Characteristics of Heat Wave Impacts for Major Cities in the US under Current and Future Climate Conditions

Adel Hanna[1], Jason Ching[1], Joseph Pinto[2]
1 UNC Institute for the Environment, Chapel Hill, NC, USA ahanna@unc.edu.
2 National Center for Environmental Assessment, US Environmental Projection Agency, RTP, NC, USA

dated : 1 July 2015

1. Introduction

Heat waves are defined as prolonged periods of excessively hot weather, accompanied in most cases with high humidity. Heat waves are measured relative to the usual weather and climate conditions for a specific area so the range of their extremes can vary from place to place. Heat waves are a major source of mortality and morbidity, particularly in urban areas, and are expected to become more frequent and severe in the future. Currently, extreme heat is blamed for an average of 688 deaths each year in the U.S., according to the Center for Disease Control (CDC). However, excess mortality can be much higher during a major heat wave. For example, the Chicago heat wave in the summer of 1995 resulted in 692 excess deaths and sent at least 3300 people to the emergency room with adverse heat related symptoms. Heat waves also incur economic costs due to reductions in labor capacity and crop yields.

Future climates have been simulated for a wide range of scenarios by a large number of global scale models. Because of resource limitations and other reasons, these models are often run at resolutions too coarse (typically ~ 1 X 1 degree) to resolve regional, much less intra-city, differences. To bridge the gap between coarse grid, global-scale models and the need for information at smaller spatial scales, regional scale models whose resolution are typically a few kilometers are used. Even this resolution is not sufficient to capture the spatial variability in urban heat islands across urban areas. Stewart and Oke (2012) developed the Local Climate Zones (LCZs) system that provides a framework for urban heat island studies by mapping different cities in terms of nine local climate zones based on building types and land cover types. Obviously there is a need to connect the information that is being modeled by the regional models and the urban characteristics needed for examining heat wave impacts.

We simulated current (2003) and future (2050) climate scenarios using WRF (at 12 km horizontal resolution) nested within the Community Climate Model System (CCSM) over the eastern half of the U.S. We then proceed to examine the intra-urban differences on heat stress using LCZs for two cities in the U.S. (Chicago and Atlanta). We use the wet bulb globe temperature (WBGT) to characterize heat stress as it is widely used around the world (given by ISO 7243). The WBGT is used as a basic measure of heat stress by a number of organizations and is the only heat index to have known thresholds relating directly to levels of physical activity.

2. Global/Regional Modeling and Downscaling

In our modeling study we simulated the months of May, June, July, and August of the years 2003 and 2050 to represent current and future climate conditions. A 10-day (April 21-30) spin-up model simulation preceded the first day of the May simulation for each year. We used dynamical downscaling of the CCSM meteorological outputs to provide initial and boundary conditions for WRF at the 36-km grid resolution, as described below (Figure 1a). This version of CCSM is described in Collins et al. (2006). We used the Special Report on Emission Scenarios (SRES) A1B-driven CCSM results used for IPCC AR4 on a T85 Gaussian grid as inputs into WRF. These files were obtained from Earth System Grid, and the atmospheric component of CCSM had 6-hour temporal resolution, while the land model had a 1-month temporal resolution. Figure 1b shows LCZ classes for several cities (including Chicago) around the world.

