Impacts of projected urban expansion and global warming on cooling energy demand over a semiarid region

Mukul Tewari,1* Francisco Salamanca,2 Alberto Martilli,3 Lloyd Treinish1 and Alex Mahalov2
1The Weather Company, IBM Thomas J. Watson Research Center, Yorktown Heights, New York, NY, USA
2School of Mathematical and Statistical Sciences and Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ, USA
3CIEMAT, Madrid, Spain

*Correspondence to: M. Tewari, The Weather Company, IBM Thomas J. Watson Research Center, I 101 Kitchawan Road, Yorktown Heights, New York, NY 10598, USA.
E-mail: mukul.tewari@weather.com

Abstract

Large impacts of global warming and urbanization on near-surface air temperature increase and cooling energy demand are expected for the American Southwest region. The relative importance of these two features and their interactions are studied by means of a mesoscale model with a multilayer building energy model that allows accounting for the feedback between cooling energy consumption and air temperature for a typical summer period in Arizona. This approach allows to separate the impact of global warming from the one due to urbanization, on energy demand and air temperature. Under the highest greenhouse gas emissions scenario (RCP8.5), adverse effects on mean air temperature of global warming overwhelm those from the urbanization of new areas. In particular, the mean temperature increase for a summer period due to global warming and urban expansion in the Phoenix metropolitan area is 3.6 °C and in the Tucson metropolitan area, it is 3.1 °C. These result in an increase in the spatial density of the cooling energy demand (MW km⁻²) by 36.2 and 42.6% in the respective regions compared to present consumption. The citywide cooling energy demand (MW) on the other hand, is expected to increase up to a factor two (Phoenix) and three (Tucson), with ~75% of this increase due to urban expansion, and ~25% due to global warming.

Keywords: global warming; urbanization; mesoscale

1. Introduction

Expeditious population expansion (40.0 and 24.6% between 1990–2000 and 2000–2010, respectively, Mackun and Wilson, 2011), and the harsh summer conditions of Arizona make this region obvious candidate for the evaluation of the cooling energy demand in the future under the global warming scenarios. The mounting concerns of power consumption, especially during the summer, become increasingly conspicuous due to urban expansion, increase of minimum temperature, and the excessive use of air conditioning systems in this region (see Figure 1, Georgescu et al., 2012; Salamanca et al., 2013). The projection for the increase in population in Arizona is associated with landscape modification in future decades (2050 state estimates range between 8 and 16 million of total people, Marshall et al., 2010). This increase in population will be associated with the conversion to engineered, impervious surfaces, which would eventually contribute to the worsening of the thermal comfort and associated cooling power consumption increase, especially during the summer. These features, together with the availability of a wide variety of data (dense meteorological network for model validation, observed city-wide electricity consumption, detailed projections of urban expansion) make this region a prototypical case to investigate how the interaction between global warming and urbanization affects air temperature and cooling energy demand for a typical summer period. The complexity of the problem lies in the feedback between outdoor temperature and space cooling energy demand, given that air conditioning devices, while they are cooling inside of buildings, heat the atmosphere. To account for this two-way feedback, a mesoscale atmospheric model coupled to a detailed multilayer building energy parameterization (composed of a simplified building energy model integrated into a multilayer urban canopy model), is used in this study. Earlier studies conducted future urban climate projection by dynamical downscaling with regional climate models (e.g. Hamdi et al., 2014 in European cities, Kusaka et al., 2012, 2016 in Asian cities and Argüeso et al., 2015 in Australian cities). However, they did not analyze the impact on urban energy demand. The atmospheric model used in the present study is run at very high horizontal resolution (1 km) to represent the future city expansion scenarios, and to capture the intra-urban variability, due to the different types of urban classes (i.e. low intensity residential, high intensity residential and commercial or industrial), of the air temperature and cooling energy demand (Figure S1, Supporting information). Moreover, given that the atmospheric model can provide a spatial distribution of cooling energy demand on an hourly basis, the diurnal cycle of electric power consumption is characterized at the
Figure 1. (a) Diurnal cycle of observed total electricity demand across the Phoenix metropolitan area for all weekdays (i.e. each DXY curve represents a particular weekday) of the 15-day summertime period in June 2012. (b) Same as in (a) but for 2-m urban air temperature.

