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Urban Effects on Regional Climate: A Case Study in the Phoenix and Tucson “Sun Corridor”^①

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ABSTRACT: Land-use and land-cover change (LULCC) due to urban expansion alter the surface albedo, heat capacity, and thermal conductivity of the surface. Consequently, the energy balance in urban regions is different from that of natural surfaces. To evaluate the changes in regional climate that could arise because of projected urbanization in the Phoenix–Tucson corridor, Arizona, this study applied the coupled WRF Model–Noah–Urban Canopy Model (UCM; which includes a detailed urban radiation scheme) to this region. Land-cover changes were represented using land-cover data for 2005 and projections to 2050, and historical North American Regional Reanalysis (NARR) data were used to specify the lateral boundary conditions. Results suggest that temperature changes will be well defined, reflecting the urban heat island (UHI) effect within areas experiencing LULCC. Changes in precipitation are less robust but seem to indicate reductions in precipitation over the mountainous regions northeast of Phoenix and decreased evening precipitation over the newly urbanized area.

KEYWORDS: Models and modeling; Coupled models; Land surface model; Mesoscale models; Regional models

1. Introduction

Since 1950, the metropolitan region of Phoenix, Arizona, has been one of the fastest-growing urban areas in the United States (Chow et al. 2012). It has undergone substantial land-use and land-cover change (LULCC) since World War II by shifting economic priorities from a mostly agrarian lifestyle to an urbanized one. The most rapid development began around 1970, when the baby boom generation reached adulthood, with a large number of job opportunities becoming available in the metropolitan area. By 2010, Phoenix (as the largest populated city in Arizona) had reached a population of 1.4 million and an urban extension of 1338.26 km² in 2010 (U.S. Census Bureau 2010). Meanwhile, Tucson has become the second largest city with an area of 588 km² and a population of about 520 116 (U.S. Census Bureau 2010). With continuing development, both cities are projected to grow toward each other, developing into what has been called the “Arizona Sun Corridor.” By the year 2050, the Sun Corridor is projected to develop (under the most intense urbanization scenario) as shown in Figure 1, at the expense of agricultural and native semidesert landscapes. Recent research has suggested that the impact of projected urbanization on summer season local to regional temperature could be as significant as those induced by large-scale climate change (Georgescu et al. 2012).

Since 1970, summers in U.S. urban areas have been recorded as being progressively warmer under the synergistic effects of global warming and urban heat island effect (NCDC, <http://www.ncdc.noaa.gov/cag/>). The 2014 Climate Central report indicates that 57 out of 60 the largest U.S. cities had measurable growth in urban heat island effect over the period 2004 to 2013 (Climate Central 2014). For Phoenix and Tucson, the mean temperatures are 1.8° and 0.22°C warmer, respectively, than in their surrounding rural areas (Climate Central 2014), and the temperature in the Phoenix urban core has been reported as being 2.2°C higher compared to the surrounding area (Brazel et al. 2007). The most significant effect of urbanization of temperature (due to the urban heat island effect) has been found to occur at night, with minimum temperatures in Phoenix and Tucson being (on average) 3.8° and 1.3°C, respectively, warmer than the surrounding rural area (Brazel et al. 2007). Svoma and Brazel (2010) reported that the daily minimum temperature is most

Figure 1. In 2005, Phoenix and Tucson are represented as the red and blue crossed region. The Phoenix–Tucson Corridor in 2050 is represented as the black slash area. Domains 1 and 2 are represented as the black dash and red box. Elevations are shown in meters.

strongly influenced by urbanization, with the mean minimum temperature during the urban period exceeding that of the preurban period by 4.4°C.

In addition to the heat island effect, urbanization may also affect regional climate by changing local circulation and precipitation patterns. Evidence from many observational studies suggests that urbanization can bring about modifications to rainfall patterns over and downwind of cities (Burian and Shepherd 2005; Changnon et al. 1977; Shepherd 2005, 2006). In the early 1970s, the Metropolitan Meteorological Experiment (METROMEX) showed that urbanization can lead to increased precipitation during the summer season (Changnon et al. 1977, 1981; Huff and Vogel 1978), with about 5%–25% increases in observed precipitation over and within 50–75 km downwind of the urban area (Changnon 1979, Huff and Vogel 1978). Shepherd (2006) studied a 108-yr precipitation historical data record for Arizona and found statistically significant increases in mean precipitation of 11%–14% in the Lower Verde basin (northeast of Phoenix) from a preurban (1895–1949) to posturban (1950–2003) period associated with the expansion of the Phoenix metro area. Studies also suggest that cities can also modify the diurnal distribution of precipitation. For instance, Balling and Brazel (1987) reported the more frequent occurrence of late-afternoon storms in Phoenix during recent years; however, they did not find evidence for significant changes in the mean precipitation amounts and frequencies during the entire summer monsoon season.