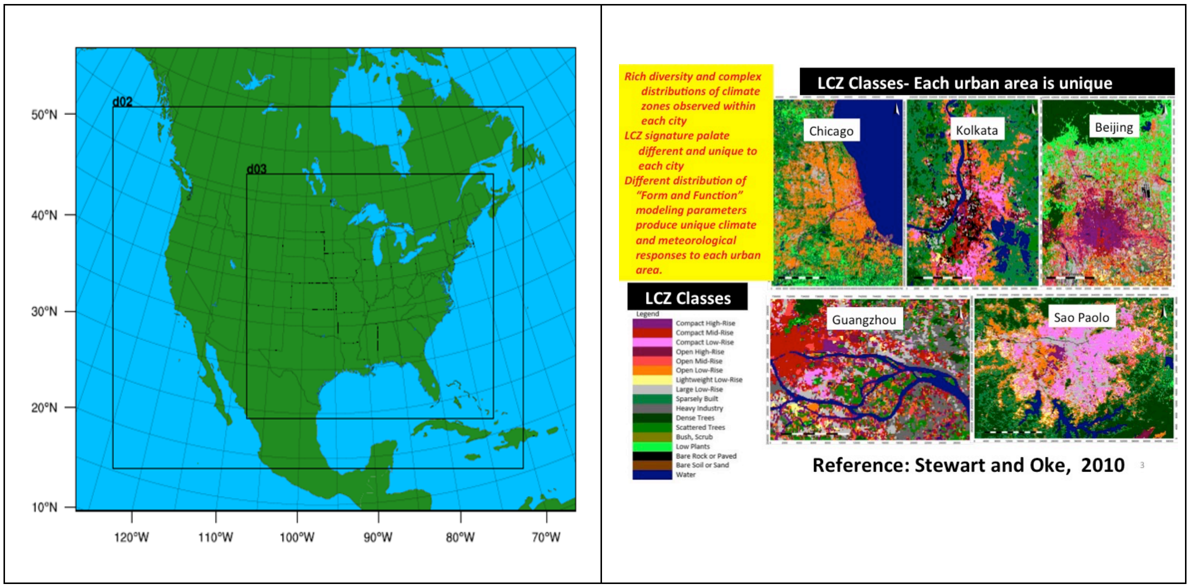


Figure 1. a) Modeling configurations domain 108 km (domain d01), 36 km (domain d02), and 12 km (domain d03); b) LCZ classifications for a few urban areas

Figure 2 shows that the large-scale synoptic features present in the CCSM outputs (surface temperature, winds and sea level pressure) translate reasonably well to the WRF (both at d01, or 108 km). However, CCSM portrays a stronger southerly flow in association with the Bermuda high, with a more uniform zonal (east-west) orientation of the pressure pattern and warmer central US than the WRF.