City scale. This is an advancement compared to previous studies that used a much coarser spatial resolution (20 km) and did not consider building energy models to estimate the energy demand, or that did not account for the feedback between energy demand and air temperature (Georgescu et al., 2012). One caveat of the present study is that we assumed the cooling technologies would remain the same as today through the end of the century.

2. Methodology and numerical experiments

Kusaka et al. (2012) studied the projected urban climate for the 2070s’ August in the three largest urban areas, Tokyo, Osaka, and Nagoya in Japan with a single-layer urban canopy model (Kusaka et al., 2001). For the present work, we used Weather Research and Forecasting (WRF) model ARW (Advanced Research WRF) core (version 3.7.1, Skamarock and Klemp, 2008) with the coupled Multi-layer Urban Canopy Model (BEP) and Building Energy Model (BEM) (BEP_BEM, Salamanca and Martilli 2010, Salamanca et al., 2011 and Salamanca et al., 2016). BEP_BEM is a multilayer building energy model fully integrated in the WRF model that resolves the exchanges of heat between the buildings and the outdoor environment. We have used NCEP (National Centers for Environment Prediction) Global Forecast System (GFS) initial and boundary conditions at 1° × 1° grid spacing to initialize the atmospheric WRF model. Fifteen days of numerical simulations (starting on 15 June 2012, 0000 UTC) are performed using a very high spatial resolution (1 km) nested domain for the present day as well as for the future warmer period. The 1 km nest resides within two parent domains of 9 and 3 km of horizontal grid spacing, respectively. The numerical experiments performed and the urban morphological parameters used in this study are documented in Tables S1 and S2, respectively (see Supporting information).

We use a pseudo global warming (PGW) approach, which was originally developed by Kimura and Kitoh (2007) and later used by Rasmussen et al. (2011). The method consists of adding a climate perturbation signal to a contemporary high-resolution analysis of the atmosphere for the future period of interest. The steps needed to generate the data for the 15-day period of control and future simulations are as follows,

a. Generate a control run by forcing a high-resolution WRF-ARW positioned over subcontinental North America with the NCEP GFS reanalysis for the 15-day (present day) simulation.

b. Generate monthly climate perturbations by subtracting the current climate state (1985–2005) from the monthly mean fields for a given 21-year future period (2070–2090) projected by the Community Climate System Model (CCSM4; Gent et al., 2011; http://rda.ucar.edu/datasets/ds316.1/) under the RCP8.5 emission scenario. The monthly
mean fields of the given 21-year period will provide the climate signal which is used for the perturbation of present day forcing data to generate forcing data for future warm period simulations.

c. Next, we generate a pseudo-future run by embedding future urban projections into the future simulations for a 15-day period, which represents a typical clear-sky summer period over Arizona.

The climate perturbation’s primary impact is on the large-scale planetary waves and associated thermodynamics, while the weather patterns entering the domain boundary remain structurally identical in both simulations in terms of frequency and intensity. The weather events, however, can evolve within the regional model domain due to the altered planetary flow and thermodynamics (Rasmussen et al., 2011). The climate change projections from global circulation models (GCMs) have their own uncertainties, which could be minimized by using ensemble mean of many climate model simulations, but we expect (also expressed in Rasmussen et al., 2011) that the general feature of the climate signal will be the same.

Figure S2 shows land use-land cover (LULC) maps for the present day major cities of Arizona and their projections near the end of the century (2070). These maps are created from the US Geological Survey’s National Land Cover Database (Fry et al., 2011) to represent the urban landscape of present-day central Arizona (a and b) and from the Integrated Climate and Land Use Scenarios (ICLUS) project (U.S. Environmental Protection Agency, 2009; Bierwagen et al., 2010; Salamanca et al., 2015) to represent future Arizona (c and d) under a low-expansion scenario (LULC_Lo) and (e and f) under a high-expansion scenario (LULC_Hi). The urban areas are categorized as low-intensity residential, high-intensity residential, and commercial or industrial urban categories in these LULC maps, which are ingested in the WRF model (Martilli et al., 2002; Skamarock and Klemp, 2008; Salamanca et al., 2011). In the future projections, most of the areas that are urban in the present day, are unchanged in the LULC_Lo scenario and become high-intensity residential or commercial in the LULC_Hi projection.

