Urban Effects on Summer Monsoon Thunderstorms in Phoenix, Arizona
A Regional Atmospheric Model Case Study of 2-3 August 2005

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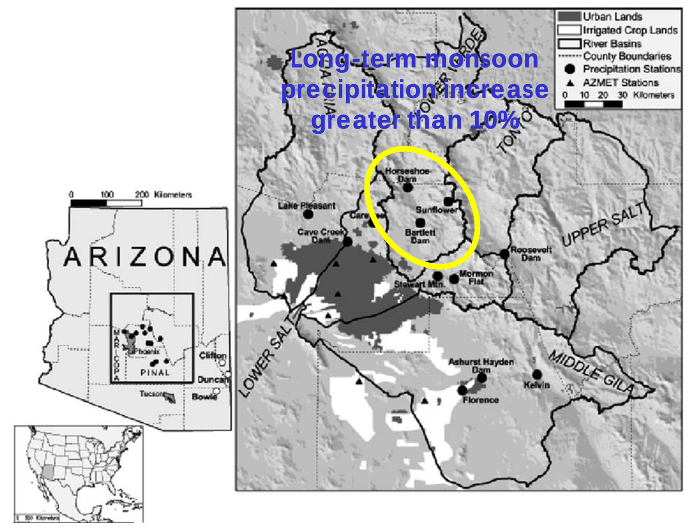
Motivation: How have monsoon thunderstorms changed due to the rapid growth of Phoenix?

For major urban areas in mid-latitude humid climates of the central and eastern U.S., there is strong evidence that urbanization has modified thunderstorms. Higher sensible heat fluxes lead to a deeper and drier planetary boundary layers, causing low-level convergence that is favorable for enhancing thunderstorms downwind of cities. Relatively unknown is how urbanization in the more arid, mountainous western U.S. may affect thunderstorms during the North American Monsoon in late summer. The focus of this study is Phoenix, Arizona. Previous statistical analyses have suggested that there have been coherent changes in the spatial distribution of summertime rainfall in the Phoenix metropolitan area. For example, Shepherd (2006) found a statistically significant increase in rainfall in mountain areas to the north and east of the city (Fig. 1), and speculated that landscaping and agricultural irrigation in the Phoenix urban core enhance the availability of moisture for monsoon thunderstorms. Here, we address whether a similar pattern of precipitation change exists within a regional model sensitivity study of a severe monsoon thunderstorm event in August 2005, in an attempt to establish physical causality for these observed changes.



Comparison of pre-urban (1895–1949) and post-urban (1950–2003) mean precipitation totals in the Phoenix and surrounding basin areas

Location	Latitude	Longitude	Region and elevation (m)	Pre-urban (1895–1949) mean precipitation (mm)	Post-urban (1950–2003) mean precipitation (mm)	Per cent change (%)
Phoenix (downtown)	33.4	111.9	Urban (610 m)	23.66	23.39	−1.1
Phoenix (SW)	33.0	112.5	Urban (304 m)	22.74	22.38	−1.5
El Mirage	33.6	112.3	Urban (~610 m)	21.00	21.63	3.0
Buckeye	33.3	112.5	Urban (304 m)	23.26	22.28	−4.2
Duncan	32.7	109.1	Monsoon (1160 m)	41.41	43.04	3.9
Clifton	33.0	109.2	Monsoon (1150 m)	46.04	46.20	0.3
Kelvin	33.1	110.9	Middle Gila (550 m)	37.73	37.15	−1.5
Florence	33.0	111.3	Middle Gila (460 m)	26.70	28.05	3.2
Stewart Mtn	33.5	111.5	East Lower Salt (430 m)	33.68	34.78	3.2
Roosevelt Dam	33.6	111.1	East Lower Salt (650 m)	38.51	40.93	6.2
Sunflower	33.9	111.4	Lower Verde (1160 m)	58.95	65.91	11.8
Horseshoe Dam	33.9	111.7	Lower Verde (615 m)	34.21	38.19	11.6
Bartlett Dam	33.8	111.6	Lower Verde (500 m)	29.48	33.59	13.9
Cave Creek	33.7	112.0	NW Lower Salt (490 m)	21.64	22.91	5.8
Carefree	33.8	111.9	NW Lower Salt (760 m)	27.55	30.05	9.0

Figure 1: Precipitation locations in the Phoenix area considered in the statistical analysis of Shepherd (2006) (left) and the corresponding percentage change from the early to late twentieth century (right). The region where statistically significant increases are noted per the table is highlighted on the map.

