (see Figure 1).

2. Model Description

[3] In this study, we used a multi-nested version of the Weather Research and Forecast (WRF) model [*Skamarock et al.*, 2005] coupled with a sophisticated single-layer urban canopy model (UCM) [*Kusaka et al.*, 2001; *Chen and Dudhia*, 2001] at grid size as fine as 500 m. The quadruply nested domains of the coupled WRF-UCM model [*Chen and Dudhia*, 2001; *Kusaka et al.*, 2001; *Skamarock et al.*, 2005] have (x, y) dimensions of 181 × 151, 244 × 196, 280 × 247, and 349 × 349 with the grid length of 13.5, 4.5, 1.5, and 0.5 km, respectively. The innermost domain covers an area that is about 60% greater than that shown in Figure 1. All the domains use 30 layers in the vertical with 20 layers in the lowest 2 km in order to better resolve the evolution of the urban boundary layer (UBL).

[4] The model is initialized at 1200 UTC (or 0700 LST) 7 July 2007 and integrated for 72 h until 1200 UTC 10 July 2007. The model initial conditions and its outermost lateral boundary conditions as well as the soil moisture field are taken from the National Centers for Environmental Prediction's (NCEP) 1° resolution Final Global Analyses.

[5] The model physics schemes used include (1) a three-class microphysical parameterization [*Hong et al.*, 2004], (2) a boundary-layer parameterization [*Janjić*, 1994], (3) a land-surface parameterization in which four soil layers and one canopy with 24 land-use categories are incorporated [*Chen and Dudhia*, 2001], and (4) an ensemble cumulus scheme [*Grell and Devenyi*, 2002] as an additional procedure to treat convective instability for the first two coarsest resolution domains.

[6] The UCM [*Kusaka et al.*, 2001] includes 3-category 30-m resolution urban surfaces (i.e., low-intensity residential, high-intensity residential, and commercial/industrial/transportation), based on the U.S. Environmental Protection Agency's NLCD of Year 2001 - the most recent year for which high-resolution land-cover data are available. The dynamic and thermodynamic properties of roofs, walls and

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0094-8276/09/2009GL041082$05.00

[3]Auxiliary materials are available in the HTML. doi:10.1029/2009GL041082.

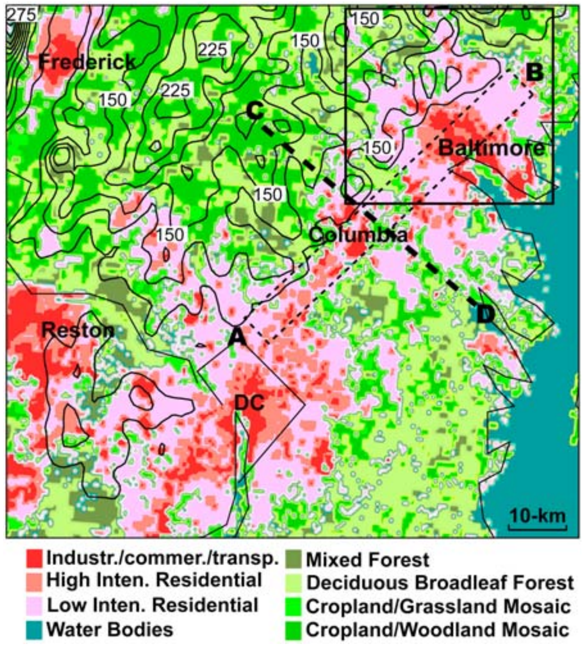

Figure 1. Dominant land-use (shaded) and elevation (solid lines, at intervals of 25 m starting from 125 m) over a subdomain of the finest-resolution mesh. The zone AB enclosed by dashed lines denotes the location of the area-averaged vertical cross section used in Figure 4; the squared box is the subdomain used in Figure 3; and line CD indicates the boundary of land-use changes used in sensitivity experiments.

roads as well as some anthropogenic effects are used to specify roughness length, albedo, emissivity and the other surface parameters influencing the surface energy budget.

3. Results

[7] During this study period, the circulation was dominated by weak, westerly flows until the late morning hours of July 9 when the surface winds backed to the southwest (see Figures 2b and S2, top). These are the two typical summertime flow regimes under the influence of the Bermuda high. In the next, we will first verify the model-simulated surface features before using the model results to examine the impact of upstream urbanization on the extreme UHI and associated urban boundary layer (UBL).