Six numerical experiments (see Table S1 for experiment design, and Table S2 for physics configurations) have been performed. Three of them are for the present summer, with actual urban expansion, low aggressive and high aggressive urban projections, and other three are for the future summer period, with the same three urban scenarios.

3. Results and conclusions

To gain confidence with the WRF-urban modeling system and its predictions for the future, its performance under actual conditions for near-surface air temperature, near-surface wind speed, wind direction, and cooling energy demand have been evaluated (hereafter denoted as CTRL_P-experiment). We found (see Figures S3–S5) that the hourly modeled 2-m air temperature, 10-m wind speed, and 10-m wind direction obtained from CTRL_P-experiment compares well to the observations (the mean absolute error was 1.8°C in the urban areas and 1.5°C in the rural areas, refer Table S3) and is well-suited for the other numerical experiments (refer Table S1). For the assessment of the air-conditioning (AC) electricity consumption (i.e. cooling energy demand), citywide observed cooling load values hourly supplied by an electric utility company are compared to the CTRL_P-experiment. Figure 1(a) shows the observed diurnal profiles of total electricity demand (for the Phoenix metropolitan area) for the weekdays of the CTRL_P-experiment (15-day period of June 2012 except for two weekends 16–17 June and 23–24 June). A significant variability in the electricity consumption is apparent, however, the shape of the diurnal variation remains similar. Figure 1(b) shows the observed 2-m urban air temperature for the same days. The total electricity demand is related to air temperature (see Figures S6 and S7 for more information) but there is an important component that depends on the human behavior and represents the electricity consumption that is not directly linked to meteorology. In other words, the observed cooling (i.e. AC) electricity demand is not the same as that of the total electricity demand. The observed AC electricity demand was calculated based on two different methodologies to estimate the human behavior component (Salamanca et al., 2013). Minimum observed electric loads occur during March and November (for the Phoenix metropolitan area) coinciding with moderate environmental conditions. To estimate the diurnal profile of electricity consumption linked to human behavior two approaches were considered for March (hereafter denoted as M1 and M2) and November (hereafter denoted as N1 and N2) assuming that heating and cooling is relatively small (negligible) for these months.

For the first method, the day with the minimum total load and the day with the minimum hourly load range (i.e. the difference between the maximum and the minimum hourly loads) for the entire month were selected. Human behavior consumption was calculated as the hourly means of both days. For the second method, the minimum hourly load (across the entire month) was selected for each hour of the day, generating a 24-h period that included observed load values from different days. Once the consumption of human behavior is determined, one can subtract it from the total electricity demand to obtain the observed AC electricity consumption. In our case, we considered the mean diurnal profile of the weekdays showed in Figure 1(a) (for the total electricity demand) and then compared the results (curves M1, M2, N1, and N2 in Figure 2) against hourly modeled (CTRL_P-experiment) AC energy consumption values. In spite of observed variability (which was as much as 500 MW) among different methods to estimate the component of human behavior consumption, there was a reasonable agreement...
between the CTRL_P-experiment with the observations (Figure 2). Hence, there is confidence in using the BEP_BEM urban modeling system fully integrated into WRF to assess energy demand for cooling in a future warm period. Figure S1 shows the diurnal mean profiles of modeled AC electricity consumption (MW km$^{-2}$) averaged for the entire 15-day clear-sky summertime period for each urban category for the control experiment for Phoenix and Tucson metropolitan areas. The high-resolution simulation shows that commercial or industrial urban type has the highest AC energy consumption (about 4 MW km$^{-2}$ higher than the peak for low intensity residential type in the Phoenix and Tucson metropolitan areas), mainly because the building density is higher, and hence, the volume of indoor air to cool is larger. It is important to note that hourly AC energy consumption, while obviously influenced by air temperature, is not fully determined by it. For the same near-surface air temperature, the total citywide electricity consumption can vary quite significantly by as much as 3000 MW for Phoenix metropolitan area (see Figures S6 and S7). Based on our simulations, (Figures 3(a) and (b): impact of global warming, Figures 3(c) and (d): impact of urban expansion, Figures 3(e) and (f): impact of urban expansion and global warming), we found that there are about a 3.3 and 3.0 °C rise in daily averaged 2-m air temperature by the year 2070 due to global warming alone in the Phoenix and Tucson metropolitan areas, respectively (see Table S4). The contribution in temperature at the American Southwest region, due to urbanization, is much smaller than due to the global warming, which is similar to the results reported by Yang et al., 2016 in the Beijing metropolitan area, despite significant differences in both the climatic conditions and scale of the urbanization in that region. When the effects of urban expansion under the most aggressive development scenario and global warming are combined, the rise in daily averaged 2-m air temperature, averaged over the whole urban area, is about 3.6 and 3.1 °C for the Phoenix and Tucson metropolitan areas, respectively (see Table S4). If only the urban expansion is considered, the spatial mean temperature increases in the Phoenix metropolitan area by about 0.2 °C for both projected development scenarios.