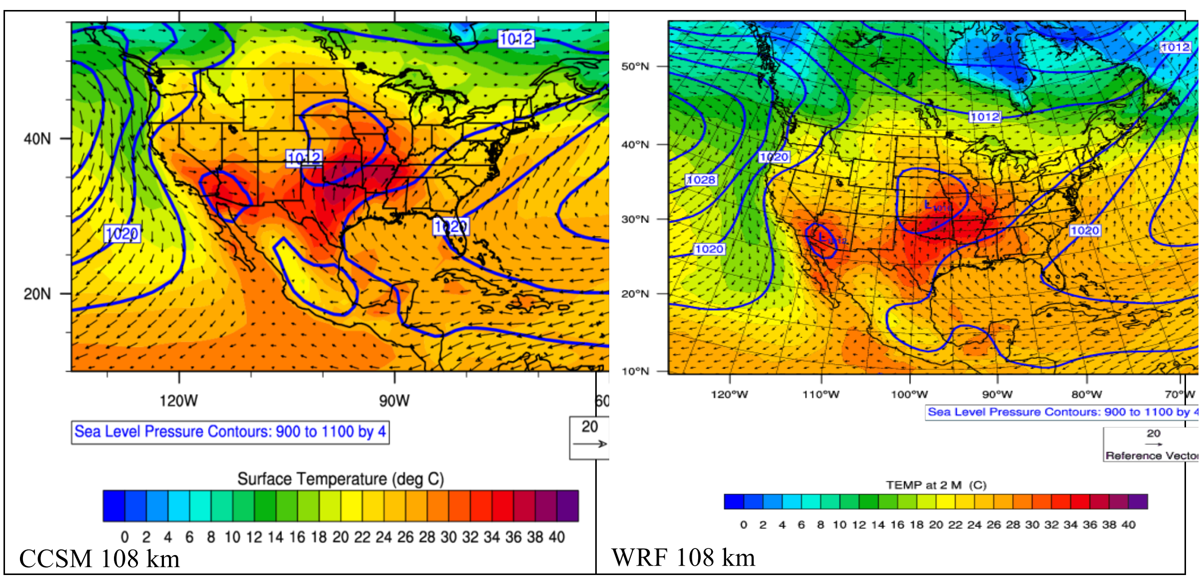


Figure 2: CCSM to WRF downscaling, July (2003) average 2m temperature (degree C), 10 meters wind (m/s), and sea level pressure (mb)

3. Local Climate Zones (LCZs)

Local Climate Zones (Stewart and Oke, 2011) are defined as regions of uniform surface cover, structure, material, and human activities that could span hundreds of meters to several kilometers in horizontal scale. Classifications of building types characterize locations based on building heights, material and land covers. Those are further differentiated according to 1) geometric and surface cover properties (Sky View Factor – SVF, aspect ratio, building surface fraction, Impervious surface fraction, height of roughness elements, and terrain roughness); and 2) thermal, radiative, and metabolic properties (surface admittance, surface albedo, anthropogenic heat output). Note that each urban area is different (see for example, Figure 1b) in the range and relative proportion of LCZs.

4. Wet Bulb Globe Temperature

A variety of temperature metrics (indices) exist for assessing the impacts of heat waves. In this study we use the wet bulb globe temperature (WBGT) to assess heat waves under current and future climate conditions for Chicago and Atlanta in the U.S. The WBGT is calculated using the equation:

$$WBGT= 0.7WBT+0.1T_d+0.2\ T_{Globe}$$

$$T_{Globe}= T_d + 0.017S- 0.208\ U + 0.5$$

where WBT is the wet bulb temperature; T_d is the air temperature (also known as the dry bulb temperature) at a reference level of 2m; and T_{Globe} is the temperature from a black globe thermometer measuring solar and other ambient radiation to represent the temperature at which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. This term is related to incoming solar radiation (S) absorbed by the surface, which could be affected by the presence of clouds, building heights, and land surface characteristics in urban areas. U is the wind speed (m/s). WBT was calculated using the equation given by (Dunne et al., 2013). We adopt the calculation of T_{Globe} used by Kusaka et al. (2011) in this study. For calculating T_{globe}, the incoming solar radiation (S) is one of the outputs of the WRF model. U was assumed to be 1 m/s.