Several modeling studies have investigated the effects of urbanization on precipitation. Baik et al. (2001) investigated dry and moist convection forced by an urban heat island (UHI) effect using a 2D, nonhydrostatic, compressible model and concluded that increased urban heat island effect can decrease the time required for rainwater formation, while moving the horizontal location closer to the heating center. Craig and Bornstein (2002) found that the UHI can induce convergence and

convection. Using the Weather Research and Forecast (WRF) Model, [Lin et al. \(2011\)](#) found that the UHI can affect the location of thunderstorms and precipitation in northern Taiwan. [Veerbeek et al. \(2011\)](#) found that extreme rainfall over the cities of Beijing, Mumbai, and Can Tho has been increasing and suggested that significant changes in flood risk and precipitation levels will likely occur.

Over our region of interest, [Georgescu et al. \(2008\)](#) used the Regional Atmospheric Modeling System (RAMS) to simulate three different dry and three different wet years with land surface data circa 1973, 1992, and 2001 over the Phoenix metro region. They concluded that the signal of increasing precipitation due to LULCC is present only during dry years. [Georgescu et al. \(2009a,b\)](#) investigated the mechanism of precipitation enhancement and concluded that precipitation recycling, rather than the direct or indirect effect of the urbanization, may be responsible for the precipitation increase.

While numerous studies such as those mentioned above suggest an enhanced signature of precipitation over and downwind of metropolitan areas, there remain reasons to be skeptical. Precipitation anomalies in the La Porte station, Indiana, studied extensively in the METROMEX program, began to shift locale in the 1950s and then disappeared in the 1960s ([Changnon 1980](#)). [Tayanç et al. \(1997\)](#) found no evidence of urban effects on precipitation for four large cities in Turkey, and a study of the Pearl River Delta of China reported reductions in precipitation ([Kaufmann et al. 2007](#)). Despite decades of work, it remains unclear why the UHI can enhance precipitation in some regions while seemingly having no effect, or leading to decreases, in other regions.

This paper investigates temperature and precipitation variations over the state of Arizona that may arise because of projected urban expansion of the Phoenix–Tucson Sun Corridor. To understand the causes for potential temperature and precipitation changes over the urban and downwind regions, we employ a numerical modeling framework to examine the changes that may arise because of projected future expansion. We use the nonhydrostatic, compressible WRF Model and account for urban characteristics by incorporating an Urban Canopy Model (UCM). Our study is similar to the work of [Georgescu et al. \(2012, 2013\)](#) in that we use the WRF + UCM to study the effects on regional climate in the Sun Corridor region. However, our goal is to examine the hydroclimate of the entire corridor region in detail, with our hypothesis being that detailed representation of the hydroclimate of the region can lead to better characterization of the impacts of urbanization on precipitation. To this end, we use a high-resolution simulation that does not require a convective parameterization and so is able to more accurately represent convective events during the monsoon season; that is, our simulations are at a 2-km resolution, while [Georgescu et al. \(2012, 2013\)](#) use 20-km resolution.

In the next section, we introduce the numerical model and experimental design. [Section 3](#) presents and discusses results from two land-use scenarios and reports additional analysis regarding the potential impacts of LULCC on future water and energy demand variation. A summary and our conclusions appear in [section 4](#).

2. Methodology

This study uses the WRF Model to simulate regional climate with two different land-use scenarios: one with historical observed land cover for 2005 and the other

for projected future land cover. We perform the simulation during the peak summer monsoon season (i.e., July and August) for each year from 1991 to 2000.

2.1. WRF Model and configuration

The WRF Model, version 3.4, is coupled to a land surface and urban modeling system that aimed to address emerging issues in urban areas (Skamarock et al. 2008). Our experiment uses the Noah land surface model (LSM) to model the land surface (Chen and Dudhia 2001), thereby providing surface energy fluxes and surface skin temperatures that serve as the boundary conditions for the atmospheric model. While the original version of Noah LSM has a bulk parameterization for urban land use, our experiment uses a single-layer UCM to better represent the energy fluxes and temperature within the urban region. This single-layer urban canopy model, first developed by Kusaka et al. (2001) and further modified by Kusaka and Kimura (2004), consists of two-dimensional symmetrical street canyons of infinite length, with treatment of momentum and energy that considers the canyon orientation and the diurnal variation of the azimuth angle (Tewari et al. 2006). The UCM model estimates temperature and energy fluxes at roof, wall, and road surfaces, which later serve as lower boundary conditions for the atmospheric model. It is important to point out that the UCM does not include urban irrigation. Other parameterizations applied in this experiment were chosen based on the operational WRF Model simulations that are continuously produced at the University of Arizona during the monsoon season; all schemes, and in particular the microphysics scheme, have been chosen to optimally represent very heavy precipitation and winds associated with the strong to severe storms during the season (M. Leuthold 2013, personal communication). The parameterizations include the Morrison double-moment scheme for microphysics (Morrison et al. 2009); the CAM scheme that allows for aerosols and trace gases for longwave and shortwave radiation (Collins et al. 2004); the Eta surface layer scheme for the surface layer parameterization; the Noah land surface model for the land surface scheme (Chen and Dudhia 2001; Janjić 1996, 2002); the Mellor–Yamada–Janjić scheme for planetary boundary layer physics (Janjić 1990, 1996, 2002; Mellor and Yamada 1982); the Kain–Fritsch convective parameterization scheme (Kain 2004) for the outer domain; and no convective parameterization for the inner domain.

