Summertime Response of Temperature and Cooling Energy Demand to Urban Expansion in a Semiarid Environment

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ABSTRACT

This article explores regional impacts on near-surface air temperature and air conditioning (AC) electricity consumption due to projected urban expansion in a semiarid environment. In addition to the modern-day urban landscape setting, two projected urban expansion scenarios are analyzed with the Weather Research and Forecasting Model coupled to a multilayer building energy scheme. The authors simulate a 10-day extreme heat period at high spatial resolution (1-km horizontal grid spacing) over Arizona, one of the fastest-growing regions in the United States. Results show that replacement of natural land surfaces by buildings and pavement increases the local mean near-surface air temperature considerably. Furthermore, present-day waste heat emission from AC systems increases the mean nighttime 2-m air temperature by up to 1°C in some urban locations, but projected urban development aggravates the situation, increasing nighttime air temperatures by up to 1.5°C–1.75°C. The contribution of anthropogenic heating due to AC systems is computed through comparison of two different types of numerical experiments: in one case, a specific urban scenario is simulated with the AC systems turned on and expelling heat into the outdoor environment, and in the second case, the same urban development (with the AC systems turned on) is simulated but with no heat expelled into the outdoor environment. The results demonstrate that projected urban expansion significantly amplifies local cooling energy demands for the Phoenix and Tucson metropolitan regions and therefore highlight the need for sustainable future energy needs to maintain thermal comfort levels.

1. Introduction

Built-up areas alter the surface energy balance components relative to their rural counterparts (Oke 1988). Radiative trapping by building walls and roads, high thermal storage capacity of unnatural surfaces, and anthropogenic heat release (originating from human activities that consume energy) reduces built environment nocturnal cooling rates, promoting the formation of the urban heat island (UHI) phenomenon (Howard 1833; Arnfield 2003). The UHI phenomenon is the manifestation of a warmer city relative to its surrounding rural neighborhoods, and its magnitude is a function of urban morphology, thermal properties of building materials, waste heat emission, and weather conditions. City dwellers are exposed to regional warming forced by greenhouse gas–induced global climate change and UHIs as a result of land-use/land-cover changes of natural land surfaces by buildings and pavements to meet the demands of a continuously growing urban population (Georgescu et al. 2013, 2014). Six billion dwellers are projected to be in urban areas by 2050, which means that over 65% of the world’s population will be urbanite (United Nations Department of Economic and Social Affairs, Population Division 2012). The observed correlation between daily mean air temperature and
urban energy demand (e.g., Valor et al. 2001) suggests that this novel setting requires assessments of the future urban climate and power demand to prevent potentially unsustainable scenarios as consequence of this rapid urban expansion worldwide.

Recent efforts have allowed incorporation of detailed urban canopy parameterizations (UCPs) in global climate models (GCMs) to investigate the climate response of urban areas to global warming (Jacobson 2001; Best et al. 2006; Oleson et al. 2008a,b). Urban–rural temperature differences exhibit a strong variability across regions and seasons and both urban and rural landscapes respond differently to climate change (McCarthy et al. 2010; Oleson 2012; Stone et al. 2012). Nichol et al. (2013) using observations reported an increase rate of 0.28°C decade⁻¹ (over the last three decades) near downtown Hong Kong, while the rate of global warming was 0.08°C decade⁻¹ (over the last two decades) in a nearby area in absence of urban development. Similarly, Comrie (2000) reported an observed maximum urban warming rate of 0.125°C yr⁻¹ over the past 30-yr period from 1969 to 1998 in Tucson, Arizona (United States). The warming trend was calculated by averaging daily minimum temperatures for each month, and the maximum urban–rural temperature difference was observed in March. The nonurban warming rate (for the former month) was 0.040°C yr⁻¹ over the same 30-yr period.

Urbanized GCMs are able to reproduce general characteristics of the climate in cities due to global warming and urban effects worldwide, but they cannot capture regional mesoscale circulations that control the UHI phenomenon. GCMs use the same atmospheric forcing over rural and urban areas within the same grid cell (±1° latitude by ±1° longitude) and, consequently, they cannot accurately replicate urban boundary layer processes (e.g., Oleson et al. 2011).

