Climatic effects of 30 years of landscape change over the Greater Phoenix, Arizona, region:

2. Dynamical and thermodynamical response

M. Georgescu, G. Miguez-Macho, L. T. Steyaert, and C. P. Weaver

Received 10 July 2008; revised 5 November 2008; accepted 13 January 2009; published 11 March 2009.

This paper is part 2 of a two-part study evaluating the climatic effect of one of the nation’s most rapidly expanding metropolitan complexes, the Greater Phoenix, Arizona, region. Part 1, using a set of sensitivity experiments, estimated the potential impact of observed landscape evolution, since the dawn of the Landsat satellite era on the near surface climate, with a primary focus on the alteration of the surface radiation and energy budgets and through use of high-resolution, 2km grid spacing, Regional Atmospheric Modeling System (RAMS) simulations with circa 1973, circa 1992, and circa 2001 landscape data sets. In this paper, part 2, we address the role of the previously discussed surface budget changes and subsequent repartitioning of energy on the mesoscale dynamics and thermodynamics of the region, the effect on convective rainfall, and their association with the large-scale North American Monsoon System (NAMS). Our results show that contrasts in surface heating resulting from landscape change are responsible for the development of preferentially located mesoscale circulations, on most days, which were stronger for the 2001 compared to the 1973 landscape, due to increased planetary boundary layer (PBL) heating via enhanced turbulent heat flux. The effect of these stronger circulations was to warm and dry the lower part of the PBL and moisten the upper part of the PBL for the 2001 relative to the 1973 landscape. The precise physical pathway(s) whereby precipitation enhancement is initiated with evolving landscape, since the early 1970s, reveals a complicated interplay among scales (from the turbulent to the synoptic scale) that warrants future research. Precipitation recycling, however, was found to be an important driver in the overall sustenance of rainfall enhancement. Although this study was not designed to investigate other radiative forcing factors such as greenhouse gas emissions and aerosols, the results of our sensitivity experiments do suggest that regional land use change is an important element of climate change in semiarid environments characterized by large urban areas with scarce water resources.


1. Introduction

This is the second of a two-part study, an extension of Georgescu et al. [2008] (hereafter referred to as GJAE08), that conducts sensitivity tests to investigate the climatic effects of actual landscape evolution, from the early 1970s through the early 2000s, over one of the most rapidly urbanizing areas in the United States, the Greater Phoenix, Arizona, region. In particular, the multidecadal evolution of the region’s landscape, with associated changes in the biophysical properties of the landscape resulting from human activities, has altered key properties of the near-surface climate, with important implications for the dynamical and thermodynamical regional atmospheric environment. Our focus is to investigate the modulation of the coupled land-atmosphere system in response to the underlying changes in landscape, during the summer season, when climatic stress on the urban and natural environment is at its peak, using a numerical modeling approach. Georgescu et al. [2009] (part 1) utilized high-resolution Regional Atmospheric Modeling System (RAMS) simula-
tions and focused on the alteration of the near-surface climate, through an investigation of the surface radiation and energy budgets.

Let us briefly review the results of part 1 prior to laying the groundwork for the current study, part 2. As the basis for the numerical modeling experiments, the initial goal of part 1 was to quantify the region’s extensive landscape modification, beginning in the early 1970s with the advent of the Landsat era, to the early 2000s. We adapted a trio of land use/land cover (LULC) data sets, previously developed by the U.S. Geological Survey (USGS) and based on interpretation and classification of circa 1973 aerial photography, circa 1992 Landsat TM images, and circa 2001 Landsat 7 ETM+ images, in order to derive three consistent land cover data sets (we refer to these as NLCD73, NLCD92, and NLCD01) for our landscape change analysis and numerical simulation experiments. The NLCD73, NLCD92, and NLCD01 data sets revealed the broad landscape changes occurring over the region during this 30-year time period (Figure 1). For example, the dominant land cover change apparent during this time was the widespread growth and expansion of the Phoenix metropolitan complex as irrigated agricultural land and seminatural shrublands were progressively converted to urban and residential land uses. Extensive landscape change, through the impact on actual and modeled local and regional albedo, impacted key components of the surface radiation budget.

Diurnal time series of modeled surface climate variables were derived by spatial aggregation and temporal averaging according to key land cover change “themes” (e.g., allocations that changed from irrigated agriculture in 1973 to urban land in 2001). These time series were used to assess and isolate the modeled effect of various landscape conversions on the near surface atmosphere. For example, two urbanization themes were analyzed (resulting from an initial landscape of irrigated agriculture and seminatural shrubland) and both resulted in an increase in surface shortwave absorption (due to a decrease in albedo, especially relative to the higher reflectivity of the preceding seminatural shrubland), a decrease in surface longwave absorption (primarily due to reduction in low-level water vapor resulting from decreased coverage of irrigated agriculture), and a small (order of 1 W m\(^{-2}\)) reduction in net radiative flux. In contrast, the repartitioning of surface absorbed energy due to increased coverage of urban land caused a domain-mean increase in sensible heating (order of 1 W m\(^{-2}\)), a decrease in latent heating (order of 1 W m\(^{-2}\)), and a domain-averaged warming of 0.12°C during the roughly three decade period of landscape evolution. Maximum warming, of the order of 1°C, and maximum drying, also of the order of 1°C, was simulated over those locations exhibiting the greatest urbanization.

In part 2, we address the role of the previously discussed surface budget changes and subsequent repartitioning of energy on the mesoscale dynamics and thermodynamics of the region, the effect on convective rainfall and their association with the large-scale North American Monsoon System (NAMS) environment and storm systems. Previous land-atmosphere interaction studies have demonstrated the importance of the landscape in the redistribution of surface absorbed energy into sensible and latent heating,

![Figure 1. Dominant LULC representation for grid 3 making use of (a) NLCD73, (b) NLCD92, and (c) NLCD01 landscape used as surface boundary conditions in ensemble simulations.](image-url)
its role as a significant driver of atmospheric flow, and influence on convective activity in many regions of the world and on a variety of scales [e.g., Pielke, 2001]. Our intention, here, is to expand upon this concept in context of the evolving landscape of the semiarid Greater Phoenix region, a rapidly expanding metropolitan complex whose current urbanization trend and population increase is expected to continue in the future [Arizona State University, 2003].

