

**Urban-Induced Rainfall Anomalies in an Arid Regime: Evidence from a 108-Year Data Record and Satellite Measurements**

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Popular Summary  
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Arid and semi-arid regions of the southwestern United States are rapidly developing and placing greater demands on the environmental system. Such rapid growth increases the potential impacts of human activities on the Earth's natural system. One particular system that is sensitive to human activity is the water cycle. The water cycle circuit is the source of potable water for sustaining life. At the same time, the water cycle components that sustain life are becoming more scarce and polluted. For example, the most recent (1999-2004) drought experienced in the southwestern United States is the seventh worst in the approximately 500-year proxy tree-ring record. As a result, many regions contemplated "drought emergencies" in which severe water restrictions are implemented.

Though large-scale forcing likely controls drought processes, there is increasing evidence that anthropogenic or "human-related" activities can significantly alter precipitation processes. Urbanization is an example of anthropogenic forcing. Recent studies continue to provide evidence that urban environments can modify or induce precipitation under a specific set of conditions. In the United States, cities in the arid Southwest like Phoenix (the fourteenth largest metropolitan area according to the U.S. Census Bureau 2001) are experiencing rapid growth. In the past fifty years, Phoenix has expanded from a predominantly agricultural center to an urbanized region with extent 700 percent larger than its size in the middle of the twentieth century. Yet, few studies have examined the impact of semi-arid and arid cities on precipitation processes.

The study employs a unique 108-year precipitation data record to identify statistically significant anomalies in rainfall downwind of the Phoenix, Arizona urban region. Our analysis reveals that during the monsoon rainfall season (July, August, September) locations in the northeastern suburbs and exurbs of the Phoenix metropolitan urban area (the so-called "anomaly region") have experienced statistically significant increases in mean precipitation of 12 to 14 percent from a pre-urban (1895-1949) to post-urban (1950-2003) period. Additionally, mean and median post-urban precipitation totals in the anomaly region are significantly greater, in the statistical sense, than regions west of the city and in nearby mountainous regions of similar or greater topography. Further analysis of satellite-based rainfall totals for the summer of 2003 also reveal the existence of the anomaly region even though the arid southwest experienced severe drought during the period. More significant mountain features do not correspond to the location of the anomaly region, and statistically significant precipitation changes are found in the anomaly region when pre- and post-urban data are analyzed. Thus, it is hypothesized that mesoscale and microphysical processes related to anthropogenic forcings (urban land use and/or aerosols) interact with the topographic circulations in the region to establish the precipitation anomaly though further modeling studies will be needed to test the hypothesis.

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## **Abstract**

The study employs a 108-year precipitation data record to identify statistically significant anomalies in rainfall downwind of the Phoenix urban region. The analysis reveals that during the monsoon season locations northeastern suburbs and exurbs of the Phoenix metropolitan area have experienced statistically significant increases in mean precipitation of 12 to 14 percent from a pre-urban (1895-1949) to post-urban (1950-2003) period. Mean and median post-urban precipitation totals in the anomaly region are significantly greater, in the statistical sense, than regions west of the city and in nearby mountainous regions of similar or greater topography. Further analysis of satellite-based rainfall totals for the summer of 2003 also reveal the existence of the anomaly region during a severe drought period. The anomaly can not simply be attributed to maximum topographic relief and is hypothesize to be related to urban-topographic interactions.

## I. Introduction

Water is essential to life in the Earth system. The water cycle components that sustain life are becoming more scarce and polluted. The most recent (1999-2004) drought experienced in the southwestern United States is the seventh worst in the approximately 500-year proxy tree-ring record (Piechota et al. 2004). As a result, many regions contemplated “drought emergencies” in which severe water restrictions are implemented. Though large-scale forcing likely controls drought processes (Hidalgo 2004), there is increasing evidence that anthropogenic or “human-related” activities can significantly alter precipitation processes. Urbanization is an example of anthropogenic forcing. Recent studies (Inoue and Kimura 2004; Burian and Shepherd 2004; Molders and Olson 2004; Dixon and Mote 2003; Shepherd and Burian; Bornstein and Lin 2000) continue to provide evidence that urban environments can modify or induce precipitation under a specific set of conditions. Results of these recent studies are consistent with previous historical work in this research area (Changnon et al. 1981; Huff 1986).

