IMPACT OF UPSTREAM URBANIZATION ON THE URBAN HEAT ISLAND EFFECTS IN HANGZHOU DURING HEAT WAVES

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China has been experiencing rapid urbanization in the past three decades and more and more urban clusters are emerging. In concomitant with the urban heat island (UHI) effect, the upstream urbanization may exert impact on the microclimate of the downwind city. In particular, under extreme weather conditions such as heat waves, the upstream impact together can exacerbate the local UHI effect. This study investigates the impacts of upstream urbanization on the UHI effects of downwind cities by conducting numeric simulations in Yangtze River Delta Region under a heat wave of 2013 with Weather Research Forecasting (WRF) model coupled with an improved single-layer urban canopy model (UCM). The simulations are first performed under three representative urbanization scenarios to assess the sprawling effect of upstream megacity (Hangzhou) on the downwind city (Haining), whose results indicating a mean 0.65 ºC (0.24 ºC) increase of nighttime (daytime) surface air temperature in Haining caused by the urban expansion of Hangzhou with a doubled built-up area. In addition, the downwind effectiveness of mitigation in upstream megacity is examined by enabling the green roof option in WRF-UCM system. It is found a green roof coverage of 50% in Hangzhou can reduce the daytime near surface temperature in Hangzhou by ~0.15 ºC. This study reveals the synergies of cities within an urban cluster in modifying urban microclimate and highlights the effectiveness of green roofs.

1 INTRODUCTION

Urban area occupies only 0.3% of Earth's land surface, but more than 50% of world's population live in cities. With worldwide continuously increasing urbanization, it is projected that more and more people will be affected by the urban environment. Emerging urban environmental issues have also been manifested by the scenario of climate change. Among these issues, the well-known urban heat island (UHI) effects are becoming more prominent, especially considering the high likelihood of more frequent and longer lasting heat wave (HW) events in the near future.

HWs are excessively hot periods that last for several days or longer. They are one of the most important regional and global causes of weather-related mortality [1] (e.g. about 70,000 people died during the 2003 Europe mega-HW event). The epidemiologic study finds that the mortality risk will increase by 4.5% given 1 ºC increase in the air temperature under HW [2]. Cities are more vulnerable to HWs due to the pre-existing or background UHI effect [3] [4]; that is, urban areas are typically hotter than the rural areas even under non-HW conditions. As such, great attention should be paid to the interactions between UHIs and HWs in the urban climate studies.

Rapid urbanization not only expands cities but also creates urban agglomeration by joining neighboring cities. The urban agglomeration is an extended urban area comprising the built-up area of a central place and many suburbs linked by continuous urban area. The interaction of cities within an urban agglomeration can be remarkable considering their potential in amplifying the impacts on the climate. Zhang et al. [5] found that the urbanization of the upwind cities can exert great impact on the UHI effect of the downwind cities. Based on a dataset of 7-year observations collected in Shanghai, Kang et al. [6] concluded that when the wind speed is lower than 5 m/s, the temperature difference between Shanghai and its neighborhood city Kunshan increases with the wind speed, indicating significant impact on downwind cities by advective heat flux from upwind ones.

In this paper, the impact of an upstream megacity (i.e. Hangzhou) on the UHI effect of a downwind city (i.e. Haining) is investigated by conducting numeric simulations using Weather Research and Forecasting model (WRF, [7]) coupled with the single layer urban canopy model (UCM). The specific purposes of this study are as follows: 1) analyzing the effect of the upstream megacity size on its UHI effect during HWs; 2) assessing the impact resulted from the spatial change and daily change of the temperature and humidity in the horizontal advection within the area between of the upstream megacity Hangzhou on the microclimate of the downwind city Haining; 3) evaluating the downwind effectiveness of mitigation measures implemented in the upstream megacity.

The rest of this paper is organized as follows: Section 2 describes the study area and simulation configurations and simulation results are presented and discussed in Section 3, prior to concluding remarks in Section 4.