2.2. Study domain

The study region mainly covers the state of Arizona, from latitude 30.7° to 35.7°N and longitude 115.2° to 108.2°W. We use two nested domains with outer grid spacing of 10 km and inner grid spacing of 2 km (see Figure 1). The inner domain has 175 grid cells in the zonal direction and 190 grid cells in the meridional direction and is chosen to correspond to the urban area and regions that may be affected by the urban corridor (i.e., including areas at least 75 km far from the urban border).

2.3. Land-use representation

Land-use characteristics for 2005 (LULC_2005) were obtained directly from default MODIS land-use data available in the WRF Model. The projected land-use

characteristics for 2050 (LULC_2050) are derived by combining three different datasets, under the most intense urbanization scenario:

- 1) SLEUTH data: A geospatial dataset describing a future current trends scenario of unmanaged exponential growth of land-use change into the year 2050 in the Santa Cruz Watershed (Tucson area) using the SLEUTH model (named as an acronym for its input data layer requirements—slope, land use, exclusion, urban extent, transportation, and hillshade data), a fuzzy constrained cellular automata model that can predict potential future urban growth in a spatially explicit fashion. The dataset has a 30-m resolution Universal Transverse Mercator projection (zone 12) and was created using input from local government to establish areas to be excluded from growth. The scenario predicts the footprint of urban growth to approximately triple from 2009 to 2050, which is corroborated by local population estimates (Norman et al. 2012).
- 2) MAG: Raster imagery describing a future scenario for 2050, for the state of Arizona, developed by the Maricopa Association of Governments (MAG; Maricopa Association of Governments 2005, unpublished report). MAG staff, working with the other councils of governments (COGs), used a “red dot” algorithm and input describing land ownership, to establish areas to be excluded from growth, along with census information, to develop a “what if” scenario to see how the state could develop. Red dots represent housing units, which are expected to triple by 2050, from 2000, when the population is expected to hit 16 million (Maricopa Association of Governments 2005, unpublished report).
- 3) NALC: The 2005 North American Land Cover (NALC) data, classified using MODIS data (250 m), describing current land use/land cover (Commission for Environmental Cooperation 2013).

The higher-resolution datasets (SLEUTH and MAG) were resampled to a uniform 250-m resolution to mimic the MODIS-derived NALC data and then reprojected into Lambert azimuthal equal area. The NALC data were reclassified to the MODIS 20-category land-use classification, where urban area is class 13. Urban classes from the MAG dataset for 2050 and the SLEUTH dataset for 2050 were overlaid and superimposed into the MODIS-style dataset to mimic the highest-resolution, most accurate future urban growth scenarios for the entire study area. This resulted in datasets describing land use/land cover for 2005 and in 2050 based on the modified IGBP–MODIS 20-category land-use classification. The datasets were converted from geospatial information systems (GIS) format into ASCII text files, culminating in 43 070 rows and 35 000 columns of information, to be used as input to the WRF Model. They were then superimposed on the default WRF Model MODIS 20-level classification scheme.

2.4. Lateral boundary conditions

The same climate forcings were used to drive the WRF Model for the two different sets of land-use data. The lateral boundary conditions were obtained from the North American Regional Reanalysis (NARR) data (Mesinger et al. 2006).

Initial soil moisture and temperature conditions were also derived from NARR data. NARR provides similar soil conditions when compared with the North American Land Data Assimilation System (NLDAS) soil moisture products (not shown). We simulated each of the years from 1991 to 2000, beginning on 1200 UTC 15 June and running through the end of August (1200 UTC 31 August) to cover the peak of the monsoon season in Arizona.

2.5. Observational temperature data

In section 3.4, we correlate urban temperatures with electricity load within Tucson and Phoenix to then be able to estimate the effect of future temperatures on electricity load under urban expansion. Near-surface air temperatures collected by the Arizona Meteorological Network (AZMET) were used; AZMET provides meteorological- and weather-based information for agriculture and horticulture in southern and central Arizona. The observation station for Tucson is located at 32°16'N and 110°56'W, very close to the city center. The station for Phoenix is the Phoenix Encanto site at 33°28'N and 112°05'W. Both sites are located within the urban region in the LULC_2005 and therefore provide a good representation of actual urban temperature. Both sites provide hourly air temperature, relative humidity, wind speed, and so on (data available online at <http://ag.arizona.edu/azmet/>).