Arid and semi-arid regions of the southwestern United States are rapidly developing and placing greater demands on the environmental system. In the past fifty years, Phoenix has expanded from a predominantly agricultural center to an urbanized region with extent 700 percent larger than its size in the middle of the twentieth century (Rex 2000). Figure 1 is a LANDSAT image depicting the rapid growth of Phoenix over the past few decades. There have been relatively few studies that focus on arid urban areas and precipitation enhancement. Balling and Brazel (1987) observed more frequent late afternoon storms in Phoenix during recent years of explosive population growth. Diem and Brown (2003) (hereafter DB03) suggested that anthropogenic activities in the Phoenix area affect summer precipitation totals, particularly the Lower Verde basin zone.

## 2. Study Objectives, Data, and Methodology

DB03 offered very compelling findings but their study was limited: (1) the study only investigated the relative increases in precipitation totals for a sample of stations in the basins east of Phoenix and (2) the study only utilized precipitation data from 1950 to 2000, which is essentially the post-urban period. Herein, urban processes are defined as including urban land use, urban aerosols, and human irrigation procedures. Our work extends DB03 in several important ways.

First, we utilize a high-quality, topographically-sensitive, 108-year precipitation data record provided by the Spatial Climate Analysis Service (SCAS) at Oregon State University. This 4-km resolution dataset resolves the *pre-urban (1895-1949)* and *post-urban precipitation* climatology for the southwestern U.S. This capability is necessary for detecting pre-urban and post-urban effects since the city cannot be physical removed for experimentation. PRISM (Parameter-Regression Independent Slopes Model) (Daly et al. 2002) is used to spatially distribute ground-based observations. The primary sources of observations currently used by SCAS for mapping precipitation are: 1) COOP (NWS COOPerative observations), 2) SNOTEL (USDA NRCS SNOW TELelemetry), and 3) ASOS (NWS/FAA Automated Surface Observing System). The total number of precipitation stations was approximately 12600 (figure 2). A particularly attractive feature of PRISM for studying mountainous regions is its ability to calculate linear climate-elevation relationships.

Second, we investigate the relative magnitude of mean precipitation totals in Phoenix and immediate surrounding regions. The goal is to verify results presented by DB03 that indicated a tendency for elevated precipitation totals in the Lower Verde basin region. We extend DB03 by integrating analysis of stations in the western and northern surrounding area as well as the Phoenix urban area. Statistical

The experimental Tropical Rainfall Measuring Mission (TRMM) 3B42 real-time rainfall product (TRP) is used to examine mean rainfall rates of the central Arizona region during the extreme drought conditions of 2003. The goal is to detect the precipitation anomaly under relatively homogeneous drought conditions. TRP provides rainfall rate and accumulation estimates at 0.25°-resolution every three hours over the latitudinal range of 60°N - 60°S. TRP is a merger of all available SSM/I and TRMM microwave imager precipitation retrievals into a "high-quality" (HQ) precipitation estimate. The product also included precipitation estimates from geostationary infrared observations that are calibrated by the HP precipitation estimate (Huffman et al. 2003)

### **3. Monsoon Climatology and Topography**

The southwest monsoon influence is greatest over portions of Mexico and extends into southeastern Arizona where average precipitation during July, August, and September exceeds 50% of the mean annual total. The Phoenix metropolitan area receives approximately 40% of its mean annual rainfall during the monsoon period. During the monsoon period, near-surface moisture availability in the Phoenix region peaks. The mean Tucson sounding (Wallace et al. 1999) in figure 3 indicates that on active monsoon days, the low-middle tropospheric flow is southeasterly. During the monsoon period, thunderstorms are an almost daily occurrence in the region. The large spatial variability of deep convection over Arizona (López et al. 1997) is directly related to the highly complex terrain of the state. Orographic effects tend to produce greater summer precipitation totals in the mountainous areas north and east of city (figure 4). In the early afternoon, convective activity peaks on the Mogollon Rim (Watson et al. 1994b). What is most interesting about the northeast Phoenix region is the apparent existence of an anomaly region (AR) where precipitation totals in the last 50 years appear to be greater than surrounding areas with similar or greater topographic relief.