[6] The underlying hypothesis of part 2 is that the modification of the land surface, resulting in mesoscale landscape heterogeneity, is responsible for the creation of thermal gradients across the landscape and in the lower atmosphere. The reorganization of lower-tropospheric pressure gradients, as influenced by the reorientation of surface thermal forcing according to the pattern of landscape heterogeneity, may modify low-level wind flow: i.e., create diurnal mesoscale atmospheric circulations similar in nature to the sea breeze [Seth and Giorgi, 1996], thereby altering the structure of the planetary boundary layer (PBL). One distinguishing feature of such circulations is their ability to transport heat and moisture into the PBL and free atmosphere (FA) [Pielke et al., 1991], and depending on the thermodynamic environment, may encourage the formation of clouds and precipitation [Pielke et al., 1998; Pielke, 2001].

[7] Until recently, the conventional wisdom derived from a number of modeling studies with idealized landscapes [e.g., Avissar and Liu, 1996] was that landscape-induced mesoscale circulations were likely only of local importance and only at certain very limited times when the large-scale background winds were extremely weak [e.g., Zhong and Doran, 1998]. However, using high-resolution RAMS simulations with a realistic, observationally derived landscape representation for the U.S. Southern Great Plains Weaver and Avissar [2001] confirmed that observed clouds and rain matched, spatially, with the locations of the model-simulated mesoscale circulations even on days when background wind speed was large. Recent work has added to the growing body of evidence indicating that land-atmosphere interactions responsible for naturally occurring mesoscale circulations have important impacts at local and larger scales [e.g., Weaver and Avissar, 2001; Pielke, 2001; Baidya Roy and Avissar, 2002; Weaver, 2004a, 2004b; Nyogi et al., 2006; Pielke et al., 2007; Holt et al., 2006; Lei et al., 2008; Douglas et al., 2009].

[8] Mesoscale circulations may affect the overlying atmosphere through both direct and indirect pathways [e.g., Weaver, 2004b]. Direct triggering of convection may result from PBL transport of heat and moisture, leading to condensation, clouds, and eventually rainfall [Weaver and Avissar, 2001]. In addition to this direct pathway, mesoscale circulations may also gradually condition, over a period of time, the overlying atmosphere through sustained moistening, heating, or some combination of both, hence destabilizing the thermodynamic profile and thereby affecting the development of subsequent storm cells. Last, both static (e.g., the presence of an urban area, which remains fixed in space/time) and dynamic (e.g., the memory from the previous day’s rainfall, lingering as a perturbation in the soil moisture state) patterns of surface heterogeneity may affect the development and eventual impact of mesoscale circulations [Weaver, 2004a, 2004b].

[9] The previous discussion lays the groundwork for the research presented here, namely the impact of the surface radiation and energy budgets, diagnosed in part 1 of this series, on the mesoscale dynamics and thermodynamics within the PBL and FA, and in context of the large-scale NAMS environment. A key question concerns the nonlinear interactions bridging the coupled land-atmosphere system, how they may scale up to larger scales, and how this interplay may improve our understanding of cloud and precipitation formation. We aim to address a central result of GJAE08, who showed that the presence of the anthropogenic landscape over the Greater Phoenix region produces a systematic increase in precipitation downwind (i.e., to the north and east) of the Greater Phoenix metropolitan complex, though only during dry NAMS seasons. The alteration of background atmospheric stability resulting from the presence of the anthropogenic landscape was hypothesized as a key physical link directly enhancing regional precipitation. Therefore, a key question of this research, part 2, is whether such a physical link is also robust for the observed, 30-year period of anthropogenic LUCC.

[10] Improving upon previous research, this work explicitly accounts for sources of landscape variability, through use of high-resolution modeling, leading to improved representation of key, altered, convective-scale parameters (e.g., mesoscale induced variability in vertical wind speed), that would otherwise be subgrid to a coarse-grid model. Such a modeling exercise is expected to improve our understanding of the chief mesoscale processes influencing this important semiarid region of human migration.

[11] It is essential to highlight that the sensitivity experiments and associated aforementioned results (e.g., domain-averaged warming of 0.12°C), including the ensuing discussion to follow below, are not meant to reproduce net climate change during the previous three decades. To do so, one would have to account for the entire spectrum of additional forcing factors (e.g., greenhouse gas emissions, aerosols, etc.); our aim was to simply better understand how the evolving landscape, alone (i.e., separate from all other forcings), has contributed to the region’s changing climate.

2. Methods

[12] All RAMS simulations are described in detail in part 1, and consequently, we will only briefly review the model configuration and experiments performed. Monthly simulations were conducted for each of three landscape scenarios (i.e., NCLD73, NCLD92, and NCLD01, where the last two digits correspond to the year of landscape representation), totaling 18 sensitivity experiments (see Table 1). RAMS’ telescoping capability was used in all simulations with all grids centered over Sky Harbor International Airport. The fine grid used a horizontal grid spacing of 2 km while covering a domain 202 km × 202 km. The intermediate grid covered a
592 km × 592 km area using 8-km grid spacing, and the parent grid enclosed a 1600 km × 1600 km domain, and covered a large portion of the NAMS region at a 32-km grid spacing in the horizontal extent. The Kain–Fritsch [Kain and Fritsch, 1992] convective parameterization scheme was turned on for the outer two grids, but was left off for the fine grid. Therefore, all convection was explicitly resolved on the fine grid.

[13] All results presented throughout the rest of this paper are for the 202 km × 202 km fine grid domain. A control experiment determining RAMS’ ability to appropriately represent the summertime weather and climate of this semiarid region was previously evaluated against suitable observations of temperature, dewpoint temperature, and precipitation (both gridded and station data) (see GJAE08).

3. Results

[14] We begin our investigation of the impact of observed landscape change over the Greater Phoenix region by initially diagnosing the effect on convective rainfall. We then present the relevant land-atmosphere interactions operating due to LULCC, and finally, discuss their possible influence on simulated rainfall.

