

# THE URBAN DESERT: A TEMPORAL STUDY OF HUMIDITY VALUES IN THE PHOENIX METROPOLITAN AREA

P. GRADY DIXON, Department of Geography, Arizona State University, PO Box 870401, Tempe, AZ 85287-0401

## ABSTRACT

Hourly surface observations from 16 weather stations in and around the Phoenix, Arizona, metropolitan area were analyzed and compared to each other to determine whether the rapid urbanization in the area has altered local humidity levels during the period 1991-2003. A single station's dew point values were also tested for trend during the period 1948-2003, as were upper-air sounding data since 1990. Each station was classified as being rural or urban at various times throughout the study, and then trends were sought in the dew point values to determine if any of the stations were experiencing systematic increases or decreases in humidity. No trends were found for any of the stations or the soundings, nor were there any trends found in the overall difference between rural and urban humidity values. Significant differences existed between the average rural and average urban dew points at every hour of the day, so urbanization can affect humidity to some degree. However, the rural-urban differences are relatively small and do not appear to increase over time.

## INTRODUCTION

Phoenix, Arizona, as well as most of Maricopa County, has experienced incredible growth since the middle of last century. According to the U.S. Census Bureau (2004), the population of Maricopa County has increased nearly 900% since 1950. To put this in perspective, the Atlanta, Georgia, metropolitan area, which has been considered a rapidly growing city over the past few decades, experienced a population growth of only 313% between 1950 and 2000. In addition, Maricopa County is showing no signs of slowing as it had the single largest population increase (by pure numbers) in the United States between 1990 and 2000. Likewise, the city of Phoenix was ranked as the fastest-growing city in the United States among those with at least one million residents between 1990 and 1998.

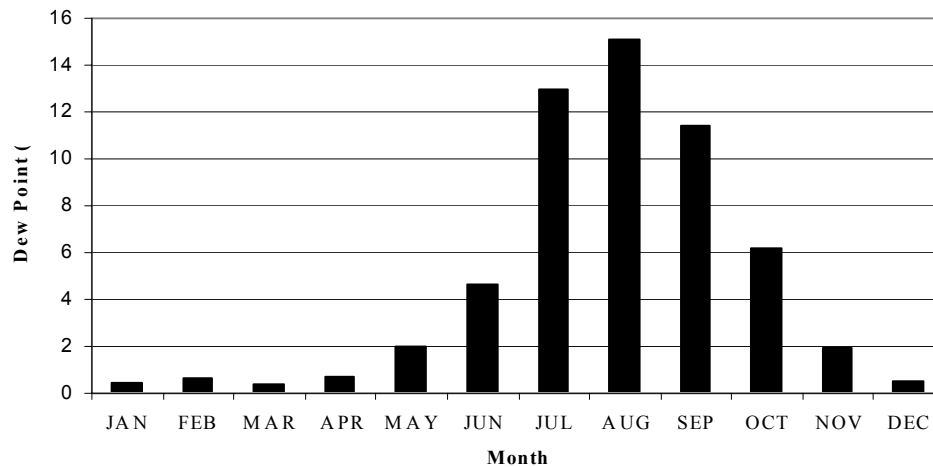
## Urban Heat Island

It is well documented that widespread urbanization alters the local climate of cities, most commonly in the form of an urban heat island (Howard 1833, Duckworth and Sandberg 1954, Bornstein 1968, Oke 1973, Ackerman 1985, Figuerola and Mazzeo 1998). Part of the reason for increased temperatures in cities is the lack of moisture due to urban drainage systems and building materials (Myrup 1969). This lack of moisture should result in lower humidity values within cities, however, the increased temperatures of urban areas allow for higher possible humidity levels if moisture is advected into the city. While humidity levels may seem secondary to actual temperatures, atmospheric moisture is very important to urban residents. According to the Intergovernmental Panel on Cli-

mate Change (1996), water vapor is the greatest contributor to the "greenhouse effect," so humidity levels actually help determine temperatures. Higher near-surface moisture levels may also play a role in limiting harmful atmospheric pollutants such as ozone (Ellis et al. 2000). Further, increased humidity near the surface has been directly linked to increased human discomfort and mortality (Greene and Kalkstein 1996).

## Monsoon

The arid climate of Arizona usually ensures that humidity levels are quite low throughout most of the year. However, the annual monsoon season, typically extending from July through mid-September, brings high levels of moisture into Phoenix and the surrounding deserts (Adams and Comrie 1997). The North American monsoon (also known as the Mexican monsoon and Arizona monsoon) is marked by a dramatic increase in rainfall following the extremely dry months of May and June in the southwestern United States and northwestern Mexico. The primary cause of this change in weather is the annual expansion of the Bermuda High to the west and northwest near the end of June. This change in circulation replaces the dry southwesterly flow over Arizona with a more humid southerly or southeasterly flow from the Gulf of California and eastern Pacific Ocean (Bryson and Lowry 1955). The annual arrival of the monsoon is identified by the associated increase in regional dew point temperatures (Fig. 1), and the official guideline used by the National Weather Service Forecast Office in Phoenix is "three consecutive days when the dew point averages 55°F (12.8°C) or higher." In Phoenix,