### **4. Analysis of Pre-Urban and Post-Urban Rainfall in an Arid Regime**

The pre-urban (1895-1949) and post-urban (1950-2003) precipitation data were grouped such that the mean precipitation totals for the monsoon period (July-September) are aggregated. Table 1 summarizes the data for selected sites identified in figure 4. Sites were selected to represent the Phoenix region and selected sites to the southwest, northwest, northeast, and southeast of the urban area. We analyzed the time series of mean monsoon season precipitation for each site to determine if any significant differences between the pre-urban and post-urban period were evident.

Stations located southeast of the Phoenix area like Clifton and Duncan receive a significant amount of the precipitation during the monsoon period. Since synoptic-scale monsoon system should cause significantly higher precipitation totals in the monsoon zone than in regions around the Phoenix area, comparisons between moderately monsoon-impacted stations (i.e. Lower Verde) and strongly monsoon-impacted stations (i.e. "monsoon zone") enable a compelling examination of possible urban-induced increases in summer precipitation totals in the Lower Verde or northeast Phoenix region (DB03). The monsoon zone stations are above 1100 m above sea level. The Sunflower station, located in the Lower Verde basin northeast of Phoenix is also at significant elevation (> 1100 m) and is the wettest location in our sample.

The most interesting result is how the *mean precipitation amounts have changed* from the pre-urban to post-urban periods. Paired t-testing reveal that differences in pre-urban and post-urban precipitation mean totals are statistically significant at the 95% level. Regardless of monsoon region or topography, our results identify a preferred region of enhanced precipitation in the Lower Verde basin 30-50 km northeast of the Phoenix metropolitan area. The only stations in table 1 that have experienced an increase

in mean precipitation greater than 10% from the pre-urban period to the post-urban period are the Lower Verde Basin stations. The station at Carefree is slightly west of Lower Verde but also exhibits a relatively significant increase (9%) over the same period. One sample t-tests were conducted for each mean value in the Lower Verde region to see if the differences relative to the other stations are statistically significant or occurred by chance. In all tests, the two-tailed P value was less than 0.0001 so by conventional hypothesis testing criteria, the difference is considered extremely statistically significant. Though DB03 did not investigate the pre-urban period, their results also identified the Lower Verde region as the region of elevated median precipitation totals over the period of 1950 to 2000. Stations in other regions have experienced essentially no change or slight decreases in mean precipitation totals. Figure 5 is a time series of monsoon period (July-September) mean precipitation totals for Sunflower (Lower Verde), Phoenix (Urban), and Clifton (Monsoon). The figure suggests that precipitation totals in the Lower Verde station (Sunflower) have trended upward over the 108-year period as compared to Phoenix and Clifton.

## **5. Analysis of the Relative Magnitude of Precipitation at the Lower Verde Stations**

Another finding of this study is that other stations in the region with comparable topographic relief and similar (and in some cases more severe) monsoonal conditions have not experienced significant increases in the post-urban period. An analysis similar to DB03 was conducted in which all sites from Table 1 that exhibited a percentage increase greater than ten in mean total precipitation were compared with stations in nearby basins and the monsoon zone. For consistency with DB03, we analyze the relative differences of the median precipitation totals (Table 2) for years 1950-2003 (post urban).

Results in table 2 are consistent with DB03. It is clear that Sunflower in the Lower Verde is the region's wettest station. In part, this is likely due to Sunflower's higher elevation although the two monsoon zone stations have comparable elevations. Sunflower may also be experiencing a combined urban and topographical effect in the post-urban period. Lower Verde's Horseshoe Dam and Bartlett Dam sites have median precipitation totals greater than sites like Cave Creek and Carefree in the northwest Lower Salt basin even though the elevations are similar (and even smaller in the case of the Carefree station). Not surprisingly, the stations in the Monsoon Zone are generally wetter than the other sites, except Sunflower, which indicates the influence of synoptic scale monsoon forcing, but it is useful to recall from the Table 1 discussion that the Monsoon Zone precipitation totals have remained fairly consistent from the pre-urban to post-urban period.

## **6. Hypothesis for the Lower Verde Precipitation Anomaly**

The results of this study were so compelling that we posed the question, "Does the Lower Verde Precipitation Anomaly reveal itself under drought conditions? To answer the question, we used the TRMM rainfall product (TRP) to construct a mean rainfall rate map for the monsoon period of July-September 2003 for the central Arizona region. In figure 6, the TRP estimate of mean rainfall rate reveals an elevated region of rates 30-50 km northeast of the Phoenix metropolitan area (approximated by the black rectangle) and the influence of mountainous terrain on precipitation as the bluish colors (indicating precipitation) essentially correlate to the mountains (see figure 4). Heavier rainfall rates on the Mexican border likely reflect both topography and stronger monsoonal precipitation. These results seem to suggest that the processes leading to the anomaly can exist under the most extreme drought conditions.