For the Tucson metropolitan area, the mean height above sea level of the projected urban expansion scenarios is higher (~50 m) compared to the present day urban landscape, which reduces the mean urban warming due to urban expansion alone. Moreover, as shown in Figure 3, the spatial distribution of the temperature increase is very different for the two phenomena. While global warming determines a rather homogeneous increase of temperature in the city and surrounding rural areas, the increase of temperature due to urban expansion is distributed unevenly through the city, with maximum increases of 2–3 °C in the newly urbanized regions of Phoenix (Figures 3(c) and (d)), that are expected to undergo a temperature increase almost double compared to the one for already urbanized areas (5.5–6.0 °C vs 3.5–4.0 °C), and slightly less for the Tucson metropolitan area (4.5–5.0 °C vs 3.5–4.0 °C) when both global warming and urbanization are taken into account. A similar, but more pronounced trend is modeled for minimum temperatures (see Figure S8). If a certain location is changed from rural to urban, due to the urban heat island, the mean air temperature for that location will increase considerably. The results show that the maximum temperature does not change significantly due to urbanization in contrast to the minimum temperature that shows a much more significant rise (see Figure S9). Regarding the total, citywide energy consumption for space cooling (Table 1), urban expansion is the main driver, generating about 75–77% of the increase, while global warming is responsible for 23–25% of the increase for both LULC_lo and LULC_hi urbanization scenarios for Phoenix and Tucson regions. Without the urban expansion, the energy consumption for cooling would increase by 19–21% due to global warming alone. On the other hand, the energy demand per unit area for cooling considering both global warming and urban growth increases more due to global warming than urban expansion. Focusing on the time evolution of the cooling energy demand per square kilometer (Figure 4), the increase due to global warming is relatively constant across the diurnal cycle (CTRL_F-CTRL_P black lines). The increase in the cooling energy consumption due to urbanization is stronger close to the time of the afternoon peak load. This effect is linked to the urbanization pattern (percentage of low- and high-intensity residential, and commercial areas), which is projected to change in the future. This characterization may be useful for

![Figure 2. Diurnal mean AC electricity consumption (MW, across the Phoenix metropolitan area) computed with CTRL_P-experiment (black curve) and with the four methodologies (M1, M2, N1, and N2 curves) to estimate the human behavior consumption component during the clear-sky 15-day summertime period in June 2012.](image)
planning the grid infrastructure. Moreover, for Tucson, the increase in cooling energy consumption per square kilometer is about 6% higher than in the Phoenix metropolitan area, which may be attributed to the different projected urbanization patterns (Table 1, Figure 4). Tucson (TUC) shows more relatively high-intensity residential areas in the future than Phoenix (PHX) compared to present day. The different repartitioning between the urban classes could be the major cause of the increase in the cooling energy consumption rather than the stronger UHI for the urban expansion scenarios. Although both metropolitan areas share the same semiarid climate, modeled profiles of AC electricity consumption (MW km\(^{-2}\)) showed higher values for the Phoenix region (Figure 4). In general, Tucson records lower temperatures because it is about 400 m