*Figure 1. Average monthly dew point temperatures (°C) for KPHX, 1948-2003.*

the average onset of the monsoon is July 7 and the average ending date is September 13. However, most climatological monsoon research focuses primarily on the months of July and August (Bryson and Lowry 1955, Hales 1977, Carleton 1985, Balling and Brazel 1987a, Maddox et al. 1995, Mullen et al. 1998, Fuller and Stensrud 2000). While it has not been clearly documented, it has often been assumed that increased low-level moisture during the monsoon months leads to increased thunderstorms and precipitation in central Arizona (Hales 1972, Brenner 1974, Adang and Gall 1989, Dunn and Horel 1994, Maddox et al. 1995, McCollum et al. 1995, Stensrud et al. 1997).

### Urban Humidity

Due to the extreme temperatures and weather stress levels during the monsoon, any altering of urban moisture levels could prove quite significant. Increased atmospheric moisture acts to increase the apparent temperature, which is a more representative explanation of how hot it “feels” to humans (Greene and Kalkstein 1996). However, Brazel et al. (2000) found that the prevalence of irrigated croplands along the urban fringe of the Phoenix metropolitan area acts to prohibit the development of a daytime urban heat island due to the conversion of more energy into latent heat rather than sensible heat. Conversely, the much drier desert lands surrounding the city convert nearly all of the impacting energy into sensible heat.

Local power companies also pay close attention to surface dew points because humidity is such an important variable in anticipating power demand (Dempsey et al. 1998). According to C. L. Dempsey (2004, pers. comm.), a representative of Salt River Project (SRP) in Phoenix, changes in humidity can

have a significant impact on power demand within SRP's service area; SRP endeavors to anticipate such changes to ensure that resources are well matched with demand so that the system operates as efficiently as possible. Higher moisture levels keep maximum temperatures lower, but air conditioning units typically become less efficient in high humidity environments because they must condense moisture from the air, and the process of condensation releases heat. However, if moisture levels are high enough, then the possibility of thunderstorm formation increases. Since real-time power transactions often require at least a 60-min notice of cancellation, the rapid cooling associated with rain and thunderstorm outflow can lead to unnecessary purchases of energy and the wasting of resources (Dempsey et al. 1998).

Therefore, with humidity being such a crucial element in the every day lives of Phoenix residents, this study asks the important question: Has urbanization in and around Phoenix altered the local humidity levels during the monsoon season?

There have been studies of moisture levels in Phoenix that analyzed trends over time as well as urban-rural differences. Sellers (1960) found anomalously high humidity levels in Phoenix that he credited to the surrounding irrigated agricultural areas as well as the city's location on the windward side of the Mogollon Plateau. Similarly, Hsu (1979) suggested that moisture content was decreasing in Phoenix after 1948 because urbanization was replacing the irrigated crops. In an attempt to determine if swimming pools, canals, lakes, golf courses, and irrigated lawns were creating an “oasis effect,” Brazel and Balling (1986) found that dew points at a single urban station in Phoenix were generally unchanged from 1896 through 1984. Relative

humidity values were shown to have dropped sharply, but that was credited to increased temperatures while dew points remained mostly unchanged. However, the study by Brazel and Balling (1986) analyzed only the months of May, June, October, and November in order to avoid the relatively active weather patterns of the summer monsoon and the winter cyclonic storms. A similar study of humidity levels in Tucson during the period 1949-1985 also shows no significant changes in moisture (Balling and Brazel 1987b). These studies suggest that Arizona does not conform to the overall national trend of increasing moisture that has been documented by other studies (Gaffen and Ross 1999, Ross and Elliot 2001). Gaffen and Ross (1999) show that surface moisture has increased significantly during the period 1961-1990, especially at night. Analysis of 850-millibars (mb) moisture showed much smaller increases in moisture during the period 1958-1995 (Ross and Elliot 2001).

Saffell and Ellis (2002) compared urban and rural humidity levels in and around Phoenix from 1990 through 1999. Results from that study show that rural locations remained inherently moister than urban areas, but urban moisture levels closely approximated, and sometimes surpassed rural moisture levels. More specifically, both urban and rural humidities increased from sunrise through midday, followed by a decrease in the late afternoon. The magnitude of these changes varied according to season and land cover. During the summer, Saffell and