2 METHODOLOGY

2.1 Study area

Hangzhou (120°12′E,30°16′N), a megacity in Yangtze River Delta Region, features a subtropical climate and is recognized as one of the China's new "four ovens" (others are Fuzhou, Chongqing and Haikou) for its humid, hot and long-lasting summer. The annual daily mean temperature of Hangzhou is ~16.5 ºC with the low as 4.3 ºC in January and the high as 28.4 ºC in July [8].

A HW event is identified in this study as follow [9]: 1) during the HWs, the daily maximum temperature should be above 97.5th percentile of the daily maximum temperature in record for at least 3 days; 2) the average daily maximum temperature should be higher than 97.5th percentile of daily maximum temperature in record; 3) the daily maximum temperature should be higher than 81st percentile of the daily maximum temperature in record. According to this, the daily maximum temperatures during the period from January 1, 1983 to May 27, 2014 measured by observation station are selected (the missing data has been excluded). The duration of the heat wave of each year in this period is shown in Fig.1. It is apparent that HWs occur much more frequently in the past decade. Especially after 2003, HWs occurred almost every year. The 2013 HW has the longest duration of 48 days in the observational period and is thus chosen as the study period.

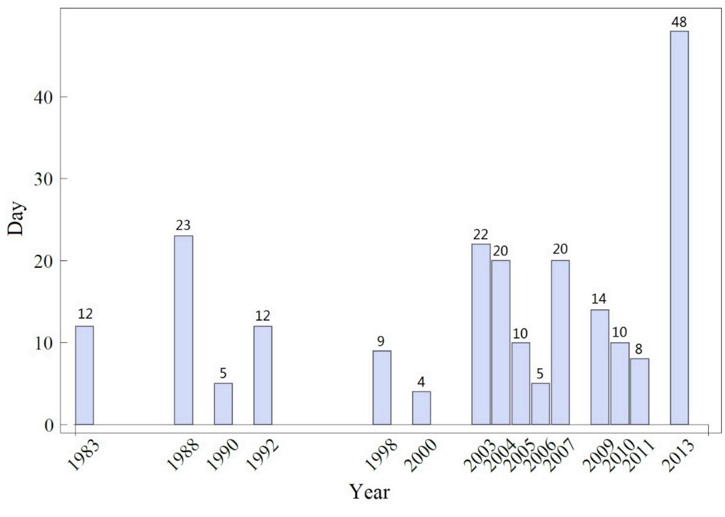

Figure 1. The duration of the heat wave of each year from January 1, 1983 to May 27, 2014.

2.2 Model configuration

The WRF model is a mesoscale numerical prediction system and is capable to perform high resolution simulations thanks to its nesting function. An improved UCM model, Princeton Urban Canopy Model (PUCM) with the consideration of sub-facets of different materials [10] [11], is coupled with WRF to better represent urban surfaces.

For this study, WRF-PUCM is set up for Hangzhou with three nested domains (horizontal grid resolutions of 9, 3 and 1 km, Fig. 2) The largest region d01 covers the most area of the east and the middle China. The region d02 covers the city of Hangzhou, the most area of Shaoxing, and a small part of Jiaxing and Zhoushan. All the analyzations will adopt the simulation result of d03. For instance, the spatially urban average air temperature and surface temperature are those of the Hangzhou pixel in d03. In vertical grids contain 55 sigma levels with the upper boundary set as 100 hPa. The study period is from 00:00 UTC July 3, 2013 to 00:00 UTC July, 5, 2013.

The WRF model physics used include 1) the 2D Smagorinsky scheme for horizontal diffusion, 2) the Mellor–Yamada–Janjić planetary PBL scheme, 3) the unified Noah land-surface model and one canopy with the IGBP-Modified MODIS 20-category land uses are incorporated, 4) the Rapid Radiative Transfer Model for longwave radiation and the Dudhia shortwave radiation scheme. Cumulus parameterization was not used for any of these domains since even the largest grid size is less than 10 km and there is no rainfall during the simulation period.