The electric load data for Tucson were provided by the Tucson Electric Power (TEP) and for Phoenix were provided by the Arizona Public Service (APS) and the Salt River Project (SRP). The electricity data were provided at a 1-min time step and were aggregated to an hourly time step to correlate with the observed temperature data.

2.6. Calculation of statistical significance

To test for temperature and precipitation change, we performed statistical tests on their mean values. Since temperature and precipitation are highly autocorrelated, a decorrelation factor was incorporated into the statistical test using the following equation:

$$z = \frac{\bar{\Delta} - \mu_{\Delta}}{(s/n)^{1/2}},$$

where $\bar{\Delta} = 1/n \sum_{i=1}^n \Delta i = \bar{x}_1 - \bar{x}_2$; n is the sample size; s is the sample variance of the n differences between x_1 and x_2 ; x_1 and x_2 are the sample data at each grid point under different landscape representations; and $\mu_{\Delta} = 0$, since the two sample means are assumed to be the same. To account for autocorrelation, we use the effective sample size n' , formulated as

$$n' \approx n \frac{1 - \rho_1}{1 + \rho_1},$$

where ρ_1 is the lag-1 autocorrelation coefficient.

The statistical significance of the temperature and precipitation results was also analyzed using the bootstrap method, a useful approach for circumstances when

sample sizes are small (Zoubir and Boashash 1998). This was performed as follows: 1) for each grid in each of the two landscape representations, the temperature and precipitation time series in LULC_2005 and LULC_2050 were resampled with replacement; 2) for each (re)sample, the corresponding mean and difference in mean were recorded; 3) steps 1 and 2 were repeated 1000 times; and 4) if 97.5% of the differences were found to be larger than 0, this was considered to represent a statistically significant increase (similarly if 97.5% of the difference were less than 0 this was considered to represent a statistically significant decrease and otherwise representing no significant change).

3. Results

3.1. Evaluation of model performance

To evaluate model performance, simulations for the period 1991–2000 were compared with PRISM data (PRISM Climate Group, available online at <http://prism.oregonstate.edu>). Figure 2 shows that WRF Model simulation can reasonably downscale the spatial pattern of temperature and precipitation from the forcing NARR data. It captures the dipole pattern of precipitation distribution as well as the gradual decrease of temperature from the southwest to the northeast of the domain. After downscaling, WRF Model simulation tends to underestimate the domain averages for both temperature and precipitation, with WRF Model–simulated temperature being about 0.91°C cooler and precipitation being about 38 mm (36%) less than PRISM for the simulated July–August period. Similarly, the original NARR data have less domain average precipitation as well (27.5 mm less) but warmer average temperature (0.90°C). Root-mean-square error (RMSE) of temperature is very close in both the WRF Model (0.98°C) and NARR (0.92°C), but the precipitation in NARR was better with RMSE equal to 29.59 mm, compared to 43.7 mm in the WRF Model. Even though WRF Model simulation underestimates precipitation as compared to NARR, it is important to note that precipitation in NARR is obtained from data assimilation and might not capture finescale precipitation features. On the other hand, because of the higher resolution in the WRF Model, much finer details in the temperature and precipitation fields are represented. Moreover, the WRF Model realistically captures the interannual variability of domain average temperature and precipitation (Figure 3), with a correlation coefficient of 0.87 for temperature variation and 0.74 for precipitation variation. Even though the magnitudes of temperature and precipitation tend to be slightly lower than the PRISM data, the WRF Model simulations can be treated as credible, given that they realistically capture the spatial pattern and interannual variability.

3.2. Urban impacts on temperature

The effects of the urban heat island on temperature are shown in Figure 4. Daily mean, maximum, and minimum temperature were obtained from hourly temperature data and then were averaged respectively during the monsoon season to represent the seasonal mean, maximum, and minimum temperature. On average,

Figure 2. (left) 10-yr summertime (July and August) mean temperature (°C) from (a) WRF Model-simulated, (c) PRISM, and (e) NARR data; (right) 10-yr July and August mean precipitation from the (b) WRF Model, (d) PRISM, and (f) NARR data.

Figure 3. (top) Domain-averaged July and August accumulated precipitation variation in WRF Model, PRISM, and NARR from 1991 to 2000. (bottom) Domain-averaged July and August domain average temperature variation in WRF Model, PRISM, and NARR from 1991 and 2000.

changes in the mean, maximum, and minimum temperature over the urbanized area are $+1.27^{\circ}$, -0.07° , and $+3.09^{\circ}\text{C}$, respectively. The difference in mean daily temperature between LULC_2050 and LULC_2005, averaged over 10 years of simulation, shows a statistically significant increase over the urbanized area. While the daily maximum temperature during the daytime is not significantly altered, the minimum temperature (occurring at night) over urbanized areas shows a significant increase. Changes in urban mean temperature and minimum temperature are found to be statistically significant and can be explained by changes in surface thermal properties such as heat capacity and thermal conductivity. This explanation is supported by Figure 5, which shows the diurnal energy cycle averaged over the regions that are transformed from native vegetation in 2005 to urban in 2050 (newly urbanized). Transforming the natural land surface to urbanized results in more energy being stored as ground heat flux during the daytime from 0700 to 1600 local time (LT), whereas more positive ground heat flux appears during the night, indicates more energy being released (warming the atmosphere) and leading to warmer air temperatures.