3.1. UHI Effects

[8] Skin temperature (T_{skin}, a radiometric temperature derived from the thermal emission of the earth surface as some temperature average between various canopy and soil surfaces) observed by the MODIS satellite instrument at 1745 UTC (1245 LST) 9 July 2007 shows pronounced contrasts between urban and rural areas (see Figure 2a), in agreement with contrasting land-cover categories (see Figure 1). Minor differences in T_{skin}, e.g., over Columbia and Frederick, are likely due to rapid urbanization since 2001. The satellite observations highlight UHI effects over Washington, Columbia, Baltimore, Reston, and Frederick as well as many small towns. The hottest T_{skin} (>46°C) occurred at the heart of these cities in areas of high intensity residential buildings and commercial/industrial activity; they were more than 10°C higher than rural regions even at this early afternoon hour.

[9] The coupled model reproduces well the observed UHI intensities, especially the sharp contrasts between urban, suburban and rural areas (see Figures 2a and 2b), despite the use of large-scale initial conditions. The model even captures the UHI effects of Interstate highways such as I-70 between Frederick and Baltimore, and I-270 between Frederick and Washington. In contrast, I-295, the Baltimore-Washington Parkway running northeast-southwest between these two cities has tree cover in the median and off the shoulders - it does not have a heat signature. The simulated UHI patterns resemble those of the land-cover map even better than the satellite observations (see Figures 1 and 2b), because of the specified Year-2001 land-cover (NLCD) data in the model. The model slightly overestimates the area of maximum T_{skin} and misses the UHI effects over some

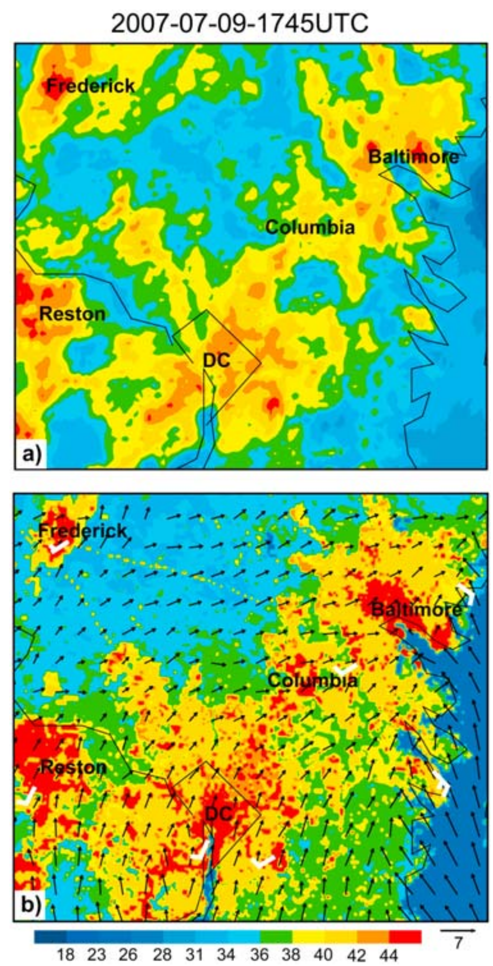

Figure 2. Horizontal distribution of skin temperature (°C, shadings) at 1745 UTC 9 July 2007: (a) observed by the MODIS satellite and (b) simulated with surface (z = 10 m) wind vectors (m s^{-1}) superposed. White wind barbs in Figure 2b denote a few observed surface winds; a full barb is 5 m s^{-1}.

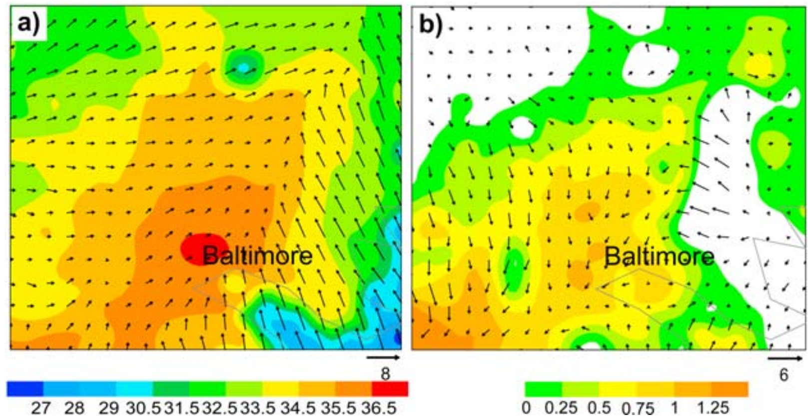

Figure 3. Horizontal distribution of (a) surface temperature (°C, shaded) and wind vectors (m s^{-1}) around Baltimore from the 56.5-h control (CTL) run, valid at 2030 UTC 9 July 2007, and (b) as in Figure 3a but for the differenced fields between the CTL and NUH (no urbanization to the south of Baltimore) runs (i.e., CTL − NUH).

towns, but this could again be attributed to land-use changes since 2001.