Severe monsoon thunderstorm event: 2-3 August 2005

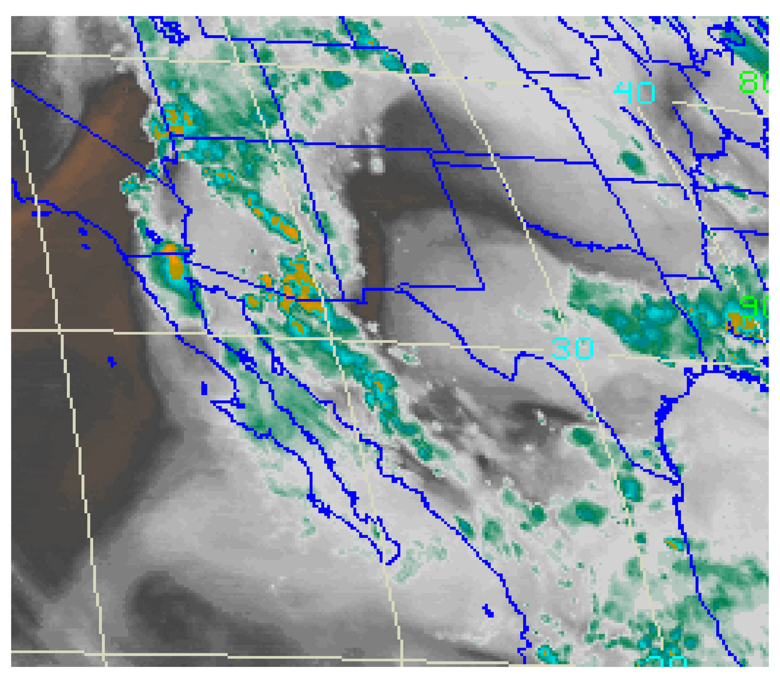


Figure 2: An upper-level low (or inverted trough) moving WNW over northern Mexico, as seen in the water vapor imagery taken at 0015z August 3, 2005.

The weather conditions for the 2-3 August 2-3 2005 event were quite typical for severe thunderstorms in the Phoenix area: 1) easterly to northeasterly winds at upper-levels due to the positioning of the monsoon ridge in the Four Corners region, 2) instability from synoptic-scale inverted trough to the southeast of Arizona, and 3) a low-level moisture surge from the Gulf of California (Fig. 2). Given these conditions, convection typically develops on the mountains to the northeast of the city in the late afternoon and propagates into the low deserts of Arizona during the evening. The time sequence of NEXRAD radar reflectivity for the event (Fig. 3) shows a severe thunderstorm hit the Phoenix area approximately 10 pm local time, with precipitation totals in the range of 1-2 inches. Damage reports included a major dust storm, golf ball size hail, damaging winds and urban flooding. Of particular interest, the heaviest rainfall is located to the north and east of the Phoenix urban core (see images on fourth row of Fig. 3). The enhancement of precipitation in the mountains and relative precipitation "hole" in middle of the city, most clear on the rightmost image on the fourth row of the radar sequence, is least qualitatively consistent with Shepard (2006). Characterizing the physical reasons for this behavior is the major analysis focus of our regional atmospheric model sensitivity experiments.