Shepherd and Burian (2003) presented evidence that convective anomalies over and downwind of Houston, Texas were related to the complex interactions between urban-induced and sea-breeze related dynamics while the role of aerosols remain uncertain. Watson et al. (1994) and DB03 have suggested that convective activity in Phoenix is enhanced by urban-related processes and the topographic relief. During the late morning to early afternoon, thunderstorms are typically confined to the highest terrain (Wallace et al. 1999). Over the central and eastern mountains there is a pronounced mid-afternoon maximum of

thunderstorm activity directly attributable to diurnal heating and mountain–valley circulations. Watson et al. (1994b) have identified an early-evening (i.e. 5 to 7 pm LST) maximum in deep monsoonal convection in the Phoenix region.

Phoenix typically exhibits a relatively weak urban heat island (UHI) and sometimes an urban heat sink because large amounts of energy are converted into latent heat rather than sensible heat because of the prevalence of irrigated lands (DB03). Thielen et al. (2000) showed in numerical simulations that when UHIs are weak, surface sensible heat fluxes, convergence, and buoyancy variations that influence rainfall development are most effective at a distance from the central heat source. Baik et al. (2001) also showed that when a heat island is present, two regime flows are established. One exhibits a stationary gravity wave near the heating region and the other is characterized by stationary gravity waves near the heating source and an updraft cell downstream from the heating source. In the case of Phoenix, these results suggest that urban-induced convective forcing can be established on the edge of the metropolitan area. Figure 7 is a schematic presenting our hypothesized reasons why the Lower Verde anomaly exists. First, convection from the mountains is established during the daytime through direct heating and mountain-valley thermal circulations. By afternoon, the storms propagate downward and to the west and south releasing evaporation-generated density currents or outflow boundaries as hypothesized by Watson et al. (1994b). Figure 8 uses the TRMM product in a Hovmoller diagram to illustrate the tendency for westward propagation of storms. The diagram plots the longitude-time variation of the mean rainfall rate averaged over the 33°–34° latitude box, including Phoenix and immediate basin sites. The figure illustrates the tendency for convection to form in the mountains and then propagate westward as indicated in this case from August 10–11 2003. Because of the location of the Lower Verde region, the outflow boundaries from storms in this region can most effectively interact with the convergence and flux forcing on the edge of the city. Additionally, figure 3 pointed out that the lower-middle tropospheric flow on active monsoon days is southeasterly. The resulting urban-mountain convergent region is continually pumped with monsoon moisture from the southeasterly flow. Numerical simulations using a coupled atmosphere-land surface model will be conducted in future studies to test this hypothesis.

## 8. Discussion and Conclusions

This study has employed a unique 108-year precipitation data record to identify statistically significant anomalies in rainfall downwind of the Phoenix, Arizona urban region. Our analysis showed that during the monsoon rainfall season (July, August, September) locations in the northeastern suburbs and exurbs of the Phoenix metropolitan urban area (the so-called “anomaly region”), primarily the Lower Verde Basin, have experienced statistically significant increases in mean precipitation of 12 to 14 percent from a pre-urban (1895–1949) to post-urban (1950–2003) period. Additionally, mean and median post-urban precipitation totals in the anomaly region were significantly greater, in the statistical sense, than regions west of the city and in nearby mountainous regions of similar or greater topography. Further analysis of satellite-based rainfall totals for the summer of 2003 also revealed the existence of the anomaly region even though the arid southwest experienced severe drought during the period. More significant orographic features do not correspond to the location of the anomaly region, and statistically significant precipitation changes are found in the anomaly region when pre- and post-urban data are analyzed.

Future work will utilize coupled atmosphere and land surface models to test the hypothesis that urban-topographic dynamics establish a preferred convective region. The role of aerosols must also be investigated. The implications of this research are wide. The results continue to suggest that weather and climate models must adequately resolve the urban environment (e.g. land use, aerosols). The results also indicate that even a fairly significant large synoptic-scale process (e.g. monsoon) might possibly interact with local and regional mesoscale circulations. Finally, our results highlight how sensitive the water cycle can be to anthropogenic forcings, even under extreme drought or arid conditions.

