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Impact of environmental flows on the daytime urban boundary layer structures over the Baltimore metropolitan region

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Abstract

The three-dimensional structures of the urban daytime boundary layer (UDBL) over Baltimore are examined using a coupled Weather Research and Forecast – Urban Canopy model. Results show the upward growth of the urban heat island (UHI) effects as the surface-based 'hot plumes' with pronounced rising motions and thermal gradients. The UDBL tends to exhibit different vertical structures and intensities, depending on the magnitude and direction of environmental flows with respect to urban morphometric distributions and its interaction with the circulations induced by differential land covers. They are determined by both the local UHI effects and the nonlocal advective processes.

Keywords: urban boundary layer; urban canopy model; urban heat islands; hot plumes; advective processes

1. Introduction

There has been growing interest in recent years in investigating the structures and evolution of the urban daytime boundary layer (UDBL) due partly to increasing environmental concerns as a result of rapid urbanization and partly to the speedy growth of computing powers for high-resolution modelling of urban-scale circulations. Because the urban surfaces, consisting of varying roughness elements, are typically warmer than their surrounding rural surfaces, and because of the extra heat generated by industrial and commercial activities as well as transportation, the UDBL is often deeper and more complicated than the rural boundary layer (Rotach *et al*., 2005).

Numerous UDBL studies have been conducted in the past decades, but most of them focused on the energy budgets and vertical profiles of thermal and flow fields in relation to the urban heat island (UHI) effects (Grossman-Clarke *et al*., 2008; Kusaka and Kimura, 2004). Only a few numerical studies have shown the three dimensional (3D) structures of the UDBL but with limited insight into the dynamical and thermodynamic characteristics because of the use of coarse grid resolutions (Lemonsu and Masson, 2002; Tong *et al*., 2005). Recently, more sophisticated urban-processes models and high-resolution urban surface data have become available for better examining the UHI effects and the UHI-related circulations (Kusaka *et al*., 2001).

The objectives of this study are to (1) examine the along- and normal-flow vertical structures of the UDBL when interacting with its adjacent circulations induced by differential land cover; and (2) explore the local UHI *versus* some nonlocal effects on the development of the UDBL structures. They will be achieved by performing a 72-h high-resolution simulation of the UHI events that occurred over the Baltimore metropolitan region on 7–9 July 2007 using the Weather Research and Forecast model (WRF-ARW, Skamarock *et al*., 2005) that is coupled with the Urban Canopy Model (UCM, Kusaka *et al*., 2001), and the US Environmental Protection Agency's 2001 30-m resolution National Land Cover Data (NLCD). On July 9 Baltimore experienced a peak (2-m) surface temperature (T_{sfc}) of 37.5 °C, which was more than 5 °C warmer than its nearby rural areas.

2. Model description

The coupled WRF-UCM model used herein is two-way interactive, quadruply nested, with the finest grid size of 500 m. The nested domains have (x, y) dimensions of 181 × 151, 244 × 196, 280 × 247, and 349 × 349 with the grid sizes of 13.5, 4.5, 1.5, and 0.5 km, respectively. The outermost domain extends from 100 °W to 65 °W and from 28°N to 49°N (not shown), and the innermost domain covers an area that is about 10 times greater than that shown in Figure 1. All the domains use 31 σ-levels in the vertical with 20 layers in the lowest 2 km to better resolve the evolution of the UDBL. The model top is defined at 50 hPa.

The WRF model physics schemes used include: (1) a three-class ice microphysical parameterization

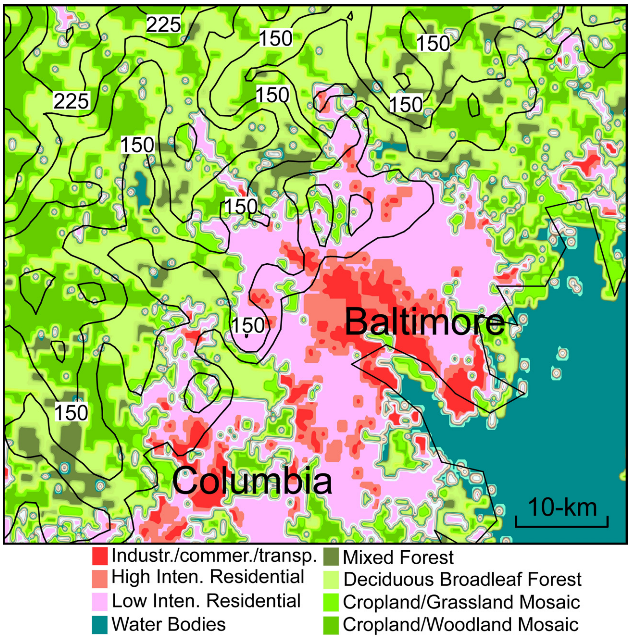

Figure 1. Dominant land use/cover (shaded) and terrain height (solid, at intervals of 25 m starting from 125 m) over a subdomain of the finest 500-m resolution mesh.