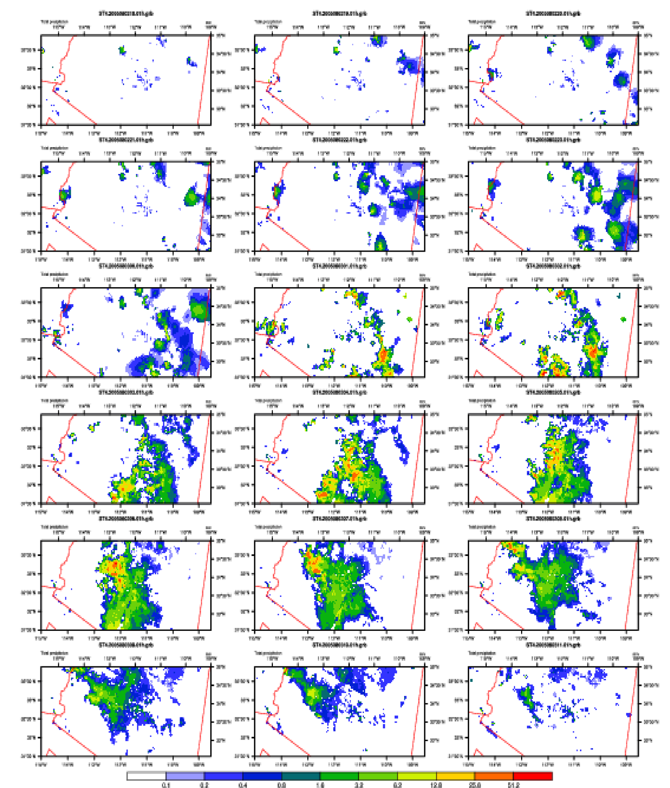


Figure 3: NEXRAD Stage IV accumulated hourly precipitation (mm) 02 August 2005 1800 UTC (1100 LST) to 03 August 2005 1200 UTC (0500 LST).

Storm event sensitivity to urbanization as evaluated with the Weather Research and Forecasting (WRF) model

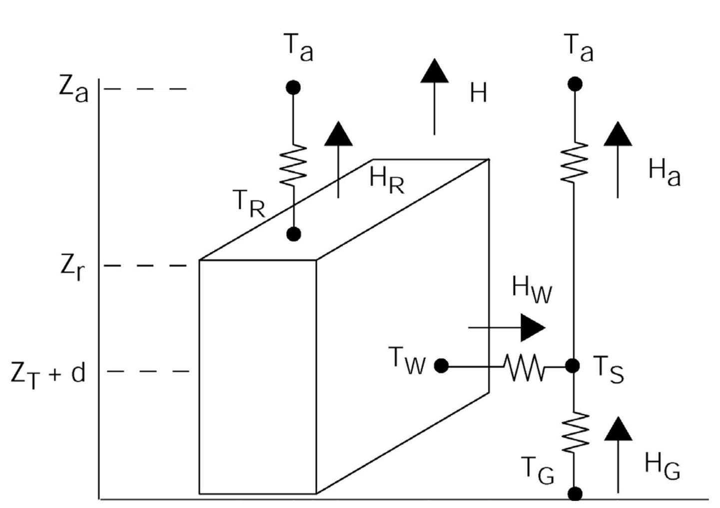


Figure 4: Simple demonstration of a single-layer urban canopy model calculation. Z = height, T = temperature and H = sensible heat fluxes. Subscripts a = atmosphere, r = roof, g = ground and w = wall.

High resolution (2.5 km) one-way nested simulations with the Weather Research and Forecast (WRF) model were performed for 2 August 2005 12 UTC through 3 August 12 UTC. The area in the outer modeling domain approximately corresponds to the Tier I region of the North American Monsoon Experiment. Model physics specifications are fairly consistent with what is used for real time forecast application at the Department of Atmospheric Sciences at the University of Arizona, with initial specification of soil moisture and lateral boundary conditions from the driving GFS analysis. To examine the sensitivity to urbanization in Phoenix, an urban canopy model (Kusaka and Kimura 2004) is applied (Fig. 4) that explicitly accounts for heat and moisture fluxes from urban surfaces using the most updated land cover classification available (Fig. 5). The moisture fluxes include the effects of the irrigated landscape, which may be an important moisture source as speculated by Shepherd (2006). This is compared with a control simulation that entirely replaces the Phoenix metropolitan area with natural desert land cover to approximately represent the pre-urban conditions.

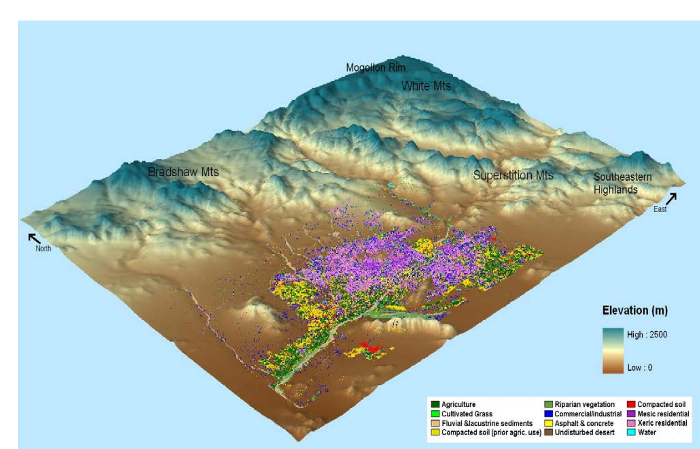


Figure 5: Terrain and 12-category land use/cover for the Phoenix metropolitan region derived from 2005 Landsat Thematic Mapper reflectance data and ancillary datasets (Stefanov et al. 2001). The spatial resolution is 30m/pixel. The east-west and north-south extent of the area shown are 200 km and 150 km respectively.

