Enhanced Urban Heat Island Effects by Upstream Urbanization

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1. Introduction

The urban heat island (UHI) problems have been well studied for many years through direct observations (e.g., Bornstern 1968; Landsberg 1981), remote sensing (e.g., Gallo et al. 1993; Jin et al. 2005), and numerical models (e.g., Kusaka and Kimura 2004; Grossman-Clarke et al. 2008). The daytime UHI appears as a result of more solar energy absorbed but less moisture evaporated by artificial surfaces and urban infrastructures than those over rural vegetated surfaces. Moreover, industrial and commercial activities as well as transportation produce extra heat in their immediate environments, elevating further the urban air temperatures. Previous studies show that the larger the city size, the greater are the UHI effects. Recently, more sophisticated urban models have been developed to better address air quality, urban environments, and the other UHI related problems (Kusaka et al. 2001; Martilli et al. 2002).

The UHI effects are pronounced on most sunny summer days along the Washington - Baltimore urban corridor (WBC), often producing extremely high ozone concentrations. Of particular relevance is that under certain weather conditions, higher surface temperatures and ozone concentrations were observed in Baltimore than those in Washington, DC. These differences could not be attributed to the size of urban coverage, since DC's coverage is relatively larger when its surrounding urbanizations are included (see Fig. 1). We hypothesize that the hotter air and higher ozone concentrations observed in Baltimore results primarily from the enhanced UHI effects by upstream urbanizations along the WBC.

Despite considerable work on the UHI during the past decades, few studies have examined the influences of urbanization on the UHI effects downstream, except for Ohashi and Kida (2004) who studied the transport of moisture and air pollutants between two neighboring cities in Japan using a simplified geometric model with idealized landscapes and calm larger-scale flows. They found that the two UHI-induced circulations could interact in transporting moisture and pollutants when the two cities are less than 40 – 50 km apart. Clearly, their results could not be applied to the above-mentioned scenarios along the WBC.

Thus, one of the objectives of this study is to test the above hypothesis using high-resolution simulations of an extreme UHI event that occurred over Baltimore on 9 July 2007. Specifically, on that day Baltimore experienced a peak (2-m) surface temperature of 38^0C, and an 8-h mean ozone concentration of 131 ppbv. The surface temperature was more than 1^0C higher than that observed in Washington, DC.

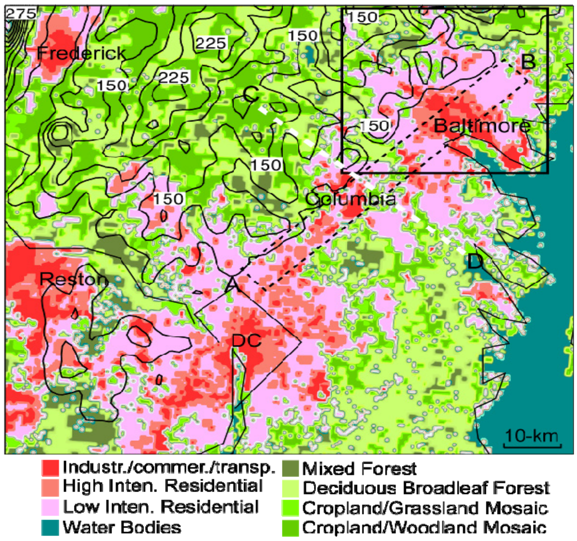

Fig.1 Dominant land use (shaded) and terrain (solid, at intervals of 25 m starting from 150 m) over a subdomain of the 500-m resolution mesh. The zone AB enclosed by dashed lines denotes the location of the area-averaged vertical cross section used in Fig. 4; the squared box centered at Baltimore is the subdomain size used in Fig. 3; and line CD indicates the boundary of land use changes used in Exp. NUH.

2. Model description

The numerical model used for the present study is a two-way interactive, quadruply nested version of the Weather Research and Forecast (WRF-ARW) model (see Skamarock et al. 2005), which is coupled with a single-layer urban canopy model (UCM) (see Kusaka et al. 2001; Chen et al. 2004). The WRF model physics used include: (i) a three-class microphysical parameterization (Hong et al. 2004); (ii) the Mellor-Yamada-Janjić planetary boundary layer (PBL) scheme (Mellor and Yamada 1974; Janjić 1994); (iii) the Noah land-surface scheme in which four soil layers and one canopy with 24-category land uses are incorporated (Chen and Dudhia 2001); and (iv) the Grell and Devenyi (2002) ensemble cumulus scheme as an additional procedure to treat convective instability for the first two coarsest –resolution domains.

The UCM includes 3-category 30-m resolution urban surfaces (i.e., low-intensity residential, high-intensity residential, and commercial/ industrial/transportation), based on the US Environmental Protection Agency's 2001 National Land Cover Data (NLCD), by taking into account the dynamical and thermodynamical properties of roofs, walls and roads as well as some anthropogenic effects.