(Hong *et al.*, 2004); (2) the Mellor-Yamada-Janjić boundary layer scheme (Mellor and Yamada, 1974; Janjić, 1994); (3) the Noah land-surface scheme in which four soil layers and one canopy with 24-category land covers are incorporated (Chen and Dudhia, 2001); (4) a rapid radiative transfer scheme (Chou and Suarez, 1994; Mlawer *et al.*, 1997); and (5) the Grell and Devenyi (2002) ensemble cumulus scheme as an additional procedure to treat convective instability for the first two lower-resolution domains.

The UCM is a single layer urban surface model built into the Noah land-surface scheme. It uses three-category urban surfaces (i.e. low-intensity residential, high-intensity residential and commercial/industrial/transportation), based on the NLCD (see Figure 1 for Baltimore and its neighbouring areas). The NLCD is used to determine roughness length, albedo, zero plane displacement height, emissivity and the other surface parameters influencing the surface energy budget. In this coupled scheme, the momentum, heat and moisture fluxes are computed according to the dominant land use/land-cover type from the NLCD. If it is one of the three urban classes, the UCM will be called after the Noah land-surface scheme handles the fluxes from natural and vegetated urban surfaces. For simplicity, an urban grid box is first treated as a crop or grass land mosaic in Noah. A weighted average of the fluxes from the Noah and UCM schemes will then be performed, depending upon the urban fraction of the grid box under consideration. See Kusaka *et al.* (2001), Chen *et al.* (2004) and Holt and Pullen (2007) for more details.

The coupled model system is initialized at 1200 UTC [or 0700 Local Standard Time (LST)] 7 July 2007 and integrated for 72 h until 1200 UTC 10 July 2007. The model initial conditions, including the soil moisture and the sea surface temperature, and its outermost lateral boundary conditions are taken from the National Centers for Environmental Prediction's (NCEP) 1° resolution Final Global Analyses with the latter updated every 6 h.

3. Results

The larger-scale environment over the mid-Atlantic states was dominated by weak westerly flows on July 8 (Figure 2(b)), and weak southwesterly flows that began to occur just after 1745 UTC 9 July (Figure 2(d)) under the influence of the Bermuda high (not shown). These are two typical summertime flow conditions over the region, which appear to produce different UHI effects and UDBL structures over the Baltimore area. In the next section, we will first verify the model-simulated UHI effects before using the model results to examine the 3D vertical structures of the UDBLs.

3.1. The UHI effects

Figure 2 compares the simulated surface skin temperature (T_{skin}) to the Moderate (1-km) Resolution Imaging Spectroradiometer (MODIS) measured at 1840 UTC 8 and 1745 UTC 9 July 2007. Sharp contrasts in the measured T_{skin} between urban (coloured in red), suburban (coloured in yellow) and rural (coloured in blue) areas are clearly evident, and they agree well with the distinct land-use categories (*cf.* Figures 1 and 2(a), (c)). The sharp thermal contrasts and pronounced UHI effects shown in Figure 2 could not be simulated in a sensitivity run in which the UCM was turned off (not shown), indicating the importance of the UCM in reproducing the observed UHI effects. Some minor differences in T_{skin} exist, which can be attributed mostly to the rapid urban expansions that occurred since 2001. It is obvious from the MODIS data that significant UHI effects were present over Baltimore, Columbia and small towns. The hottest locations with the peak T_{skin} of more than 45 °C in Baltimore correspond to its commercial/industrial/transportation and high-intensity residential areas (*cf.* Figure 1, and 2(b), (d)); they are more than 10 °C warmer than their ambient rural regions. Note the generation of a large hot spot on July 8 (Figure 2(a)) but two small hot spots on July 9 (Figure 2(c)) in the heart of Baltimore. The latter relatively colder mean T_{skin} could be attributed to the large errors in retrieving the MODIS measurements in the presence of high aerosol concentrations on such a hot day having a peak T_{sfc} of 37.5 °C, as compared to that on July 8 with a peak T_{sfc} of 35.5 °C. Wan (2008), and Wan and Li (2008) showed that such errors could be more than 2 °C in cases of heavy aerosol loading over urban regions.

