Long-Term Associations between Wind Speeds and the Urban Heat Island of Phoenix, Arizona

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ABSTRACT

The association between a developing urban heat island and local monthly averaged wind speeds is examined in this investigation. Results from a series of statistical analyses show a significant increase in wind speeds in Phoenix, Arizona during the period of rapid heat island development. The increase in winds is found to be much stronger at 0500 MST than at 1400 MST. Increased instability and the development of a strong heat low circulation in the urban environment are suggested as probable causes for the increased wind speeds.

1. Introduction

A number of investigators have revealed the existence of a strong urban heat island developing in the rapidly growing Phoenix, Arizona metropolitan area (Cayan and Douglas, 1984; Balling and Brazel, 1986a and b, 1987; Brazel and Balling, 1986). This emerging thermal gradient between the urban center and the surrounding desert may lead to substantial changes in the airflow of the local environment (Chandler, 1965). However, temporal associations between thermal changes in urban areas and the wind speed levels have received remarkably little attention in the literature due, in part, to insufficient long-term representative wind data (Bornstein and Johnson, 1977).

The purpose of this study is to identify trends in Phoenix wind speeds that may be directly linked to the emerging heat island of the area. Phoenix represents an excellent location for examining heat island and wind speed interactions for the following reasons:

1) The predominance of high pressure in Phoenix throughout the year produces relatively light local winds (Balling and Cerveny, 1984). Any signal in wind speeds from the heat island is likely to be recognizable in this low wind speed environment.

2) The tremendous population growth and resultant heat island development have occurred largely within the last few decades. The changes in the metropolitan area have taken place during a recent period of reliable wind speed data.

3) The temperature gradients and spatial extent of the Phoenix heat island (Balling and Brazel, 1986a and b, 1987) are of sufficient magnitude to generate some identifiable effect upon the local airflow patterns.

4) The valley location and predominance of high pressure combine to produce unusually high atmospheric pollution levels in the Phoenix area (Idso, 1974). Studies on local windflow changes are extremely important in the assessment of the pollution problems of the city.

2. Background

Many investigators (e.g., Landsberg, 1956; Frederick, 1964; Chandler, 1965; Munn and Stewart, 1967; Graham, 1968; Vukovich et al., 1976; Bornstein and Johnson, 1977; Lee, 1984; Draxler, 1986) have examined the effects of urbanized landscapes upon local wind speeds. The focus of the majority of these studies was upon the impact of surface roughness and friction of the urban surface on decreasing wind speeds. Chandler (1965) demonstrated that the distribution of surface wind speeds in and around urban centers depends on a number of variables, including upwind rural wind speed, season, and time of day. Under weak regional flow, mean hourly urban wind speeds have been found, often during nighttime periods, that are consistently higher than the rural velocities (Chandler, 1965; Bornstein and Johnson, 1977; Wong and Dirks, 1978; Lee, 1979). The increase in wind speeds at night appears to be directly related to the strength of the local heat island.

Bornstein and Johnson (1977) showed that the urban heat island affects the windflow in two distinct ways. The first involves the formation of a heat low over the city and the consequential development of a convergent surface circulation. Flow near the surface is oriented towards the warmer city from the cooler surrounding landscapes. The local flow is obviously superimposed over any existing regional circulation patterns. Although some evidence exists to the contrary (Shreffler, 1978, 1979a and b), many investigators (Chandler, 1965; Bornstein and Johnson, 1977; Wong and Dirks, 1978; Lee, 1979) have suggested that increased wind speeds in urban areas can occur only when the regional wind speed is below some critical velocity that may vary spatially and temporally. The low wind speeds common in the Phoenix area should produce many occasions when regional winds are light enough to allow strong local effects.

Reduced nighttime stability is the second way for an urban heat island to affect local airflow. When stability of the urban atmosphere is reduced, the vertical flux of momentum downward is increased over the city, resulting in a rise in surface wind speeds.

Both of these processes imply a direct relationship between the urban heat island and the surface wind speeds recorded in the city. An increase through time in the thermal gradients between the city and its surroundings should be associated with an upward trend in the long-term wind speeds. The analyses presented in this study were conducted to test this relationship for the rapidly developing heat island of Phoenix, Arizona.