[15] It is also important to note, prior to delving into the results, our usage of the term “ensemble” and its application in the remainder of the paper. We use the term in a more generic sense, rather than the traditional numerical prediction sense, to describe our paired, high-resolution simulations, using a trio of different LULC reconstructions (NLCD73, NLCD92, NLCD01) with variable large-scale forcing (the three wet and three dry monsoon seasons). Therefore, when we discuss the ensemble difference for a particular variable (e.g., Figures 2a and 2b), we are referring to the difference between three model realizations (where the three runs each consist of the variable large-scale forcing making up either a wet or dry set of years) with usage of a particular landscape, and another set of three realizations (where the three runs each consist of the identical variable large-scale forcing) using another landscape (e.g., NLCD01 ensemble minus NLCD73 ensemble).

[16] Of the trio of landscape snapshots in time (Figure 1), NLCD73 and NLCD01 illustrate the most extreme combinations, with NLCD73 having the greatest coverage of irrigated agriculture and the least coverage of urban land, while NLCD01 contains the least coverage of irrigated agriculture and the greatest coverage of urban land. Consequently, results presented from this point forward will reflect differences among parameters resulting from the most extreme landscape cases, i.e., differences between NLCD01 and NLCD73.

3.1. Effect on Simulated Precipitation

[17] Figures 2a and 2b illustrate the RAMS simulated ensemble differences in total accumulated precipitation (NLCD01 minus NLCD73) for all three wet and dry years, respectively. The difference pattern for the wet years does not indicate a systematic landscape-induced impact on rainfall, although the pattern for the dry years appears very similar to the ensemble differences noted between the NLCD92 and presettlement cases, as presented in GJAE08. To assess the possible impact of landscape evolution with time, we compare ensemble rainfall differences for our successive landscape reconstructions, i.e., NLCD92 – NLCD73 and NLCD01 – NLCD73. We focus on each of the trio of dry years (1979, 1989, and 1994) because it is during this hydrometeorological regime that convective triggering is most sensitive to land surface changes (see also GJAE08).

[18] Ensemble differences in total accumulated precipitation for July 1979 are presented in Figure 2c for the difference between NLCD92 and NLCD73 and in Figure 2d for the difference between NLCD01 and NLCD73. Precipitation enhancement for NLCD92 relative to NLCD73 is apparent to the north and east of the Greater Phoenix area. The magnitude of increase is generally in excess of 20 mm, with local differences reaching as high as 60–80 mm. This same pattern of precipitation enhancement is apparent for the NLCD01 minus NLCD73 difference, but with positive difference values expanded in territorial coverage and increased in magnitude. This systematic strengthening of the precipitation signal from the NLCD92 to the NLCD01 landscapes suggests a consistent response of the atmosphere to the land surface forcing.

[19] We next present ensemble differences in total accumulated precipitation for July 1989 (Figures 2e and 2f) and July 1994 (Figures 2g and 2h). For 1989, although precipitation differences are negative between NLCD92 and NLCD73, NLCD01 does indicate an enhancement (relative to NLCD73), of generally 20 mm, to the north and east of Greater Phoenix. For 1994, any coherent landscape-induced effect on precipitation seems much weaker. In several ways (e.g., precipitation amounts, large-scale NAMS dynamical environment), 1989 and 1994 are significantly more “wet” as compared to the dominant “dry” year of 1979; this will also be apparent below, when we discuss the signal of the landscape changes and the effect on the mesoscale atmospheric dynamics.

[20] We next examine these mesoscale dynamics to gain insight into the dynamical impact of the evolving landscape.

3.2. Mesoscale Dynamics: Flow

[21] To highlight the impact of land surface heterogeneity the focus will be once again on the dry years. We look primarily at early afternoon conditions when the thermal gradient is at its peak and landscape-induced circulations are expected to form. From this point forward, results are presented as ensemble differences between NLCD01 and
Figure 2. RAMS simulated ensemble differences in (a) total accumulated precipitation (mm) for all 3 wet years (NLCD01 – NLCD73) and (b) total accumulated precipitation (mm) for all 3 dry years (NLCD01 – NLCD73). RAMS simulated accumulated precipitation (mm) difference for 1979 (c) NLCD92 – NLCD73 and (d) NLCD01 – NLCD73; (e) same as Figure 2c but for 1989 and (f) same as Figure 2d but for 1989; (g) same as Figure 2c but for 1994 and (h) same as Figure 2d but for 1994.
NLCD73, as these landscape representations illustrate the most extreme combinations of LULC.

[22] Figure 3a presents the monthly averaged wind speed difference for 1979, at 1400 LT, for the lowest model atmospheric level. Overlaid are the monthly averaged wind vector differences for 1979, also calculated at 1400 LT. Close inspection reveals well-defined areas of both convergent and divergent airflow. In the southwestern quadrant of the domain, the predominantly southwest flow of air displays directional (wind vectors are directed toward one another) convergence related to the presence of a small lake in NLCD73 that had dissipated in the NLCD01 reconstruction (comparison of independent aerial photography has verified lake dissipation). However, changes in wind speed are not particularly large in this region, and changes in wind direction are confined to a small area. In the southeast quadrant of the domain there is little change in either the speed or direction of the overall flow. For the most part, modifications to the low-level airflow occur only over those areas over the Greater Phoenix region that experienced changes in land cover. Once air enters the northern tier of the Greater Phoenix metro complex, toward the central portion of the domain, an organized line of convergence at or just south of 33.7°N becomes evident. The predominantly southwesterly flow simulated during the NLCD73 experiment veers, due to a strengthened northerly flow, in direct response to the regional landscape discontinuity created by urban development. Despite the modest increase in the roughness length resulting from increases in urban land (at the expense of shrubland and irrigated agriculture), it is the thermal gradient that is the driving influence on the changing wind flow. Landscape heterogeneity has also augmented the wind speed over this area (positive wind speed differences), adding to the overall convergence. In other words, shifts in both wind speed and direction have aided in the establishment of low-level wind convergence. This simulated convergence pattern is several tens of kilometers in length and delineates the northern extent of the transition of urban land to shrubland.