It is encouraging from Figure 2(b) and (d) that despite the use of large-scale initial conditions, the

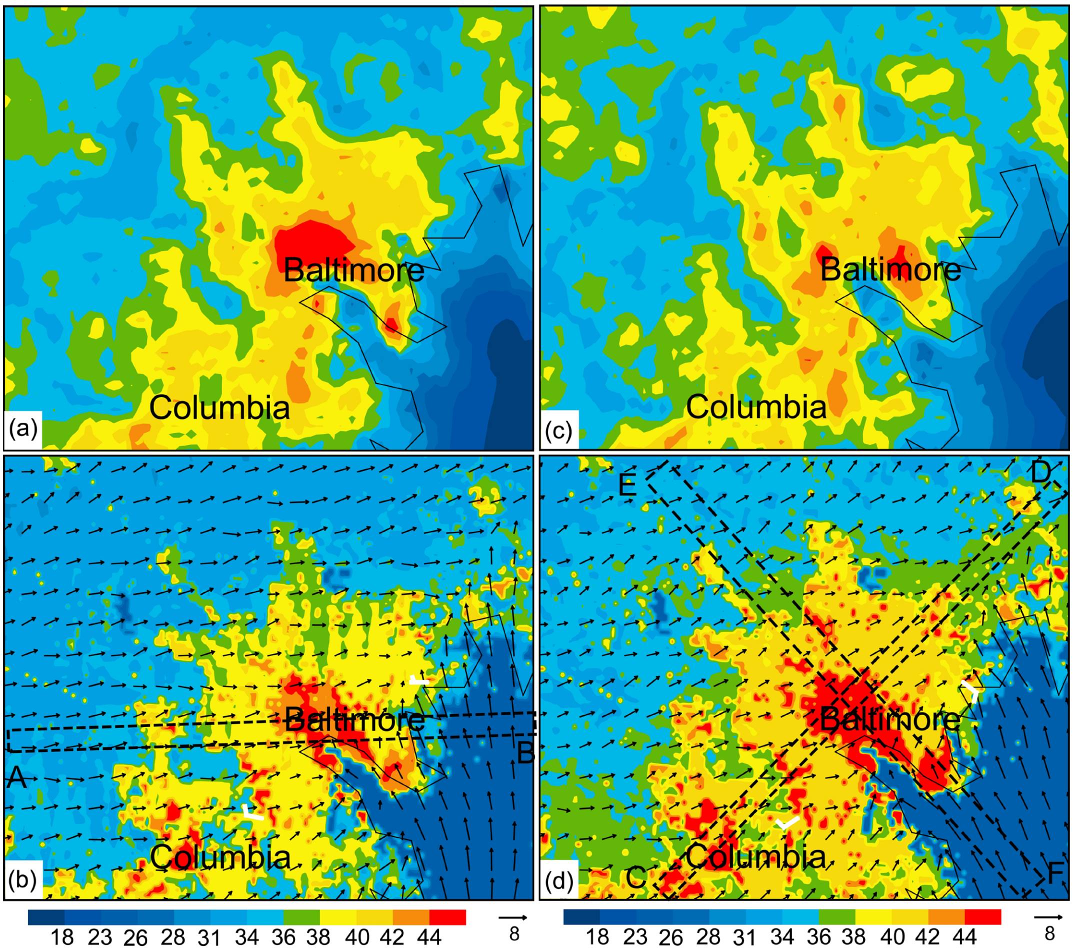

Figure 2. Comparison of (b, d) the simulated skin temperature (T_{skin}) from the 500-m resolution domain with (a, c) the MODIS observed (at the resolution of 1 km) at 1840 UTC 8 and 1745 UTC 9 July 2007, respectively. Wind barbs in (b) and (d) denote a few available observed surface winds; a full barb is 5 m s^{-1}. The simulated surface wind vectors are also given in (b) and (d). Zones A–B, C–D and E–F enclosed by dashed lines denote the location of the area-averaged vertical cross sections used in Figures 3 and 4.

coupled WRF-Noah-UCM model reproduces relatively well the observed UHI effects. In fact, the simulated UHI patterns resemble those of the land cover better than the measured (*cf.* Figures 1 and 2(b), (d)) because of the used Year-2001 land-use forcing. The simulated T_{sfc} also compare favourably to the observed at a few stations (not shown). Of course, some differences still exist. For instance, (1) the UHI effects over some small towns are missed or underestimated because of the use of the outdated land-use data; and (2) the coverage of $T_{\mathrm{skin}} = 44 \sim 46\,^{\circ}\mathrm{C}$ over the urban areas is overestimated.