3. Data

Two basic data sets were used in this investigation of heat island and wind speed interactions. The first set of data included mean monthly maximum and minimum temperatures (degrees centigrade) from the National Weather Service (NWS) Office at the Phoenix Sky Harbor Airport and the cooperative observer station at Wickenburg, Arizona. Wickenburg was selected for analysis because (a) it is located far enough from Phoenix (87 km northwest) to escape the heat island effects (Balling and Brazel, 1987) but sufficiently close to establish a meaningful horizontal temperature gradient away from the Phoenix metropolitan area, and (b) it had been chosen by Bradley (1982) as a station with outstanding data quality. All mean monthly maximum and minimum temperature data from Phoenix and Wickenburg extended from January, 1948 to December, 1985.

The second data set included the mean monthly 0500 and 1400 MST wind speeds (m s^{-1}) recorded at the NWS station at the Phoenix airport. The instruments at the airport have not been moved more than 1500 m over the 1948 to 1985 study period and a constant height of observation has been maintained. The 0500 and 1400 MST periods were selected for analysis to roughly correspond to the timing of the minimum and maximum temperatures.

The potential influence of local topography on surface wind speeds may be of concern in the use of Phoenix data. Draxler (1986, p. 1125) stated, "The effect of local terrain on the airflow near a city is . . . not well defined and might be difficult to separate from the effects of the urban 'heat island'." Shreffler (1978) found faster winds along the river valley in St. Louis but did not find a significant link between the stronger winds and any terrain-induced funneling effects. Wong and Dirks (1978) found no significant contribution of the higher relief south of St. Louis to the general airflow of the area. Results from several modeling studies (Vukovich et al., 1976; Rakovec, 1986) suggest a relatively small effect of surface roughness on the character of the heat island circulation. Because the present study is concerned primarily with the temporal aspects of wind speed and urban heat island growth, the fixed topography of the Phoenix area is not a major influencing factor in the interpretation of the results.

4. Analyses and results

a. Temperature patterns

The magnitude of the Phoenix urban heat island has been described in detail in several other studies (e.g., Cayan and Douglas, 1984; Balling and Brazel, 1986a and b, 1987; Brazel and Balling, 1986). In general, statistically significant increases in temperature have been identified for all months and all times of day. The strongest heat island effects appeared in the early morning hours of the summer months; temperature increases of over 4.5°C from 1948 to 1984 were reported for 0200 MST summertime data (Balling and Brazel, 1986a and b).

Several tests were conducted on the raw Wickenburg temperature data to identify any temperature trends. The Mann–Kendall Rank Statistic (Mann, 1945; Mitchell et al., 1966) was used to identify any linear or nonlinear temporal trends in the data. A simple regression analysis with the year of record and the independent variable was also used in the search for trends. The results indicated that none of the arrays of monthly minimum temperatures contained any significant trend. Additionally, the maximum monthly temperatures at Wickenburg displayed no evidence of an urban heat island effect. Thus, the Mann–Kendall Rank Statistic and the regression analysis verified that Wickenburg's temperature record had not been significantly affected by the nearby heat island of Phoenix.

The differences in both the maximum and minimum temperatures between Phoenix and Wickenburg were calculated for each month and the resultant values were analyzed (Table 1). The means, standard deviations (*s*), correlation coefficients (*r*) between the temperature differences and year of record, and linear regression slopes (b) suggested the following:

1) The temperature differences between the two sites were much larger (often more than five-fold) for the minumum temperature values when compared to the spatial gradients for the maximum temperatures.

2) The temperature gradient between the two sites generally increased at a statistically significant rate.

3) The horizontal gradient in the minimum temperatures increased much more rapidly than the gradient in the maximum temperatures.

4) With essentially no change occurring in the

TABLE 1. Statistics for monthly temperature differences (°C) between Phoenix and Wickenburg (1948–1985).