Regional model simulated thunderstorm event evolution with urban vs. natural desert land cover

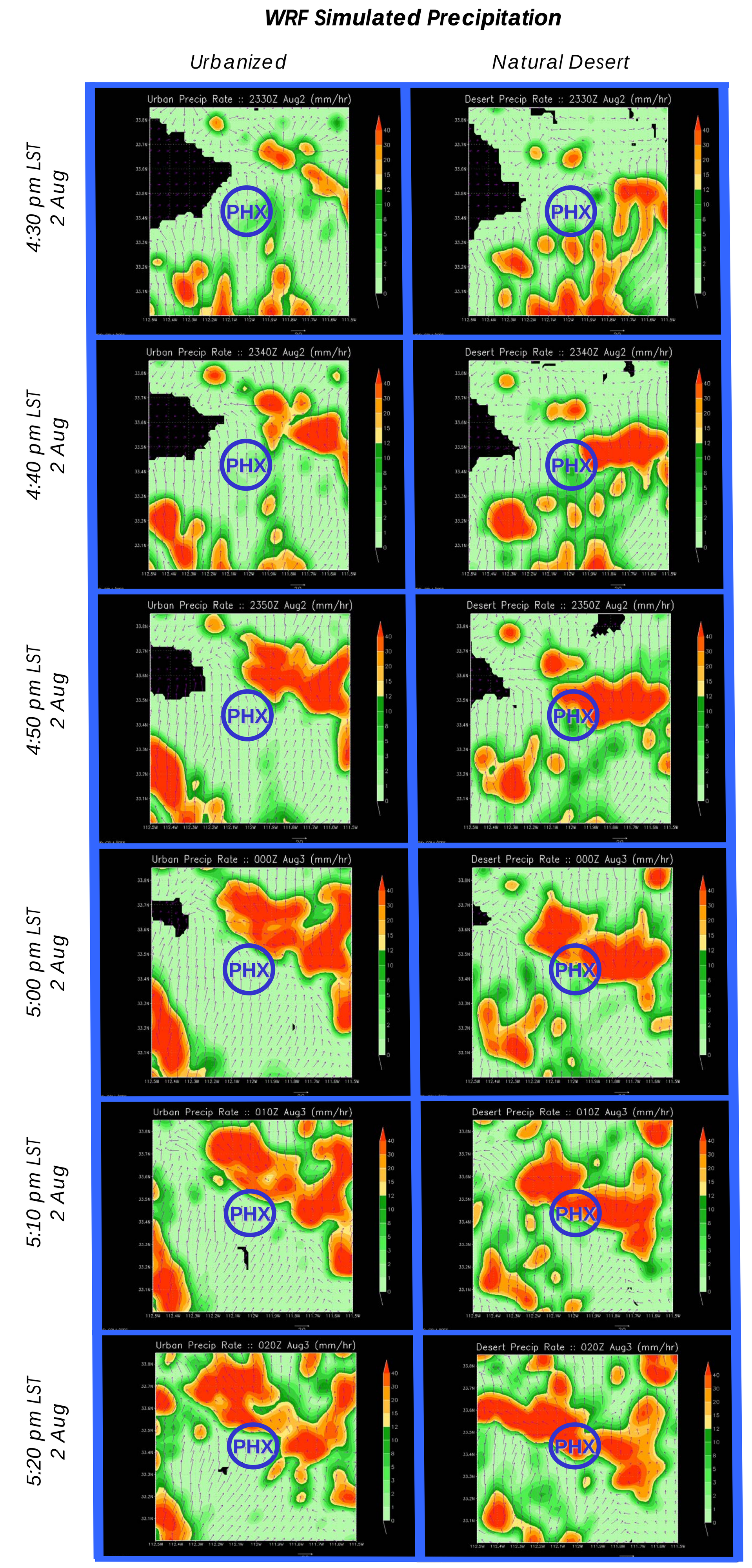


Figure 6: Precipitation rate (mm/hr) at 10 minute intervals during the time of the thunderstorm event in Phoenix simulated by WRF, urban vs. desert land cover. The approximately location of Sky Harbor Airport (PHX) is indicated. Wind vector length is 20 m/s.