The model also reproduces reasonably well the observed surface winds (coloured in white) at the two stations, which were near-westerly on July 8, and begun to shift to southwesterly along the Washington-Baltimore corridor at 1745 UTC 9 July (*cf.* Figure 2(b) and (d)). Moreover, one can see the distribution of Chesapeake Bay breezes and its associated convergence zone, part of which has entered the city of Baltimore from its harbour, and urban surface winds that are about 2–4 m s^{-1} weaker than those over rural areas as a result of the presence of high roughness elements in the city.

3.2. The along-flow UDBL structures

Figure 3 compares the vertical cross sections of in-plane flow vectors and perturbation potential temperature (θ') through the city of Baltimore along the two different mean flows, where θ' is obtained by subtracting the mean potential temperature profile in a rural area of 10 km × 10 km upstream of Baltimore. Of particular significance is the upward growth of the UHI effects during the afternoon hours, looking like a ‘bell-shaped hot plume’ rooted at the urban surface, which represents roughly the depth of the well-mixed UDBL over the city of Baltimore. The nearby rural boundary layer at its peak stage is 200–300 m shallower but a few degrees colder than the UDBL (not shown), so the UHI intensity decreases upward, as denoted by the stratified hot plume in the vertical. To our knowledge, the previous studies have examined the urban effects mostly in the context of T_{sfc} and T_{skin}, but with little attention to such vertical structures.

The above-mentioned UDBL structures and intensities differ substantially from each other, depending on the magnitude of the mean flows and on the