5. Results and Discussion

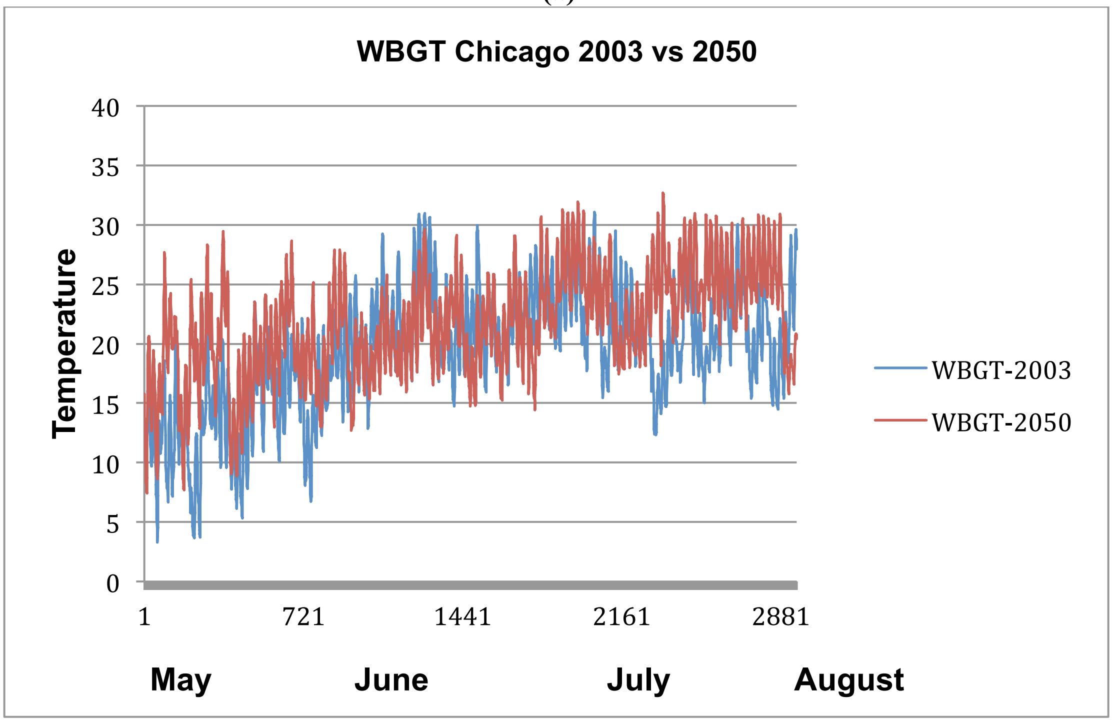
For each of the cities in this analysis (Chicago and Atlanta) we have hourly time series (starting May1 at 00Z to August 31 at 2300Z) output of basic model variables for the grid box (12km x 12km) representing each city for years 2003 and 2050. Figures 3a and 3b show the hourly distribution of WBGT (°C) for Chicago and Atlanta respectively during the period May 1 to August 31 for the years 2003 and 2050. The general trend of warming for year 2050 is noticeable in both cities, with a tendency for Atlanta to potentially reach a higher number of heat stress-related health impacts.

Figures 4a and 4b show differences in WBGT between 2003 and 2050 for Chicago and Atlanta, respectively. As can be seen, there is an overall increase across the distribution for both cities from 2003 to 2050. Values are summarized in Table 1. These values were calculated based on an SVF of one, using the characterization of land surface cover in WRF for the grid cell over the city center. Figure 5 shows the sensitivity of WBGT to sky view factor (SVF) in the range from 0 to 1 for the simulation for Chicago 2050. As can be seen from the figure, the maximum difference is about 3.5 degrees Celsius.

Table 1: Values shown in Figure 4

	Chicago		Atlanta	
	WBGT-2003	WBGT-2050	WBGT-2003	WBGT-2050
Min	3.3	7.4	7.7	12.4
Q1	16.4	18.6	20.3	21.7
Q3	23.0	24.7	26.8	27.4
Max	31.1	32.6	32.5	33.4

(a)



(b)