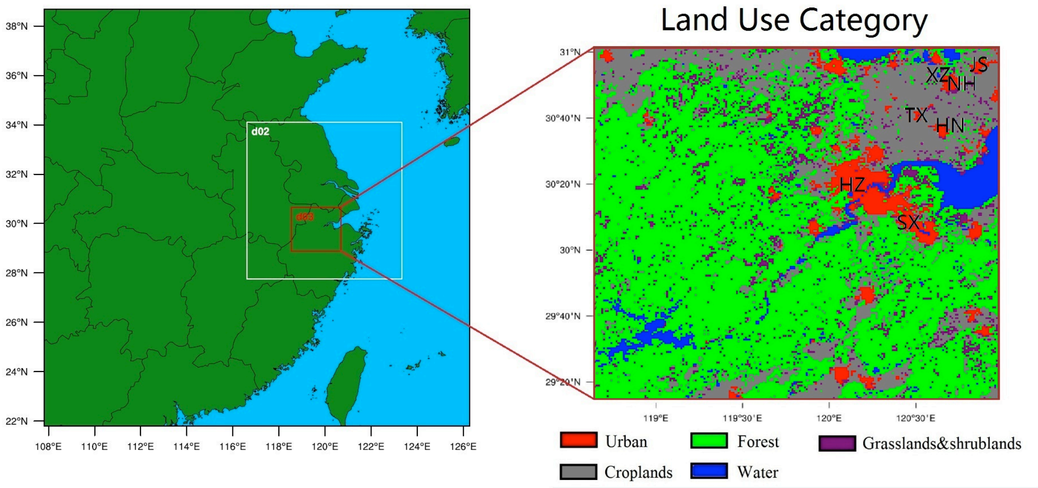

Figure 2. WRF modelling domain and location of observation sites: (a) model nested meshes with the horizontal spacing of 9, 3, and 1 km for domain d01, d02, and d03, respectively; (b) the land-use categories over the innermost domain.

2.3 Observation data and WRF data evaluation

The performance of WRF-UCM is first evaluated with near surface observations collected from meteorological stations curated by China Meteorological Administration. Figure 3 shows the comparison in air temperature at 2m agl between observation and simulation results. The measured data of the temperature at 2 meters high accords well with the simulation result that the moments when both reaches the maximum or the minimum are the same. However, the value of the WRF simulation result is relatively low. Both daily results are consistent with each other, having a low difference value, while there is a temperature difference of 2 to 5 ºC at night, which is likely due to the neglect of anthropogenic heat in WRF simulation as the anthropogenic heat can cause a rise of 1–3 ºC in the near surface temperature. The comparison is also conducted based on land use and suggests a better performance of WRF-UCM for urban area (Fig. 3a) than forest/grass (Fig. 3b) and cropland(Fig. 3c).

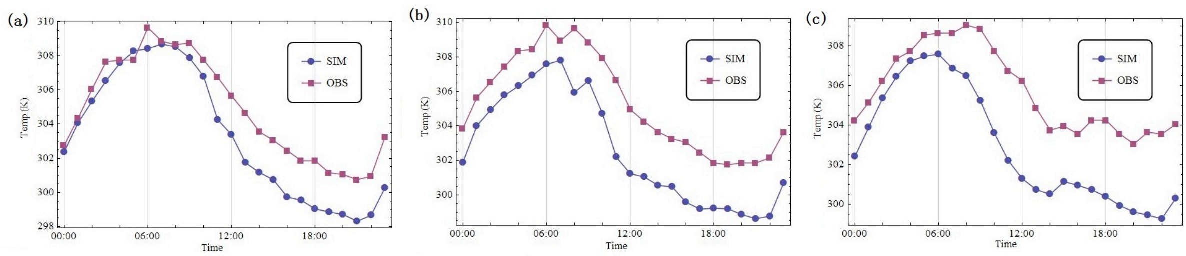

Figure 3. 2-m air temperature comparison of observed and simulated in (a) urban, (b) forest and grasslands, (c) croplands from 00:00 UTC August 4 to 00:00 UTC August 5, 2013, in d03 region.