[23] In the southeastern region of the Greater Phoenix area, centered about 33.4°N/111.7°W (still examining Figure 3a), a second, stronger region of enhanced low-level convergence is evident. Urbanization in this area resulted primarily from loss of irrigated agriculture. The near-present landscape (i.e., NLCD01) has urban areas flanked by natural shrubland to the east and southwest, and by still lingering plots of irrigated agriculture to the north and south. This particular landscape patterning (urban area bounded by irrigated agriculture to the north and south, and shrubland to the southwest and east) creates a particularly strong thermal gradient. Consequently, wind vectors that have a predominantly southwesterly flow in the NLCD73 simulation veer by more than 45° in the NLCD01 simulation (note the nearly opposing wind vectors centered about 111.7°W/33.4°N). In response to daytime heating of the urban area and relative cooling due to irrigated agriculture located to the south, winds back from the primarily southwesterly orientation and provide an increasingly southerly trajectory, just north of 33.2°N. The simulated readjustment of low-level atmospheric circulation in response to the horizontal variability in landscape heterogeneity results in a compact area of nearly completely opposing wind flow. Because of the enhanced thermal gradient, contribution to the total convergence is again aided by the increase in local wind speed (note the positive wind magnitude difference over this area). Overall, the two convergence zones loosely define an extended line of enhanced convergence, oriented in a northwest to southeast fashion, in NLCD01 compared to NLCD73. That this enhanced convergence is such a distinctive signal on the monthly timescale provides confidence that it is a robust feature resulting from changes in the underlying landscape.

[24] Figures 3b and 3c present the monthly averaged wind speed difference for 1989 and 1994, respectively, also at 1400 LT, for the lowest atmospheric model level. As before, simulated wind vector differences between the pair of landscape reconstructions are overlaid. Compared to 1979, the overall pattern is similar, though the signal of
enhanced convergence is somewhat weaker and less extensive, particularly for 1994.

[25] Figures 4a, 4b, and 4c show the vertical longitude cross section of RAMS-simulated monthly averaged u wind speed difference for 1979, 1989, and 1994, calculated at 1400 LT along 33.65°N latitude (i.e., the region roughly corresponding to the northern diagnosed area of wind convergence). Figure 4 illustrates three main points. First, the increase in simulated low-level u wind speed centered at about 112.3°W longitude, coupled with counter flow (i.e., negative differences in u wind speed) further east, for each of the 3 years, along with opposing wind flow in the upper portions of the PBL (indicative of the diverging portion of the cell), clearly demonstrates the significance of the change in underlying land surface for modulating PBL flow. Second, simulated wind speed differences are greatest for 1979, with variation between the simulations exceeding 1.25 m s⁻¹. Although the magnitude is weaker for 1989, differences still exceed 1.0 m s⁻¹, while variation between the pair of landscape reconstructions is weakest for 1994. Third, it is evident that each of the circulations, for each of the trio of years, is tilted to the east, revealing the influence of the mean flow. In 1994, the convergent component of the mesoscale circulation shows evidence of being sheared apart, away from its low-level source region. The circulations for 1979 and 1989, though tilted to the east, remain united in a single, coherent element.

[26] Figures 4d, 4e, and 4f show a pattern similar to Figures 4a, 4b, and 4c for each of the three dry years but computed along 33.4°N latitude (i.e., the southern area of convergent low-level wind flow). Results for 1979 again illustrate the presence of a classic landscape-heterogeneity-induced mesoscale circulation pattern, with a distinct region of low-level convergence in the lower portions of the PBL leading to an enhancement of upper PBL divergence. Wind speed differences between the pair of land surface reconstructions exceed 1.5 m s⁻¹. The circulation is similar in pattern, though weaker in magnitude for 1989, although wind speed differences between NLCD01 and NLCD73 exceed 1.25 m s⁻¹. Horizontal u wind speed differences for 1994 retain similarity in both pattern and magnitude but also display evidence of shearing by the background wind. As a result, the circulation, to an extent, loses the classic appearance most evident in the 1979 experiment.

[27] In order to assess the direct impact of landscape modified wind flow on changing vertical velocity, we next present simulated monthly averaged differences in w wind for 1979, 1989, and 1994, at 1400 LT, for our initially diagnosed region of interest at 33.65°N latitude (Figures 5a, 5b, and 5c). Results for 1979 illustrate the formation of a focused area of upward motion. Monthly mean vertical velocity differences between the two landscape reconstructions reach to nearly 0.3 m s⁻¹. Deviations between the two sets of experiments are less for 1989 and 1994, though
Figure 4. Altitude-longitude cross section (with altitude displayed in meters) of RAMS simulated monthly averaged u wind (m s\(^{-1}\)) speed difference (NLCD01 – NLCD73) for (a) 1979; (b) same as Figure 4a but for 1989; (c) same as Figure 4a but for 1994. All calculations are at 1400 LT (where LT = LST) and at 33.65\(^\circ\)N; (d) same as Figure 4a but at 33.4\(^\circ\)N; (e) same as Figure 4b but at 33.4\(^\circ\)N; (f) same as Figure 4c but at 33.4\(^\circ\)N. Vertical axis is displayed in meters.
Figure 5. Altitude-longitude cross section (with altitude displayed in meters) of RAMS simulated monthly averaged wind speed difference (NLCD01 – NLCD73) for (a) 1979; (b) same as Figure 5a but for 1989; (c) same as Figure 5a but for 1994. All calculations are at 1400 LT (where LT = LST) and at 33.65°N; (d) same as Figure 5a but at 33.4°N; (e) same as Figure 5b but at 33.4°N; (f) same as Figure 5c but at 33.4°N. Vertical axis is displayed in meters.
upward motion is clearly enhanced for NLCD01 relative to NLCD73, for both years. Monthly mean w wind differences, at 33.4°N latitude, are presented in Figures 5d, 5e, and 5f for each of the three dry years, also at 1400 LT. All 3 years again depict the systematic enhancement of vertical velocity for NLCD01 as compared to NLCD73. Moreover, the circulation for 1979 is both stronger in magnitude (peak w wind differences exceed 0.5 m s⁻¹) and penetrates higher into the atmosphere.