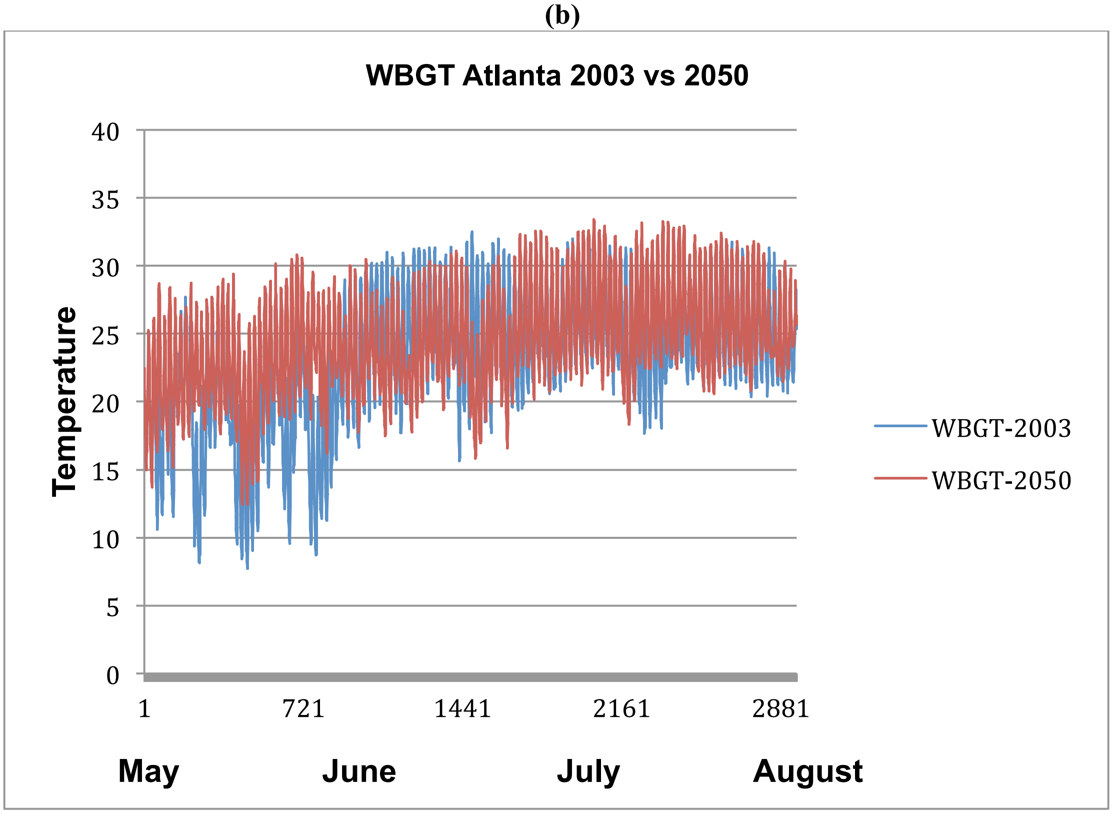


Figure 3. Hourly time series of WBGT (°C) calculated using the WRF outputs (for the period May 1, August 31) for years 2003 and 2050 for a) Chicago and b) Atlanta U.S.

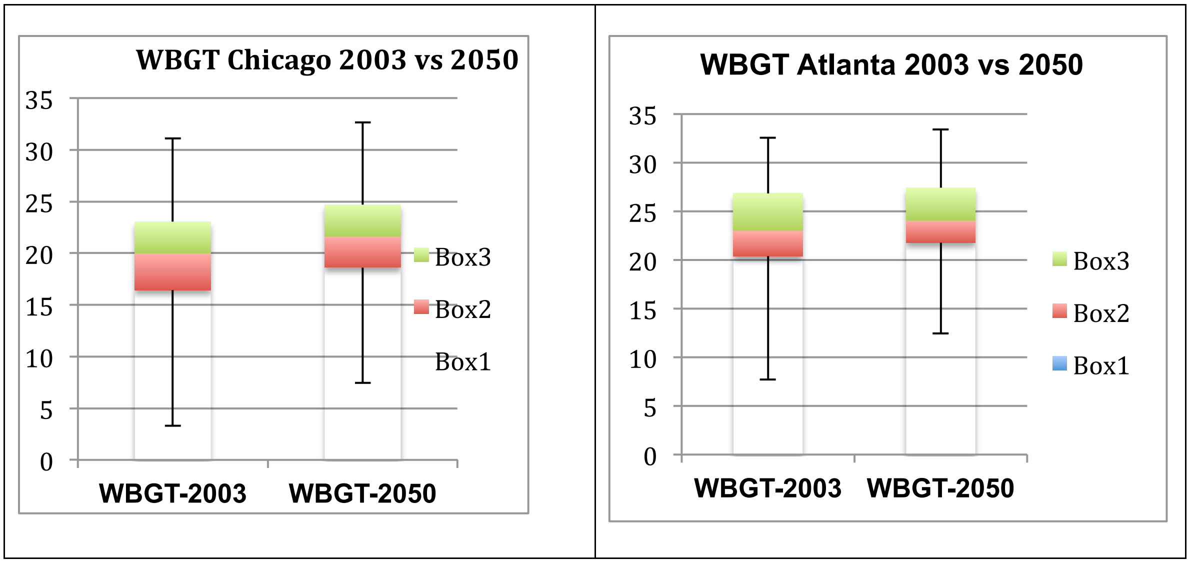


Figure 4. Differences in WBGT between 2003 and 2050 for Chicago and Atlanta.

