3.6 **MULTI-SCALE STUDY OF CHICAGO HEAT ISLAND AND THE IMPACTS OF CLIMATE CHANGE**

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1. INTRODUCTION

Urban heat island (UHI) impacts negatively on the well-being of urban dwellers in densely built cities such as Chicago. In July 1995, Chicago inhabitants experienced the dangers of UHI when a major heat wave enveloped the metropolitan area, causing a record number of heat-related deaths (Whitman et al., 1997). As concerns over climate change have increased in recent years, the combined risks of global climate change and UHI have motivated the city's commitment to pursuing adaptation strategies for the future (Coffee et al., 2009). Understanding the interaction between global climate and UHI of cities necessitates approaches that dynamically downscale climate model output to provide results at scales relevant to UHI, which range from regional to city to neighborhood to street canyon scales.

Statistical downscaling has been applied widely to link climate change and UHI (Wilby and Dawson, 2013). Such purely statistical approaches face limitations because they are based on past observations and do not account for unknown emergent properties. Relationships based on past may not be applicable to cases that exceed previously recorded extremes (Thorrson et al., 2011) and in the face of regime shifts. Numerical modeling provides a promising technique to bridge the scales via dynamical downscaling. Previously, general circulation model (GCM) output has been fed into Weather Research and Forecasting (WRF) model to study city-scale impacts of UHI in future scenarios (Kusaka et al., 2012). Chen et al. (2012) recognized the need to resolve finer resolutions within urban areas by coupling mesoscale models with micro-scale computational fluid dynamics (CFD) models. Successful coupling of CFD and mesoscale models have been performed (Wyszogrodzki et al., 2012). GCMs are yet to be connected to CFD models in a complete model chain, with the exception of interpolated CFD output at 50 m resolution employed by Früh et al. (2011) in a "dynamical-statistical" downscaling of GCM output.

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This paper employs a repertoire of available numerical models to explicitly represent atmospheric circulation at all scales necessary for a comprehensive study of UHI and climate change. Community Climate System Model (CCSM5) is used to feed the (mesoscale) WRF model, which utilizes the multi-layer Building Environmental Parameterization (BEP) scheme (Martilli et al., 2002) coupled with the Building Environment Model (BEM) scheme (Salamanca and Martilli, 2010). Further, WRF model is coupled with a micro-scale CFD model called ENVI-met, which provides output at a fine resolution (~2 m) necessary for pedestrian comfort analysis within street canyons. With this model chain and nesting, shown in Figure 1, we achieve a full dynamical downscaling from global climate scale to 2 m resolution within the urban canopy. This multi-scale approach allows for assessment of climate change impacts on UHI which cover a wide range of spatio-temporal scales. The micro-scale ENVI-met model and its application to pedestrian comfort are the focus of this paper.

2. MICRO-SCALE MODEL

The 3D ENVI-met model (Bruse and Fleer, 1998) combines a non-hydrostatic CFD model with explicit treatment of radiation fluxes, vegetation model, and soil model. It employs the incompressible Reynolds averaged Navier-Stokes equations with the Boussinesq approximation. A k-ε 1.5 order turbulence closure scheme simplifies the nonlinear Reynolds stress term. This fine resolution (~0.5-10 m) model is available as freeware and has been widely applied within the urban planning community to assess aspects of neighborhood-scale urban design, often with relevance to human thermal comfort. (Ali-Tourdert and Mayer, 2007; Müller et al., 2014).

In addition to the 3D model, ENVI-met utilizes 1D model extending from the surface to 2500 m to provide lateral and upper boundary conditions for the 3D domain. The initial conditions from observations are fed to ENVI-met 1D model, and thereafter the model marches forward with no further nudging via observations. Thus, the model is most efficient to simulate periods of relatively steady regional atmospheric circulation. All previous ENVI-met studies have made the assumption of steady conditions, but only rarely have they delved into or verified this assumption. This study undertook careful analysis of a suitable period selected for validation to investigate the upshot of this assumption. Upon validation, the model could be used with confidence for climate change applications where only the change in average conditions is the concern, not individual mesoscale events that are of interest in, for example, weather forecasting. This paper also represents the first attempt to couple ENVI-met with a mesoscale model; all previous studies have used observations for model initialization.