Alternatively, regional climate models (RCMs) can be used to investigate local effects of urbanization under climate change projections by downscaling large-scale climate data from GCMs. Using this methodology, Argueso et al. (2013) reported that urban expansion for Sydney (Australia) would considerably affect seasonal minimum temperatures in winter and spring, doubling the increase due to global warming alone by 2050. Nevertheless, an impact on seasonal maximum temperature due to urban development was not detected during the year. This result is not surprising because maximum daytime temperatures are at times observed outside the urban cores (e.g., Brazel et al. 2000; Basara et al. 2008; Grossman-Clarke et al. 2010). Other researchers use present-day climate conditions to isolate regional impacts of urban expansion from global warming due to greenhouse gas–induced global climate change. For instance, Georgescu et al. (2012) performed 3-yr (2006–08) multi-member ensemble continental-scale simulations (at 20-km spatial resolution) and reported summertime averaged warming exceeding 1°C for a maximum urban expansion scenario for the entire state of Arizona. The statewide seasonal warming was substantial during spring and fall (~0.9°C) and less significant in winter (~0.5°C).

Using modern-day weather conditions (specifically, we analyze a 10-day extreme heat period), the present paper explores regional impacts on near-surface air temperature and air conditioning (AC) electricity consumption due to projections of future urban expansion in a semiarid environment. Summertime extreme heat days (EHDs) are projected to increase in frequency, intensity, and duration as a result of climate change (Tebaldi et al. 2006), and present-day extreme heat conditions may dominate summer months across the United States by the mid-twenty-first century (Miller et al. 2008; Duffy and Tebaldi 2012). Examination of AC electricity consumption is critical for rapidly expanding cities located in regions where cooling energy demands are excessive, because the combined effects of greenhouse gas–induced climate change and the expanding built environment are expected to raise summertime temperatures considerably (e.g., Georgescu et al. 2013, 2014).

Our focus is on Arizona, which is located in a desert environment and is one of the fastest-growing regions in the United States. According to some projections, Arizona is expected to double its current population by 2050 (www.america2050.org) and because of its harsh summer conditions experiences massive use of AC systems (Salamanca et al. 2013, 2014). An evaluation of regional effects on 2-m air temperature (in this manuscript, near-surface air temperature and 2-m air temperature are used without distinction) and cooling energy demand due to the projected urban expansion for Arizona (see section 2b) can be crucial for urban planners and energy providers in order to prevent negative consequences of urban development, such as blackouts, during extreme heat conditions (Sailor and Pavlova 2003; U.S. Department of Energy 2013). Although previous investigations have documented regional hydroclimatic effects of urban expansion in semiarid environments (e.g., Georgescu et al. 2012, 2013), these preceding investigations were carried out at medium-range (20-km grid spacing) spatial resolution. The emphasis here is focused on analysis of the diurnal cycle of 2-m air temperature and cooling energy demand at high spatial resolution (1-km horizontal grid spacing).

The outline of the manuscript is as follows: methodology and numerical experiments are described in section 2. The discussion of the results is presented in section 3; conclusions and future research are presented in section 4.
2. Methodology

We conduct six numerical experiments using the nonhydrostatic (version 3.4.1) version of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) coupled to the Noah land surface model (LSM; Chen and Dudhia 2001a,b; Ek et al. 2003) to evaluate regional impacts of urban expansion on near-surface air temperature and AC electricity consumption. The Noah LSM was applied to the fraction with natural cover within a grid cell, and the multilayer building energy parameterization (BEP+BEM) was applied to the fraction with built-up cover. BEP+BEM is a box-type building energy model dynamically integrated in a multilayer UCP that resolves the exchanges of energy between the buildings and the outdoor environment as well as the impact of the AC systems (Martilli et al. 2002; Salamanca et al. 2010; Salamanca and Martilli 2010). Buildings of several floors can be considered in the model and the time evolution of indoor air temperature (and moisture) is computed separately for each floor, solving an energy conservation equation that takes into account the heat diffusion through roofs and vertical walls, natural ventilation, solar radiation through the windows, and heat generated by occupants and equipment. In BEP+BEM, when the indoor temperature reaches a fixed target, all the “extra” sensible heat $Q_H$ is extracted and transported to the outside environment by the AC systems to maintain a constant indoor temperature. Once $Q_H$ is calculated, the AC electricity consumption (EC) is computed and the resultant anthropogenic heat ($Q_H + EC$) is added as a source term (at each level) to the energy conservation equation of the outdoor temperature.