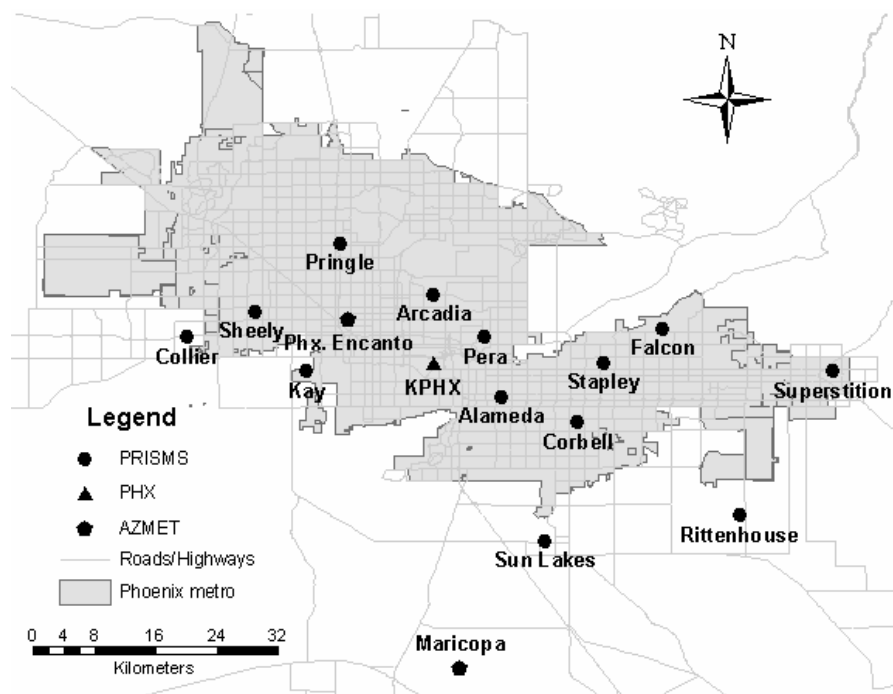
Ellis (2002) showed that urban and rural moisture values were quite similar during early morning hours, followed by a tremendous gradient between the two by midday.

## Hypothesis

Based on previous research findings, moisture values in and around Phoenix for the period of study in this paper ought not to display significant temporal trends. Further, urban and rural humidities should differ from each other only slightly, with rural values being higher. Therefore, as locations gradually change from rural to urban, their moisture levels should drop, but that will be a relatively quick transition from rural levels to urban levels.

## DATA

This project relied primarily on surface humidity measures in and around the city of Phoenix. While there were more weather stations within Maricopa County, there were only 16 stations that provide data useful to this research (Fig. 2). The stations include Phoenix Sky Harbor International Airport (KPHX), 13 from the Phoenix Realtime Instrumentation for Surface Meteorological Studies (PRISMS) network, and 2 from the Arizona Meteorological (AZMET) network. Actual dew point measurements from KPHX and the PRISMS network were used in this study. Since the AZMET stations record relative humidity as the only moisture



**Figure 2.** Weather stations in and around the Phoenix metropolitan area used in this study.

variable, the air temperature and relative humidity values were used to calculate dew point values for each observation time.

Upper-air sounding data were also used in this study in order to determine if moisture content in the lower atmosphere above Phoenix has changed over time. The sounding data were obtained from SRP in Phoenix for the years 1990, 1993-1997, and 1999-2003. Regular soundings are not performed in Phoenix, so the only available data were from the periods when there was major atmospheric research ongoing (SouthWest Area Monsoon Program [SWAMP]) or when SRP funded them for their own research. These soundings use the Vaisala RS80 radiosonde to record atmospheric variables. The relative humidity sensor in this radiosonde is a Humicap® thin film capacitor with an accuracy of  $\pm < 3\%$ . These observations were made only during the monsoon season in Phoenix, and are not always continuous. Observations were most commonly taken at 0000 UTC and 1200 UTC. For this study, the 850-mb level, which is approximately 1 km above ground level in Phoenix during the monsoon months, is analyzed for 0000 UTC and 1200 UTC, separately.

Unfortunately, there is a lack of archived moisture data prior to the 1990s for most stations in Arizona. KPHX is the only station in Maricopa County that has an extended record of moisture values before 1987. Therefore, despite their relatively short periods of record, if it were not for the PRISMS and AZMET networks, this project would have an even shorter period of record along with many fewer stations. The lack of available moisture data, “contrary to popular opinion,” was confirmed by the Assistant State Climatologist of Arizona (N. Selover 2004, pers. comm.).

KPHX is the official National Weather Service (NWS) station for Phoenix, and it also has the longest continuous record of data in Maricopa County. Hourly data from KPHX are easily accessible for the period 1948-present, and it was actually the only station in Arizona with reliable moisture data archived continuously before 1984. KPHX is an automated surface observing system (ASOS) station, so the hourly data were actual observations on the hour rather than averages of the previous hour. Federal standards for data-recording equipment and methods are detailed in the Federal Meteorological Handbook No. 1, and the Federal Standard for Siting Meteorological Sensors at Airports details requirements for the locations of all official weather stations (Office of the Federal Coordinator for Meteorological Services and Supporting Research 1994, 1995). The archived KPHX data were obtained from the Office of the State Climatologist for Arizona.

