Sensitivity of Summer Climate to Anthropogenic Land Cover Change over the Greater Phoenix, AZ, Region

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This work evaluates the first-order effect of land-use/land-cover change (LULCC) on the summer climate of one of the nation’s most rapidly expanding metropolitan complexes, the Greater Phoenix, AZ, region. High-resolution - 2-km grid spacing - Regional Atmospheric Modeling System (RAMS) simulations of three “wet” and three “dry” summers were carried out for two different land cover reconstructions for the region: a circa 1992 representation based on satellite observations, and a hypothetical land cover scenario where the anthropogenic landscape of irrigated agriculture and urban pixels was replaced with current semi-natural vegetation. Model output is evaluated with respect to observed air temperature, dewpoint, and precipitation. Our results suggest that development of extensive irrigated agriculture adjacent to the urban area has dampened any regional-mean warming due to urbanization. Consistent with previous observationally-based work, LULCC produces a systematic increase in precipitation to the north and east of the city, though only under dry conditions. This is due to a change in background atmospheric stability resulting from the advection of both warmth from the urban core and moisture from the irrigated area.

Keywords: land use-land cover change; land-atmosphere interactions; anthropogenic impact; precipitation; regional climate modeling; Phoenix, Arizona
1. **Introduction**

In addition to global-scale climatic forcings, anthropogenic land-use and land-cover change (LULCC) has the potential to be a highly significant driver of climate change at regional scales [NRC, 2005; Feddema et al., 2005; Davin et al., 2007]. The potential effects of human-induced conversion of the landscape in urban/suburban complexes are particularly important, because the majority of the world’s population resides in urban areas (and the percentage is growing). For example, the Greater Phoenix region, located in the semi-arid Sonoran Desert, has a regional population of nearly 4 million and was recently ranked as the 14th largest metropolitan city in the U.S. [GP Regional Atlas, 2003]. Throughout the 20th century Maricopa county (Arizona’s most populous and home to Phoenix) has undergone extensive modifications to its pre-1900 landscape as a result of the rapid population growth and territorial expansion in which semi-natural shrublands were replaced by irrigated agriculture and widespread urban/residential development [Knowles-Yanez et al., 1999]. The potential impacts of this development raise concerns about future water supplies [Grimm and Redman, 2004] and anthropogenic air pollution [Lee at al., 2003].

The urban fabric has long been known to exert a warming influence on the local environment [e.g., Bornstein, 1968], also known as the urban heat island (UHI) effect. The UHI occurs due to the alteration of the thermal, radiative, moisture, and aerodynamic characteristics of the land surface [Oke, 1987]. Hedquist and Brazel [2006] collected observations along mobile transects during the summer season to identify the strength of the summertime Phoenix UHI and to measure its variability from urban to residential to rural locations. Their measurements indicated the presence of a strong UHI, with a mean
evening urban-to-rural temperature difference of 7.3 °C. They also observed more than a 3 °C increase in dew-point from the drier urban to moister rural agricultural locations resulting from fewer water sources and reduced evapotranspiration (ET) from vegetation in urban areas, in contrast to increased evapotranspiration from irrigated agriculture in rural areas.

In addition to temperature, mid-latitude urban areas also affect precipitation [Huff and Changnon, 1973; Bornstein and Lin, 2000; Burian and Shepherd, 2005]. There are at least three widely accepted mechanisms for this influence [Changnon, 1992]. First, changes in surface roughness affect forward propagation of precipitating systems with an increase in low-level convergence over and downwind of an urban area [Loose and Bornstein (1977)]. Second, urban areas typically consist of impermeable, lower-albedo, heat-retaining surfaces lacking in vegetation, so enhanced warming relative to adjacent rural areas creates a deeper, more turbulent boundary layer and promotes increased vertical lift [Lemonsu and Masson, 2002]. Third, increased amounts of polluting material supply cloud condensation nuclei (CCN) which can alter cloud droplet concentrations, thereby affecting cloud formation and downwind precipitation [e.g., Van den Heever and Cotton, 2006].