BEP+BEM’s ability to reproduce near-surface meteorology (air temperature, wind speed, and wind direction) has been demonstrated multiple times for different cities and weather conditions (e.g., Salamanca et al. 2011, 2012; Liao et al. 2014). Specifically, Salamanca et al. (2013, 2014) reported that the multilayer building energy scheme was able to accurately reproduce the near-surface meteorology and the observed citywide diurnal profile of AC electricity consumption (supplied by an electric utility company) for several recent extreme heat events (including the one that is analyzed here) that have occurred in the Phoenix metropolitan area (Arizona). The excellent agreement obtained in previous work provides confidence (we utilize here the same WRF Model configuration but with different numerical domain sizes to include both Phoenix and Tucson regions) to assess regional impacts of projected urban expansion on near-surface air temperature and AC electricity consumption.

<table>
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<th>TABLE 1. Physical parameterizations and urban parameters used within WRF experiments.</th>
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<tr>
<td>WRF’s physical parameterizations</td>
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<tr>
<td>Shortwave radiation scheme</td>
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<td>Microphysics scheme (no cumulus cloud scheme was considered in the two inner domains)</td>
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<tr>
<td>Urban morphological characteristics</td>
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<td>Urban fraction</td>
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<td>Building plan area fraction</td>
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<tr>
<td>Percent of buildings 5 m high</td>
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<td>Percent of buildings 10 m high</td>
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<td>Percent of buildings 20 m high</td>
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<td>Percent of buildings 30 m high</td>
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<tr>
<td>Thermal properties of building materials</td>
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<tr>
<td>Urban vegetation</td>
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<tr>
<td>Roof</td>
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<tr>
<td>Wall</td>
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<tr>
<td>Road</td>
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<tr>
<td>Thermal conductivity (W m$^{-1}$K$^{-1}$)</td>
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<tr>
<td>Specific heat ($\times$10$^6$ J m$^{-3}$ K$^{-1}$)</td>
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<tr>
<td>Surface’s emissivity</td>
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<tr>
<td>Surface’s albedo</td>
</tr>
<tr>
<td>Total thickness (m)</td>
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<tr>
<td>Thickness of insulating material (m) (internal layer)</td>
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<tr>
<td>Thermal conductivity (W m$^{-1}$K$^{-1}$) of insulating material</td>
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<tr>
<td>Specified heat ($\times$10$^6$ J m$^{-3}$ K$^{-1}$) of insulating material</td>
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<tr>
<td>Percent air-conditioned floor area to total floor area</td>
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<tr>
<td>Target internal temperature (°C)</td>
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<tr>
<td>Urban vegetation</td>
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a. Model setup

All WRF experiments use the same numerical grid and physical parameterizations (a detailed description of the selected options is presented in Table 1). The horizontal domain was composed of four two-way nested domains (Fig. 1a) with $135 \times 115$, $201 \times 183$, $390 \times 321$, and $615 \times 555$ grid points, and with a spatial resolution of 27, 9, 3, and 1 km, respectively. The inner domain covers nearly the entire state of Arizona for both modern-day (Fig. 1b) and projected urban landscape scenarios (Fig. 2). The vertical resolution consisted of 40 eta levels, with 14 within the lowest 1.5 km to better characterize urban boundary layer processes. WRF experiments were conducted with initial and boundary conditions obtained from NCEP final (FNL) data (number ds083.2), which are available with a grid spacing of 1° × 1° and every 6 h.