Figure 4. July- and August-simulated temperature difference between LULC_2050 and LULC_2005: (a) mean temperature in LULC_2005 and (b) mean temperature difference between LULC_2050 and LULC_2005. (c) Student's t test and bootstrap test for mean temperature difference; orange (blue) indicates significant increase (decrease) in both statistical tests. (d), (e), (f) As in (a)–(c), but for maximum temperature. (g), (h), (i) As in (a)–(c), but for minimum temperature.

Figure 5. (top) Energy diurnal cycle over the newly urbanized area, including sensible heat flux (SH), latent heat flux (LH), ground heat flux (GRD), and net radiation (Net) for LULC_2005 (solid line) and LULC_2050 (dashed line). (bottom) Temperature diurnal cycle over newly urbanized area for LULC_2005 (solid line) and LULC_2050 (dashed line).

At the same time, urbanization results in decreased latent heat flux throughout the day, and the reduced evaporation limits the availability of atmospheric column water for convective processes. This result is similar to the findings of Georgescu et al. (2012). Meanwhile, our results show that greater sensible heat flux difference is positive during the night as expected, causing urban nighttime air temperatures to be larger. However, daytime sensible heat flux differences are negative. This somewhat surprising result agrees with previous findings (Cao and Lin 2014) and can be attributed to the decrease in turbulent activity associated with the canyons of the urban canopy scheme. The vertical wind speed profile in the UCM follows that in previous literature (Swaid 1993), with in-canyon wind speed being exponentially proportional to the wind speed above the canyon and helping to determine the heat flux exchange between the canyon wall, street, and the air. When canyon wind speed is reduced because of the canyon structure following the exponential

relation, the sensible heat flux from the wall and street to canyon is reduced as well, as reflected by the reduced sensible heat flux.

The diurnal temperature variation over the newly urbanized areas is also shown in [Figure 5](#). The magnitude of difference in maximum and minimum temperature is consistent with the previous analysis. However, the occurrence of maximum and minimum temperatures is delayed by about 1 h and 30 min, respectively. This means a longer duration of higher temperature during the day for LULC_2050, potentially leading to stress for the population residing in the urban areas.

The spatial pattern of sensible and latent heat flux is shown in [Figure S1](#) in the supplemental information. Sensible heat flux is larger in the western part of the domain (in the lower desert) and smaller in the northeast (higher elevations). In contrast, latent heat flux is greatest in the northeastern mountains and gradually decreases toward the western desert. The differences in the mean sensible heat flux due to urbanization indicates an increase in sensible heat flux (and decrease in latent heat flux) over Tucson and surroundings and the northeast high mountains, indicating a change in the partitioning of available energy. While increased sensible heat flux can indicate less stable conditions that could lead to increased precipitation, the reduced evapotranspiration results in less water available for convection; that is, the two processes act in opposite directions. As we will show below, decrease in moisture availability leads to less precipitation.

3.3. Urban impacts on precipitation

3.3.1. Urban impacts on summer mean precipitation

[Figure 6](#) shows the 10-yr average summertime precipitation difference between LULC_2005 and LULC_2050. A pattern of decreasing precipitation dominates the northeastern mountainous part of the domain and some parts of the urban corridor. A Student's t test of the difference in daily mean precipitation at each grid cell suggests that this change is statistically significant. However, the bootstrap test does not indicate a statistically significant change and so the results must be considered to be inconclusive.

Focusing on the diurnal cycle of precipitation, we analyze the precipitation differences for newly urbanized regions ([Figure 7](#)). The results indicate that while the timing of the peak in the diurnal cycle remains unchanged, there is a marked decrease precipitation (about 6%) during the late afternoon and early evening (1400–2100 LT). This suggests reduced precipitation in the newly urbanized areas likely due to reduced evapotranspiration.

To explain the fact that precipitation decreases over the northeastern part of the domain and parts of the urban corridor, we hypothesize that urbanization leads to a decrease in evapotranspiration ([Figure S1](#)), so that less moisture is available to precipitate in the mountainous areas via regional precipitation recycling [similar to the suggestion by [Georgescu et al. \(2009b, 2012\)](#)]. It is important to point out, however, that monsoonal precipitation in the southwest United States is highly variable both in terms of location and intensity. [Figure S2](#) (in the supplemental information) shows the monsoon seasonal (July and August) accumulated precipitation for each year, from which it is clear that precipitation does not show a consistent pattern within the model domain for this 10-yr timespan. Therefore,

Figure 6. (a) Average July and August accumulated precipitation from 1991 to 2000 in LULC_2005. (b) July and August precipitation difference between LULC_2050 and LULC_2005 from 1991 to 2000, normalized by number of days. (c) Bootstrap test of difference in daily precipitation between LULC_2005 and LULC_2050, blue (orange) indicates statistically significant decrease (increase). (d) As in (c), but for Student's *t* test; blue indicates statistically significant decrease.

even if downwind precipitation is indeed changed because of urbanization, the small differences in the location of precipitation from year to year would show up as negligible changes when averaging over time. Add to this the fact that different patterns of precipitation are associated with different dominant wind directions and any signal can disappear simply because of changes in wind direction.