They will be used to determine roughness length, albedo, zero plane displacement height, emissivity and the other surface parameters influencing the surface energy budget. See Kusaka et al. (2001), Chen et al. (2004), and Holt and Pullen (2007) for more details.

The quadruply nested domains have (x, y) dimensions of 181 × 151, 244 × 196, 280 × 247, and 349 × 349 with the grid size of 13.5, 4.5, 1.5, and 0.5 km, respectively. The outermost domain extends from central Colorado to 65^0W and from 28^0N to 49^0N (not shown), and the innermost domain covers an area that is much greater than shown in Fig. 1. All the domains use 31 σ–levels in the vertical with 20 layers in the lowest 2 km in order to better resolve the evolution of the PBL. The model top is defined at 50 hPa.

The coupled WRF-Noah-UCM system is initialized at 1200 UTC (or 0800 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 are taken from the National Centers for Environmental Prediction's (NCEP) 1^0 resolution Final Global Analyses with the latter updated every 6 hours.

3. Results

The larger-scale environment along the WBC during the integration period was dominated by weak westerly to southwesterly flows under the influence of Bermuda's High (not shown). These are typical summertime conditions over the region, but there was a short-wave trough passed by prior to the model initial time, bringing some precipitation over the WBC. In the next, we will first verify the model-simulated surface features before using the model results to validate our hypothesis.

Fig. 2 compares the simulated surface skin temperature (T_{skin}) to the Moderate (1-km) Resolution Imaging Spectroradiometer (MODIS) measured at 1745 UTC 9 July 2007. Pronounced contrasts in the measured T_{skin} between urban and rural areas are clearly evident, and they agree reasonably well with the distinct land-use categories (cf. Figs. 2a and 1). Some minor differences in T_{skin} exist, e.g., over Columbia and Frederick, but they can be attributed to rapid urbanizations that occurred since 2001. It is obvious from the MODIS data that significant UHI effects are present over DC, Columbia, Baltimore, Reston and Frederick as well as many small towns. The hottest locations with the peak T_{skin} of more than 45^0C in Baltimore, Reston and Frederick correspond to the commercial/industrial/transportation and high intensity residential categories; they are more than 10^0C higher than their ambient rural regions even at this early afternoon hour. It should be mentioned that the UHI effects were much less significant on July 8 due to ample surface evaporation after the rainfall on the previous day.

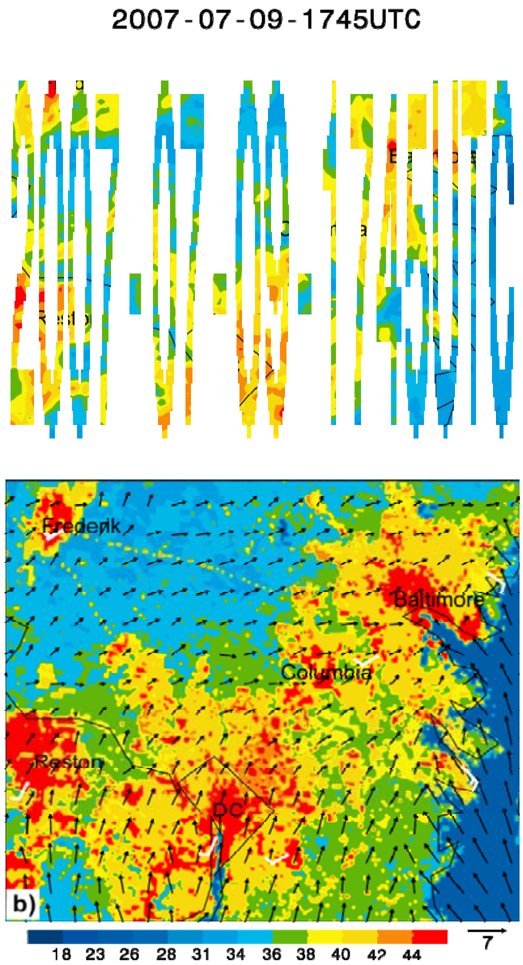

Fig.2 Horizontal distribution of skin temperature (T_{skin}) at 1745 UTC 9 July 2007: (a) the MODIS observed; and (b) the simulated with surface wind vectors superposed. Wind barbs in (b) denote a few available observed surface winds; a full barb is 5 m s^{-1}.

It is encouraging from Figs. 2a and 2b that the coupled model reproduces well the observed UHI effects, especially for the sharp contrasts between urban and rural areas. The simulated UHI patterns also resemble those of the land uses even better than the measured (cf. Figs. 1 and 2b), because of the specified Year-2001 land-use data. In particular, the model could even capture the UHI effects of in-state highways of 70 (between Frederick and Baltimore) and 270 (between Frederick and DC) as well as the other major highways.