The modern-day urban landscape setting was characterized using the U.S. Geological Survey 30-m 2006 National Land Cover Dataset (Fry et al. 2011) in the inner domain. For the nonurban part, land-use categories were
implemented using the MODIS land-cover classification at 1-km spatial resolution. Based on the concentration of buildings, three different urban categories were defined and describe the morphology of the built-up areas: commercial or industrial (COI), high-intensity residential (HIR), and low-intensity residential (LIR). Urban morphology and building parameters (Table 1) were extracted from Burian et al. (2002), who describe building morphological characteristics for these urban categories. Thermal properties for roofs, roads, and vertical walls were extracted from Clarke et al. (1991) and correspond to standard building materials (Salamanca et al. 2013, 2014).

**b. Numerical experiments**

To evaluate regional impacts of urban expansion on near-surface air temperature and AC electricity consumption a 10-day clear-sky extreme heat period (10-day EHD period) from 10 to 19 July (2009) was simulated. During this time, the center of a high pressure system (Fig. 3) was located over Arizona and the southwestern United States. The high pressure system was displaced west and north relative to its typical location during the summer. This large-scale setup together with a temporal suppression of the North American
monsoon (Adams and Comrie 1997), which generally occurs during July and August, favored the formation of the extreme heat event. During the 10-day EHD period, Phoenix registered daily maximum temperatures of 45.6°C and Tucson 41.7°C, whereas the observed monthly mean maximum temperature was 42.8°C for Phoenix and 38.3°C for Tucson during July 2009 (http://ag.arizona.edu/azmet/). All WRF experiments were initiated 7 h previously, and this time interval was considered as the model spinup period. Besides the modern-day urban landscape setting (CTRL_AC experiment), two projected urban expansion scenarios with identical urban extent but different urban morphology were considered. The least aggressive development (LOW_AC experiment) preserves the modern-day urban landscape (Fig. 2a), whereas the most aggressive development (HIGH_AC experiment) does not (Fig. 2b). Both projected urban expansion scenarios fall within the most extensive development projected for Arizona by the end of the twenty-first century (A2 projection) under the Integrated Climate and Land Use Scenarios (ICLUS) project of the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency 2009). ICLUS scenarios are consistent

FIG. 2. (a) Representation of urban land-use categories of projected urban expansion within LOW_AC and LOW_AC_NoOut WRF experiments. (b) As in (a), but for HIGH_AC and HIGH_AC_NoOut WRF experiments.
with the projections of global change described in the Special Report on Emissions Scenarios by the Intergovernmental Panel on Climate Change (Nakicenovic and Swart 2000). Limited by U.S. census population projections, ICLUS use standard demographic approaches and spatial allocation models to create scenarios of housing density changes with national coverage at 1-ha spatial resolution (Bierwagen et al. 2010). Recently, Georgescu et al. (2014) have used ICLUS data to model seasonal hydroclimatic impacts of twenty-first-century urban expansion and adaptation across the United States at 20-km spatial resolution. For this study, we spatially aggregated housing density projections from continuous values into three urban classes (COI, HIR, and LIR) at 1-km spatial resolution and the resulting data were implemented into the WRF Preprocessing System.

During the 10-day EHD period it was assumed that every building made use of AC systems and the resulting anthropogenic heat was ejected as sensible heat into the outdoor environment. This assumption is completely justified because AC systems that eject latent heat into the urban canopy are limited to cooling towers in large buildings in COI areas [based on AC market, the ratio of sensible to latent heat emission from AC systems ranges between 1 and 1.5 in commercial areas (Kondo and Kikegawa 2003; Ohashi et al. 2007)], and these areas make up less than 1% of present-day urban landscape in Arizona (Fry et al. 2011). Three additional WRF experiments (CTRL_AC_NoOut, LOW_AC_NoOut, and HIGH_AC_NoOut) were performed to evaluate the effect of AC systems on near-surface air temperature (a complete list of all WRF experiments is shown in Table 2). For these

![Geopotential height (m) and wind vector fields at 500-hPa on 0000 UTC (a) 12, (b) 14, (c) 16, and (d) 18 Jul 2009.](image)

**FIG. 3.** Geopotential height (m) and wind vector fields at 500-hPa on 0000 UTC (a) 12, (b) 14, (c) 16, and (d) 18 Jul 2009.