To dig further into this, we further characterized precipitation based on predominant wind patterns. Previous research defines the relative upwind and downwind region based on seasonal or annual dominant wind (Burian and

Figure 7. Diurnal cycle of precipitation over the newly urbanized area in LULC_2050 (red) and LULC_2005 (blue).

Shepherd 2005; Georgescu et al. 2008; Shepherd 2006). However, moisture sources over the North American Monsoon (NAM) region vary daily. Moisture may come from the Gulf of Mexico, the Pacific Ocean, the Gulf of California, as well as terrestrial recycling from the monsoon region (Hu and Dominguez 2015). Different sources of moisture are characterized by different synoptic conditions and have different associated upwind and downwind regions. We therefore defined eight flow regimes based on the hourly wind direction at 500 hPa. If the wind direction in more than 50% of the urban area (in 2050) was coming from a particular direction, then that hour was assigned that particular wind direction. We compared the vertically integrated moisture flux to the wind at the 700- and 500-hPa levels, and results indicate that the direction of the wind at the 500-hPa level is more similar to the direction of the vertically integrated moisture flux.

Figure 8 shows the accumulated precipitation differences for different wind regimes. While the way to define wind flow regime is subjective, we checked the number of hours that fall into each category and found that (in total) more than 80% of simulated time steps fall in one of the eight categories; during the remaining 20% of the time steps, the wind direction is spatially variable and does not fall into any category. The most frequent wind directions are southeasterly, southerly, and southwesterly, accounting for 64% of all time steps. The least frequent wind patterns are northerly and northwesterly, accounting for less than 5% of the entire simulation period. This result agrees with previous studies analyzing wind flow patterns and the corresponding moisture sources during the monsoon season (Hu and Dominguez 2015). The results show high spatial heterogeneity with regions of increasing precipitation and regions of decreasing precipitation. The decrease in precipitation seen in the mean (Figure 6b) seems to arise due to precipitation differences when the wind comes from the southeast and the south, but again the results are noisy and not statistically significant (see Figure S3 in the supplemental

information). Even when analyzed based on the dominant flow conditions, the results remain inconclusive.

3.3.2. Urban impacts on precipitation occurrences

Previous research suggests that urban regions may initiate convection (Balling and Brazel 1987; Changnon and Westcott 2002; Takahashi 2003), and hence it is reasonable to expect a larger number of convective days in urban regions, as compared to the native land cover. Here, we define a precipitation day when more than 0.1 mm day^{-1} of precipitation falls over 20% or more of the urban area in 1 day. However, these area and precipitation thresholds are subjective, so we tested different thresholds of precipitation and areal cover. Depending on whether the day is designated as a precipitation “p” or not “n” in the current “c” and future “f” land-cover experiments, we have four possible categories: 1) rains in both LULC_2005 and LULC_2050 (cpfp); 2) no rain in LULC_2005 and rains in LULC_2050 (cnfp); 3) rains in LULC_2005 and no rain in LULC_2050 (cpfn); and 4) does not rain in either (cnfn). Precipitation days in each of the four categories are shown in Table 1. By comparing cnfp and cpfn, we can determine whether more precipitation days occur because of urbanization. As expected in an arid region, most days are “not precipitation” days in both LULC scenarios. When looking at the other cases, our results suggest a reduction in precipitation days due to urbanization (six out of nine cases); however, the results depend on the precipitation and areal cover thresholds used.

3.4. Urban impacts on water and energy demand

Our results suggest that projected expansion of the urban corridor in the Phoenix–Tucson area (as simulated by the WRF Model) may affect both temperature and precipitation, which can be expected to affect water and energy demand in the region. The Arizona Department of Water Resources (ADWR) provides water demand information and assessments for each active management area (i.e., area that heavily relies on the groundwater supply). The goal is to ensure that, by the year 2025, groundwater is withdrawn at a rate that equals the recharge. Tucson and Phoenix are located in the Tucson Active Management Area (TAMA) and Phoenix Active Management Area (PAMA), respectively. Historically, Tucson municipal water demand has increased by 68% from $1.39 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$ in 1985 to $2.33 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$ in 2006. During the same period, Phoenix municipal water demand grew by 76%, increasing from $7.82 \times 10^8 \text{ m}^3$ to $1.38 \times 10^9 \text{ m}^3 \text{ yr}^{-1}$. The total water demand increase for both cities was roughly 75%. At the same time, Tucson’s area grew by 124% and Phoenix’s area grew by 50%; the area of the two cities combined grew by 68%. This indicates that during this period, the water demand for the two cities combined grew almost linearly with area (with Tucson growing more but conserving more water per area than Phoenix). Based on these estimates, the land-use projections used in this study (that urban extent in 2050 is about 7 times larger than in 2005), and an assumption that water usage intensity remains the same in year 2050 as in 2005, we estimate that water demand will grow (linearly) to around $1.12 \times 10^{10} \text{ m}^3$ for the entire corridor. Bear in mind that this urban projection is made by assuming a scenario of high rates urban expansion, and