**Figure 3.** (a,b) Modeled mean 2-m air temperature difference \(T_{2m}(\text{CTRL}_F) - T_{2m}(\text{CTRL}_P)\) averaged for the entire 15-day summer-time period for Phoenix (left) and Tucson (right) regions, respectively. (c,d) Same as in (a and b) but for \(T_{2m}(\text{HIGH}_P) - T_{2m}(\text{CTRL}_P)\). (e and f) Same as in (a and b) but for \(T_{2m}(\text{HIGH}_F) - T_{2m}(\text{CTRL}_P)\). The figure is generated using the NCAR command language (version 6.3.0) [Software]. (2015). Boulder, Colorado: UCAR/NCAR/CISL/TDD. http://dx.doi.org/10.5065/D6WD3XH5.
higher than the Phoenix metropolitan area. There are some limitations of the current study that need to be commented,

1. We generated future climate conditions using CCSM4 data. There could be uncertainties in using a single model as compared to the ensemble of climate projections generated from different GCMs.

However, as indicated by Rasmussen et al. (2011), general features of the climate signal are expected to be similar and hence the general conclusions derived from the data of a single GCM may not alter the results significantly.

2. A short simulation period of 15-day for current and future climate was considered for the present study. Since these are clear sky days and are representative of a typical summer time period we think that the results would provide guidance to the longer-term simulations, which are planned as a future study.

The main findings of this study are summarized as follows:

1. In average, over the city, the contribution to temperature increase at the American Southwest region by urban expansion is much lower than that due to global warming. However, locally, and in particular in the newly urbanized areas, the contribution of urbanization is comparable to the one of global warming, both for the daily mean and – even more remarkably – for the minimum temperature.

Figure 4. (a) Diurnal cycle of modeled air-conditioning electricity consumption (MW km$^{-2}$ of urban land) averaged for the entire 15-day summertime period and across the Phoenix metropolitan area. (b) Same as in (a) but for the Tucson metropolitan area. (c) Diurnal cycle of modeled air-conditioning electricity consumption differences across the Phoenix metropolitan area. (d) Same as in (c) but for the Tucson metropolitan area.
2. Urban expansion is the main driver for the total, citywide daily energy consumption for space cooling. About 75–77% of the increase comes from the urban expansion, while global warming is responsible for 23–25% of the increase for both LULC_lo and LULC_hi urbanization scenarios projected for Phoenix and Tucson regions.

3. The increase in the local consumption for space cooling (MW km⁻²) due to urbanization is stronger close to the time of the afternoon peak load, which is linked with the different projected urban morphology. Such information is useful for the energy sector for the future planning needs. On the other hand, the energy increase (for space cooling) due to global warming is relatively constant across the diurnal cycle.

4. Both Phoenix and Tucson belong to the same semi-arid climate but their projected cooling energy demand increase is different which is attributed to the urbanization pattern, although Tucson shows lower temperature increase as compared to the Phoenix metropolitan area. This dependency on urbanization pattern is particularly important because it indicates that with a careful planning of the type of new urban areas (more or less compact, for example) the increase of energy demand can be managed.

5. Projected citywide energy cooling demand cannot simply be extrapolated from present-day energy observations because near-surface temperature and energy consumption are not linearly correlated.

6. Advances in air conditioning technologies and their assessment using the present methodology would provide guidance for the future planning in managing increases in electricity consumption and maintaining thermal comfort.

Acknowledgements

This work has been funded by National Science Foundation grant DMS 1419593 and USDA NIFA grant 2015-67003-23508. The author MT would like to thank Dr. Prabir Patra (Senior Scientist, JAMSTEC, Japan) for providing helpful comments while finalizing the manuscript. The authors also like to thank Dr. Jimy Dudhia (NCAR, Boulder, CO) for his suggestions. All the figures in this work are generated using the NCAR command language (version 6.3.0) [Software]. (2015). Boulder, Colorado: UCAR/NCAR/CISL/TDD. http://dx.doi.org/10.5065/D6WD3XH5.