[28] As mentioned in the Introduction, it was previously thought that only under highly idealized (i.e., very low horizontal wind) synoptic-scale conditions could landscape-induced circulations develop and maintain their integrity. Here we add to the recent body of evidence suggesting that the background wind may work in concert with landscape-induced mesoscale circulations, in some cases reorienting and translating these cells across the landscape, away from the location of genesis (i.e., advecting and steering them as coherent dynamical objects). Figures 6a and 6b show the monthly averaged vertical velocity difference, for 1979, at an altitude near the location of maximum w wind speed difference (924 m), at 1400 LT (Figure 6a) and 1700 LT (Figure 6b). As seen earlier in this section, two individual circulations are observed during the midafternoon hours, resulting from the preferential low-level airflow arising from underlying landscape heterogeneity. Three hours later, these circulations have been advected eastward under the influence of the background flow. These circulations are generated and similarly translated to the east for both 1989 (Figures 6c and 6d) and 1994 (Figures 6e and 6f), though variability in shape, strength, and rate of eastward translation exists among the three case study years due to variations in the prevailing large-scale wind.

3.3. Mesoscale Dynamics: Moisture Transport

[29] The aforementioned focused areas of rising motion contain characteristics of air from locations adjacent to the rising branch of the cell. For example, the area of low-level convergence at 33.6°N latitude includes both warmer and drier air from the north of the convergence line and cooler and moister air originating southwest of the convergence line, from nearby plots of irrigated agriculture (e.g., recall Figure 3a).

[30] Figures 7a, 7b, and 7c show the vertical cross section of RAMS simulated water vapor mixing ratio difference for 1979, 1989, and 1994, calculated for the entire month at 1400 LT along 33.6°N latitude. In the lower half of the PBL, air adjoining the discontinuity in landscape properties is retrieved from nearby locations. Simultaneously, the vertical circulation cell moves moist air from near the surface to higher altitudes. Consequently, the upper parts of the PBL are moistened and the lower parts dried for each of the dry case study years. Figures 7d, 7e, and 7f show the same mixing ratio difference plots, but for the circulation cell originating at 33.4°N latitude. For both cells, maximum mixing ratio differences are once again greatest for 1979, least for 1994, and enhanced for the second focused area of convergence relative to the first.

[31] Figure 8 shows the 1979 monthly averaged water vapor mixing ratio differences for 1400, 1700, and 2000 LT at 1330 m. This height roughly corresponds to the elevation above ground level where water vapor differences between the pair of experiments are greatest (see also Figure 7), allowing us to see the maximum effect. The dense area of enhanced moistening in the center of the domain, evident at 1400 LT, is amplified by 1700 LT, and is mixed with the ambient air and advected east/northeastward by 2000 LT, under the influence of the background flow. Although dilution has occurred by 2000 LT, due to mixing with drier air from above the PBL, the eastern half of the domain still remains moister for the NLCD01 relative to the NLCD73 experiment.

[32] This general pattern of daytime PBL moistening is similar for both 1989 (Figure 9) and 1994 (not shown). The pattern, and magnitude of differences, from the 1989 experiment most resembles those from the 1979 experiment, maintaining a positive water vapor difference in the eastern region of the domain well into the evening and nighttime hours. A more mixed signal is shown for 1994: by the evening and nighttime hours, water vapor enhancement in the NLCD01 experiment has virtually dissipated.

[33] We now examine a bit more systematically the role and significance of these mesoscale circulations in the overall water vapor transport in the domain over the course of the month. We focus on 1979, because this July provides the clearest illustration of the influence of the surface forcing on the mesoscale dynamics, in context of the evolving large-scale background meteorology.

[34] Just to provide a reminder of the day-to-day context for the mesoscale dynamics, Figure 10 shows the 3-hourly accumulated rainfall in the sub-domain of interest (over the identical 1° × 1.2° region presented in Figure 6 of GJAE08), over the course of July 1979, for the NLCD73, NLCD92, and NLCD01 landscape reconstructions. Figure 10 reveals two important features. First, the entire month may be broken down into three characteristic regimes: a dry regime present during the initial half of the month (i.e., a preconvection period), when no rainfall occurs for any of the experiments; a less than 1 week long wet period from about 16 to 21 July; and a second, extended dry period continuing through the end of the simulation month. Inspection of upper air daily weather maps (courtesy of the online archive available at the NOAA Central Library: http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html) of July 1979 revealed that the westward expansion of the Bermuda High reached the general vicinity of the four corners area during a one week period from about 16 to 21 July. Consequently, it was during this several day period that a considerable majority of the precipitation in Arizona fell, and RAMS was able to correctly simulate this convective activity. Second, Figure 10 also shows that a series of three sizable and distinct events propagated through the domain during the wet period, with domain averaged rainfall accumulations exceeding 1 mm 3 h⁻¹ for all three sets of landscape reconstructions. For each of these events, however, NLCD01-simulated rainfall significantly exceeded accumulations in the NLCD92 and NLCD73 experiment. During the overnight of 19 July, the domain-averaged precipitation exceeded 20 mm 3 h⁻¹ for NLCD01, more than twice the accumulation of NLCD92 and NLCD73. This particular event was the largest of the month for all sets of experiments. Although precipitation in the NLCD92 experiment was slightly less in comparison to that of NLCD73 for this event, rainfall was enhanced for the two remaining
Figure 6. RAMS simulated monthly averaged wind (m s$^{-1}$) speed difference (NLCD01 – NLCD73) at 924-m altitude at (a) 1400 LT and (b) 1700 LT (where LT = LST), for 1979; (c) same as Figure 6a but for 1989; (d) same as Figure 6b but for 1989; (e) same as Figure 6a but for 1994; (f) same as Figure 6b but for 1994.
Figure 7. Altitude-longitude cross section (with altitude displayed in meters) of RAMS simulated monthly averaged water vapor mixing ratio (g kg\(^{-1}\)) difference (NLCD01 – NLCD73) for (a) 1979; (b) same as Figure 7a but for 1989; (c) same as Figure 7a but for 1994. All calculations are at 1400 LT (where LT = LST) and at 33.65°N. (d) Same as Figure 7a but at 33.4°N; (e) Same as Figure 7b but at 33.4°N; (f) Same as Figure 7c but at 33.4°N. Vertical axis is displayed in meters.
Figure 8. RAMS simulated monthly averaged water vapor mixing ratio (g kg⁻¹) difference (NLCD01 − NLCD73) at 1330-m altitude at (a) 1400 LT, (b) 1700 LT, and (c) 2000 LT (where LT = LST), for 1979.