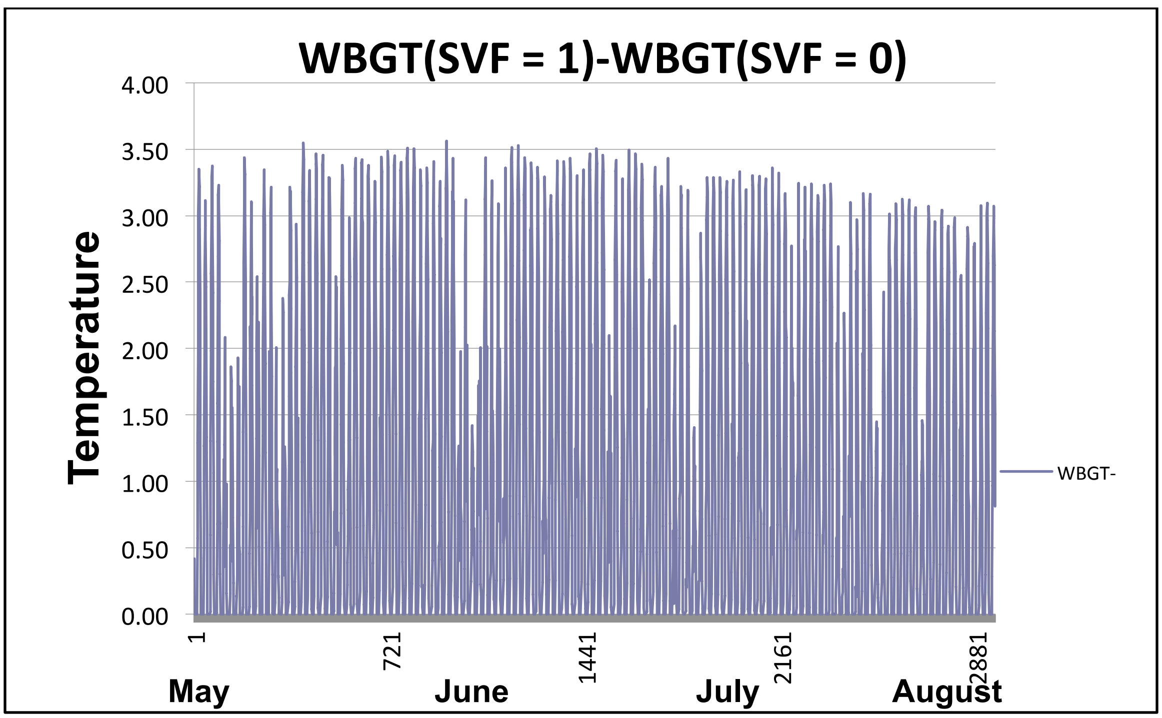


Figure 5. Range of the effect of LCZ (based on Sky view factor) on Chicago WBGT and Atlanta WBGT during 3033 and 2050.