Figure 8. Precipitation difference between LULC_2050 and LULC_2005 under each of the flow regime.

Table 1. Number of days in each category (as discussed in the text) with regard to whether it was convective day or not in each land-cover representation; T indicates that cnfp is greater than cpfn, which means more convective days occur due to urbanization, and F indicates less convective days occur due to urbanization.

Precipitation threshold (mm day ⁻¹)	Area threshold (%)	cnfn	cpfn	cnfp	cpfp	More precipitation in future LULCC
0.1	20	305	21	23	241	T
0.5	20	367	27	14	182	F
1	20	408	16	14	152	F
0.1	30	370	22	12	186	F
0.5	30	431	11	16	132	T
1	30	459	16	17	98	F
0.1	40	411	18	15	146	F
0.5	40	470	19	13	88	F
1	40	494	11	16	69	T

it is not likely that this water demand will be easily satisfied, especially given the water-limited nature of the state of Arizona.

Groundwater is an important water source in the state of Arizona, accounting for 64% of water supply in TAMA and 31% in PAMA in 2006. The ADWR projections of future water demand are based on population growth rate and water use, with the assumption that when the full utilization of all other water sources cannot meet the demand, groundwater can be utilized to meet the remainder. In their highest water demand scenario, municipal water demands are 3.80×10^8 and 2.59×10^9 m³ for TAMA and PAMA, respectively, requiring groundwater overdrafts in 2025. Our estimates indicate a much larger water demand by 2050 (under the assumptions stated above), suggesting there will simply not be enough water to sustain that level of urbanization. Thus, urban growth to the extent portrayed by LULC_2050 is probably unsustainable, with water being an important limitation to future urbanization unless alternative sources are found.

Meanwhile, temperature increases within the urban area (along with the greenhouse gas-induced global climate change) are likely to increase energy demands for electricity cooling needs (Georgescu et al. 2013). Cooling demands in the urban areas are known to account for more than 50% of the total electricity demand, with this ratio climbing to as high as 65% during the hot season evening hours in semiarid urban environments (Salamanca et al. 2013). Here, we use electric load data for Tucson and Phoenix and assume the ratio of air conditioning (AC) consumption to total electric load as following the diurnal pattern as shown in Salamanca et al. (2013). The data are provided at the intradaily time scale by Tucson Electric Power for Tucson and APS and SRP for Phoenix. The diurnal AC consumption in each city is obtained by multiplying the diurnal total electric load to the corrected ratio. Figure 9 shows that the AC consumption follows a very similar diurnal pattern to the diurnal temperature observed within the urban area for the same period.

To project AC consumption under warmer temperatures, temperature and electric load were fitted to a polynomial function (with a linear correlation coefficient of 0.85 for Tucson and 0.85 for Phoenix); the results clearly suggest that temperature plays a significant role in influencing the AC consumption (see Figure 10). Then for each hour during the day, the increased energy load due to

Figure 9. Diurnal cycle of AC consumption and temperature at the (a) Phoenix and (b) Tucson metropolitan areas.

UHI-induced temperature increase can be obtained from the fitted function. Consequently, the projected future total AC consumption accounts for increase in temperature as well as the urban expansion. Even though there are many other factors that may affect the energy consumption, it is safe to assume that areal enlargement and temperature are likely to be among the most important factors affecting future AC consumption. Considering larger area and temperature simultaneously, the projection of future additional AC consumption demand for Tucson and Phoenix is shown in Figure 11. Overall, the areal enlargement due to urban expansion appears to be the dominant factor affecting energy consumption in the future.

4. Conclusions

This study has examined the climatological effects associated with potential expansion of the Phoenix–Tucson urban corridor on summer monsoonal (July and August) climate in Arizona. It needs to be emphasized that only the impact of urbanization is studied here, while the expected global warming effect from 1991 to 2050 is not considered. Given that the Phoenix metropolitan area has been one

Figure 10. Scatterplot of the AC consumption and temperature data; the green line indicates the fitted polynomial function.

the most rapidly developing areas in the United States during the past 30 years, and that the Phoenix–Tucson Sun Corridor is still expected to add another 5 to 6 million inhabitants from 2000 to 2030 (U.S. Census Bureau 2005), it is useful for planners to understand how urbanization can affect the hydroclimate of the region. We used high-resolution simulations of 10 monsoon seasons (from 1991 to 2000) generated by the WRF Model under a current representation of land cover (LULC_2005) and a projected land cover representative of high rates of urban expansion (LULC_2050).