In this paper, we evaluate the potential first-order impact of LULCC over the last century on the summertime climate of the Greater Phoenix region. To accomplish this, we conducted paired, high-resolution simulations using the Regional Atmospheric Modeling System (RAMS) with two different LULC reconstructions: one based on a circa 1992 representation of the area’s landscape, and the other a pre-1900, hypothetical
The anthropogenic influence (in terms of irrigated agriculture and urbanization) was replaced by semi-natural vegetation. In contrast to previous high-resolution numerical modeling simulations that focused on short time-scale weather events (e.g., 72-hours or less) based on the use of recent land cover data, our high-resolution study (2–km horizontal grid) assessed the potential climatic impact of historical land cover change at the seasonal timescale. The focus was on the summertime and the associated North American Monsoon System (NAMS) when the public and city infrastructure experience the greatest climate-related strains: i.e., extreme high temperatures, with associated heat stress and limited water availability, combined with periodic, intense convective precipitation, with associated flash flooding.

2. Model Description and Methods

We used RAMS version 4.3 [Walko and Tremback, 2000] to conduct sensitivity experiments that quantify the impact of hypothetical LULCC over the Greater Phoenix, Arizona, region. RAMS is a non-hydrostatic model that solves the full nonlinear equations of motion, includes a comprehensive soil and vegetation component, the Land Ecosystem-Atmosphere Feedback Model (LEAF-2 [Walko et al., 2000b]), as well as multiple parameterization options for convection, turbulence, radiation and cloud microphysics.

2a. Model Domain

We centered our simulation domain over Phoenix’ Sky Harbor International Airport located at 33.43°N and 112.02°W. We used three multiple nested grids that permitted the downscaling of the large-scale synoptic flow from the coarse outer grid to the fine inner grid in order to better resolve the dynamic and thermodynamic details related to
our imposed landscape change. The parent grid (grid 1) covers a significant portion of
the North American Monsoon region, including the majority of the Gulf of California
and the eastern Pacific Ocean, and encloses a 1600-km X 1600-km domain using a 32-
km grid spacing in the horizontal. The intermediate grid (grid 2) covers a 592-km X
592-km area using 8-km grid spacing, while the fine grid (grid 3) encloses a 204-km X
204-km domain using 2-km grid spacing. For each grid we use 38 vertical levels with a
stretched vertical coordinate, ranging from $\Delta z = 50\text{m}$ at the surface to $\Delta z = 1000\text{m}$ at
and above 5-km to the model top at 21.4-km. The lowest 1.5-km is resolved with the
initial 15 vertical levels to capture the composition of the planetary boundary layer. A
graphical representation of the model domain showing the topography and nested grid
configuration is presented in Figure [1a]. We turn on the Kain-Fritsch convective
parameterization scheme [Kain and Fritsch, 1992] on Grids 1 and 2, but leave it off for
Grid 3.

2b. Landscape Representation

The circa 1992 land cover data on Grid 3 was derived from the U.S. Geological
Survey’s (USGS) 30-m 1992 National Land Cover Dataset (NLCD) (Vogelmann et al.,
2001). We aggregated the 21-class NLCD dataset to derive an alternate LULC
classification (henceforth termed NLCD92) for LEAF-2. We also derived a LEAF-2
biophysical parameter table for the NLCD92 land cover classes with parameter values
and characteristics appropriate for the Sonoran Desert and the Greater Phoenix region
(see Table 1). LEAF-2 permits the division of each RAMS grid cell into multiple
patches, so we divided each 2-km cell into five patches of decreasing LULC fractional
area (four plus water), thus retaining much of the information available in the high-
resolution 30-m NLCD data. Figure 1[b] shows the dominant LULC classes for the circa 1992 land cover that was used in the representation of our fine grid. To replicate the effects of irrigation, we forced the irrigated agricultural land cover type to saturation at each model time step. (We discuss the sensitivity of our results to this assumption in more detail later in the paper.) We compared these simulations to an equivalent set carried out for a pre-1900, hypothetical (hereinafter referred to as the Pre-Settlement case) dataset, constructed by replacing that part of the altered landscape attributed to anthropogenic influence (defined as irrigated agriculture and urbanized pixels) with semi-natural shrubland (Figure 1[c]). For the outer two grids in both sets of simulations, we used the standard RAMS LULC dataset that is based on the USGS 1-km Advanced Very High Resolution Radiometer (AVHRR) Olsen Global Ecosystem (OGE) land cover data [Olson, 1994a]. We configure our model to use 11 soil layers, from the surface down to a depth of 2m.