The exact location of the KPHX weather station has been relocated 11 times since 1948. It was moved twice during the period 1991-2003. In March 1994, the station was moved approximately 3 km to the northeast of its previous location. The 1994 relocation was when the ASOS station was first implemented at KPHX. The NWS, along with the Federal Aviation Administration, converted all of their hourly reporting stations to ASOS during 1994 in an effort to automate the data collection process. Research comparing ASOS observations to conventional observations suggest that the difference in sensors may account for a very small, systematic error on the order of a few tenths of a degree, although federal standards for dew point sensors require accuracy of only  $\pm 2.2^\circ\text{C}$ . However, it seems that the relocation of weather stations can be a more significant source of inconsistent data if the two sites are not nearly identical (Guttman and Baker 1996).

The PRISMS network is composed of 17 stations across the Phoenix area, and they are maintained and operated primarily by SRP. The first PRISMS stations began operating in 1990, but several others were added over the following couple years. All PRISMS stations record numerous meteorological variables at the standard height of 1.5 m every 5 minutes. For the purposes of this study, the 5-min data were averaged over each hour so that the 1200 MST value is actually an average of the 12 observations from 1100 to 1155 MST. Humidity was measured using a Rotronic MP-100F combined humidity/temperature probe with an accuracy of  $\pm 0.5^\circ\text{C}$ . The archived PRISMS data were obtained from the Office of the State Climatologist for Arizona.

The AZMET network includes 27 stations that are currently active across central and southern Arizona along with another 6 stations that are no longer in operation. The stations are operated and maintained primarily by the University of Arizona in order to provide climate and meteorological data for agricultural purposes. The first AZMET stations began operating in 1987, but several stations have been added and removed since that time. Data were averaged and recorded each hour at the standard 1.5-m height, so the 1200 MST value is actually an average of the 12 observations from 1100 to 1155 MST. The measuring devices are Vaisala capacitive relative humidity sensors with a sensitivity of  $\pm 2\%$ . The archived AZMET data were obtained from the AZMET website (<http://ag.arizona.edu/azmet>).

Each weather station used in this project was classified as either “urban” or “rural.” Sites were considered urban if they are located within areas of commercial or industrial development, residential

development, or areas dominated by concrete and asphalt land cover. Land cover classifications were determined for each station for the years of 1990, 1993, and 1998 using Landsat Thematic Mapper (TM) images. The images are separated into 12 major classes that were designated as urban or rural. Land cover classifications were determined for each station in 2004 through visual inspection of the actual sites. Land cover classifications for each station during each time period is shown in Table 1.

## METHODS

### Data Preparation

All of the data used in this study were checked for quality before any analyses were conducted. Each data set was formatted to correspond with the others. AZMET stations recorded relative humidity values instead of dew point, so these moisture measures were converted to dew points with the help of the associated air temperature values. The SRP soundings also measure relative humidity, but those values are converted to dew points before being published. All temperature and dew point values were converted to Celsius degrees (°C), if necessary. Each file was checked for completeness, and that is why there are some PRISMS and AZMET stations in Maricopa County that are not being used in this study. Missing observations and data flags were all accounted for and removed, if necessary.

Due to the relatively short period of record for most of the stations used in this study, four methods are applied to determine whether urbanization has altered local humidity levels in and around Phoenix:

- trend analyses on humidity data from all stations for the period 1991-2003
- trend analysis solely on the 56 years (1948-2003) of surface data from KPHX
- trend analysis on low-level atmospheric moisture since 1993
- spatial analyses on urban-rural humidities during the shorter period of 1991-2003

While data from a single station (KPHX) may not be completely representative of the entire metropolitan area, it should certainly display any major changes in local moisture during the extended period of 1948-2003. Also, since all urban stations used to be rural, it can be implied that the rural

**Table 1.** Designation of urban or rural for each of the weather stations used in this study during the years 1990, 1993, 1998, and 2004.

Station	1990	1993	1998	2004
Alameda	urban	urban	urban	urban
Arcadia	urban	urban	urban	urban
Collier	rural	rural	rural	urban
Corbell	rural\$	rural\$	urban	urban
Falcon	rural	rural	rural	urban
Kay	rural	rural	rural	urban
Maricopa	rural	rural	rural	rural
Pera	urban#	urban#	urban#	urban#
KPHX	urban	urban	urban	urban
Phoenix Encanto	urban	urban	urban	urban
Pringle	urban	urban	urban	urban
Rittenhouse	rural	rural	rural	rural
Sheely	urban	urban	urban	urban
Stapley	urban	urban	urban	urban
Sun Lakes	rural*	rural*	rural*	urban
Superstition	rural	rural	rural	urban

\$ Corbell was rural in 1990 and 1993, but it was surrounded by urban/residential development on three sides

# Pera is situated on undisturbed land, but it is completely within the greater urban area.

\* Sun Lakes was near some commercial and residential development, but still outside of the greater urban area during 1990–1998.

stations in the area may approximate the moisture levels of present-day urban stations before they were urbanized. Therefore, a spatial, urban-rural comparison is conducted. However, as pointed out by Brazel et al. (2000), rural locations in central Arizona can vary widely in their land cover type, and therefore their humidity levels may vary also. For example, undeveloped rural deserts should be much drier than rural irrigated croplands.