Our results suggest that urbanization will likely not impact the magnitudes of daily maximum temperatures but may result in significant increases in daily minimum (night time) temperatures over the urban corridor. This agrees with previous research indicating that the urban heat island is mainly a nocturnal phenomenon. Accordingly the increases in daily mean temperature are mainly due to increased nighttime temperatures. These results agree with Georgescu et al. (2013). However, both the daily maximum and minimum temperature are delayed, with about an hour for the maximum and 30 min for the minimum temperatures, resulting in longer periods of hotter temperatures. Such increased temperatures will likely increase the risk of heat-related health issues and even death (McGeethin and Mirabelli 2001). Of course, it is possible that the implementation of “cool roof” technology could help to reduce the UHI phenomenon, providing a potential solution to relieve the impact on temperature (Georgescu et al. 2013).

Surprisingly, our energy diurnal cycles over the newly urbanized region suggest that sensible heat flux will increase during the nighttime and decrease during the day (because of sensible heat flux calculations in the urban canopy model, as explained earlier). Meanwhile, latent heat fluxes are likely to decrease dramatically

Figure 11. AC consumption of Tucson and Phoenix in 2005 and 2050, considering both areal enlargement and warmer temperature.

throughout the day, resulting in less evaporation over urban regions and downwind mountainous areas. The overall effect of urbanization is likely to be less moisture available for convection. Overall, our results indicate that the ground heat flux difference will be negative during the day and positive during the night, indicating energy storage within the soil column during the day and release to the atmosphere during the night.

We also examined the potential changes in 10-yr climatological summertime precipitation because of urbanization. Decrease in precipitation over the mountainous higher elevations in the northern part of the domain and part of the newly urbanized region remains inconclusive because of the inconsistency between the Student's t test and bootstrap test. Meanwhile the simulations indicate decreased evening precipitation in the newly urbanized region. However, an analysis based on dominant wind direction did not provide statistically significant evidence for changes in precipitation patterns. These results are consistent with those of Georgescu et al. (2012). However, unlike Georgescu et al. (2012), our results are much more spatially heterogeneous (a result of using very high resolution to conduct the simulations) and reductions are only seen in the mountainous north-eastern part of the domain and part of the urbanized region.

Overall, while our temperature results appear to be robust, our precipitation results must be treated as inconclusive. Because of the complex nature of convective precipitation in the southwest United States, each precipitation event has its unique intensity and location. Consequently, precipitation changes over the downwind region will likely not result in robust changes to spatial patterns. While this problem might potentially be solved by use of a larger sample size, it seems unlikely. We hypothesize that because the ambient air is very dry, impacts of urbanization on energy partitioning at the surface will not result in significant changes in precipitation because there is simply not enough available specific humidity. In contrast, similar research conducted in Tokyo, Japan, where summertime

relative humidity is usually above 70%, reported increased precipitation over the metropolitan area (Kusaka et al. 2014).

Finally, we developed rough estimates of future water and energy demand based on urban expansion and temperature change. Assuming that increase in urban area is the main factor influencing the water demand, our estimates indicate that about 7 times the current water supply would be needed to sustain an urban scale like LULC_2050, which would require extensive access to groundwater storage. This suggests that projected urban expansion to the extent represented by LULC_2050 will be very difficult to achieve without access to new sources of water. Meanwhile, energy supplies will have to be expanded to meet future air conditioning needs to deal with the longer durations of high daytime and nighttime temperatures.

There are limitations to our study that must be accounted for in any analysis involving urban planning. In particular, we did not consider the impacts of aerosol, even though the role of aerosols in urban environments will likely be an important factor. Other limitations include the lack of consideration of irrigation effects in the land surface representation, which can be expected to have a significant impact on the water and energy budget over the region. Irrigation over urban areas can actually increase the latent heat flux while decreasing the sensible heat flux, which leads to the so-called oasis effect (Georgescu et al. 2011) and potentially contributes to changes in precipitation. It is important to emphasize that our study does not include urban irrigation, which could be important in cities like Phoenix and Tucson. To evaluate the potential impact of urban irrigation in our results, we performed a sensitivity study with a rough characterization of urban irrigation where soil moisture was set to saturation over 15% of the urban area. Our results show that with and without urban irrigation, temperature increases over the newly urbanized region and precipitation decreases over the entire domain and in particular over the newly urbanized region. While including urban irrigation generates a weaker response (there is more precipitation in the urban irrigation case), there is still an overall decrease in precipitation due to increased urbanization. Another important factor affecting regional precipitation may be precipitation recycling (Georgescu et al. 2009b). Studies exploring these and other effects will be reported in future papers.

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