For both the urbanized and natural desert land cover cases, WRF simulates a thunderstorm event over the Phoenix metropolitan area, though the event occurs several hours before when it was actually observed in NEXRAD radar data in Fig. 3. Comparing the two simulations during the height of the model-simulated storm in Fig. 6, thunderstorm cells tend to remain over the mountains to the north and east of Phoenix slightly longer in the urban simulation. The model simulated storm with the urban modifications more closely matches the radar-derived precipitation, with less in the urban core and more to the north and east of the city—qualitatively similar to what has been observed climatologically in Shepherd (2006). To determine the cause of the differences in the WRF simulations, further simulations were performed to examine the influence of the individual components within the urban canopy model using a factor separation approach (Fig. 7, right). A decrease in sensible heat flux due to the presence of irrigated landscape in the urban simulation best explains the urban vs. desert precipitation differences. A slightly cooler and shallower planetary boundary layer in the mid-afternoon decreases the convective available potential energy (2610 J/kg urban compared to 3041 J/kg desert) over the urban core (Figs. 8 and 9).

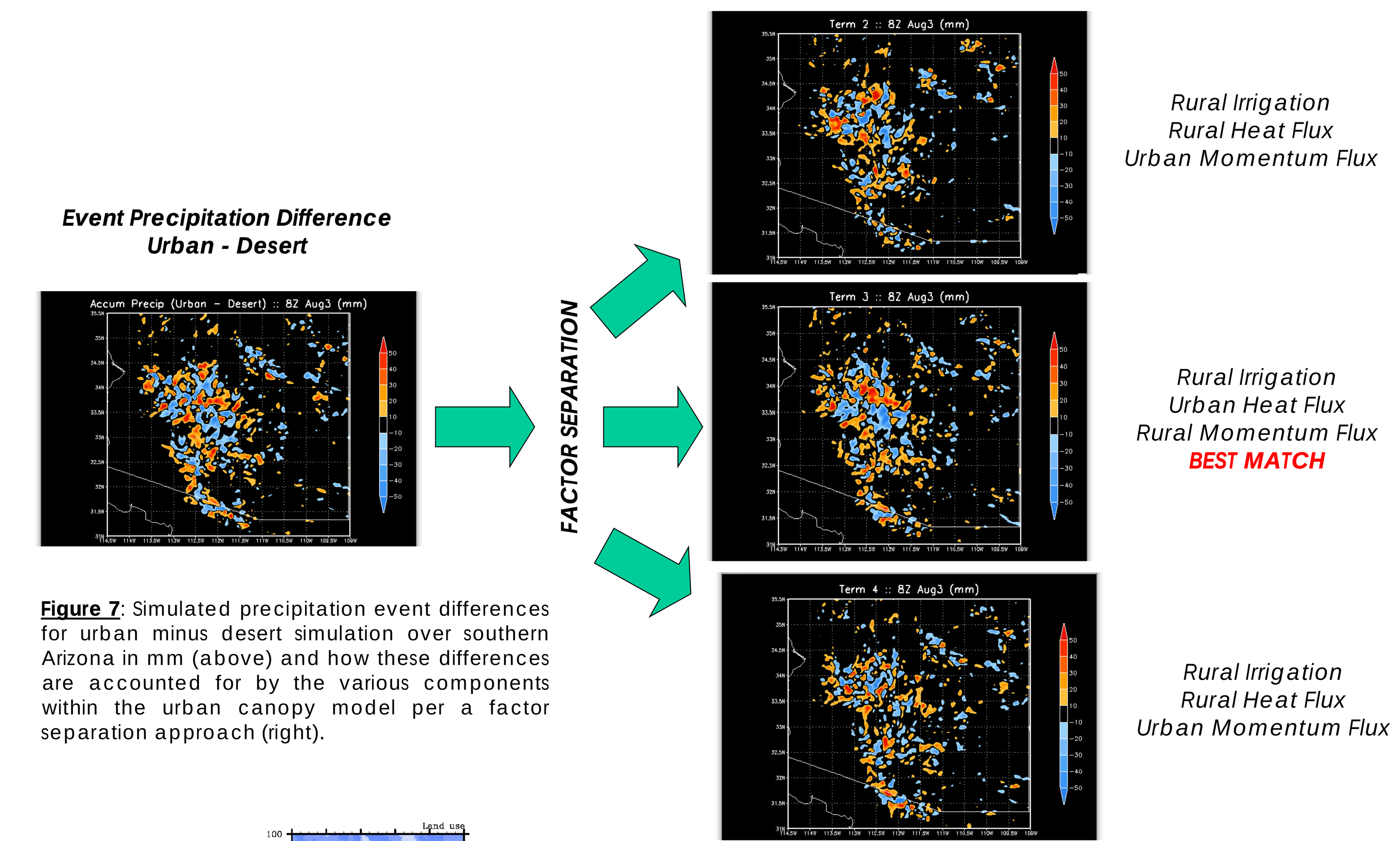


Figure 7: Simulated precipitation event differences for urban minus desert simulation over southern Arizona in mm (above) and how these differences are accounted for by the various components within the urban canopy model per a factor separation approach (right).