Before comparing urban and rural moisture data, each station had to be classified as urban or rural (Table 1). Landsat TM images for 1990, 1993, and 1998 were used to determine land cover for those years, but some field observations were required for present classifications. Therefore, each station that was in a rural location in 1998 was observed in person in January 2004. However, this method is rather subjective. For example, the Falcon station sits within a relatively new, expensive neighborhood with many irrigated lawns, bushes, and trees. Falcon is definitely within a mesic residential area, so it is considered urban for this study. Nevertheless, because of the vegetation and shading of trees, Falcon should be less likely to experience increases in temperature usually associated with urban development. Likewise, the Pera station is located on land classified as “undisturbed” on the Landsat

TM imagery. However, Pera is near the middle of the Phoenix metropolitan area and it is surrounded by urban development, so the station is considered urban. These types of inconsistencies in urban and rural land cover were expected as Hawkins et al. (in press) noted that average urban heat island values for Phoenix ranged from 9.4°C to 12.9°C depending on what rural site was used for comparison. All stations that were urban in 1998 were assumed to have remained urban since they are all now well within the boundaries of urban development.

From 1990 to 1998, Corbell was the only station that changed classifications as urban development gradually surrounded the area (Table 1). After 1998, there were five more stations (Collier, Falcon, Kay, Sun Lakes, and Superstition) that changed from rural to urban. Since it is difficult to determine, even with annual land cover data, exactly when a station became surrounded by urban development, it is assumed that the changes took place halfway between the two observation times. For example, all stations that were rural in 1998 and became urban in 2004 are treated as if they were rural through 2000 and urban beginning in 2001.

## Analyses

Due to the limited availability of data, this study encompasses the years 1991-2003 for 16 stations throughout Maricopa County. Phoenix and Maricopa County both experienced incredible population growth during this period. The population of Maricopa County increased from approximately 2.2 million, in 1990, to approximately 3.0 million in 2000, which was the single largest numerical increase for a county in the United States. During this same period, the Phoenix-Mesa metropolitan statistical area increased its population from approximately 2.2 million to over 3.2 million, ranking fifth in actual population increase, eighth in percentage increase, and first in percentage increase for cities with at least 1 million residents (U.S. Census Bureau 2004).

Each station's hourly moisture data were compiled for the months of July and August in order to represent the annual monsoon period. To avoid any seasonal signals, the data were aggregated by year for trend analyses. The standardized coefficients of skewness,  $z_1$ , and kurtosis,  $z_2$ , were both determined for each 13-year dataset. These values were used to test the null hypothesis that the individual temporal samples came from populations without a normal distribution. If the absolute value of  $z_1$  or  $z_2$  is  $>1.96$ , the sample does not conform to a normal curve, and a transformation function must be applied to the series to make it normally distributed (Brazel and Balling 1986).

Using the normally distributed data, the number-of-runs test was applied to each dataset in order to test for randomness and determine if there is a trend in the series. A "run" was defined as an unbroken sequence of like items surrounded by unlike items. In this case, the data were divided into two groups (values greater than the median and values less than the median; values equal to the median are ignored). This test was derived as:

$$A = \left( \frac{2n_1n_2}{n_1+n_2} + 1 \right) - z_\alpha \sqrt{\frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1+n_2)^2(n_1+n_2-1)}} \quad (1)$$

where  $n_1$  is the number of values less than the median,  $M$ ,  $n_2$  is the number of values above the median, and  $z_\alpha$  is the one-tailed probability of the normal distribution at the 95% confidence level, which is equal to 1.645. The series was indicated to be increasing or decreasing if the value of  $A$  is greater than the number of runs in the series,  $R$  (Burt and Barber 1996).

Each station's 13-year dataset was also divided diurnally in order to detect any possible trends in daytime or nighttime humidity values. According to the U.S. Naval Observatory Astronomical Applications Department (<http://aa.usno.navy.mil>), sunrise occurs in Phoenix at 0522 MST on July 1 and at 0602 MST on August 31. Sunset occurs at 1942 MST on July 1 and at 1854 MST on August 31. Therefore, for this project, the hours of 0600-1900 MST were considered daytime hours, while 2000-0500 MST were considered nighttime hours. The same tests for normal distribution, randomness, and trend described above were also applied to both the annual daytime and nighttime data for each station. Further, the same tests were also applied to: 1) all stations for the three daily divisions (total day, daytime only, and nighttime only), 2) the annual aggregated urban and rural station values for the three daily divisions, and 3) the annual aggregated rural minus urban values for the three daily divisions.