2c. Boundary Conditions

We initialized RAMS with surface (soil moisture and temperature) and lateral boundary (geopotential height, relative humidity, temperature, and horizontal winds) conditions extracted from the North American Regional Reanalysis (NARR) data [Mesinger et al., 2006] (available at http://www.emc.ncep.noaa.gov/mmb/rreanl/). All simulations were initialized on June 30, 00Z, forced at the lateral boundaries by NARR data, and continued through July 31, 12Z. The initial 30 hours were discarded prior to analysis and results were written out every three hours.

2d. Experiments
We simulated six different Julys for both the NLCD92 and Pre-Settlement LULC scenarios. Within the Greater Phoenix region, a significant amount of the annual precipitation (about 40%) falls during a three-month period each year during the summertime season associated with the NAMS [Adams and Comrie, 1997]. Increased atmospheric instability results from large-scale moisture transport (from the tropical eastern Pacific, Gulf of California, and to a lesser extent, upper-air transport from the Gulf of Mexico) and intense heating of the land-surface produces convective precipitation that is highly variable in space and time. We selected the three wettest and three driest monsoon seasons during the time period for which NARR data were available (1979-present) according to the Daily UNIFIED Precipitation dataset [Higgins, et al., 2000] (see Table 2 for a summary of all experiments performed). We made the distinction between wet and dry monsoon years to better distinguish the effect of landscape-imposed forcing on the atmosphere. Our hypothesis was that, during times of heavy and widespread rainfall, the regional contribution of the landscape will be difficult to distinguish given the large-scale forcing and atmospheric (as opposed to surface) control of precipitation, consistent with expectations based on previous work [e.g. Findell and Eltahir, 2003; Koster et al., 2004; Anyah et al., 2007]. By keying on wet and dry NAMS conditions, we were able to better investigate the possibility of greater or lesser sensitivity to LULCC given contrasting hydro-meteorological regimes.

3. Results

3a. Model Evaluation
Before assessing the impact of hypothetical LULCC, we present a comparison between the control simulation and available observations. We begin with a comparison between RAMS-simulated 2-meter temperatures and observed temperatures from six stations in and around the *Greater Phoenix* area. Five of the stations were available courtesy of the Arizona Meteorological Network (AZMET) ([http://ag.arizona.edu/azmet/](http://ag.arizona.edu/azmet/)) while the sixth station - Phoenix Sky Harbor airport – was available courtesy of the National Climatic Data Center (NCDC) and represents the only available first-order National Weather Service (NWS) station available within our Grid 3 domain. We note here that due to variability between actual station elevation and the surface elevation used in the RAMS model we retain only those stations where elevation differences are within 30 meters – of the seven available AZMET stations in operation during July 1990, we retained five.

Figure 2[a] shows the comparison between AZMET observed, three-hourly air temperatures and RAMS simulated 2-meter air temperatures, while Table 3 shows a comparison between simulated and observed monthly averaged daily maximum and minimum air temperatures, for each station, for July 1990. We also present, in Table 4, a station-to-station comparison involving daily cooperative meteorological station (COOP) data (as before, we retain only those stations where elevation differences between model and station are within 30 meters). Overall, RAMS captured the roughly weeklong warm and cool periods, as well as the daily maxima and minima with reasonable fidelity, though with a noted cool bias that is more pronounced in the simulated minima (see Table 3), for the entire month, averaged across all 6 stations.