An ENVI-met model was set up to study Chicago UHI at pedestrian-scales, and the domain included a western portion of the DePaul University campus and residential Lincoln Park neighborhood. This domain was centered at 41° 55’ 26” N, 87° 39’ 26” W with 430 x 438 m^2 (215x219 grid cells) area at 2 m horizontal resolution. The model had 2 m vertical resolution up to maximum building height, above which grid cells were telescoped vertically, for a total vertical extent of 162 meters. These model dimensions were selected based on computational limits of ENVI-met software and to ensure proper boundaries recommended for urban applications of CFD models. Certain ENVI-met parameters were adjusted to better suit the domain, such as overall heat transfer coefficient for buildings and soil temperature for WRF-initialized simulations.

3. MODEL VALIDATION

A dedicated field campaign was conducted in July and August 2013 in order to obtain observational data for initialization and validation of model, parallel with previous applications of ENVI-met (Chow et al., 2011). Equipment was distributed on campus of DePaul University as displayed in Figure 2.

Observations were scrutinized to determine a suitable period for model validation. Few periods during the experiment satisfied the requirement of steady regional atmospheric conditions, but one such a period did occur on August 17 and 18. A high pressure ridge settled in the region, causing low synoptic gradient winds. These regional conditions are ideal for the establishment of an easterly lake breeze (Laird and Kristovich, 2001), which peaks during the day and ebbs at night, as shown in Figure 3. These relatively steady conditions shifted suddenly at 0100 local standard time (LST) on August 19 with a change in wind direction signifying the passage of a synoptic front. The North American Regional Reanalysis 850 millibars wind vector matches the new southwesterly winds observed near surface.

The front passage significantly affected local conditions. Figure 4 shows the vertical temperature gradient changes, leading to more pronounced stable stratification in the nocturnal urban canopy layer. The stratification inhibits turbulent heat transfer so that sensible heat flux (*H*) approaches zero at both locations of flux measurements (Figure 5). The ENVI-met model cannot capture these modifications of atmospheric stability as well as turbulent fluxes caused by shifting synoptic environment. As such, ENVI-met predictions diverged from observations following 0100 LST August 19.

ENVI-met simulations were tested using initial conditions obtained from observations as well as WRF output at 0.333 km resolution based on grid cell located within ENVI-met domain. Two simulations with 24 hour duration were initialized at 0600 LST on August 17 and 18. The results were then compared with observations as displayed in Figures 6 and 7 for August 17 and 18 respectively. Three measures suggested by Wilmott (1982) were employed to evaluate model performance: root mean square error (RMSE), mean absolute error (MAE), and the index of agreement (*d*). Low RMSE and MAE are preferred, while *d* values approaching 1 indicate perfect model performance. These measures are reported in lower panels of Figures 6 and 7.

The use of WRF model output to initialize ENVI-met led to noticeable improvement of model’s accuracy, as evidenced by lower RMSE and MAE as well as index of agreement closer to 1 at all locations. WRF output is more area-representative than observations, which were taken in vegetated courtyard expected to have a cool bias. As expected at 0100 LST August 19, ENVI-met model predictions begin to diverge significantly from the observations, because regional circulation significantly impacted local conditions, as shown in Figures 7a-b. Figure 7c displays no noticeable change after 0100 LST, which is inconsistent with the micrometeorological changes occurring at all other locations displayed in Figures 3-5. We hypothesize that this difference is due to measurement errors at this one location or a highly local phenomenon which ENVI-met cannot resolve.

4. PEDESTRIAN COMFORT AND CLIMATE CHANGE IMPACT

ENVI-met has the ability to predict the mean radiant temperature (T_{mrt}), one of the most important indicators of human thermal comfort. Other thermal comfort indices such as physiological equivalent temperature (PET) and predicted mean vote (PMV) depend on a number of additional meteorological variables including ambient temperature (T_a), relative humidity, and wind speed. T_{mrt} certainly has the greatest spatial variability within a micro-scale urban area due to complex geometry and heterogeneous surface characteristics. Therefore, the results presented here will be limited to T_{mrt} as well as T_a due to concerns over global air temperature rise associated with climate change.