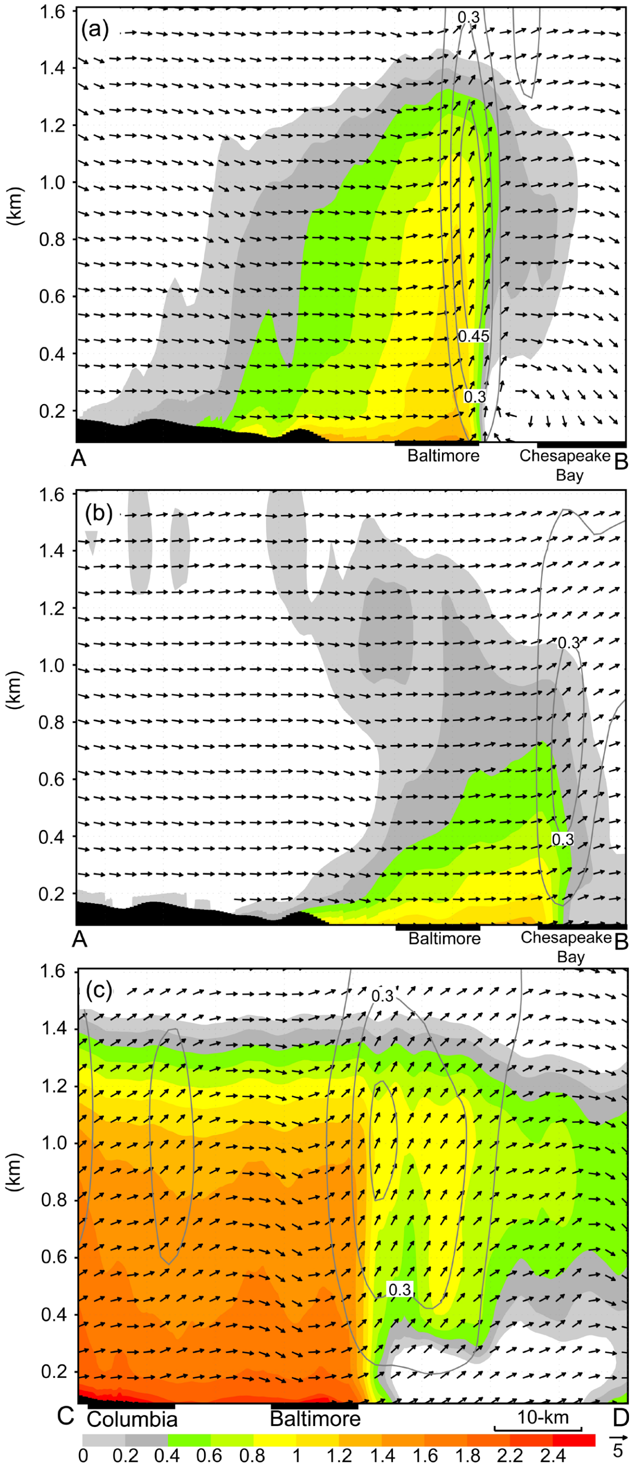

Figure 3. Along-flow vertical cross sections of potential temperature perturbations (θ', shaded) and upward motion (solid, m s^{-1}), superposed with in-plane flow vectors, over the 1.5-km resolution domain from (a) 32-h; (b) 35-h; and (c) 56-h simulations that are valid at 2000 and 2300 UTC 8, and 2000 UTC 9 July 2007, respectively.

interaction with nearby circulations induced by differential land cover. For example, the UDBL exhibits downstream-tilted interfaces between the urban, suburban and rural/Bay boundary layers, with significant horizontal thermal gradients (Figures 3 and 4). In general, the westerly flows are weakly descending

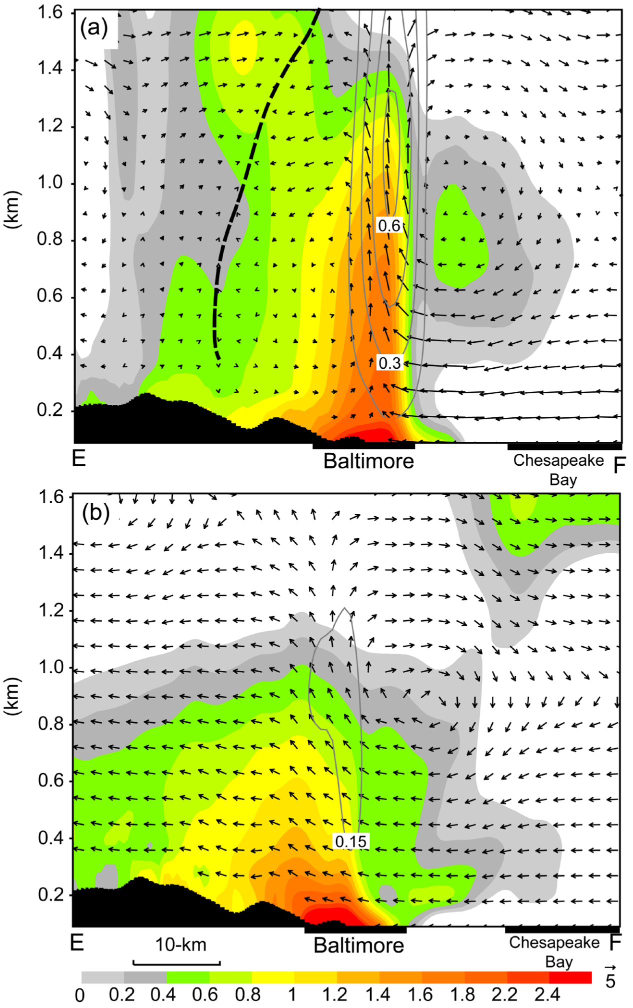

Figure 4. As in Figure 3 but for normal-flow vertical cross sections over the 1.5-km resolution domain from (a) 57-h; and (b) 60-h simulations that are valid at 2100 UTC 9 and 0000 UTC 10 July 2007, respectively (the dark long dash lines in (a) indicate the interface between the rural and urban vertical circulations).

upstream on July 8 as a result of the influences of both the subtropical high and the downslope mountain surface, but ascending downstream as a result of the convergence with the Bay breezes (*cf.* Figures 3(a) and 2(b)); the peak vertical motion is close to 0.5 m s^{-1}. A weak suspended 'urban plume,' caused by thermal advection, overlays the Bay's boundary layer being about 100–200-m deep.