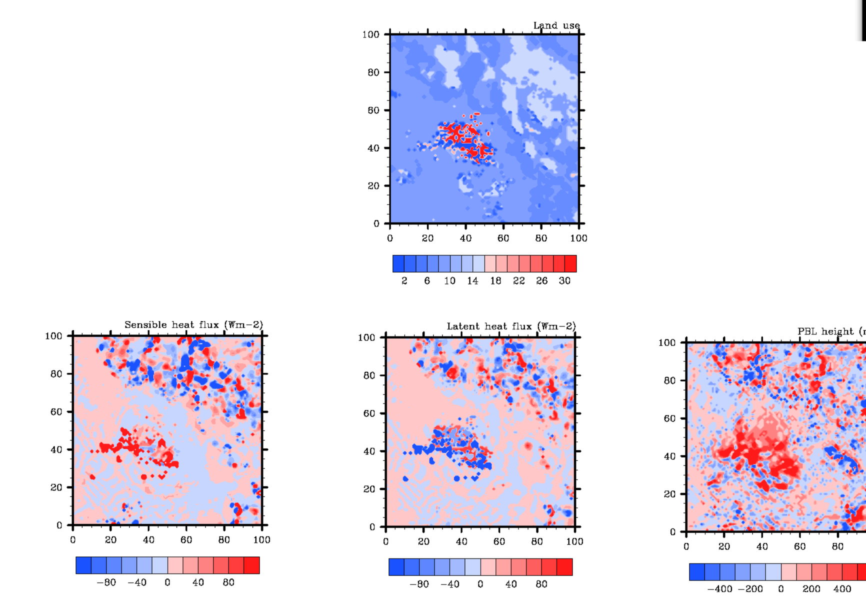


Figure 8: Top: differences in land use patterns from desert to urban simulation. Bottom: simulated sensible heat, latent heat, and PBL height differences (desert minus urban) at 3 pm in Phoenix area. Units given on the figure.

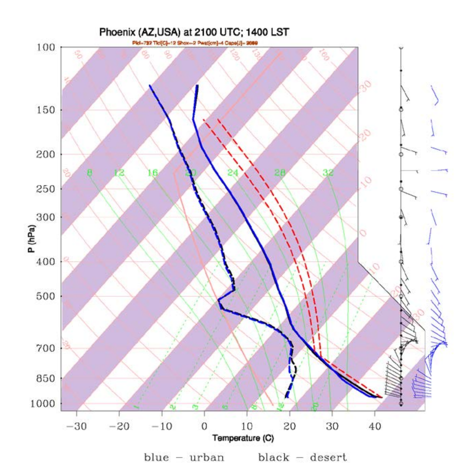


Figure 9: Simulated atmospheric sounding data at Sky Harbor Airport at 2 pm prior to storm development plotted in a standard skew-T, log P plot.

Summary and Conclusions

URBANIZATION HAS CHANGED MONSOON RAINFALL IN PHOENIX: The Phoenix metropolitan has had spatially coherent changes in summer monsoon precipitation associated with its rapid urbanization. Specifically, long-term precipitation records show an statistically significant increase in summer precipitation to the northeast of the urban core.

APPROPRIATENESS OF A REGIONAL MODEL FOR EVENT SIMULATION: A regional atmospheric model (WRF) has been used to retrospectively simulate a typical severe thunderstorm event in Phoenix, considering urban vs. natural desert land cover. The spatial distribution of precipitation of the urban simulation is more consistent with the radar-derived rainfall and shows a greater amount to the northeast of the urban core

PHYSICAL EXPLANATION FOR PRECIPITATION DIFFERENCES WITH URBANIZATION: Irrigated surfaces partition a greater amount of surface energy flux to latent heat, leading to a cooler, shallower planetary boundary layer and less convective available potential energy in the urban core in late afternoon. Thus, the onset of precipitation in the urban core is delayed and precipitation persists longer in the mountains. The influence of urbanization on summer convection in Phoenix, at least in this case, appears to be very different than for central and eastern U.S. cities that have more humid environments with relatively homogenous topography.

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