Of course, some differences still exist. For instance, (i) the UHI effects over some small towns are missed due to the use of the outdated land-use data; and (ii) the coverage of T_{skin}= 44 ~ 46^0C over the urban areas is slightly overestimated (cf. Figs. 2a and 2b). Like the simulated T_{skin}, the simulated surface temperature (T_{sfc}) exhibits more than 5^0C UHI effects in the early afternoon (i.e., 1345 LST), and commercial/industrial/transportation areas, often located at a city's center, are at least 1^0C warmer than residential areas (see Fig. 3a). The simulated Baltimore's and DC's peak T_{sfc} are 36.5 and 35.5°C compared to the observed 37.5 and 36.5°C, respectively. As mentioned earlier, the

1^0C negative (positive) bias in T_{sfc} (T_{skin}) is not relevant, since T_{sfc} is a diagnostic variable in the coupled model; but the 1^0C T_{sfc} difference between DC and Baltimore is.

Fig. 2b also shows good agreements between the simulated and a few observed surface winds. We see the convergence of southwesterly flows with the Chesapeake Bay breezes, and urban surface winds that are about 1 m s^{-1} weaker than those over rural areas due to the presence of high roughness lengths. Note that the regional surface winds are near-westerly during the early morning hours (not shown), but the southwesterly flows begin to intrude the WBC near the noon time and progress into Columbia by 1345 LST 9 July (Fig. 2b), and 3 h later pass over Baltimore (Fig. 3a). Although the area-averaged PBL winds at Columbia exhibit an inertial oscillation, similar to that shown in Zhang et al. (2004), they vary slightly from west-southwesterly to north-southwesterly during the afternoon hours (not shown). Based on the WBC's urban configuration given in Fig. 1, the warm air advection by the southwesterly flows is of our interest in understanding the enhanced UHI effects over Baltimore by the upstream urban heat sources.

Before studying the upstream effects, Fig. 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 the WBC (see Fig. 2b). Of particular interest is the upward extension of the stratified UHI effects that exhibit like "hot plumes" with different intensity layers up to about 1.4 km, which represents roughly the depth of the well-mixed PBL at this time. These layered "hot plumes" correspond well to individual local towns along the BWC (cf. Figs. 4a and 1). To our knowledge, the previous studies have examined the UHI effects mostly in the context of T_{sfc} and T_{skin}, but with little attention on such vertical UHI structures due likely to the lack of high-resolution urban models. 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 PBL. Their magnitudes decrease rapidly upward and become negative above z = 4 km. They are not likely part of gravity waves associated with the nearby topography (cf. Figs. 4a and 1) because of (i) the near neutral lapse rates in the mixed layer and (ii) their absence over the rural areas (e.g., Fig. 4b). Clearly, the upward motion of this magnitude could help trigger cumulus clouds near the top of the PBL or the urban-rural boundaries.

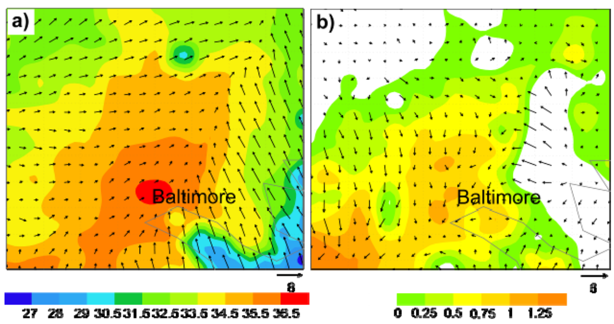

Fig.3 Horizontal distribution of (a) surface temperature (shaded) and wind vectors around Baltimore from the 32.5-h CTL run, valid at 2030 UTC 9 July 2007; and (b) As in (a) but for the differenced fields between the CTL and NUH runs (i.e., CTL – NUH).

Of relevance is that each layer of the surface-rooted "hot plume" over Baltimore (e.g., θ'= 2 ~1.5^{0}C) is generally deeper and more robust than that at its upstream, i.e., Columbia (Fig. 4a), which is hypothesized earlier to result from the upstream urbanization. To validate this hypothesis, a simple numerical experiment is conducted, in which the urban surfaces to the south of Baltimore are replaced by mixed forests (NUH) as those over nearby rural areas (Fig. 1), while holding all the other parameters identical to the control run (CTL).