However, the along-flow behaviours differ in the presence of southwesterly flows on July 9 due to the extensive urbanization along the Baltimore-Washington corridor. That is, Figure 3(c) shows a much more robust 'hot plume' over Baltimore and a much more extensive 'urban plume' into the rural boundary layer downstream than those occurred on July 8. The 2 °C θ'-layer depth and the plume length are about 1 km and more than 30 km on July 9, respectively, as compared to less than 100 m and a few kilometers on July 8 (*cf.* Figure 3(a) and (c)). The former occurs because of the large volume of warm air masses from the UDBL upstream, i.e. from Washington to

Columbia, which could be advected into the vertical column of Baltimore. In a separate paper, Zhang *et al.* (2009) has examined the impact of upstream urbanization on the enhanced UHI effects in Baltimore. Deep rising motions as strong as $0.3 \sim 0.6$ m s^{-1} on the scale of 10–20 km are also evident in the wake regions of Columbia and Baltimore as a consequence of the convergence between the two returning flows that are enhanced by the Bay breeze.

Of particular interest is that most of the warm UDBL could be advected downstream as the 'hot plume' weakens in intensity and loses its surface root after sunset, e.g. on July 8 (Figure 3(b)). In essence, the advective processes tend to make the downstream suburb warmer than in the city. Similar scenarios also occur on July 9 in the suburb to the northeast of Baltimore. Again, such nonlocal (advective) UHI effects have not been explored by previous researchers, and appear to have important implications to the understanding of many air quality and environmental problems.

3.3. The normal-flow UDBL structures

Figure 4 shows that the vertical UDBL structures normal to the low-level mean flow also differ substantially from those along the mean flow given in Figure 3. Note that Figure 4 is taken almost normal to the Bay breeze front (see Figure 2(d)). Transverse circulations, with the sharp upward motion at the leading Bay breeze front, are evident, and they result from the interaction between the UDBL and the breeze. The compensating descending flow to the west delineates roughly the interface between the UDBL and rural boundary layer, as denoted by the thick dashed lines, whereas the compensating subsidence to the east produces weak warming above the Bay boundary layer (Figure 4(a)). The higher θ' volume at the upper right corner of Figure 4(b) can be attributed to some warm air advected from upstream, i.e. Washington, DC (*cf.* Figures 2(d) and 4(b)).

Because of the above-mentioned advective UHI effects, the UDBL at 0000 UTC 10 July is about 1.5 °C warmer than that at 2300 UTC 8 July, especially in the lowest 200–300 m layer (*cf.* Figures 3(b) and 4(b)), while the observed suburban T_{sfc} on the 2 days are similar in magnitude (not shown). Unlike the Bay breeze on July 8 that weakens rapidly during the afternoon hours as a result of the influence of westerly flows, it could be continuously fed by the relatively colder air mass from the Atlantic Ocean through the south–north oriented Bay surface on July 9. So the Bay breeze tends to push the warm UDBL westward and spread the warm urban air mass over a larger area after sunset (*cf.* Figure 4(a) and (b)).

4. Concluding remarks

In this study, we have examined the 3D structures of the UDBL over Baltimore under different flow regimes using a coupled WRF-Noah-UCM simulation with the finest grid size of 500 m and the high-resolution NLCD. It is shown that the coupled model could reproduce reasonably well 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, surface winds and the Bay breezes. In particular, the vertical growth of the UHI effects could be clearly shown as the urban surface-based 'hot plumes' with pronounced rising motions and horizontal thermal gradients.

Results show different 3D structures and intensities of the UDBL over Baltimore, depending on the magnitude and direction of the mean flows and its interaction with nearby circulations induced by differential land cover. The city tends to be warmer (colder) and has a more (less) robust UDBL, more (less) intrusion of the Bay breeze, and a more (less) extensive plume downstream under the influence of southwesterly (westerly) flows. The different characteristics have been explained herein in terms of advective processes. This nonlocal effect appears to account for the displacement of a warm UDBL to its downstream suburb, especially after sunset. Results also show different structures of the transverse circulations normal to the mean flows from those along the flows, particularly when interacting with the Bay breeze.

It should be mentioned that several sensitivity simulations have been carried out to further validate the above results, such as treating Columbia or Baltimore as a rural region, reducing the terrain height, or turning off the UCM. These sensitivity results will be published in a future journal article. It should also be mentioned that although more case studies may be examined for the Baltimore metropolitan area, the results presented herein have important implications to regional weather and climate, and useful applications to the other urban areas.

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