	Maximum temperature				Minimum temperature			
Month	Mean	s	r*	b	Mean	s	r*	b
Jan.	0.72	1.21	0.15	0.016	5.19	1.78	0.22	0.035
Feb.	1.14	1.02	0.05	0.005	5.13	1.52	0.42	0.057
Mar.	1.44	0.86	0.14	0.011	5.49	2.00	0.33	0.058
Apr.	1.34	0.85	0.31	0.024	6.01	2.09	0.52	0.098
May	1.37	1.10	0.44	0.044	6.60	2.27	0.45	0.092
June	1.07	1.12	0.27	0.027	6.82	2.36	0.51	0.109
July	0.45	1.46	0.35	0.047	5.35	2.36	0.74	0.157
Aug.	0.76	1.17	0.39	0.042	5.66	2.08	0.64	0.120
Sept.	0.98	1.24	0.37	0.041	6.41	1.90	0.56	0.096
Oct.	0.90	1.05	0.32	0.031	6.31	1.74	0.56	0.089
Nov.	0.56	1.08	0.45	0.045	5.71	1.57	0.41	0.059
Dec.	0.59	0.89	0.09	0.007	5.26	1.45	0.44	0.058

* Correlation coefficients above 0.30 are statistically significant at the 0.95 confidence level.

monthly temperatures at Wickenburg, the observed patterns in the horizontal temperature gradients were being forced largely by changes in Phoenix.

b. *Wind speed patterns*

The standardized coefficients of skewness (z_1) and kurtosis (z_2) for the wind speed data from Phoenix revealed no departures from normality in any month for either of the two time periods (Table 2). The means and standard deviations showed that, in general, low wind speeds are recorded throughout the year in Phoenix. These low wind speeds reflect the relatively minor influence of regional wind patterns and suggest that circulations associated with the heat island could have a pronounced effect upon the resultant windflows of the city. The means and standard deviations also show that winds normally increase by approximately 1 m s^{-1} between 0500 and 1400 MST. Strongest winds occurred in the spring and early summer months while December and January experienced the weakest winds. Many of the climatological aspects of these wind patterns were discussed in detail and placed into a regional context in a study by Balling and Cerveny (1984).

With the exception of the 1400 MST wind speeds in June, all wind data for Phoenix displayed a statistically significant increase over the 1948 to 1985 study period (Table 3). The general strength of these wind speed increases were determined by (a) r between the wind speeds and the year of record, (b) b of regression analyses between year and wind speed and (c) the percent linear increase in wind speeds from 1948 to 1985 calculated as $100\ (|v|_{85} - |v|_{48})/|v|_{48}$ where the $|v|$ wind speed terms are estimated from the linear regression equations.

These three statistics suggested three fundamental patterns in the change in Phoenix wind speeds:

1) Both the 0500 and the 1400 MST wind speeds have increased dramatically over the duration of the study period (Table 3). The wind speeds recorded in

TABLE 2. Descriptive statistics for monthly wind speeds (m s^{-1}) in Phoenix (1948–1985).

	1400 MST wind speed				0500 MST wind speed			
Month	z_1*	z_2*	Mean	s	z_1*	z_2*	Mean	s
Jan.	−0.29	−0.14	2.74	0.52	−0.32	−0.81	2.26	0.56
Feb.	−0.96	0.60	3.09	0.59	−0.88	−0.56	2.44	0.68
Mar.	1.03	0.53	3.60	0.64	−0.81	−1.20	2.64	0.68
Apr.	−0.73	−1.12	3.98	0.64	−0.81	−1.31	2.65	0.71
May	0.41	−1.33	3.94	0.55	−0.73	−1.65	2.62	0.63
June	−0.33	−1.19	3.85	0.59	−1.18	−0.85	2.48	0.68
July	−0.52	−1.14	3.76	0.58	−0.54	−1.00	2.50	0.72
Aug.	0.18	−1.53	3.43	0.42	−0.18	−1.27	2.44	0.63
Sept.	−1.30	0.52	3.44	0.53	−1.11	−1.10	2.49	0.70
Oct.	−0.10	0.09	3.18	0.57	−1.01	−0.60	2.53	0.70
Nov.	−1.01	0.33	2.81	0.55	0.63	−0.99	2.41	0.64
Dec.	−0.54	−1.17	2.66	0.58	−0.35	−0.90	2.40	0.59

*Absolute values of z_1 or z_2 above 2.02 are significant at the 0.95 confidence level.

TABLE 3. Linear wind speed changes in Phoenix (1948–1985).