Supporting information

The following supporting information is available:

**Figure S1.** CTRL_P modeled diurnal mean Phoenix’s (continuous curves) and Tucson’s (dashed curves) AC electricity consumption (MW km⁻²) profiles averaged for the entire 15-day clear-sky summertime period for each urban category, namely, low intensity residential (LOW), high intensity residential (HIG), and commercial or industrial (COI).

**Figure S2.** Urban land use categories (low intensity residential 31, high intensity residential 32, and commercial or industrial 33) for the present day (a and b), and projected LULC_lo (c and d) and LULC_hi (e and f) urban scenarios over the Phoenix (left) and Tucson (right) regions of Arizona. The figure is generated using the NCAR command language (version 6.3.0) [Software]. (2015). Boulder, Colorado: UCAR/NCAR/CISL/TDD. http://dx.doi.org/10.5065/D6WD3XH5.

**Figure S3.** (a) Time series of observed (black curve) and CTRL_P modeled (blue curve) 2-m air temperature (°C) averaged over the eleven AZMET (Arizona Meteorological Network) rural weather stations during the 15-day summertime period in June 2012. (b) Same as in (a) but averaged over the four AZMET urban weather stations.

**Figure S4.** (a) Time series of observed (black curve) and CTRL_P modeled (blue curve) near-surface wind speed (ms⁻¹) averaged over the eleven AZMET rural weather stations during the 15-day clear-sky summertime period in June 2012. (b) Same as in (a) but averaged over the four AZMET urban weather stations.

**Figure S5.** (a) Time series of observed (black curve) and CTRL_P modeled (blue curve) near-surface wind direction (°) averaged over the eleven AZMET rural weather stations during the 15-day clear-sky summertime period in June 2012. (b) Same as in (a) but averaged over the four AZMET urban weather stations.

**Figure S6.** Scatter plot of hourly-observed total electricity demand (MW) (across the Phoenix metropolitan area) versus urban 2-m air temperature (°C) during the entire 15-day clear-sky summertime period in June 2012.

**Figure S7.** Scatter plot of hourly CTRL_P-modeled AC electricity consumption (MW) (across the Phoenix metropolitan area) versus urban 2-m air temperature (°C) during the entire 15-day clear-sky summertime period in June 2012.

**Figure S8.** (a and b) Modeled mean minimum 2-m air temperature differences T2m, min(CONTROL_F)-T2m, min(CONTROL_P) averaged for the entire 15-day summertime period for Phoenix (left) and Tucson (right) regions, respectively. The figure is generated using the NCAR command language (version 6.3.0) [Software]. (2015). Boulder, Colorado: UCAR/NCAR/CISL/TDD. http://dx.doi.org/10.5065/D6WD3XH5.

**Table S1:** Description of numerical experiments performed.

**Table S2:** Physical parameterizations and urban morphological parameters used within WRF-experiments.
Table S3. RMSE and MAE for the near-surface variables T2m (°C), WS10m(ms⁻¹), and WDI10m (°C) at the urban and rural stations for the CTRL_P WRF-experiment.

Table S4: Increase in spatial mean (considering all urban grid points) of 2-m air temperature for future urban/warm scenarios compared with present day.

References

Argüeso D, Evans JP, Pitman AJ, Luca AD. 2015. Effects of city expansion on heat stress under climate change conditions. *PLoS One* **10**: e0117066. https://doi.org/10.1371/journal.pone.0117066.

Bierwagen BG, Theobald DM, Pyke CR, Chotea A, Groth P, Thomas JV, Morefield P. 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proceedings of the National Academy of Sciences of the United States of America* **107**: 20887–20892. https://doi.org/10.1073/pnas.10020961.

Fry JA, Xian G, Jin S, Dewitz JA, Homer CG, Yang L, Barnes CA, Herold ND, Wickham JD. 2011. Completion of the 2006 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing* **77**: 858–864.

Gent PR, Danabasoglu G, Donner LJ, Holland MM, Hunke EC, Jayne SR, Lawrence DM, Neale RB, Rasch PJ, Vertenstein M, Worley PH, Yang Z-L, Zhang M. 2011. The community climate system model version 4. *Journal of Climate* **24**: 4973–4991.