<table>
<thead>
<tr>
<th>WRF experiment</th>
<th>Urban landscape</th>
<th>Waste heat emission from AC systems ejected into the outdoor environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL_AC</td>
<td>Modern day</td>
<td>Yes</td>
</tr>
<tr>
<td>LOW_AC</td>
<td>Projected</td>
<td>Yes</td>
</tr>
<tr>
<td>HIGH_AC</td>
<td>Projected</td>
<td>Yes</td>
</tr>
<tr>
<td>CTRL_AC_NoOut</td>
<td>Modern day</td>
<td>No</td>
</tr>
<tr>
<td>LOW_AC_NoOut</td>
<td>Projected</td>
<td>No</td>
</tr>
<tr>
<td>HIGH_AC_NoOut</td>
<td>Projected</td>
<td>No</td>
</tr>
</tbody>
</table>
additional simulations, waste heat emission from AC systems was not released outside into the atmosphere although the indoor temperature of buildings was maintained cooled (25°C) as in the previous three WRF experiments.

3. Results and discussion

a. Thermal impacts due to urban expansion

In this section summertime temperature response to urban development is analyzed. Figure 4 shows the modeled mean impacts of urban expansion on near-surface air temperature for the most aggressive development $T_{2m}(\text{HIGH}_AC) - T_{2m}(\text{CTRL}_AC)$. Areas located at the west and southeast of present-day Phoenix experienced the greatest warming (Fig. 4a), with prevailing magnitudes that ranged from 2.75° to 3.75°C during the night (the time interval from 2000 to 0600 LT unless specified otherwise). Regions located northwest of present-day Tucson and along the Colorado River also underwent significant warming, as near-surface temperature increased by 1.75°–2.75°C. The mean nighttime spatial warming was 1.80° ± 0.76°C across the entire innermost domain. For the former spatial average only the grid cells that experienced land-use change (i.e., urbanizing grid cells) were taken into account. This local warming induced by urban expansion is not surprising because replacement of natural land surfaces by buildings and pavements can increase considerably the near-surface air temperature during the night. In general, the UHI phenomenon appears late during the evening and lingers through the early morning hours. Figure 4b shows the same thermal effects of urban expansion but this time calculated across the diurnal cycle. During the day (understood as the time interval from 0700 to 1900 LT unless specified otherwise), the urban expansion had a reduced impact on 2-m air temperature and, consequently, the maximum

![Fig. 4](image-url)
warming range was reduced to 0.75°–1.75°C. For the same reason, the daily spatial warming was smaller than the nighttime spatial warming (the mean value was 0.83° ± 0.42°C) across the entire innermost domain.

Figure 5 shows the mean modeled impacts of urban expansion on near-surface air temperature for the least aggressive development [\(T_{2m}(LOW\_AC) - T_{2m}(CTRL\_AC)\)]. Figures 4 and 5 display similar results except for the regions where modern-day Phoenix and Tucson are located. The HIGH_AC expansion scenario assumes conversion of most of present-day LIR areas to HIR and, consequently, the resulting warming is greater than the impact because of the LOW_AC urban development over these regions. The daily spatial warming for the least aggressive urban development scenario [\(T_{2m}(LOW\_AC) - T_{2m}(CTRL\_AC)\)] was 0.88° ± 0.40°C, which demonstrates that both LOW_AC and HIGH_AC projected urban expansion scenarios resulted in considerable warming.