Figure 9. Same as Figure 8 but for 1989.
events, leading to an overall increase in monthly averaged rainfall for NLCD92 compared to NLCD73 (see also Figure 2c). Though domain-mean precipitation rates are not extreme for any of the experiments, local accumulations were significant, and the memory of the land-atmosphere system may lead to subsequent impacts of the initial rainfall events on the later ones.

[35] A major characteristic of landscape-induced mesoscale circulations is their facility in transporting heat and moisture away from the surface and out of the PBL, into the lower FA. For moisture flux, this “mesoscale flux” [\( F_q \)] can be calculated by multiplying the instantaneous, grid cell deviations from the large-scale average of vertical velocity and water vapor mixing ratio. For example, as discussed by Weaver [2004b],

\[
F_q = \rho L \overline{w} \overline{q}' = \rho L [w - \overline{w}] (q - \overline{q}).
\]

where \( \rho \) is air density, \( L \) is latent heat of evaporation, \( w \) and \( q \) are vertical velocity and mixing ratio, respectively. The overbar indicates averaging over the domain, while the prime represents the deviation at each grid cell from this average.

[36] The 3-hourly mesoscale moisture flux, \( F_q \), averaged over the \( 1^\circ \times 1.25^\circ \) subdomain discussed earlier in this section is shown in Figures 11a and 11b, for the duration of the month, for NLCD01 and NLCD73, respectively; differences between the pair of experiments are presented in Figure 11c. The emphasis is on these two experiments (i.e., NLCD01 and NLCD73) because, in addition to providing the largest contrast in LULC, they span the widest spectrum of variability in the mesoscale dynamics. During the dry periods before and after 16–21 July, mesoscale moisture flux displays a characteristic diurnal cycle for both NLCD01 and NLCD73 (see Figures 11a and 11b). However, it is apparent that more moisture is transported to higher levels in the atmosphere for the NLCD01 experiment, consistent with previous results showing enhanced vertical velocities. These differences are in excess of 100 W m\(^{-2}\) for several days, from about 8 to 11 July and are magnified considerably during the convective period in the middle of the month.

[37] During the wet period, the enhanced mesoscale moisture flux evident in Figure 11 occurs as a result of the deep convective elements propagating through the domain [e.g., Weaver, 2004b] and the extensive cloud cover and rainfall temporarily shuts off the energy supply, i.e., surface sensible heating, for the landscape-induced mesoscale circulations.

[38] Because of the enhanced rainfall and wetting of the soil, resulting in reduced thermal gradients across the region, mesoscale moisture flux is initially less for NLCD01 relative to NLCD73, immediately after the conclusion of convective activity. As the surface dries out, however, positive differences reassert themselves during the remainder of the month.

[39] While mesoscale circulations represent an optimal mechanism of moisture transport, enhanced mesoscale heat fluxes in NLCD01 relative to the NLCD73 landscape, are due to turbulent processes (Figures 11d, 11e, and 11f). Mesoscale heat flux was calculated in the same way as moisture flux but with \( \theta \) (potential temperature) instead of \( q \). As with the mesoscale moisture flux, mesoscale heat flux displays a diurnal signature, waxing and waning with the onset of maximum sunlight and heating resulting from the expansion of the urban area. Again, there is an enhancement
Figure 11. RAMS simulated subdomain (latitude, 33°N to 34°N; 112.2°W to 111°W) vertical profiles of mesoscale moisture flux (W m⁻²) for 1979 for (a) NLCD01, (b) NLCD73, and (c) the NLCD01 – NLCD73 difference. (d) Same as Figure 11a but for mesoscale heat flux (W m⁻²); (e) same as Figure 11b but for mesoscale heat flux (W m⁻²); (f) same as Figure 11c but for mesoscale heat flux (W m⁻²). Vertical axis is displayed in meters.
for NLCD01 as compared to NLCD73 of at least 20–40 W m\(^{-2}\) during the dry periods of the month. However, distinct from moisture flux, the peak mesoscale heat flux is confined lower in the atmosphere, well within the PBL [e.g., Pielke et al., 1991]. Therefore, the vertical signature of the mesoscale circulations is significantly different for moisture than for heat, with potential implications for atmospheric vertical thermodynamic structure. We examine such changes in the vertical profiles next.

### 3.4. Vertical Thermodynamic Profile

[40] Figure 12 shows a similar time series of subdomain averaged water vapor mixing ratio as the mesoscale flux results presented in Figures 11a–11c and 11d–11f. This is revealing, for two reasons. First, for the initial half of the month (through about 16 July), large-scale subsidence is evident, consistent with the large-scale dynamical situation and the monthly averaged precipitation time series presented earlier (recall Figure 10). On 16 July, the atmosphere begins to moisten considerably as subsidence weakens with the approach of unsettled conditions. For the next several days, mixing ratio values are at their monthly peak, before a gradual decline commences once again after the conclusion of the convective period. Second, the diurnal presence of the mesoscale circulations, and their enhancement from NLCD73 to NLCD01, are once again evident. In particular, the surface layer drying and upper PBL and lower FA moistening effects are apparent (Figure 12c). This characteristic pattern of low-level drying and upper PBL moistening reverses immediately after the wet period concludes on about 21 July. Enhanced precipitation for the NLCD01 experiment wets the soil beneath, and it takes several days for evapotranspiration to occur and once again allow the rolls to resume their daily, preconvective period, behavior.