[10] The urban area T_{sfc} at 2-m altitude, like T_{skin}, exhibits substantially more warming (>5°C) than that over the rural area in the mid-afternoon (i.e., 1530 LST), and the commercial-industrial-transportation areas, often located near a city's center, are 3–4°C warmer than the suburbs (see Figures 3a and S2, top). The simulated peak T_{sfc} at Baltimore and Washington are 36.5 and 35.5°C, respectively, as compared to the observed 37.5 and 36.5°C. This 1°C negative bias is not detrimental to the present study, since T_{sfc} is a diagnostic variable between T_{skin} and the model surface layer (centered at z = 12 m) temperatures, but the 1°C T_{sfc} difference between Baltimore and Washington is significant.

[11] Figure 2b also shows general agreement between the simulated surface winds and the few observations available. We see the convergence of southwesterly flows with the Chesapeake Bay breeze, with urban surface winds 2–3 m s^{-1} weaker than those over rural areas due to the presence of high roughness elements. Confluence of the two air streams in the northeast portion of Baltimore led to an area of stagnant winds (Figures 2b and 3a) and locally high pollution (e.g., ozone) concentrations in the late afternoon of 9 July (see http://www.airnow.gov/). The southwesterly flows began to intrude the study area near noon 9 July, progressed onto Columbia by 1245 LST (see Figure 2b), and passed over Baltimore 3 h later (see Figure 3a).

3.2. Upstream Effects

[12] To reveal how the upstream urbanization (i.e., in Columbia and Washington) could exacerbate the UHI effects over Baltimore, the southwesterly flows are superimposed on the urban distribution of the Washington-Baltimore corridor. Figure 4a shows an along-wind vertical cross section of in-plane flow vectors and the perturbation potential temperature θ', through Columbia and Baltimore in the mid-afternoon of July 9, where θ' is obtained by subtracting the mean potential temperature profile in the rural environment to the west of Baltimore. (The potential temperature at a pressure level is the temperature that the air would have after it is adiabatically brought to a reference

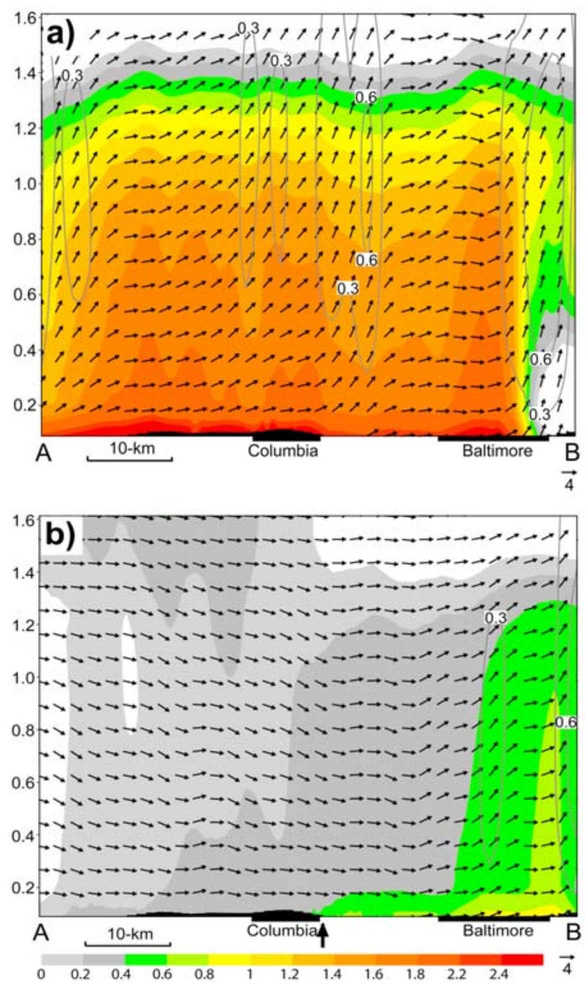

Figure 4. Comparison of the vertical cross sections of potential temperature perturbations (θ') (°C, shaded) and upward motion (gray lines, m s^{-1}), superposed with in-plane flow vectors (m s^{-1}), from the 56.5-h simulations valid at 2030 UTC 9 July 2007, between (a) the control run and (b) the no urbanization to the south of Baltimore run. They are taken from zone AB (see Figure 1).

pressure.) The upward extension of the UHI effects with different intensity layers extend up to ~1.4 km altitude, the approximate depth of the well-mixed UBL at this time. The stratified UBLs appear as layered "hot plumes" (columns of rising air) corresponding to individual local towns along the Washington-Baltimore corridor (see Figures 4a and 1). To our knowledge, previous studies have examined the local UHI effects mostly in the context of T_{sfc} and T_{skin}, but with little attention to such vertical UHI structures due to the lack of high-resolution data. Moreover, deep rising motions on the scale of 10–20 km and as strong as 0.6 m s^{-1} occur in the well-mixed UBL. These are unlikely due to gravity waves associated with the nearby topography (see Figures 4a and 1) because of the near neutral lapse rates in the mixed UBL and their absence over the rural areas (see Figure 4b). The upward motion of this magnitude could affect urban weather conditions such as triggering cumulus clouds near the top of the UBL or the urban-rural boundaries [e.g., *Bornstein and Lin*, 2000].