2.4 Numerical Experimental Design

To assess the impact on UHI effect exerted by urban expansion, three sets of runs with different urban areas were undertaken, where the urban grids are set as 50%, 100% and 150% of present-day coverage (Fig. 4), and they were named as UC (urban coverage) 0.5, UC 1.0, UC 1.5, respectively.

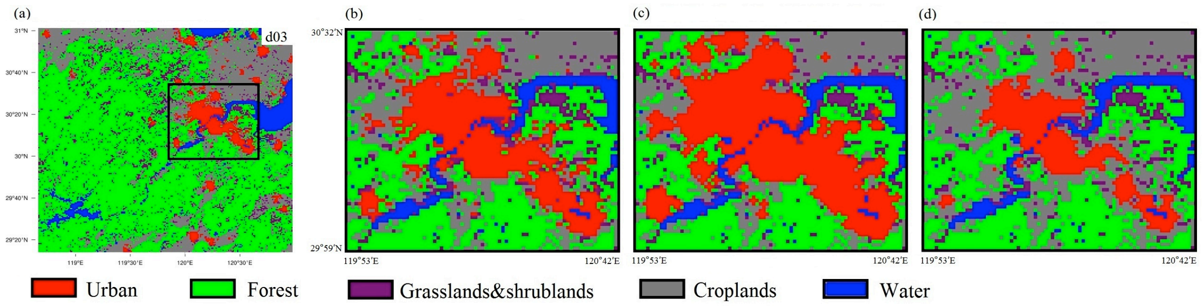

Figure 4. The land-use categories over (a) d03; (b) present-day scenario; (c) 150% coverage scenario; (d) 50% coverage scenario.

The effectiveness of upstream mitigation is realized by enabling the green roof option the PUCM module. Green roofs (GRs) are an ecological approach for UHI mitigation along with other benefits (e.g. stormwater retention, building energy saving, etc.) and thus widely implemented in the world. In this study, a roof coverage of 50% greenery is prescribed to investigate its effect on UHI mitigation. Furthermore, three location-based GR scenarios are designed to examine its spatial effect (Fig. 5), and they are named as ALLGR (Fig. 5a), HZGR (Fig. 5b), and JXGR (Fig. 5c).

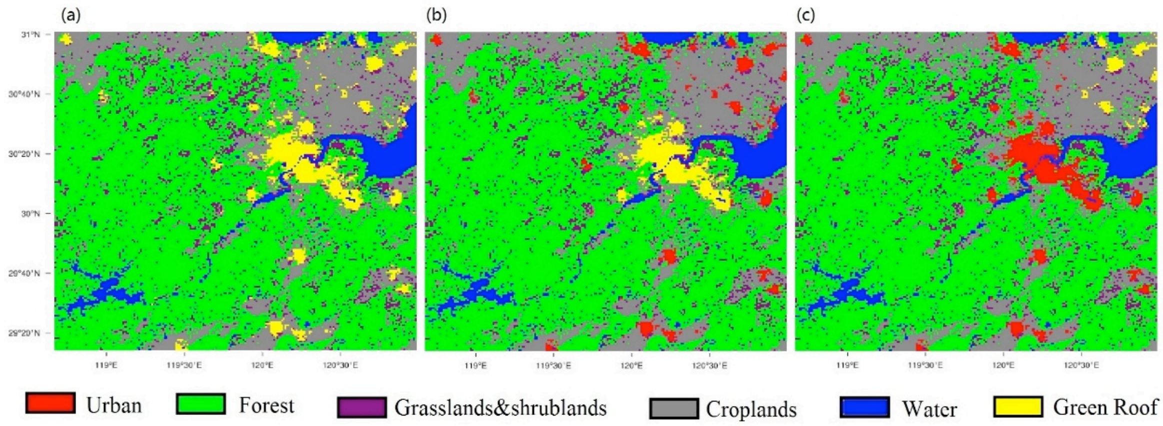

Figure 5. (a) All the urban grids over d03 are added with GRs. Only the urban grids of (b) Hangzhou, (c) Jiaxing are added with GRs.