Analyses of the extended data record of KPHX included the same methods described above, only for the 56-year period of 1948-2003. Hourly surface dew point values from the monsoon months (July and August) were averaged annually, and tested for normal distribution, randomness, and trend. The data were also divided into daytime observations and nighttime observations in order to test for trends during either of those periods. If increasing population has affected local humidity levels, the signal should be easily seen during this period. The 1950 population of Maricopa County was 331,770. The 2002 population estimate (the most recent year

available) for Maricopa County is over 3.3 million (U.S. Census Bureau 2004).

The SRP sounding data were also tested for normal distribution, randomness, and trend using the methods described above. These data were separated by 0000 UTC and 1200 UTC observations, and then averaged by year.

To compare urban and rural humidity values, the paired-observations difference-of-means t test was applied to the annual mean value of all rural stations and all urban stations. Since some stations switched classifications from rural to urban during the study period, data from the rural years are used for rural station analyses, while data from the urban years are used for urban station analyses. This statistic is derived as:

$$T = \frac{\bar{D} - D_0}{\frac{S_d}{\sqrt{n}}} \quad (2)$$

Where  $\bar{D}$  is the average difference between the two samples,  $S_d$  is some threshold difference (in this case equal to zero),  $S_d$  is the standard deviation of the differences, and  $n$  is the number of cases.  $T$  is used to determine the probability value of the dataset, and if the probability value is less than  $\alpha$  (usually 0.05), then the null hypothesis is rejected. The paired-observations method is used because the two sets of means (urban and rural) are not completely independent of each other. Both urban and rural stations were recording the same variables at the same times under the same general atmospheric conditions. A standard difference of means test would require the assumption that the two samples are completely independent of one another. However, this method actually improves the chances of detecting population differences (Burt and Barber 1996). The difference in the means of urban and rural values each year is normally distributed, so no transformation techniques were required. This test was also applied to the dataset aggregated by hour (i.e., all 0100 MST observations from rural sites were compared to 0100 MST observations from urban sites).

**Table 2.** KPHX dew point time series descriptive statistics (1948-2003)

Diurnal period	M	$z_1$	$z_2$	R
Total day	14.79	0.140	-0.420	27
Daytime	14.51	0.153	-0.364	31
Nighttime	15.02	0.097	-0.459	27

Difference-of-means analyses were not performed on yearly data because there are too many other variables influencing each year's humidity values. The change in humidity values due to El Niño, La Niña, hurricane landfall, or a number of other possible variables would be much greater than the differences due to urbanization.

## RESULTS

All of the individual stations (including the entire KPHX record) and the sounding data display normal distributions with the exceptions of Maricopa and Phoenix Encanto. Squared transformations were applied to both stations in order to achieve normal distributions. The number-of-runs test determined that none of the individual stations display a trend over the study period of 1991-2003, KPHX showed no trend over the period 1948-2003, and the SRP soundings show no trend in moisture since 1993.

Table 2 displays the results of the trend tests for KPHX during the period 1948-2003. Given the numerous runs for each group, none of the series illustrated any significant trends in the humidity data. A trend would have been present only if the number of runs (R) was less than the test statistic, which was 22.65, 22.79, and 22.65 for the total period, daytime period, and nighttime period, respectively.

The results of the SRP sounding moisture trend tests are displayed in Table 3. Both the 0000 UTC and 1200 UTC soundings displayed six runs with test statistics of 3.89. Therefore, no significant trend exists in the 850-mb moisture data during the short study period.

Table 4 displays the results of the surface dew point trend tests for the period 1991-2003. It is seen that no station possesses fewer than six runs. If a trend existed, then a station's number of runs would be less than the test statistic, which is 4.64 for all stations based on their  $z_1$  and  $z_2$  values during the shorter time period.

**Table 3.** 850 mb dew point time series descriptive statistics

Observation time	M	$z_1$	$z_2$	R
0000 UTC	8.66	0.437	-0.457	6
1200 UTC	7.48	-0.375	0.007	6

**Table 4.** Dew point time series descriptive statistics (1991–2003).

Station	<i>M</i>	<i>z</i> <sub>1</sub>	<i>z</i> <sub>2</sub>	R
Alameda	12.06	0.793	-0.561	6
Arcadia	11.46	0.240	-0.471	6
Collier	14.17	-0.823	0.640	7
Corbell	12.04	0.330	-0.316	6
Falcon	13.15	-0.159	-0.159	7
Kay	14.00	-0.566	-0.097	7
Maricopa				
(raw)	15.91	-1.605	2.907	6
(squared)	253.24	-0.770	0.313	6
Pera	12.60	0.518	-0.889	10
KPHX	13.61	0.098	-0.579	11
Phoenix Encanto				
(raw)	14.97	-1.419	2.153	7
(squared)	224.25	-1.025	0.730	7
Pringle	12.13	0.555	-0.813	10
Rittenhouse	14.04	0.736	0.298	9
Sheely	14.67	-1.081	1.270	8
Stapley	12.92	0.648	0.860	10
Sun Lakes	11.88	0.230	-0.484	8
Superstition	12.21	0.380	-0.118	8
Rural	13.44	0.279	-1.172	10
Urban	13.21	0.132	-0.684	10
Rural – Urban	0.23	0.081	-0.997	8
Total	13.33	-0.881	1.037	10

There are also no trends found when testing only daytime (0600-1900 MST) observations from each station or using only nighttime (2000-0500 MST) observations from each station. Table 5 shows the results of the daytime analyses and Table 6 displays the nighttime results. The daytime analyses required squared transformations for Collier, Maricopa, and Phoenix Encanto in order to achieve a normal distribution. Only Maricopa required a squared transformation in the nighttime series.