6. Summary and future plans.

This pilot study was designed to explore heat stress indices for current and mid century climate prediction scenarios for two cities, Chicago and Atlanta. It utilized offline outputs of meteorological variables from 12 km grid regional mesoscale prediction model simulations as inputs to the heat stress indicator, WGBT. Within (subgrid) heat stress variability for the urban grid cell was diagnosed as sensitivity in the WGBT formulations through the potential range of SVF values 0 to 1. The results show (a) a climate change signal, showing higher heat stress in the 2050 simulations for both cities, (b) synoptic responses between the base and future year for each city differed during the 4 month period, and (c) significant diurnal variabilities in WGBT for both cities, and significant range of intra-urban variability due to potential range of SVF that may exist in an urban grid cell. This methodology demonstrates that when using WGBT as a heat stress index, the use of regional scale modeling is appropriate for practical operational purposes. We will continue to explore and compare results for other cities and the impact on mortality and morbidity.

We will also pursue fine grid heat stress assessments using finer grid simulations as was performed for Japanese cities (Kusaka et al., 2012). That investigation was performed using urbanized WRF model with 3-km grids. Given the value of such an approach, it is conceivable that models can be set up with fine grids anywhere in the world for present and future climate change conditions. In this regard, we anticipate the utilization of results from WUDAPT to provide a modeling database for fine to mesoscale meteorological models for general worldwide applications. Implementation of WUDAPT (World Urban Database and Access Portal Tools, http://www.wudapt.org/) is currently underway (Mills et al., 2015, Ching et al., 2014, 2015). WUDAPT will collect, generate and provide gridded mesoscale model-ready urban canopy parameters, including buildings, street canyon, impervious and vegetative surface fractions, surface roughness and reflectivity details, anthropogenic heating, and sky view factor (SVF) for all the world's major cities (with resolution of 120m). This provides an opportunity to perform urban applications to address requirements associated with assessing heat stress risks to human health and morbidity for all cites, worldwide at both high as well as coarse resolution grids. Of relevance to coarse grid operational modeling for heat stress as explored here, intracity SVF values are expected to vary considerably throughout the city. With WUDAPT, the within grid heat stress index in operational models could be spatially conditioned (weighted) with the spatial maps of SVF at the higher resolutions, enhancing its benefits for heat tress advisories, and for assessing of impacts on mortality and morbidity. Eventually, it is envisioned (Ching et al., 2015) that applications using portals can be designed to run models for heat stress impacts in coarse and fine mesoscale context, or climate models that can set the stage for future climate scenarios applicable anywhere on the globe.

6. References

Ching, J, Mills, G., See, L., et al., 2014: WUDAPT: Facilitating advanced urban canopy modeling for weather, climate and air quality applications. *Proceedings, 94th American Meteorological Society Annual Meeting*, Atlanta, GA.

Ching and others, 2015: The Portal component, strategic perspectives and review of tactical plans for full implementation of WUDAPT, *Proceedings, GD2-ICUC9*, Toulouse, Fr

Dunne, J.P., R.J. Stouffer and J.G. John, 2013, Reductions in labour capacity from heat stress under climate warming, Nature Climate Change, 3, 563-566.

Kusaka, H., M. Hara, and Y. Takane, 2012, Urban climate projections by the WRF model at 3-km horizontal grod increment; Dynamical downscaling and predicting heat stress in the 2070's August for Tokyo, Osaka, and Nagoya Metropolises. *J of the Meteor. Soc. Of Japan*, 90B, pp 47-63. Doi: 10.2151/jmsj, 2012-B04

Mills, G., Ching, J., See, L., Bechtel, B., 2015: An introduction to the WUDAPT project, *Proceedings, GD2-ICUC9,* Toulouse, Fr.

Stewart, I.D. and T. Oke, T., 2012, Local Climate Zones for urban temperature studies, *Bul. Amer.. Met. Soc. (BAMS)*, Dec2012, pp1880-1900. DOI:10.1175/BAMS-D-11-00019.1

Merino, L, E. Antaluca, B. Akinogulo, and B. Deckers, 2010, Solar Energy inputs estimation for urban scales applications. 8th Inter. Conf. on System simulation in buildings, Leigo, Dec 13 -15, 2010.

Acknowledgement:

Part of the research presented here was funded by EPA STAR grant R832751010. The views expressed are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.