Future conditions were simulated by using a downscaling procedure similar to that utilized for model validation. The WRF model for upper Midwest was initialized using output from CCSM5 averaged over years 2076 to 2081. Such a procedure tends to average out any year-to-year extremes. The WRF model was run for Chicago area with a resolution of 1 km, which was selected over previously used 0.333 km above because of high computational cost of running entire future year simulations. Output from future WRF model run was averaged over the entire month of August. This average "Future August" day provided initial conditions to ENVI-met. ENVI-met results could then be used to investigate pedestrian comfort through T_a and T_{mrt} contours.

For present conditions, course resolution GCM output was not utilized to determine climatological conditions. Instead the record of the nearest meteorological station to the domain (KILCHICA52 from Wunderground® network) was analyzed to estimate average August conditions within this neighborhood from 2006 to 2013. The overall August average temperature at the station was 23.7 °C, which compares well with August 18, 2013 average temperature of 22.5 °C from same station, within a standard deviation of 5.0 °C. August 18 average values were also within a standard deviation of average August daily high and low temperatures, wind speed, and relative humidity. Therefore, August 18 was taken as a "typical" August day under current climate, which is dubbed "Present August" in pedestrian comfort comparisons.

Simulations for Future and Present August allowed investigation of changes in 2 m T_a at fine resolution over the domain. Figures 8a-c displays color contours of T_a for Present August, Future August, and their difference at 1200 LST. The areas which undergo relatively less heating in the future, as shown by Figure 8c, include the three most highly vegetated areas within domain: DePaul's central quad, Munroe Courtyard (MC), and a park to southwest of domain. The popular UHI mitigation strategy of green space could thus offer even more benefits in future as vegetated areas warm less than the surrounding urban surface types. Another notable feature of Figure 8c is the intense heating in the southwest corner of the domain. The reason for this is changes in the average wind direction between Future and Present August. Mean wind direction is from NE and SE in Present August (Figure 8a) and Future August (Figure 8b), respectively. The mean wind causes advection of near-surface turbulence over vegetated park, resulting in a cooling effect downwind of the park. Therefore, changes in the mean wind direction due to climate change are important for urban planners to consider in the design of green space for maximal cooling effect.

Figure 9 displays the 2 m T_{mrt} for entire domain for Future August at 1200 LST. Clearly T_{mrt} has significant spatial variations with a range of approximately 50 °C and is quite sensitive to the surface type. DePaul's campus is on the average a more comfortable location for pedestrians than residential neighborhood to south due to larger coverage by vegetation and better shading by large buildings. T_{mrt} is at minimum to the north of the buildings due to shade provided, whereas southern facades of buildings have the highest T_{mrt} values. This suggests that constructing buildings with long east-west corridors affords thermal comfort on walkways north of the buildings. Other walkways, especially south of the buildings, must provide pedestrian comfort through strategies like shade from vegetation or alternative walkway coverings. T_{mrt} in Present August does not differ substantially from Future August contour in Figure 9 because T_{mrt} is most sensitive to geometry and materials of surrounding environmental surfaces and incoming solar radiation. These were not changed between Future and Present August as we are only considering changes in meteorological conditions caused by climate change. However, the substantial (~3.5 °C) change in T_a and other environmental factors still result in decreased pedestrian comfort in Future August.

5. CONCLUSIONS AND FUTURE WORK

The nested modeling presented in this paper allows a multi-scale study of UHI and its response to climate change. This combination of global climate, mesoscale, and micro-scale models via dynamical downscaling establishes a comprehensive modeling tool for studying multi-scale phenomena such as UHI. For effects like pedestrian thermal comfort, micro-scale is the relevant scale, which was the focus of this paper. ENVI-met micro-scale model was used, and its evaluation elicited the advantages and disadvantages of its utility in the model chain. Typically, the difficulty of providing proper initial and boundary conditions for micro-scale models, such as ENVI-met, using observations limited at a single-point (or at few points) negatively impacts the model performance. Utilizing output from a mesoscale model provides a more robust source of (spatially averaged) initial conditions as compared to local observations.