[13] Each layer of the surface-rooted "hot plume" over Baltimore (e.g., $\theta' = 2\sim1.5°C$) is generally deeper and more robust than those upstream, i.e., Columbia (see Figure 4a). Because of the southwesterly advection of the warm air from the upstream UBL, little additional heat from the surface is needed to maintain the warm column above Baltimore. Instead, most of the local surface heat flux is used to heat the column and increase the depth of the mixed UBL. Entrainment into the potentially warmer air aloft helps further increase the temperature in the mixed UBL [e.g., *Zhang and Anthes*, 1982; *Oke and Cleugh*, 1987] leading to the generation of robust hot plumes over the city of Baltimore.

[14] To supplement the above results, we conducted a numerical sensitivity experiment in which the urban areas to the southwest of Baltimore are replaced by a vegetated surface (NUH), as indicated by line CD in Figure 1, while holding all the other parameters identical to the control simulation (CTL) shown in Figures 2 and 3. The differenced fields of T_{sfc} and surface winds between the CTL and NUH simulations (see Figure 3b) show a city-wide reduction in T_{sfc} in experiment NUH, with 1.25–1.5°C peak differences or more than 25% reduction of the UHI effects. Based on observations of *Bloomer et al.* [2009], also given in Figure S1, the 1.25–1.5°C cooling corresponds to a reduction of 3–4 ppb ozone and ~2 μg m^{-3} particulate matter in the summer. In addition, the well-mixed UBL in the NUH experiment is about 200 m shallower and the hot plume over Baltimore is weaker than that in CTL (see Figures 4a and 4b). Vertical motion to the south of Baltimore is mostly downward due to the Bermuda high, confirming further the importance of the urban-surface-rooted hot plumes in generating the pronounced upward motion. Upstream urbanization also appears to cause (see Figures 3 and 4) enhanced convergence along the Bay and greater intrusion of the Bay breeze into the city of Baltimore.

[15] In another sensitivity simulation, Baltimore is treated as a rural area (i.e., the area to the northeast of line CD in Figure 1) while holding the other conditions identical to the control simulation. Although there is little change in T_{sfc} over Washington, and Columbia (see Figure S2), Baltimore's T_{sfc} is higher than expected for a "rural" area, offering additional evidence for a non-local UHI effect involving advection of warmer air from upstream.

4. Concluding Remarks

[16] In this study, we tested the hypothesis that the UHI effects can be markedly enhanced by upstream urbanization. This is achieved by performing high-resolution control and sensitivity simulations of an extreme UHI event that occurred over Baltimore on 9 July 2007, using a coupled WRF-Noah-UCM model with the finest grid size of 500 m. It is found that the coupled model could reproduce the observed UHI effects in terms of T_{skin} and T_{sfc}, such as the 5°C (10°C) T_{sfc} (T_{skin}) contrasts between the urban and rural areas, and the Bay breezes. In particular, the vertical growth of the UHI effects is shown as layered "hot plumes" that are rooted at the urban surfaces with pronounced rising motions.

[17] A comparison between the control and sensitivity simulations reveals the important roles of upstream urbanization in enhancing the UHI effects over Baltimore through the (nonlocal) advective processes. Without the upstream influences, the UHI effects over Baltimore would be 1.25°C colder or reduced by 25%, with a 200-m shallower mixed UBL and a much less robust "hot plume". The enhanced UHI effects are argued to result from the (nonlocal) thermal advection of warm air upstream, the local upward surface heat fluxes and entrainment of the potentially warmer air aloft.

[18] Our study shows that while individual cities alone can do little to diminish the harmful impacts of global climate change they can take steps to mitigate changes in local climate. By taking into consideration the interaction of surface properties with atmospheric physics, chemistry and dynamics, informed choices in land use can help lessen heat waves and smog episodes. This could be an especially powerful tool in the developing world where urbanization is proceeding rapidly and adverse impacts on the environment and human health are substantial.

[19] **Acknowledgments.** We wish to thank Fei Chen of the National Center for Atmospheric Research for his helpful advice and two anonymous reviewers for their helpful comments. This work was funded by Maryland's Department of Environment.

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