	1400 MST observations			0500 MST observations		
Month	r*	b	Percent increase	r*	b	Percent increase
Jan.	0.54	0.025	41.3	0.52	0.026	54.1
Feb.	0.33	0.018	23.7	0.47	0.029	55.5
Mar.	0.47	0.027	31.8	0.63	0.038	73.9
Apr.	0.45	0.026	27.2	0.56	0.036	66.7
May	0.36	0.018	18.5	0.63	0.036	67.9
June	0.21	0.011	11.6	0.34	0.021	36.8
July	0.32	0.017	17.9	0.44	0.029	54.4
Aug.	0.58	0.022	27.0	0.58	0.024	45.4
Sept.	0.56	0.027	33.8	0.32	0.020	35.7
Oct.	0.44	0.022	30.1	0.51	0.032	61.1
Nov.	0.56	0.028	44.6	0.48	0.028	54.7
Dec.	0.51	0.027	45.7	0.30	0.016	27.9

* Correlation coefficients, *r*, greater than 0.30 are statistically significant at the 0.95 confidence level.

the 1980s have increased up to 173% of their 1948 levels.

2) The 0500 MST wind speed have increased much more rapidly than the 1400 MST values. In many months the rate of increase at 0500 MST is 50% to over 100% the rate observed for the afternoon winds.

3) Despite large intermonthly variations in the rate of wind speed increases, the very large increases observed for the 0500 MST winds during the spring season are particularly prominent.

5. Discussion

The developing urban heat island in Phoenix appears to have produced similar trends in both the temperature and wind speed data. The heat island, as depicted by the Phoenix to Wickenburg temperature gradients between 1948 and 1985, intensified far more during the morning hours than during the afternoon period. Over the same time period, the early morning wind speeds increased more rapidly than the afternoon winds. As Bornstein and Johnson (1977) suggested in their study of New York City, these increased winds are probably caused by a general reduction in nighttime stability resulting from the growth of the urban heat island. The increasing atmospheric instability promotes downward momentum flux over the city, thereby increasing the nighttime wind speeds.

The results from modeling studies incorporating extensive micrometeorological networks (e.g., METROMEX, 1981) have suggested that the local circulation of an urban area is strongly influenced by the thermal gradient existing throughout the city. The general lack of wind data through time and space for the Phoenix area does not permit such a rigorous evaluation of any numerical simulation of the long-term associations between the local heat island and the resulting adjustments in the wind speeds. However, circulation simulations from other urban areas substantiate the relationships suggested in this study.

Using an adaptation of Atwater's (1975) numerical model, Draxler (1986) noted a 17% increase in the wind speed of Washington, D.C. given a city core that is 5°C warmer than surrounding areas. Vukovich and Dunn (1978) used a three-dimensional primitive equation model (Vukovich et al., 1976) to simulate the circulation effects of the St. Louis heat island. When the initial thermal gradient was increased by a factor of 4 in their model, the resultant convergence in the circulation increased by a factor of 10. Our empirical results from Phoenix similarly show a 50 to 100% increase in wind speeds associated with a 30 to 60% increase in the local temperature gradient.

Although the data suggest a strong correspondence between the increases over time of the Phoenix to Wickenburg temperature gradient and the Phoenix wind speeds, the strength of the relationship may be weakened by intervening factors. The greatest changes in wind speeds over time were evident in the spring months, but the largest changes in the urban heat island appeared during the summer months in Phoenix. Other factors such as seasonal changes in the regional wind flow, the representativeness of a single transect to depict the temperature gradient of the Phoenix heat island, and seasonal variations in other climatic variables (e.g., vertical momentum transfer) may be influential in promoting changes in the urban wind patterns.

6. Conclusions

The analyses presented in this investigation revealed the existence of a statistically significant increase in mean monthly wind speeds in Phoenix, Arizona over a 1948–85 study period. The increases in wind speed were particularly large during the early morning hours; some months showed more than a 60% increase in wind speeds through the 38-year record. The changes observed in the Phoenix winds were found to be directly related to the emergence of a particularly large and well-defined urban heat island. The increased thermal gradients surrounding the metropolitan area and the decrease in atmospheric stability appeared to be responsible for the observed increases in local wind speeds.

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