Multi-scale model chains offer a plausible and sophisticated pathway for UHI and urban climate change studies. The particular approach used herein can easily be applied in other studies because all presented models are widely available freeware. Furthermore, the approach is portable because the model architecture and equations are universally applicable and requires only minor adjustments of model parameters to suit local conditions. This approach, however, has high computational cost, and other model chains could provide more efficient solutions depending on what UHI problems are being investigated. As numerical modeling capabilities continue to improve at all scales, higher accuracy, lower computational cost, and easier multi-model coupling will allow significant improvements to nested modeling. Multi-scale numerical studies that employ dynamical downscaling, therefore, represent a promising tool for climatologists, meteorologists, urban planners, engineers, and policymakers jointly to evaluate climate change adaptation strategies in urban areas.

In the future, we plan to study climate change impacts on building-scale energy consumption. ENVI-met model output will be applied to a simple building energy model to assess changes in future cooling loads. This development of a parsimonious building energy model, its implementation in ENVI-met, and resultant energy load calculations for future climate is discussed in Conry et al. (2014).

6. ACKNOWLEDGEMENTS

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8. FIGURES

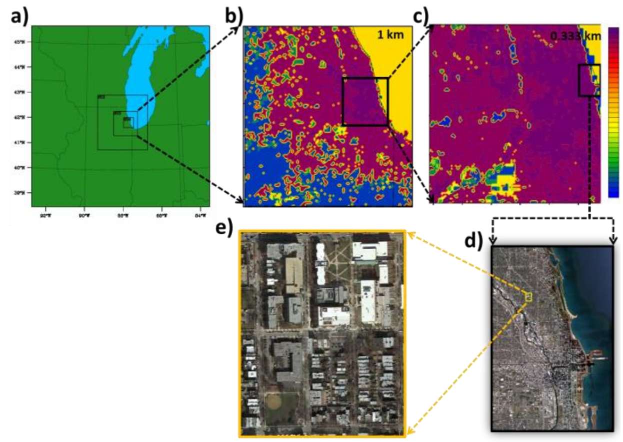


Figure 1: Dynamical downscaling for Chicago area using NARR dataset: (a) configuration of the WRF model domain with nested grid sizes 27 km > 9 km > 3 km > 1 km > 0.333 km for regional climate modeling; (b) Land cover for Chicago metropolitan area at 1 km resolution. Urban area is shown in brown; (c) Innermost 0.333 km very-high resolution regional climate model domain that is to be coupled with a micro-scale model; (d) image from Google maps to show extensive urbanized region surrounding the city of Chicago; and (e) zooming the area of interest for ENVI-met micro-scale model.