3 RESULT

The impacts of increasing city size on the near surface temperature (~30 m agl) are examined (Fig. 6) and larger differences are found in the nighttime. Also, the difference between UC 1.5 and UC 1.0 is smaller than that between UC 0.5 and UC 1.0, implying a saturated effect of increasing city size on the near surface temperature (Fig. 6c). With the increasing city size from 50% to 100%, an increase of 0.49 ºC (0.65 ºC) in the nighttime near surface temperature is simulated for Hangzhou (Haining), suggesting significant impacts of upstream urbanization on the UHI effects of downwind cities.

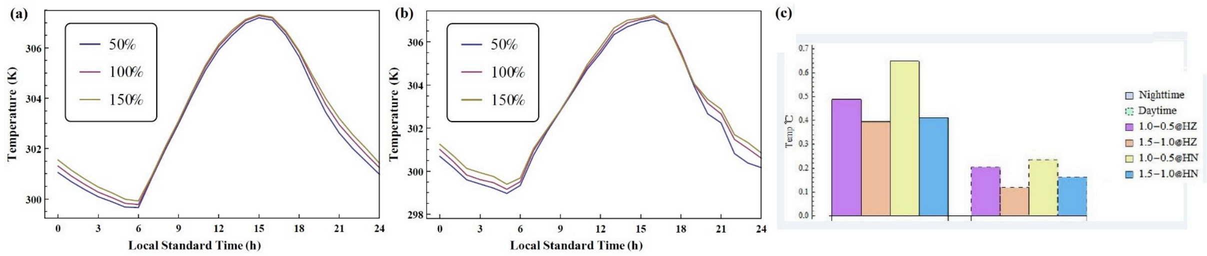

Figure 6. The impact of the city size change of Hangzhou on the urban area near surface temperature of (a) Hangzhou (b) Haining. (c) The average value of the near surface temperature difference of each scenario in daytime and night time.

Besides the near surface temperature, the potential temperature within the planetary boundary layer (PBL) is found to change under different urban coverage scenarios. Larger differences are simulated in daytime as compared with the nighttime temperature and the maximums (0.2 ºC) appear at 14:00. Meanwhile, the changes in potential temperature are consistent with that in PBL height, indicating the role of the continuous urban expansion in modifying the thermal regime within PBL. In addition, a deeper PBL can result in more heating from the PBL top thanks to the entrainment effect. It is noteworthy that a decrease of 0.2 ºC in potential temperature is simulated at 23:00 near the PBL top (~200 m agl), which can be attributed to the temperature inversion in entrainment zone.