The last four rows in Tables 4-6 show the results of the statistical analyses performed on the aggregated rural stations, the aggregated urban stations, the rural minus the urban values, and all of the stations for the entire day, daytime only, and nighttime only. Consistently, there are no trends found in the data. Therefore, the chances of the humidity values consistently increasing or decreasing at rural or urban sites over the period 1991-2003 is statistically insignificant.

Tables 4-6 show the mean dew point values for both rural and urban sites throughout the entire period, during daytime hours only, and during nighttime hours only. The rural locations experienced higher moisture values than the urban locations most of the time. Comparison of the annual mean rural and urban dew points does not yield a significant difference for the total period or for the nighttime values. However, the annual daytime values over the entire study period prove significantly different at the 90% confidence level, but the null hypothesis that there is no difference could not be rejected with  $\alpha = 0.05$ . Nevertheless, the accuracy of this assessment may be hindered by the relatively small number of cases (13). Therefore, the same paired-observations difference-of-means t test was applied to the average hourly rural and average hourly urban values. This time each test contained over 4,000 cases, and each of the 24 hours showed significant differences between the rural and urban values well above the standard 95% confidence level. These results differ from those of Saffell and Ellis (2002), which found no statistical differences between monthly rural and urban moisture values during the 1990s. However, Saffell and Ellis (2002) used a one-way analysis of variance (ANOVA) test to compare monthly rural and urban differences. The ANOVA test is less likely to be accurate in this case because it seeks to prove that the two datasets are completely independent of each other, and it is known that the data are related as they are collected at the same times, in

the same manner, under the same general atmospheric conditions. Fig. 3 clearly shows that the average rural dew points are consistently higher than the urban values throughout most of the day, with the exception of predawn hours. The rural locations reach a maximum dew point that is nearly 0.5°C greater than the urban location's maximum. However, the more pronounced difference is between the minimum values as the rural locations remain approximately 1° C above the urban locations.

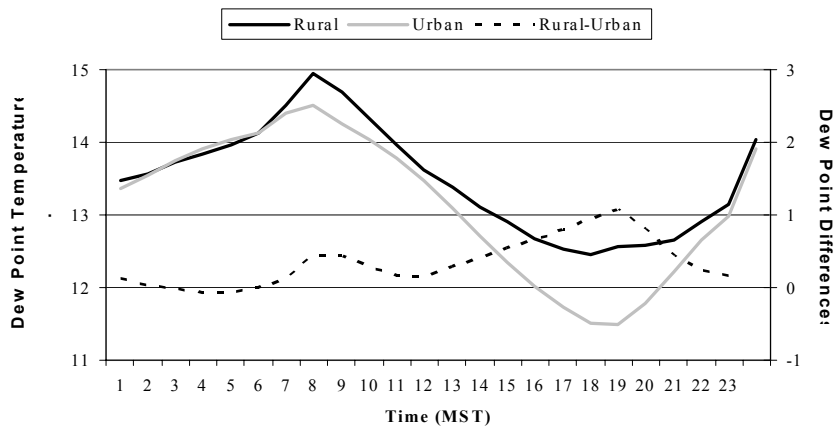
Since the dew point differences mentioned above are actually smaller than the accuracy range of some of the sensors used, the validity of these results should be addressed. First, random measurement errors should decrease with an increasing number of observations (*N*). In this case, *N* is well over 4,000, so the random errors should be minimal. Further, the smoothing of the data (i.e., averaging, aggregating by year, etc.) acts to enhance the

**Table 5. Daytime dew point time series descriptive statistics (1991–2003)**

Station	<i>M</i>	<i>z</i> <sub>1</sub>	<i>z</i> <sub>2</sub>	R
Alameda	11.88	0.790	-0.677	6
Arcadia	12.09	0.005	0.203	6
Collier				
(raw)	15.27	-1.331	2.139	5
(squared)	233.13	-0.992	1.103	5
Corbell	12.12	0.348	-0.366	6
Falcon	13.22	-0.597	1.180	5
Kay	14.29	-0.726	0.261	7
Maricopa				
(raw)	15.84	-1.593	2.619	6
(squared)	250.82	-0.795	0.126	6
Pera	12.67	0.310	-0.572	10
KPHX	13.39	-0.003	-0.420	11
Phoenix Encanto				
(raw)	14.99	-1.590	2.873	7
(squared)	224.96	-1.122	1.147	7
Pringle	12.28	0.653	-0.724	10
Rittenhouse	14.49	0.704	0.741	9
Sheely	14.73	-1.053	1.719	8
Stapley	13.12	0.338	1.107	8
Sun Lakes	11.76	-0.052	0.196	8
Superstition	12.21	0.045	-0.268	6
Rural	13.64	0.216	-0.980	10
Urban	13.38	-0.180	-0.245	10
Rural – Urban	0.26	-0.243	-0.079	8
Total	13.51	-0.972	1.468	10