We suggest two possible reasons for this disagreement. First, prior to 1994, the station
at Sky Harbor airport was located at the airport’s runway premises (Brazel et al., 2000), possibly contributing to an observed warm bias at that station due to a lower surface albedo (resulting in higher daytime temperatures) and enhanced night-time heat loss from an underlying paved surface (resulting in higher night-time temperatures).

Probably due to nighttime heat loss from an extensive paved surface, we note that the modeled negative minimum temperature bias at Sky Harbor is roughly twice as large as that at other stations. Second, the lack of a sophisticated urban parameterization scheme within RAMS hindered our ability to account for some urban processes known to enhance the UHI effect, including daytime shadowing and heat trapping effects (that may increase daytime temperatures of stations within the Greater Phoenix limits), the impact of decreased nighttime urban longwave cooling as compared to rural localities, a characteristic largely attributed to the reduction in sky view factor (SVF) (e.g., Oke, 1987), and the impact of anthropogenic heat flux. Using an identical resolution over a similarly sized domain, Grossman-Clarke et al. (2005) conducted 72-hour simulations and noted that the effect of the SVF and anthropogenic heat flux parameters significantly improved their ability to model the nighttime temperature regime of the Phoenix urban area. As a result of the likely underestimate of urban warming, we suggest that the results presented here serve as a baseline minimum effect of LULCC on temperature.

Direct measurements of dew point are made only at Sky Harbor airport, while the AZMET stations measured relative humidity (RH) as their moisture metric (the COOP stations do not have any sub-daily data). Using observed values of temperature and RH we calculated the dew point at each of the five AZMET stations according to the
definition of saturation vapor pressure (1), RH (2) and an approximation of the
Clausius-Clapeyron equation (3):

\[ E_s = E_0 \exp\left[\frac{L}{R_v} \times \left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \]  

(1)

\[ RH = 100\% \times \frac{E}{E_s} \]  

(2)

\[ E = E_0 \times \left[\frac{L}{R_v} \times \left(\frac{1}{T_0} - \frac{1}{T_D}\right)\right] \],  

(3)

where \( E_s \) is the saturation vapor pressure, \( E_0 \) is 0.611 kPa, \( L \) is the latent heat of
vaporization, \( R_v \) is the gas constant for water vapor, \( T_0 \) is a reference temperature
(273K), \( T \) is the observed temperature, \( E \) is the calculated vapor pressure, and \( T_D \) is the
dew point. We note that calculation of dew point is sensitive to very low values of RH,
as may be expected during dry breaks of the monsoon period.

As the AZMET site dew points are derived and not directly measured, we compared
the lowest atmospheric level (24.3m) simulated and observed dew-point separately for
the AZMET stations (Figure 2[b]) and Sky Harbor (Figure 2[c]). We can see that the
d control experiment does a reasonable job of capturing the day to day variability in low-
level moisture throughout the month, including the gradual moistening during the first
half of the month and the drying trend observed during the latter half of the month. We
do note, however, that model simulated dew point values fluctuating between 9-20 °C
from about July 27th onward are significantly higher than calculated values at the
AZMET sites (Figure 2[b]). We attribute this discrepancy to the sensitivity of our
calculations to RH, which was frequently below 20% during this dry period and on
several occasions closer to 10%. In contrast, directly measured dew point at Sky
Harbor airport does indeed suggest that actual dew point values were generally between 9-15 °C during this time (see Figure 2[c]).