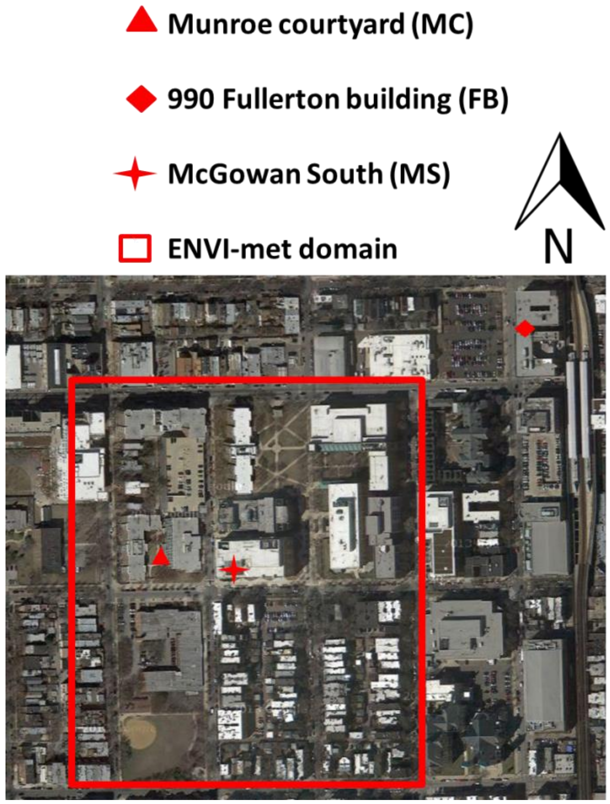


Figure 2: Location of measurement stations used in the field experiment to collect data and validate against regional WRF model and micro-scale ENVI-met model. All three stations are used to initialize ENVI-met model, but only Munroe courtyard (MC) and McGowan South (MS) are within the ENVI-met domain and thus used for validation.

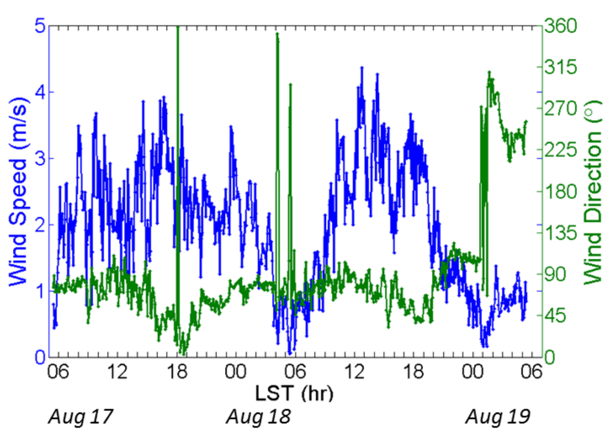


Figure 3: Wind speed and direction from the location FB. Wind direction remains easterly on August 17 and 18, and at 0100 LST on August 19 wind direction suddenly shifts to southwesterly.

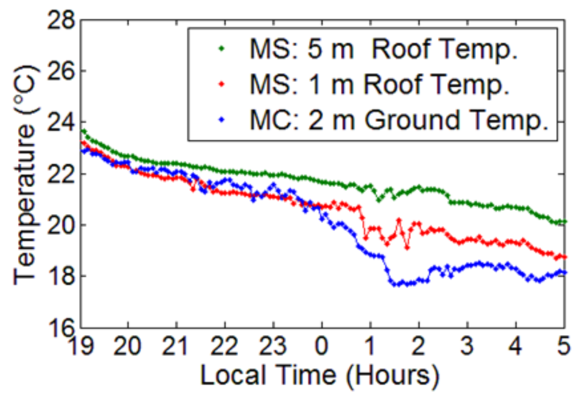


Figure 4: Temperatures at three observational locations. The x-axis ranges from 1900 LST August 18 to 0500 LST August 19. There is a noticeable vertical temperature gradient change at 0100 LST. Decreasing temperature at two locations causes stable stratification, with cooler air at surface and air temperatures rising vertically.