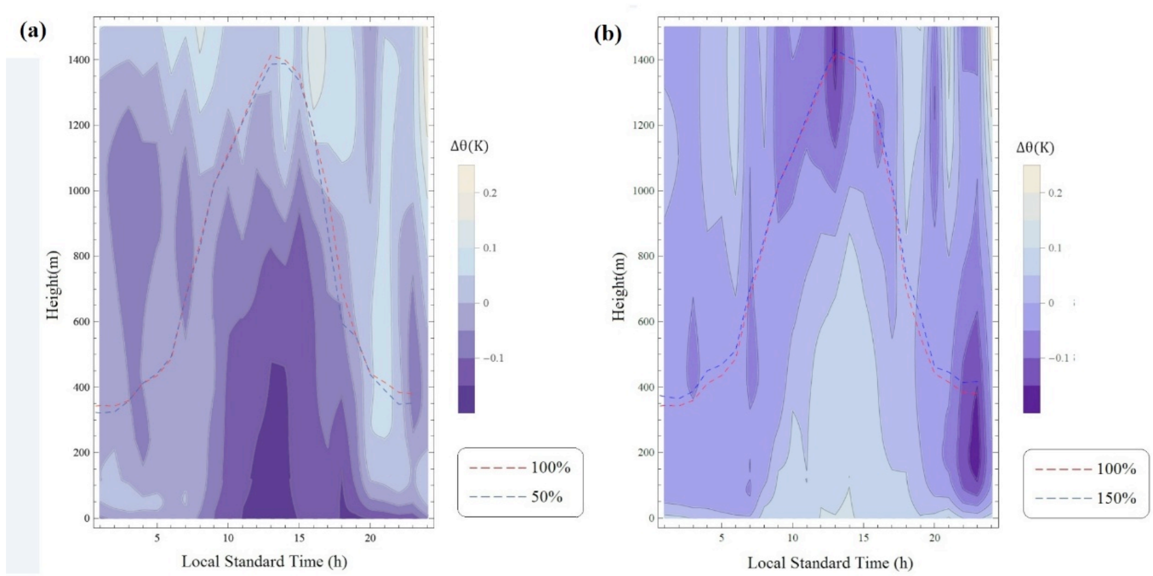

Figure 7. The time series plots of the vertical potential temperature difference between (a) 50% coverage scenario and present-day scenario (b) 150% coverage scenario and present-day scenario, as well as the height of urban boundary layer in Hangzhou urban area.

The mitigation of urban temperature by GRs are investigated under different location-based scenarios (Fig. 8). With a GR coverage of 50% in all urban grids of d03, a daytime (nighttime) temperature reduction of 0.3 ºC (0.4 ºC) is simulated for Hangzhou (Haining). Similar results are obtained under the scenario where GRs are only implemented in Hangzhou, indicating the dominant role of GRs in upstream cities (i.e. Hangzhou) in controlling the mitigation. In other words, the GRs in the downwind cities have minimal effect in local temperature reduction.

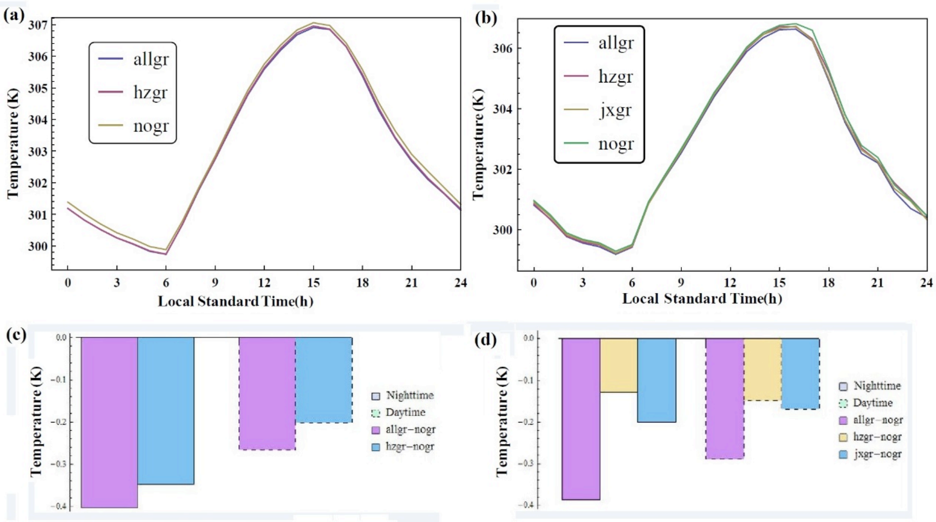

Figure 8. The impact of the GR on the near surface city temperature at (a) Hangzhou and (b) Haining, and the daytime and nighttime average near surface temperature difference of each scenario at (a) Hangzhou and (b) Haining.