We next present a comparison between model simulated precipitation and available observations. First, we compare daily rainfall accumulation across the entirety of our fine grid against the .25° x .25° gridded Daily U.S. UNIFIED Precipitation dataset for July 1990 (Figure 3[a]). The model is able to capture both the timing and magnitude of most precipitation events. More often than not, when precipitation occurred according to the UNIFIED dataset, RAMS was able to correctly reproduce this rainfall. However, a noted deficiency is evident over the last week to ten days as RAMS considerably underestimates the second largest rainfall event of the month. When comparing monthly accumulations, RAMS simulates a rainfall total of 64.5 mm as compared to 67 mm for the UNIFIED dataset. Next, we show a station average of the three-hourly modeled and observed precipitation for the five AZMET locations and Sky Harbor for July 1990 (Figure 3[b]). More often than not, RAMS is able to simulate rainfall when it was observed. The model was able to capture the rainfall occurring over the initial two days of the month, the ensuing dry period, and the subsequent heavier rainfall toward the middle of the month. However, RAMS was not able to reproduce two of the more significant events observed to occur during the latter third of the month. Among the AZMET stations and Sky Harbor airport, RAMS was able to simulate the monthly accumulated precipitation within 50% of each of the station’s totals (not shown). At Phoenix Encanto, more than 50% of the monthly rainfall total occurred during an isolated thunderstorm event that produced 45 mm, during the overnight of July 24th. This event produced more than seven times the amount of rainfall than at Phoenix
Greenway (6.1 mm) and nearly five times more than was observed at Sky Harbor (9.9 mm), both roughly the same distance from Phoenix Encanto. RAMS was not able to reproduce this localized cell, underscoring the impact of solitary convective elements in this region and the difficulty in simulating such events at precise locations. The RAMS regional average precipitation total for July 1990, however, does compare favorably with the regional average of both the monthly station and gridded product data, thereby providing an increased level of confidence for the precipitation analysis based on RAMS simulations with each of the land cover reconstructions.

3b. Effect of LULCC on simulated temperature

RAMS simulated ensemble differences (i.e., NLCD92 minus Pre-settlement) in first atmospheric level air temperature and dew-point, for the WET and DRY years are presented in Figure 4[a - d]. A dipole pattern of differences is visible for both temperature and dew-point. For the WET years, the largest positive differences [> 0.5 °C] in temperature occur over the central urban area, with lower magnitude cooling [-0.1 to -0.2 °C] located south of the metro area, primarily over the plots of irrigated agriculture. This pattern is reversed for dew-point, which shows a decrease over urban areas of greater than 0.6 °C and increases, primarily over plots of irrigated agriculture, of at least 0.2 °C. These findings are in qualitative agreement with the magnitude of the Phoenix UHI ascertained from previous transect measurements over this area [Hedquist and Brazel, 2006]. The same patterns, but with more pronounced maxima and minima, are evident for the DRY year simulations for both temperature and dew-point (compare Figure 4[c, d] to Figure 4[a, b]). Maximum warming for the DRY years exceeds 0.7 °C over urban areas while irrigation-induced cooling is enhanced and covers a greater
fractional area of the domain. Due to the increased surface-to-air water vapor concentration gradient experienced during dry atmospheric regimes, enhanced urban drying and increased moistening over irrigated agriculture occurs.

In a regional-mean sense, the competing impacts of irrigated agriculture and urbanization largely tend to counteract each other for both the WET and DRY sets of runs.

The landscape induced effects on near-surface temperature arise due to a variety of pathways, some resulting from changes in the local vegetation, others taking place due to atmospheric transport. We address some of the possible pathways involved below.