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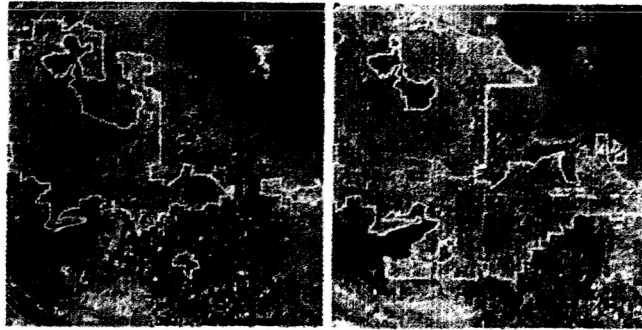
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**Table 1-Comparison of pre-urban (1895-1949) and post-urban (1950-2003) mean precipitation totals in the Phoenix and surrounding basin areas.**

Location	Latitude	Longitude	Region and Elevation (m)	Pre-Urban (1895-1949) Mean Precipitation (mm)	Post-Urban (1950-2003) Mean Precipitation (mm)	Percent 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%

**Table 2-Relative Differences (mm) between Median Summer Precipitation Totals at Lower Verde Stations and other study station. and (Years 1950-2003).**

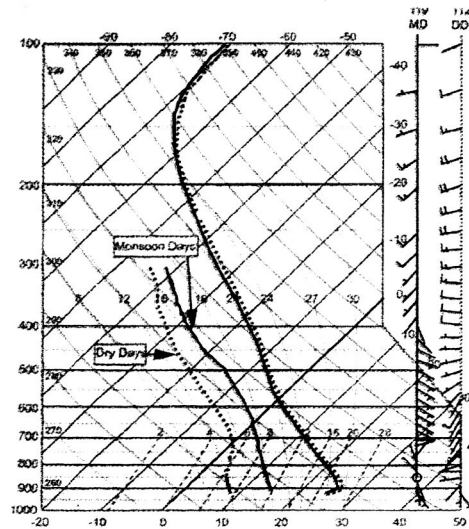
Location	Bartlett Dam (500 m)	Horseshoe Dam (615 m)	Sunflower (1,160 m)	Region
Phoenix (downtown) (610m)	+7.05	+12.97	+40.03	urban
Phoenix (SW) (304 m)	+8.41	+14.33	+41.39	urban
El Mirage (~610 m)	+11.64	+17.56	+44.62	urban
Buckeye (304 m)	+10.68	+16.60	+43.66	urban
Duncan (1,160 m)	-11.43	-5.51	+21.55	monsoon zone
Clifton (1,150 m)	-19.91	-12.12	+14.94	monsoon zone
Kelvin (550 m)	-7.06	-1.14	+25.92	middle gila
Florence (460 m)	+3.45	+9.37	+36.43	middle gila
Stewart Mtn (430 m)	-2.73	+3.19	+30.25	lower salt
Roosevelt Dam (650 m)	-9.9	-3.98	+23.08	lower salt
Cave Creek (490 m)	+7.83	+14.25	+41.31	nw lower salt
Carefree (760 m)	+1.8	+7.79	+34.85	nw lower salt



**Figure 1-**LANDSAT images illustrating the growth of the Phoenix metropolitan area from 1973 to 1989. The yellow outline encompasses the urban region. Red colors are crops or vegetation.



**Figure 2-** Map of approximately ~12,600 stations comprising the Spatial Climate Analysis Service 108-year precipitation time series. (<http://www.ocs.oregonstate.edu/prism/>)