b. Anthropogenic heating of the urban environment

This section describes the contribution of AC systems on near-surface air temperature. Figure 6 shows the mean modeled impact of AC systems on near-surface air temperature for the present-day urban setting [\(T_{2m}(CTRL\_AC) - T_{2m}(CTRL\_AC\_NoOut)\)]. During the night (Fig. 6a), the majority of neighborhoods in Phoenix experienced local warming ranging between 0.5° and 1.0°C, with maximum warming up to 1.0°C computed for several central areas. These results are in complete agreement with those presented in Salamanca et al. (2014), who analyzed anthropogenic heat impacts in Phoenix due to present-day AC use. For Tucson, the spatial variation of the impact of AC systems matched the typical distribution of the UHI intensity across a city. The largest effect (between 0.75° and 1.0°C) was concentrated in the central part of the metropolitan area, and the minimum impact was computed in suburban areas near the urban–rural boundary. During the day, the anthropogenic heat from AC systems did not significantly impact the near-surface air temperature (Fig. 6b). Salamanca et al. (2014) reported the same occurrence; the effect of AC systems was negligible during the day but considerable during the night. In general, anthropogenic heat impacts (on near-surface air temperature) are important from late afternoon to early morning when solar
radiative fluxes do not dominate the surface energy balance.

Figure 7 illustrates the mean modeled impacts of AC systems on near-surface air temperature for the least aggressive urban development \([T_{2m}(LOW\_AC) - T_{2m}(LOW\_AC\_NoOut)]\). During the night (Fig. 7a), a large region that covers and surrounds present-day Phoenix experienced a significant temperature increase of 0.75\(^\circ\)C–1.0\(^\circ\)C. The maximum local warming ranged between 1.0\(^\circ\)C and 1.5\(^\circ\)C, and it was concentrated in a few inner neighborhoods. Present-day central Tucson and various urban settlements along the Colorado River also underwent significant local warming, with a temperature increase greater than 1.0\(^\circ\)C. During the day (Fig. 7b), regional warming of 0.25\(^\circ\)C–0.5\(^\circ\)C highlights the greater nighttime relative to daytime impacts.

\[c.\] Air conditioning electricity consumption

1) Spatial distribution

In this section the spatial distribution of AC electricity consumption for the present-day urban landscape and projected urban expansion scenarios are analyzed. Results show that considerable differences exist between Phoenix and Tucson cooling energy demands. The Tucson metropolitan area is situated in a wide flat valley at 750–800 m above sea level and is surrounded by mountain ranges with peaks up to 2750-m elevation. On the other hand, the Phoenix metropolitan area is located in a nearly flat plain at a mean elevation of 340 m above sea level in the center of the dry Salt River valley. Although the Phoenix and Tucson regions share the same

![Figure 6](1764 JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY VOLUME 54)
In a semiarid climate, they regularly experience diverse near-surface meteorological conditions because of their different topography [a review of the dynamics governing the airflows intrinsic to urban areas in complex terrain can be seen in Fernando (2010)]. For instance, the observed monthly mean maximum 2-m air temperature during July 2009 was 42.8°C for Phoenix and 38.3°C for Tucson.

Figure 9 shows the spatial distribution of diurnal mean AC electricity consumption averaged for the entire 10-day EHD period for the CTRL_AC urban scenario. The diurnal mean was calculated by averaging the hourly loads of each day at the same time, generating a 24-h period. At 0600 LT, when AC electricity consumption is approximately minimum [see section 3c(2)], Phoenix (Fig. 9a) displayed two distinct large regions with cooling energy demands from 0.6 to 0.8 MW km$^{-2}$ and from 0.8 to 1.0 MW km$^{-2}$, respectively, whereas Tucson exhibited nearly a homogeneous AC electricity consumption of 0.4–0.6 MW km$^{-2}$. At 1700–1800 LT, both Phoenix and Tucson areas experience maximum AC electricity consumption, and both cities displayed similar spatial cooling energy demand patterns as previously (Fig. 9b). Two distinct and sizeable regions are apparent in Phoenix with cooling energy demands from 2.0 to 2.5 MW km$^{-2}$ and from 2.5 to 3.0 MW km$^{-2}$, respectively, and one large region that covered almost all of Tucson, which produced a cooling energy demand of 1.5–2.0 MW km$^{-2}$ [similar findings have been reported by Salamanca et al. (2014) for Phoenix]. In general, minimum cooling energy demands are observed shortly after sunrise, whereas maximum cooling energy demands occur during late afternoon hours.