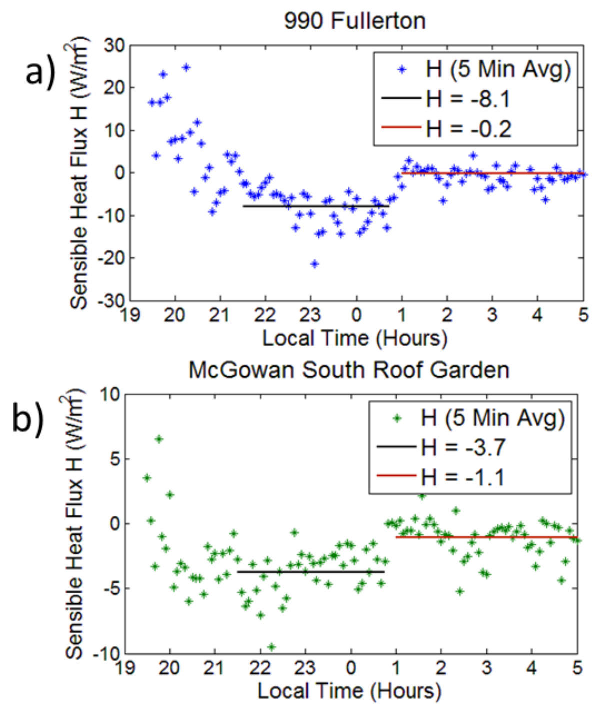
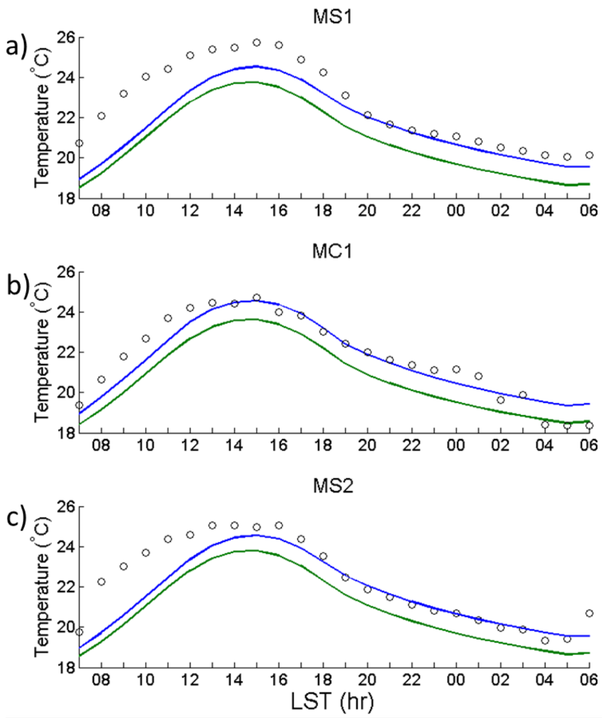
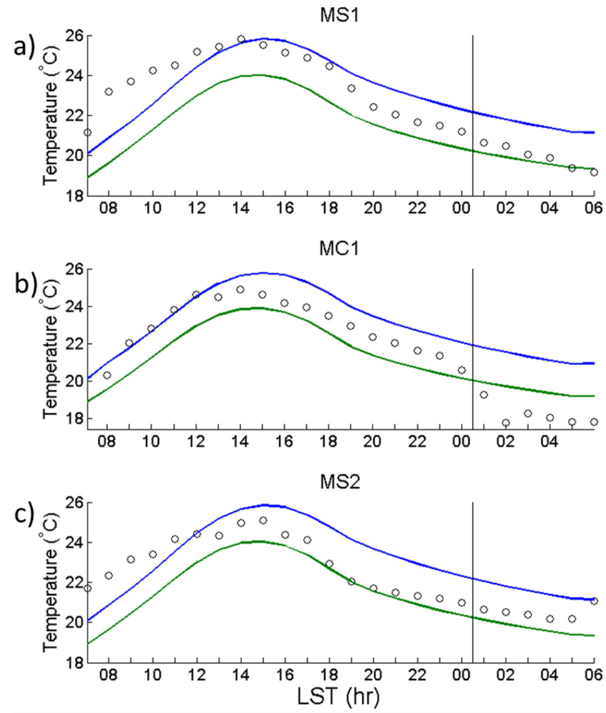


Figure 5: Sensible heat flux (*H*) at MS and FB measurement locations. The x-axis ranges from 1900 LST August 18 to 0500 LST August 19. Sharp shift to magnitudes approaching zero occurs at 0100 LST due to more intense stable stratification. Different *H* magnitudes at two locations are due to presence of roof garden in (b) leading to different partitioning within energy balance at surface because of latent heat flux. Results presented are from 5 minute averaging period of Young 81000 sonic anemometer which collected data with frequency of 20 Hz.



	RMSE (°C)		MAE (°C)		*d*	
Initialization	*WRF*	*Obs*	*WRF*	*Obs*	*WRF*	*Obs*
a)	1.29	1.9	1.01	1.8	0.891	0.802
b)	0.65	1.2	0.52	1.1	0.971	0.907
c)	1.06	1.54	0.72	1.37	0.921	0.855

Figure 6: Comparisons of observations (black) with August 17 ENVI-met simulations initialized by observations (green) and WRF output (blue) for (a) roof garden of McGowan South, (b) Munroe courtyard, and (c) reflective roof of McGowan South. Panel beneath shows difference measures.