Our experiments accounted for two main changes in land cover. The replacement of the urban landscape with semi-natural vegetation results in an increase in albedo, effectively reducing the surface absorbed energy for the Pre-Settlement experiments. Figure 5 [a-b] indicates a sharp decrease (for NLCD92 in comparison to Pre-Settlement) in albedo across the urban landscape as well as over the plots of irrigated agriculture. Minor differences in albedo between the WET and DRY years are due to variations in surface moisture which is used to calculate albedo in LEAF-2. Incident radiation is correspondingly altered (see Figure 5 [c-d]) (where albedo decreases the incident radiation increases) though the signal is much more evident during the DRY rather than the WET years. In addition to the signal resulting from land cover changes, incident radiation is also influenced by changes in cloud cover. The mixture of variously scaled precipitating systems, and their associated cloudiness, is exhibited as more of a mixed signal for the WET years. Nonetheless, both sets of experiments indicate an increase in incident radiation for NLCD92 as compared to Pre-Settlement.
While changes in albedo across the urban and agricultural areas reinforce their effect on simulated temperature (they both act to increase low-level temperature), we have seen previously (see Figure 4) that warming occurs over the urban landscape as opposed to a lesser magnitude cooling over the adjacent agricultural areas. This occurs because of simulated differences in the sensible heat flux resulting from both changes in incident radiation and vegetation. The conversion of shrubland to irrigated agriculture has decreased the Bowen ratio acting to partition less energy into sensible heating (Figure [e-f]) at the expense of increased latent heating. The magnitude of changes imposed on the sensible heat flux outweigh the impact of incident radiation and counter the effect of decreased albedo over plots of irrigated agriculture resulting in cooling over these particular regions.

3b. Effect of LULCC on simulated precipitation

To assess whether the Greater Phoenix landscape possesses a discernible influence on modeled precipitation, we next present simulated differences (i.e., NLCD92 minus Pre-settlement) in accumulated monthly precipitation for both the WET [Figure 6a] and DRY [Figure 6b] simulation years. Mean differences for the WET years show a patchwork of increases and decreases in precipitation and do not indicate a systematic alteration in rainfall pattern or magnitude related to our imposed change in landscape. Additionally, there is no uniformity of trend or pattern across individual simulation years (not shown). This may be because the sensitivity of convective precipitation to near-surface thermodynamic perturbations can be reduced in moist regimes with strong atmospheric control of precipitation [e.g., see Findell et al., 2003; Koster, 2004; Anyah et al., 2007]. This possible explanation is consistent with the fact that differences
between the pair of ensembles for the DRY years present a much more coherent and consistent signal both in ensemble mean [Figure 6b] and across individual years. Figure 7 [a-c] illustrate the simulated precipitation differences for each of the DRY years. The member differences show an increase in total domain precipitation for the NLCD92 landscape, with regions of most pronounced rainfall enhancement (at least 20-40 mm) situated generally east and north of the urban area.

These results are also broadly consistent with recent observational analysis suggesting a Greater Phoenix-imposed enhancement of precipitation (Diem and Brown, 2003; Diem, 2006; Shepherd, 2006). Shepherd (2006) used a 108-year precipitation data record and noted that positive precipitation anomalies, during monsoon season (July-September [JAS]), exist to the northeast of the Phoenix metro area in a “post-urban” period defined as 1950-2003 as compared to a 1895-1949 “pre-urban” period. Despite this qualitative agreement between the two studies, we advise caution on a quantitative comparison of precipitation differences. First, Shepherd (2006) compared monsoon season averages of two periods, each consisting of in excess of 50 years, while our analysis is based on two relatively short-term, single-month periods each consisting of 3 years (as the WET year results show no discernible signal). Second, our work isolates the impact of LULCC alone, whereas the Shepherd (2006) results include an assortment of effects due to a shifting landscape and a shifting climate during each time segment.

Finally, to gain insight on the mechanism responsible for the simulated rainfall enhancement during DRY years, we focused our attention to the area of observed increase. Here we show (Figure 8[a]) vertical profiles of $\theta_e$ difference averaged over a
1° X 1.2° region (see rectangular sub-domain in Figure 6b]) for three selected pre-storm cases. We selected one case, for each year, which best illustrates the degree of impact on total static energy for the area of interest. For each case subsequent rainfall accumulation for NLCD92 was significantly enhanced relative to Pre-Settlement. The trio of profiles exhibit considerable increase in conditional instability extending upwards of the lowest kilometer of the atmosphere. The net difference in $\theta_e$ for all cases is large, on the order of 5-10 K. Over timescales longer than that of an individual storm event, assuming that the background synoptic-scale is not competing with the local/regional scale, the accumulated landscape signal may modify regional stability sufficiently to allow for repeated enhancement of storm cells. Figure 8[b] shows that the net impact of LULCC is systematic and not specific to preferentially selected events, and that the chief influence is a destabilization of the layer between the surface and 1.5 km. The monthly averaged net difference in $\theta_e$ for all 3 simulated Julys is on the order of 1 K.