The differenced fields of T_{sfc} and surface winds between the CTL and NUH runs are given in Fig. 3b, which shows a city-wide reduction in T_{sfc} in Exp. NUH, with about 1.25^{0}C peak differences or 25% reduced UHI effects in the heart of Baltimore and at its southwestern corner. Similar patterns but nearly doubled magnitudes also occur in the T_{skin} differences between CTL and NUH (not shown). As a result, Exp. NUH produces a shallower (~ 200 m) mixed PBL with a much weaker "hot plume" over Baltimore than that in CTL (cf. Figs. 4a,b). In

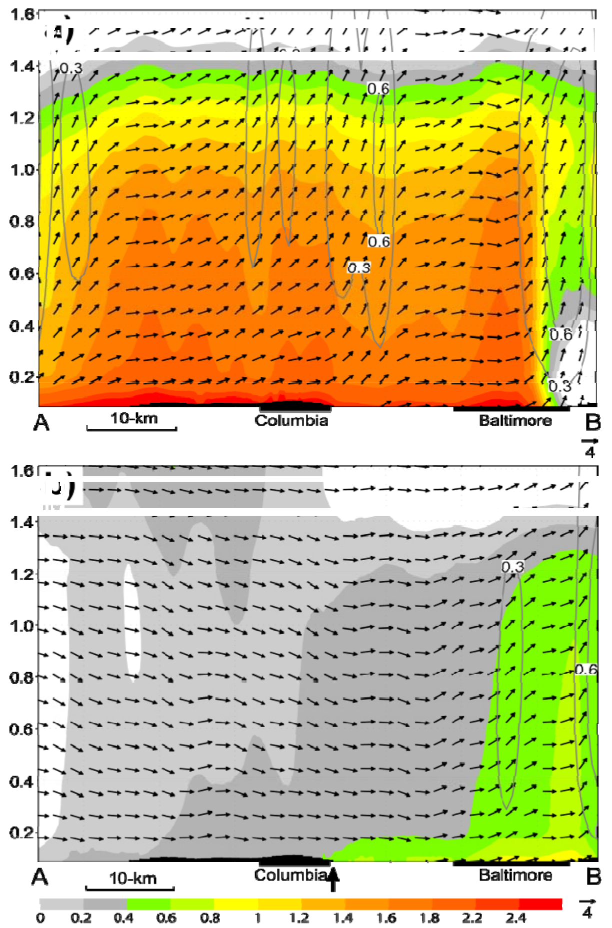

Fig. 4. A comparison of the vertical cross sections of potential temperature perturbations (shaded) and

vertical motion (solid, m s^{-1}), superposed with in-plane flow vectors, from the 32.5-h simulations that are valid at 2030 UTC 9 July 2007, between (a) CTL; and (b) NUH.

addition, the vertical motion to the south of Baltimore is mostly downward due to the influence of the Bermuda High, confirming further the importance of the urban-surface-rooted "hot plumes" in generating the pronounced upward motion. A slightly warmer PBL to the south of Baltimore can be attributed to the use of mixed forests compared to nearby irrigated croplands (cf. Figs. 1, 2b and 4b). Figs. 3 and 4 also show the structures of the Bay breezes to the east of Baltimore, and the enhanced convergence along the Bay breeze and into the urban regions in CTL, as compared to those in NUH.

While the above comparisons between the CTL and NUH runs reveal clearly the importance of the upstream urbanization in making T_{sfc} and the "hot plume" over Baltimore warmer than those occurring upstream, one may wonder how the warmness could be achieved since a similar amount of the warm air over Baltimore would be advected downstream.

Apparently, because of the southwesterly advection of the warm air from the upstream urban-heated PBL, little additional heat from the surface would be needed to maintain the warm column above Baltimore. Instead, most of the local surface heat fluxes will be used to heat the column and increase the depth of the mixed PBL. Then, entrainment into the potentially warmer air aloft helps further increase the potential temperature in the mixed PBL (Zhang and Anthes 1982), thereby leading to the generation of the more robust "hot plumes" over the city of Baltimore.

4. Concluding remarks

In this study, we examined an extreme UHI event that occurred over Baltimore on 9 July 2007, and 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 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 5^0C (10^0C) 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.

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 1.25^0C colder or reduced by 25%, with a 200-m shallower mixed PBL and a much less robust "hot plume" (and likely a significant reduction in ozone concentrations). 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. We have conducted another sensitivity simulation, in which the urbanizations between DC and Baltimore are treated as rural, and found that Baltimore would be about 1^0C colder than the CTL-simulated. This weak UHI influence from DC can be attributed partly to the deflection of wind direction (see Fig. 2b) and partly to the relatively longer distance between the two cities (Fig. 1). A more detailed analysis of the enhanced UHI effects associated with the two urban regions will be presented in a forthcoming journal article. In addition, Zhang et al. (2009) discussed how some cities can take steps to mitigate changes in local climate by considering the possible enhanced UHI effects as a result of inadvertent upstream urbanization.

Acknowledgements

We wish to thank Dr. Fei Chen of the National Center for Atmospheric Research for his helpful advice. This work was funded by Maryland's Department of Environment.

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