	RMSE (°C)		MAE (°C)		*d*	
Initialization	*WRF*	*Obs*	*WRF*	*Obs*	*WRF*	*Obs*
a)	1.13	1.96	0.97	1.77	0.863	0.709
e)	0.99	1.08	0.89	0.98	0.915	0.897
f)	1.38	1.44	1.28	1.12	0.782	0.777

Figure 7: Comparisons of observations (black) with August 18 ENVI-met simulations initialized by observations (green) and WRF output (blue) for (a) roof garden of McGowan South, (b) Munroe courtyard, and (c) reflective roof of McGowan South. Vertical black line indicates a front arriving at approximately 0100 LST. Panel beneath shows difference measures calculated neglecting data to right of the black line.

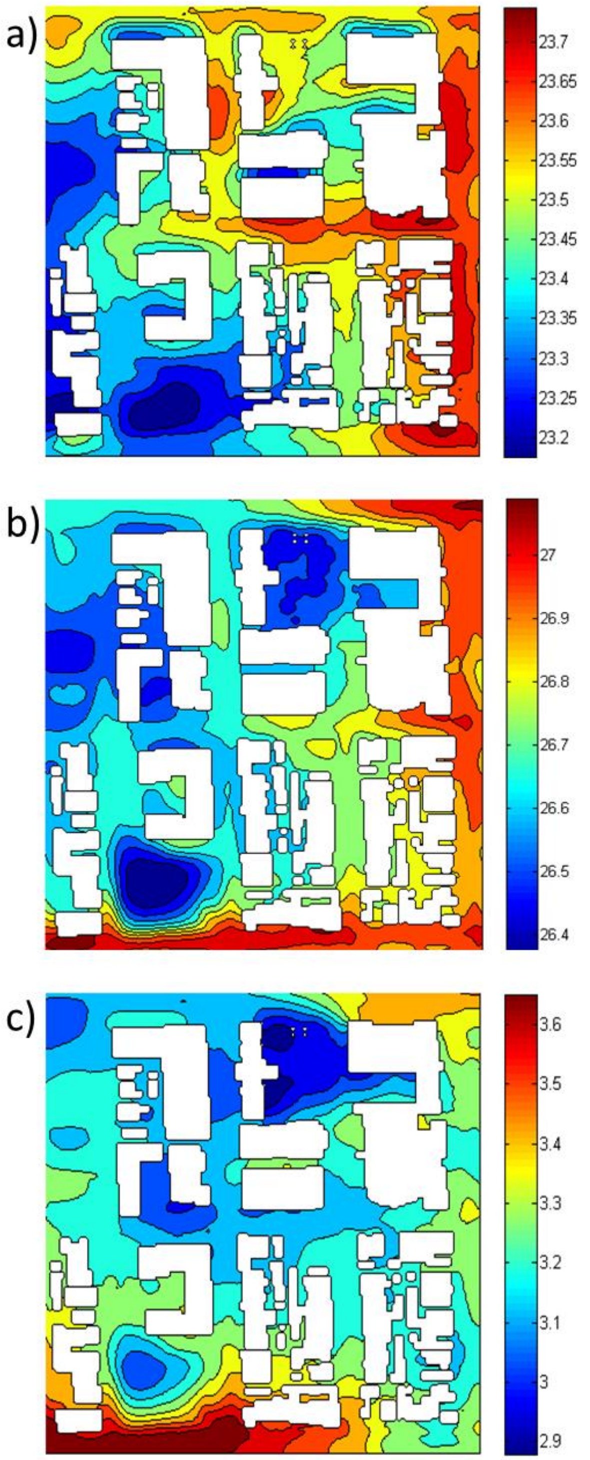


Figure 8: Contours of T_a (°C) at 1200 LST for (a) Present August, (b) Future August, and (c) the difference between them. The buildings are indicated in white.

Figure 9: Contours of T_{mrt} (°C) at 1200 LST in Future August. The buildings are indicated in white.