Figure 10 shows the spatial distribution of diurnal mean AC electricity consumption averaged for the entire 10-day EHD period for the LOW_AC urban development. At 0600, projected urban expansion in Phoenix (Fig. 10a) produced three distinguishable AC electricity consumption areas. Two larger areas showing cooling energy demands from 0.6 to 0.8 MW km$^{-2}$ and from 0.8 to 1.0 MW km$^{-2}$, respectively, and one-third smaller area located at the south-southwest of present-day Phoenix that exhibited the largest cooling energy demand with a magnitude of 1.0–1.25 MW km$^{-2}$. On the other hand, projected urban development for Tucson produced two evident large areas in terms

![Figure 7](image_url)
of AC electricity consumption. The first area that covered and surrounded present-day Tucson exhibited the less significant cooling energy demand with an electricity consumption of 0.4–0.6 MW km\(^{-2}\). The second area, situated at the northwest of present-day Tucson, showed the largest cooling energy demand with magnitudes from 0.6 to 0.8 MW km\(^{-2}\). Significant cooling power demand (>0.8 and up to 1.25 MW km\(^{-2}\)) was computed for projected future urban settlements along the Colorado River. At 1700 LT, when approximately maximum cooling energy demand occurs (Fig. 10b), two large areas were evident for the future Phoenix and Tucson regions, respectively. The AC electricity consumption ranged from 2.0 to 2.5 MW km\(^{-2}\) and from 2.5 to 3.0 MW km\(^{-2}\) for the case Phoenix, and from 1.5 to 2.0 MW km\(^{-2}\) and from 2.0 to 2.5 MW km\(^{-2}\) for the case of Tucson.

Finally, Fig. 11 shows the spatial distribution of diurnal mean AC electricity consumption averaged for the entire 10-day EHD period for the HIGH_AC urban development scenario. A remarkable characteristic of the most aggressive development is the important number of COI areas (relative to the least aggressive urban expansion) that is projected for both the Phoenix and Tucson regions. COI areas have taller buildings and greater urban fractions than residential areas leading to larger cooling energy demands. At 0600 (Fig. 11a), projected urban development in Phoenix produced a major region with cooling energy demands from 0.8 to 1.0 MW km\(^{-2}\). Excluding the COI areas, the maximum AC electricity consumption ranged between 1.0 and 1.25 MW km\(^{-2}\), and it was concentrated in a large region situated at the south of present-day Phoenix. At this time, cooling energy demands from 0.6 to 0.8 MW km\(^{-2}\) dominated the Tucson region. At 1700 (Fig. 11b), excluding the COI areas, the spatial distribution of AC electricity consumption was practically homogeneous for both the Phoenix and Tucson regions. Phoenix exhibited local AC electricity consumption from 2.5 to 3.0 MW km\(^{-2}\), and for Tucson it went from 2.0 to 2.5 MW km\(^{-2}\).

2) DIURNAL CYCLE

In this section citywide diurnal profiles of AC electricity consumption for the present-day urban landscape and projected urban expansion scenarios are analyzed. Figure 12 shows the modeled diurnal mean...
AC electricity consumption profiles averaged for the entire 10-day EHD period for the CTRL_AC, LOW_AC, and HIGH_AC urban scenarios. The diurnal profiles were computed by aggregating all the urban grid cells within the black rectangles outlined previously in Fig. 9a. Once the total AC electricity consumption was aggregated for each metropolitan region and urban scenario, it was normalized via division by the corresponding urban area.

It is evident from Fig. 12 that minimum cooling energy demand occurs at ~0600, and maximum cooling energy demand at 1700–1800 LT. Furthermore, it was not surprising that Phoenix’s AC electricity consumption profiles (continuous curves) were greater than the corresponding profiles for Tucson (dashed curves) because Phoenix’s region usually experiences higher temperatures because of its lower elevation. Finally, it is noteworthy to point out that projected urban development increased local cooling energy demands significantly for both Phoenix and Tucson regions. The daily averaged increase due to the projected LOW_AC urban development was 3.5% for the Phoenix region and 7.6% for the Tucson region, whereas the daily averaged increase due to the projected HIGH_AC urban development was 13.2% and 17.1% for the Phoenix and Tucson regions, respectively.