4. Discussion and Conclusions

Using month-long, high-resolution (2-km grid spacing) RAMS simulations, we investigated the first-order impact of LULCC on the summer meteorology and climate of one of the nation’s most rapidly expanding metropolitan complexes, the Greater Phoenix, AZ, region. Results illustrate a distinct dipole pattern for simulated temperature and dew-point, with positive temperature differences evident over urban areas and cooling over the plots of irrigated agriculture, with the reverse situation for dew-point. DRY and WET year simulations show a similar pattern but with more pronounced maxima and minima in the DRY runs. The opposing impacts of irrigated
agriculture and urbanization tend to offset each other in a regionally-averaged sense.

Methodological factors that may affect these results include an underestimate of urban warming as RAMS does not include a sophisticated urban parameterization scheme. Additionally, cooling resulting from irrigated agriculture, due to our assumption of soil saturation, may be overestimated. To test the sensitivity of this assumption, we performed a repeat of the control experiment whereby we forced the irrigated agricultural land cover type to field capacity at each model time step. With this change, cooling from the agricultural zones decreased considerably, with widespread drying over a majority of the domain, and the effects of urbanization dominated the domain-average signal. Our assumption of soil saturated irrigated agriculture, however, produced better simulation results compared to observations of temperature and dew-point, possibly because it effectively accounts for additional water sources not explicitly modeled, such as mesic landscaping and surface water reservoirs.

While LULCC effects on simulated precipitation are not clear for WET years, the DRY years present a more coherent picture consistent with our initial hypothesis. The WET simulation years consist of a combination of precipitation scales ranging from the large-scale, subtropical ridge establishment to the regional (e.g., Gulf of California “surges”), to locally generated thunderstorms, making the unambiguous identification of a landscape induced signal difficult. By experimental design, we attempted to simulate periods both when the large-scale signal is weaker, and when it is stronger. The issue of scale interaction is an important one and we made an effort to ensure that the clear identification of the landscape forcing (local/regional scale) is distinguishable from the forcing of the synoptic-scale. Because the sensitivity of convective
precipitation to near-surface thermodynamic perturbations can be reduced in moist
compared to dry atmospheric regimes, the detection of local land-induced forcing is
possible during DRY years. While previous statistical work has argued in favor of
anthropogenically enhanced precipitation in central Arizona, to our knowledge this
paper is the first to present numerical modeling results consistent with these findings.
This paper illustrates the important competing (for temperature) and reinforcing (for
precipitation) effects of irrigated agriculture and urbanization on the Greater Phoenix
area. The relative coverage of irrigated agriculture and extent of urbanization has
shifted significantly since the 1970’s. Improving our understanding of the evolution of
regional climate in response to this landscape alteration in this rapidly expanding region
is essential for assessing future climate and water-related vulnerabilities, given a
number of land use projections suggesting population values reaching between 10 and
30 million by the year 2050 [GP Regional Atlas, 2003].