[41] During most days, FA water vapor shows a characteristic diurnal increase. However, there is no ongoing accumulation from one day to the next, building up a progressively moister layer. One thing that is occurring is that at least some of the water transported vertically by the mesoscale circulations makes it high enough to escape the PBL into the FA, where it is more easily advected out of the domain by the large-scale background wind. Figures 8 and 9 provide some evidence for this occurrence.

[42] Figure 13 shows the vertical evolution of \( q \) differences, averaged over the previously defined subdomain of interest, from 1 to 16 July (i.e., during the preconvection period) for 0800, 1100, 1400, and 1700 LT. The corresponding calculations for water vapor mixing ratio difference evolution and \( \theta_e \) (equivalent potential temperature) are presented in Figures 14 and 15, respectively. Figure 13 demonstrates the full heating effect due to urban expansion and illustrates the evolving buildup of low-level dry static energy during the course of the day. This excess dry static energy remains confined to the PBL even during the nighttime, though differences between NLCD01 and NLCD73 diminish to about \( 0.1^\circ C \) (as shown in Figures 11d, 11e, and 11f, the heat flux due to the mesoscale circulations is confined to these low levels).

[43] By contrast, Figure 14 illustrates the dual upper PBL moistening and surface layer drying as a result of the mesoscale dynamics. While the peak effect of turbulent heating due to urban expansion is confined to the surface...
layer, peak moistening due to the mesoscale dynamics occurs in the vicinity of the PBL top. Contributions from both heating and moistening are shown in the evolution of the $q$ profile in Figure 15, illustrating the relative importance of the enhanced moisture transport due to strengthened mesoscale circulations in the NLCD01 simulation.

3.5. Physical Mechanism(s) Responsible for Rainfall Enhancement

[44] The final question is, what role, if any, do the aforementioned mesoscale-induced changes in the vertical thermodynamic structure of the atmosphere play in the simulated enhancement of 16–21 July precipitation in the NLCD01 simulation? The NLCD01 profiles are warmer and
drier in the lower PBL but significantly moister in the upper part of the PBL and lower portions of the FA (between 1 and 3 km, as shown in Figure 15). While this additional moist static energy does not lead to convection on most days, since the atmosphere is too dry, it is plausible that, when a storm moves into the domain, the lifting of this moister layer releases additional instability, fueling stronger updrafts and hence more convective rainfall. Close inspection of the simulated storm cells, however, reveals that the preponderance of precipitation occurs during the nighttime hours, primarily after local midnight. As noted in the thermodynamical profiles presented in Figure 15, the land surface impact on vertically distributed moist static energy is greatest during middle to late afternoon, begins to dissipate during the evening, and is least during nighttime (i.e., profile differences are smallest during the time of greatest rainfall frequency). Consequently, the direct dynamical forcing (hypothesized as a possible mechanism in the Introduction) resulting from landscape forced mesoscale circulations does not seem to be the explanation for either

**Figure 14.** Same as Figure 13 but for water vapor mixing ratio difference (g kg⁻¹).

---

18 of 22
the initial storm enhancement or the subsequent rainfall events.

Rainfall enhancement may also take place indirectly, through the gradual accumulation of moist static energy within the PBL. Figure 11c does indicate that moisture transport is enhanced for the NLCD01 experiment, in the upper reaches of the PBL/lower FA, relative to the NLCD73 experiment, on a diurnal basis. However, with the gradual waxing of moisture resulting from landscape-induced mesoscale circulations appears a waning of equal magnitude as the background flow advects the air out of the fine grid, suggesting that the indirect mechanism is also unlikely to play a large role in precipitation enhancement.

While the cause of initial triggering of the precipitation enhancement remains unknown, one mechanism suspected to play an important role in enhancing the initial difference in precipitation between NLCD01 and NLCD73 is local recycling. The simulated subdomain averaged latent heat flux difference (NLCD01 minus NLCD73) for 1979 displays consistently negative values during the first half of

Figure 15. Same as Figure 13 but for $\theta_e$ difference.
the month, indicating that NLCD73 evapotranspiration was greater than that of NLCD01 (not shown). As the ensuing period of convective activity approaches, however, differences become positive as NLCD01 evapotranspiration exceeds that of NLCD73. Immediately after the initially enhanced rain event, the subsequent day’s additional water, according to these differences in latent heat fluxes, seems to moisten the atmosphere and aids to further feed rainfall enhancement. As the convective period ends the diurnal pattern of greater NLCD73 evapotranspiration eventually resumes, once the extra soil water from the additional rainfall, in NLCD01, has evaporated and moved out of the domain. One additional simulation was performed to test the recycling hypothesis. The NLCD01 experiment, using the 1979 lateral boundary conditions, was restarted on 17 July (i.e., just after the initial rainfall had fallen over the subdomain of interest; see also Figure 10), and integrated for the remainder of the month with a single change: evaporation from the land surface component was set to zero. Figure 16 shows the simulated difference in end of July accumulated rainfall that had occurred solely due to the limitation of surface evaporation from 17 July onward. A significant region of precipitation enhancement is apparent to the immediate north and east suburbs of the Greater Phoenix region, extending further northward and eastward where rainfall accumulation differences as large as 100 mm are found, thus supporting our hypothesis of rainfall recycling.

The importance of the large-scale environment, in terms of storm movement during 1979, and its effect on precipitation recycling require further explaining. Precipitation recycling may be enhanced if cell motion follows similar trajectories over a period of successive days, a feature that was noted during the 1979 simulations, but was less apparent during 1989 and largely absent in 1994. During 1994, for example, convective elements moved through the domain from all directions with relatively equal frequency, while during 1979 convective elements traced out similar paths on successive days, feeding on the evaporated water from the previous day’s rainfall.