**Table 6. Nighttime dew point time series descriptive statistics (1991–2003)**

Station	<i>M</i>	<i>z</i> <sub>1</sub>	<i>z</i> <sub>2</sub>	R
Alameda	11.95	0.553	-0.388	6
Arcadia	11.74	0.188	-0.691	8
Collier	13.80	-0.160	-0.744	7
Corbell	12.26	0.229	-0.125	6
Falcon	13.42	0.012	-1.176	7
Kay	13.59	-0.389	-0.573	7
Maricopa				
(raw)	16.15	-1.604	3.280	8
(squared)	260.88	-0.795	0.126	8
Pera	12.52	0.657	-0.985	10
KPHX	13.91	0.218	-0.747	11
Phoenix Encanto	15.22	-1.009	0.436	7
Pringle	11.94	0.329	-0.895	10
Rittenhouse	13.94	0.682	-0.515	10
Sheely	14.39	-0.729	0.251	10
Stapley	12.96	0.783	0.389	10
Sun Lakes	12.46	-0.052	0.196	6
Superstition	11.65	0.045	-0.268	8
Rural	13.16	0.305	-1.373	10
Urban	12.98	0.438	-0.914	10
Rural – Urban	0.10	0.869	0.371	6
Total	13.08	-0.756	0.451	10



**Figure 3.** Average 24-hour variation in dew point for rural and urban locations and the difference between the two.

accuracy of the values beyond the sensor's capabilities (Christy and Spencer 2003) since a sample's mean is an unbiased estimator (Burt and Barber 1996).

## CONCLUSIONS

The city of Phoenix and its surrounding urban area has experienced incredible growth in population and physical area, and there have yet to be any signs of slowing. This increased urbanization has created a well-documented urban heat island that keeps the urban area warmer than the surrounding rural areas at night. Urban areas are designed to remove water from the city as rapidly as possible to avoid street flooding, so a decrease in moisture is also a likely side effect of urbanization. Past research has confirmed many cities experience overall lower humidity levels compared to nearby rural locations while regional moisture values are increasing slightly. Further, the largest rural-urban differences occur during the daytime when solar radiation and evaporation are greatest. At night, many cities may achieve higher moisture levels than rural locations due to the warmer urban temperatures and rural dewfall.

The findings of this study are consistent with past research, but more recent and varied data, along with multiple methods, strengthen previous claims. Therefore, it appears clear that urbanization has not created temporal trends in humidity, and any spatial humidity variations are quite small. Rural and urban humidity values were found to be significantly different at all hours with the greatest differences occurring from mid-afternoon through a couple hours after sunset. The smallest rural-urban differences occurred from around midnight through sunrise with the urban area possessing higher moisture levels during a couple of the predawn hours. Both rural and urban stations reached their maximum humidity values a couple hours after sunrise and both reached their minimum humidity values around sunset. It should take a couple hours for the morning sun to warm the surface enough for evaporation to begin taking place while evaporation stops rather suddenly once the incoming solar radiation ceases.

There were no significant temporal trends found in this study, which is consistent with past research. It was thought that because rural and urban humidity levels are different, that the gradual urbanization of rural locations might create trends of decreasing dew points over time at some stations. However, this is not the case. As hypothesized prior to this investigation, the urbanization of a particular station will likely result in a relatively quick (depending on the rate of urbanization) shift from rural values to

urban values. This process is probably due somewhat to the microclimate surrounding many urban weather stations, especially in a city with relatively little vegetation. Therefore, as the urban fringe moves farther away from the center of Phoenix, it is unlikely that the humidity levels in the city will continue to decrease. Rather, the humidity levels of the urban fringe will decrease from representative rural values to representative urban values and then likely remain rather constant given no other major changes in land cover. So, based on the results of this study, it is unlikely that Phoenix will be any more or less humid 10 or 20 years from now. On the other hand, if urbanization continues at its present rate, it is probable that many locations in or near Queen Creek and Buckeye will experience the shift from rural to urban humidity levels within the next decade or so.

Future work on this topic will require many more years of data than are presently available, and it would be ideal to have a network of weather stations distributed across the Phoenix urban area for the purpose of measuring humidity. The network of stations used in this study provides very little coverage of the northern and western sections of the urban area. Therefore, any future studies of Phoenix humidity over an extended period of record will require the deployment of new stations along with their maintenance and data archiving for many years. If this is to happen, then each station should ideally be situated with the humidity study in mind, and all of the stations' equipment, ground cover, and enclosures should be identical.

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