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paper are his own and those of the other authors and do not necessarily reflect the views
or policies of the U.S. Environmental Protection Agency.
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**Table 1.** Biophysical parameters used in LEAF-2 land-use class description. $\alpha =$ albedo; $\varepsilon =$ emissivity; LAI = Leaf Area Index; vfrac = vegetation fraction; zo = roughness length (m).
<table>
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<td>1979</td>
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Table 2. Summary of all 12 experiments performed. For each experiment, the analysis time consists of the period lasting from July 1, 12Z through July 31, 12Z. ** denotes experiment used as Control simulation which was validated against observations.
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<td>36.9</td>
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Table 3. Daily maximum and minimum monthly temperature comparison between RAMS simulated control experiment, AZMET stations, and first order National Weather Service station (Sky Harbor) observations for July 1, 12Z - July 31, 12Z, 1990. Also shown is monthly accumulated precipitation [mm] and monthly averaged soil temperature [°C] comparison at two levels (see text for details).
<table>
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<tr>
<th>Coop Station</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
<th>RAMS Monthly Temperature Average [°C]</th>
<th>COOP Station Monthly Temperature Average [°C]</th>
<th>RAMS Monthly Precipitation Total [mm]</th>
<th>COOP Station Monthly Precipitation Total [mm]</th>
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Table 4. Monthly averaged temperature and accumulated precipitation [mm] comparison between RAMS-simulated control experiment and Cooperative (COOP) meteorological stations.
Figure 1. Geographical representation of the RAMS nested grid configuration with topography overlaid and the number of grid cells for each grid shown as numbers in parentheses (a). Dominant LULC representation for fine grid making use of (b) NLCD92 and (c) Pre-Settlement landscape used as surface boundary conditions in ensemble simulations.
Figure 2. Observed (black) three-hourly air temperatures and RAMS simulated (red) air temperatures from the control run experiment during the period July 1\textsuperscript{st} -12Z to July 31\textsuperscript{st} -12Z, 1990 (a): the time series represent observations averaged over all AZMET stations and KPHX; (b) as a, but for observed (black) and RAMS simulated (red) three-hourly dew point averaged only over the AZMET stations; (c) as (b) but for observed (black) and RAMS simulated (red) three-hourly dew point averaged only for KPHX.
Figure 3. AZMET station observed and KPHX (black) three-hourly precipitation accumulation and RAMS simulated (red) three-hourly precipitation accumulation from the control run experiment during the period July 1st -12Z to July 31st -12Z, 1990 - the time series represent observations averaged over all AZMET stations and KPHX (a); (b) as (a), but for UNIFIED Precipitation daily precipitation accumulation (black) and RAMS simulated daily precipitation accumulation (red) averaged over the entirety of Grid 3. All units are in [mm].
Figure 4. RAMS simulated ensemble differences (NLCD92 - Pre-Settlement) in (a) first atmospheric level [24.1 m] air temperature [°C] and (b) dew point [°C], for the WET years; (c) first atmospheric level [24.1 m] air temperature [°C] and (d) dew point [°C], for the DRY years. Each calculation is for the analysis period: July 1, 12Z – July 31, 12Z.
Figure 5. RAMS simulated ensemble differences (NLCD92 - Pre-Settlement) in surface albedo for the (a) WET years and (b) DRY years; as (a) but for (c) incident radiation [W m$^{-2}$] for the WET years and (d) as (b) but for incident radiation [W m$^{-2}$], for the DRY years; as (a) but for (e) surface sensible heat flux [W m$^{-2}$] for the WET years and (f) as (b) but for surface sensible heat flux [W m$^{-2}$] for the DRY years. Each calculation is for the analysis period: July 1, 12Z – July 31, 12Z.
Figure 6. RAMS simulated ensemble differences (NLCD92 - Pre-Settlement) in (a) total accumulated precipitation [mm] for all 3 WET years; (b) total accumulated precipitation [mm] for all 3 DRY years.
Figure 7. RAMS simulated accumulated precipitation [mm] difference (NLCD92 - Pre-Settlement) for each DRY year: (a) 1979, (b) 1989, and (c) 1994.
Figure 8. RAMS simulated domain-averaged [lat: 33 to 34/lon: -112.2 to -111.0] vertical profile of equivalent potential temperature difference (NLCD92 - Pre-Settlement) for selected DRY year cases (a); (b) as (a), but averaged over each DRY year simulation for the analysis period: July 1, 12Z – July 31, 12Z.