As a final point and to further validate the current CTRL_AC simulation, we compared the present

![AC Electricity Consumption (MW / km²)](image_url)
CTRL_AC experiment with a previous WRF experiment carried out over just the Phoenix region conducted during the same period of time. This prior WRF experiment used an identical setup and differed only by varying numerical domain sizes (more details can be found in Salamanca et al. 2013, 2014). Figure 13a shows both present (black curve) and previous (red curve) citywide diurnal profiles of AC electricity consumption averaged for the entire 10-day EHD period. Even though both WRF simulations have different horizontal domains, Phoenix’s AC electricity consumption profiles were almost identical as a result of a similar prediction of the 2-m air temperature (Fig. 13b). Despite the larger coarse domain (from the current set of simulations) introducing additional grid points compared to the smaller coarse domain (from the previous set of simulations), both WRF experiments predicted a similar near-surface air temperature, thereby demonstrating the robustness of the results presented in this paper (i.e., the results presented here are independent of the numerical domain size).

4. Summary and conclusions

In this paper, summertime regional impacts of urban expansion on near-surface air temperature and AC electricity consumption have been investigated with the multilayer building energy parameterization BEP+BEM coupled to the atmospheric WRF Model. In addition to the modern-day urban landscape setting, two projected urban expansion scenarios with identical urban extent but different urban morphology have been investigated. Replacement of natural land surfaces by buildings and pavements increased the near-surface air temperature considerable during nighttime hours. This
substantial nighttime temperature increase was not homogeneous across the entire inner domain. Areas located at the west and southeast of present-day Phoenix showed the greatest impacts (>2.75°C) with maximum local warming exceeding 3.75°C. The daily spatial warming across the state of Arizona (considering just the areas that experienced land-use changes) was considerable with a mean temperature increase of 0.8°–0.9°C.

The effect of AC systems on near-surface air temperature was also analyzed. Anthropogenic heat emission from AC systems increased significantly the 2-m air temperature during the night. During the day, the impact of AC systems was negligible except for the most aggressive urban development, which produced a local warming of 0.25°–0.5°C over modern-day Phoenix. During the night, various interior neighborhoods of Phoenix and Tucson regions experienced temperature increases of 0.75°–1.0°C because of present-day AC use. Projected urban development intensified these impacts (especially for the Phoenix region) and increased the nighttime air temperature by 1.0°–1.75°C.

Finally, spatial distribution of cooling energy demands and citywide diurnal profiles of AC electricity consumption were analyzed. Minimum cooling energy demands occurred at ~0600, and maximum cooling energy demands at 1700–1800 LT. The Phoenix and Tucson regions displayed distinct cooling energy demand profiles because of their different topography. Phoenix experiences higher temperatures than Tucson leading to larger local cooling energy needs. As in the case of anthropogenic heating due to AC systems, projected urban development increased significantly.
the local cooling energy demands for the Phoenix and Tucson regions.

This work presents for the first time, to our knowledge, reliable projections of diurnal profiles of cooling energy demand for the rapidly growing state of Arizona. The importance of energy availability cannot be overemphasized for this semiarid region, large portions of which regularly experience summertime temperatures in excess of 40°C. The results presented here have global implications for urbanizing areas over similarly warm biomes that will demand sufficient energy (for AC systems) for continued maintenance and improvement of living standards. Although we consider our results robust, we recognize that existing differences between present-day and future climate conditions could modify our conclusions. However, given that we only take urban-induced warming into account, our conclusions can be considered conservative. Quantifying projected AC demand owing to urban expansion simultaneously with large-scale climate change is an important next step in preparing for anticipated warmer climates. Future work will therefore evaluate regional impacts of urban expansion under various climate change scenarios that account for effects of increased emissions of long-lived greenhouse gases. Finally, a sensitivity study should be conducted with a refined vertical structure so as to better characterize urban boundary layer processes (Mahalov and Moustaoui 2009).

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REFERENCES