Furthermore, the modification of GRs on thermal regime within PBL is investigated through potential temperature and PBL height (Fig. 9). Consistent with the findings in near surface temperature, the GRs in upstream cities governs the mitigation of potential temperature with PBL as well as the near surface temperature: the reduction of potential temperature under HZGR scenario (Fig. 9b) is much comparable as ALLGR (Fig. 9a). In addition, with the coverage of GRs, a daytime decrease of ~50 m in PBL height is also simulated under the GR scenarios, which may contribute to alleviates the UHI effect.

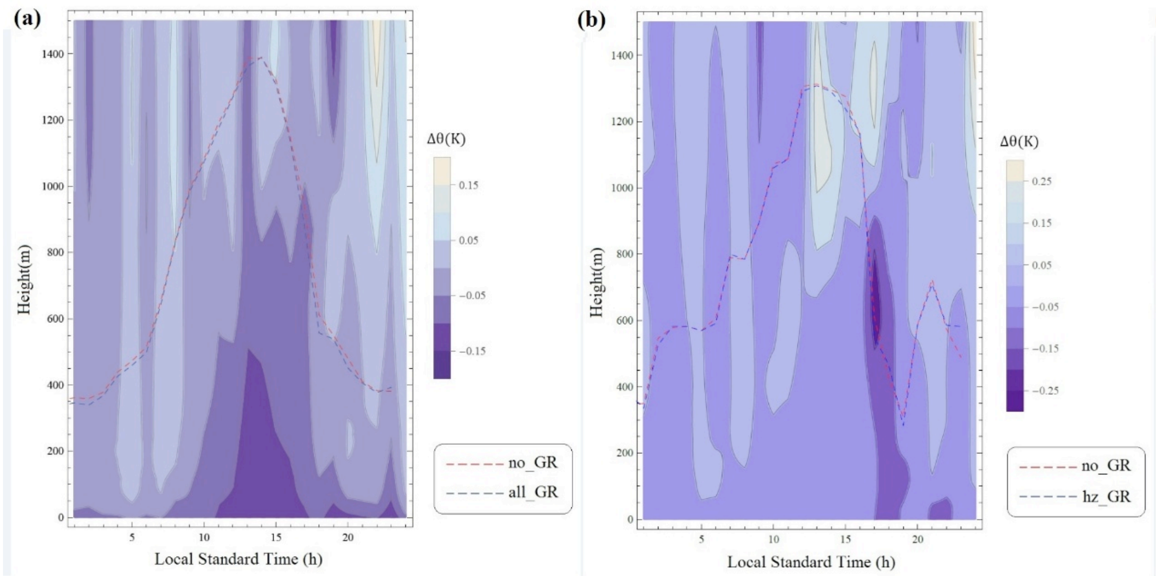

Figure 9. The time series plots of the vertical potential temperature difference between the GR coverage in the full region and merely in Hangzhou, as well as the urban boundary layer altitude on (a) Hangzhou (b) Haining

4 CONCLUDING REMARKS

This study investigates the impacts of upstream urbanization on the UHI effects of downwind cities by conducting numeric simulations in Yangtze River Delta Region under a heat wave of 2013 with Weather Research Forecasting (WRF) model coupled with an improved single-layer urban canopy model (UCM).

The simulations are first performed under three representative urbanization scenarios to assess the sprawling effect of upstream megacity (i.e. Hangzhou) on the downwind city (i.e. Haining). The simulation results demonstrate a mean 0.65 ºC (0.24 ºC) increase of nighttime (daytime) surface air temperature in Haining caused by the urban expansion of Hangzhou with a doubled built-up area. In addition, the downwind effectiveness of mitigation in upstream megacity is examined by enabling the green roof option in WRF-UCM system. It is found a green roof coverage of 50% in Hangzhou can reduce the daytime near surface temperature in Hangzhou by ~0.15 ºC. These results reveals the synergies of cities within an urban cluster in modifying urban microclimate and highlights the effectiveness of green roofs.

The limitation of this study resides in the limited test of parameterizations used in the simulations, which might cause the bias of simulation results to the observations. More simulations for different heat wave cases should be performed in the future to generalize the findings of this study.

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