**Figure 3-**Mean monsoon (MD) and dry (DD) soundings for south-central Arizona (following Wallace et al. 1999)

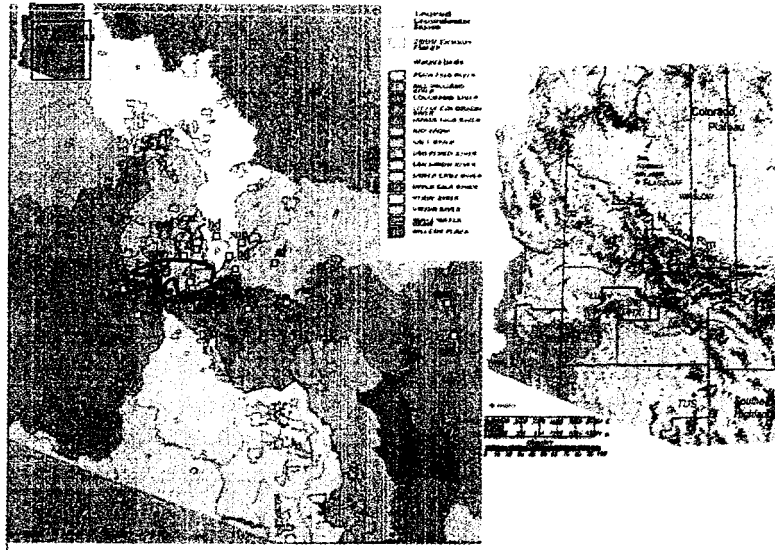


Figure 4-Location of stations examined relative to central Arizona basins. Dark line represents the approximate location of the Phoenix urban area. The map on the right is a corresponding relief map of Arizona.

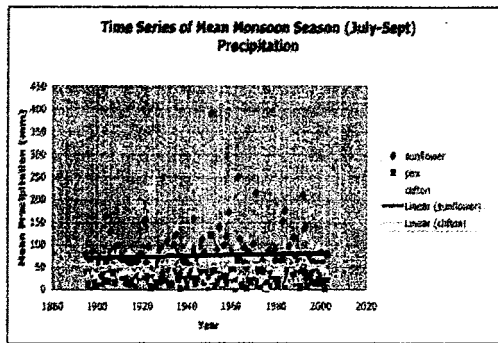


Figure 5-Time series of mean precipitation totals (July-September) for Sunflower, Phoenix, and Clifton sites.

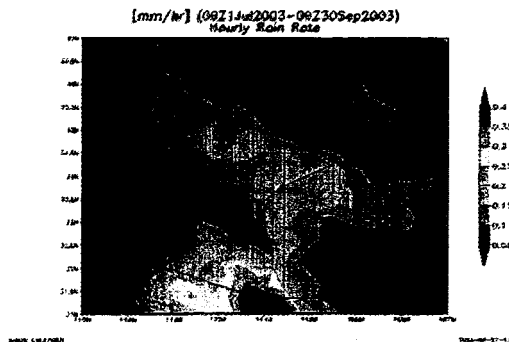
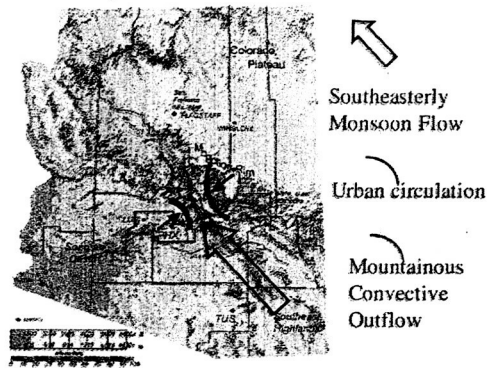
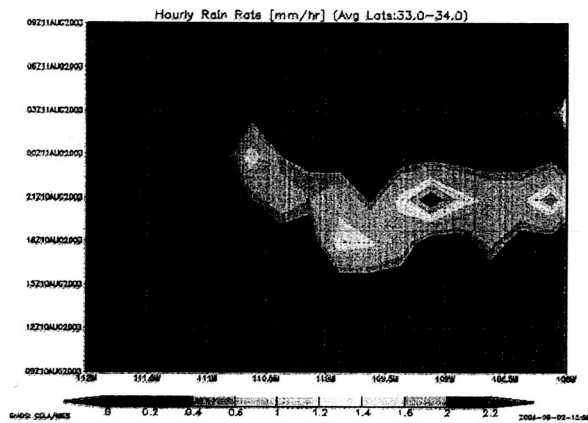


Figure 6-Mean rainfall rates for the 2003 monsoon period (July-September) derived from the real-time TRMM 3B42 rainfall product. Black rectangle is the approximate location of the Phoenix urban area.



**Figure 7-**Schematic of the hypothesized urban-topographic interactions in the Phoenix region during a typical monsoon season.



**Figure 8-**TRMM 3B42RT Hovmoller diagram illustrating the tendency for Phoenix area monsoon convection to develop in the mountains east of Phoenix then propagate down in the Phoenix-urban valley area with a westward component. The plot represents mean rainfall rate for a convective period of 09 UTC 10 August to 09 UTC 11 August.