4. Discussion and Conclusions

This is part 2 of a two-part study investigating the summer climate impact of actual landscape evolution, from the early 1970s to the early 2000s, over one of the fastest urbanizing metropolitan complexes in the United States, the Greater Phoenix area. The premise of this series of papers, an extension of GJAE08, was that LULCC caused by human activities has had a significant impact on the region’s changing climate. The focus was on the summer season, the time period wherein the NAMS is active and when climatic effects on the human and natural systems, due to excessive heat and flood-producing rains, are at their annual peak. Part 1 examined the effect of LULC reconstructions based on circa 1973, circa 1992, and circa 2001 data on the near surface climate. The effect of increasing urban land in conjunction with decreasing plots of irrigated agriculture was examined through their collective and individual impacts on the surface radiation balance. Distinct land use conversion themes illustrated the greatest contributions to warming: the conversion of irrigated agriculture to urban area, and shrubland to urban area. The loss of irrigated agriculture coverage contributed to an overall reduction of

![Figure 16](image-url)
low-level atmospheric humidity, contributed to a change in the partitioning of sensible and latent heating and in part helped explain the simulated regional mean warming of 0.12 °C between the most recent and oldest landscape reconstructions. In part 2, the effect of the altered surface radiation balance on atmospheric dynamical processes and convection, and the interactions between the turbulent-scale, mesoscale, and large-scale dynamics over the monthly timescale were evaluated. Contrasts in surface heating were found to produce preferentially located mesoscale circulations, on most days, which were stronger for NLCD01 relative to NLCD73, due to increased planetary boundary layer (PBL) heating via enhanced turbulent heat flux. The effect of these stronger circulations was to warm and dry the lower part of the PBL and moisten the upper part of the PBL for NLCD01 relative to NLCD73, due to increased planetary boundary layer (PBL) heating via enhanced turbulent heat flux. The effect of these stronger circulations was to warm and dry the lower part of the PBL and moisten the upper part of the PBL for NLCD01 relative to NLCD73, due to increased planetary boundary layer (PBL) heating via enhanced turbulent heat flux. The effect of these stronger circulations was to warm and dry the lower part of the PBL and moisten the upper part of the PBL for NLCD01 relative to NLCD73, due to increased planetary boundary layer (PBL) heating via enhanced turbulent heat flux.

[49] We now briefly revisit the hypothesis outlined at the conclusion of GIAE08 (i.e., that the accumulated landscape signal may modify regional stability sufficiently to allow for repeated enhancement of storm cells). Reexamination of the hypothesis based on the results presented here reveals that the precise pathway(s) leading to the initial augmentation of precipitation resulting from the effect of enhanced warming (due to urban area expansion), and enhanced moistening (due to the presence of irrigation), is more complicated than their collective effect on the increase of moist static energy of the PBL. The interplay among the continuum of scales, from the turbulence to the large-scale, underscores some of the nonlinearities and complexities involved in the coupled land-atmosphere system, and warrants future research.

[50] The interplay between three scales of motion, i.e., (1) background large-scale flow and the NAMS storm systems, (2) landscape-induced mesoscale circulations, and (3) differential turbulent heating and moistening of the PBL across the heterogeneous landscape, defines the regional weather and climate of Greater Phoenix, at least during climatologically dry summers and with use of this particular numerical model.

[51] With the goal of presenting a more unambiguous synopsis, Figure 17 illustrates a qualitative summary of the questions answered as part of this overall research along with lingering issues. In Figure 17 (top), the rectangles define the extent of the fine grid domain and display, in a qualitative manner, the quantity of irrigated agriculture and urban land (i.e., the two primary landscapes considered in this work). The thermal impact of the evolution of the Greater Phoenix landscape may be subdivided into two primary elements: (1) the effect due to changing coverage of irrigated agriculture, and (2) the effect due to changing coverage of urban land, from presettlement to the NLCD01 landscape. The thermal impact of continued urbanization has caused a constant increase in
temperature while the effect of changing irrigated agriculture forced a nonlinear response that initially resulted in lowered temperatures (due to its initial presence) before warming ensued (due to decreases in irrigated agricultural coverage). The main question is what, if any, are the reinforcing/competing roles of urbanization and irrigated agriculture in driving changes in precipitation? While results presented from 1979, and to a lesser extent 1989, point toward a complex interaction between the turbulent, mesoscale, and large scales, pathways whereby this enhanced precipitation is initially triggered, remain elusive. Precipitation recycling, given large-scale conditions allowing for similar storm cell movement over a period of days, has shown to be an important factor in the maintenance and amplification of rainfall enhancement. We find that the simulated precipitation enhancement (i.e., enhancement to the north and east of the metropolitan area) is most apparent for our dry experiments (i.e., during hydrometeorological conditions when convective precipitation is most sensitive to near-surface thermodynamic perturbations), but that even during these regimes storm cell movement over a period of successive days, as guided by the large-scale circulation, plays a significant role in precipitation augmentation.

[52] It is also essential to mention that, as described in detail in GJAE08 and part 1 of this series, RAMS does not include a comprehensive urban canopy parameterization and is unable to account for the presence of and interaction between building walls, rooftops, road surfaces, and the overlying atmosphere. Consequently, our results are an underestimate of the nocturnal UHI intensity and therefore, the effects of urbanization we present (on temperatures and atmospheric processes) likely represent underestimates as well.

[53] Finally, current population projections of the Greater Phoenix area suggest that the region may surpass 10 million inhabitants by 2050 [Arizona State University, 2003]. Continued landscape conversion, at the expense of both semi-natural shrubland and still lingering plots of irrigated agriculture, is expected to parallel unrelenting population rise, despite the climatological scarcity of water. How future projections of the area’s landscape would impact weather and climate is thus of vital concern. In particular, analysis of the effect of future landscape change in context of future projections of large-scale climate and increasingly scarce water resources may provide us with the ability to better understand the full range of anthropogenic impact over this area.

[54] Acknowledgments. This work was funded by NASA through Earth System Science Fellowship grant NNG04GQ47H. C.P.W. states that the views expressed in this 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. The authors also wish to thank two anonymous reviewers for their extensive comments. Last, M.G. would like to thank Tom Atkins for his artistic assistance in the creation of Figure 17.

References