Georgescu M, Moustauoi M, Malahov A, Dudhia J. 2012. Summer-time climate impacts of projected megalopolitan expansion in Arizona. *Nature Climate Change* **3**: 37–41.

Hamdi R, Van de Vyver H, De Troch R, Termonia P. 2014. Assessment of three dynamical urban climate downscaling methods: Brussels’s future urban heat island under an A1B emission scenario. *International Journal of Climatology* **34**: 978–999. https://doi.org/10.1002/joc.3734.

Kimura F, Kito K. 2007. Downscaling by pseudo global warming method. In *The Final Report of the ICCAP Research Institute for Humanity and Nature (RIHN)*, Kyoto, Japan: 1–4.

Kusaka H, Kondo H, Kikegawa Y, Kimura F. 2001. A simple single-layer urban canopy model for atmospheric scenarios: Comparison with multi-layer and slab models. *Boundary-Layer Meteorology* **101**: 329–358.

Kusaka H, Hara M, Takane Y. 2012. Urban climate projection by the WRF model at 3-km horizontal grid increment: dynamical downscaling and predicting heat stress in the 2070’s August for Tokyo, Osaka, and Nagoya metropolises. *Journal of the Meteorological Society of Japan* **90B**: 47–63.

Kusaka H, Suzuki-Parker A, Aoyagi T, Adachi SA, Yamagata Y. 2016. Assessment of RCM and urban scenarios uncertainties in the climate projections for August in the 2050s in Tokyo. *Climatic Change* **137**: 427–438. https://doi.org/10.1007/s10584-016-1963-2.

Mackun P, Wilson S. 2011. Population Distribution and Change: 2000 to 2010. http://www.census.gov/prod/cen2010/briefs/c2010br-01.pdf (accessed 03 January 2011).

Marshall RM, Robles MD, Majka DR, Hany JA. 2010. Sustainable water management in the southwestern United States: reality or rhetoric? *PLoS One* **5**: e11687.

Martiili A, Clappier A, Rotach MW. 2002. An urban surface exchange parameterization for mesoscale models. *Boundary-Layer Meteorology* **104**: 261–304.

Rasmussen R, Liu C, Ikeda K, Gochis D, Yates D, Chen F, Tewari M, Barlage M, Dudhia J, Yu W, Miller K, Arsenault K, Grubisic V, Thompson G, Gutmann E. 2011. High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *Journal of Climate* **24**: 3015–3048.

Salamanca F, Martilli A. 2010. A new building energy model coupled with an urban canopy parameterization for urban climate simulations-Part II: validation with one dimension off-line simulations. *Theoretical and Applied Climatology* **99**: 345–356.

Salamanca F, Martilli A, Tewari M, Chen F. 2011. A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with WRF. *Journal of Applied Meteorology and Climatology* **50**: 1107–1128.

Salamanca F, Georgescu M, Mahalov A, Moustauoi M, Wang M, Svoma BM. 2013. Assessing summertime urban air conditioning consumption in a semiarid environment. *Environmental Research Letters* **8**: 1–9.

Salamanca F, Georgescu M, Malahov A, Moustauoi M. 2015. Summer-time response of temperature and cooling energy demand to urban expansion in a semiarid environment. *Journal of Applied Meteorology and Climatology* **54**: 1756–1772.

Salamanca F, Zhang Y, Barlage M, Mahalov A, Chen F, Miao S. 2016. Evaluation of coupling the Noah-MP land surface model with urban canopy models in WRF for a semiarid urban environment, 17th Annual WRF Users’ Workshop, June 27–July 1, Boulder, CO, USA.

Skamarock WC, Klemp JB. 2008. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *Journal of Computational Physics* **227**: 3465–3485.

U.S. Environmental Protection Agency. 2009. Land-use scenarios: National-scale housing-density scenarios consistent with climate change storylines. EPA Final Rep. EPA/600/R-08/076F. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203458.

Yang L, Niyogi D, Tewari M, Aliaga D, Chen F, Tian F, Ni G. 2016. Contrasting impacts of urban forms on future thermal environment: example of Beijing metropolitan area. *Environmental Research Letters* **11**: 1–10.