



Anomalous monsoonal activity in central Arizona, USA

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Received 16 June 2006; revised 18 July 2006; accepted 24 July 2006; published 26 August 2006.

[1] Published research has suggested that urban and agricultural activities in central Arizona may be enhancing monsoonal precipitation in the region; therefore, this study employed cloud-to-ground lightning data and topographic data to reveal spatially anomalous zones of lightning activity in central Arizona. A multiple linear regression model with topographic variables as predictors explained 85% of the variance in gridded lightning-flash counts. Clustering of large positive residuals of lightning flashes existed between 40 km and 100 km north/northeast of urbanized Phoenix. Observed lightning flashes in this zone were ~40% more frequent than lightning flashes predicted by the model. Two plausible causes of the enhanced lightning activity are intensified convective storms due to Phoenix-derived water vapor and altered microphysical processes in storm clouds due to Phoenix-derived atmospheric pollution. It is possible that the positive-anomaly zone also had enhanced rainfall. **Citation:** Diem, J. E. (2006), Anomalous monsoonal activity in central Arizona, USA, *Geophys. Res. Lett.*, 33, L16706, doi:10.1029/2006GL027259.

1. Introduction

[2] Central Arizona is at the northwestern extremity (i.e. northern periphery) of the Mexican-monsoon region [Douglas *et al.*, 1993; Diem, 2005]. Monsoonal activity in central Arizona – which can begin as early as June 5 and end as late as October 9 – is not an expected daily occurrence; rather, it occurs within “burst” events [Carleton, 1986; Ellis *et al.*, 2004]. “Bursts” are associated with increased atmospheric instability, thus lightning is an expected characteristic of monsoonal activity [Carleton, 1986; Watson *et al.*, 1994a]. Consequently, lightning activity in central Arizona has been suggested as a suitable temporal proxy for precipitation [Watson *et al.*, 1994b].

[3] Cloud-to-ground lightning data collected by the National Lightning Detection Network (NLDN) are optimal for examining spatial variations in storm activity in central Arizona and the rest of the northern periphery of the monsoon region, because there are no significant spatial or temporal gaps in the lightning data. Through precipitation regionalization [Diem and Brown, 2006], regression modeling of precipitation [Michaud *et al.*, 1995; Diem, 2005], precipitation mapping [Comrie and Broyles, 2002; Skirvin *et al.*, 2003], and lightning mapping [King and Balling, 1994; Watson *et al.*, 1994b; López *et al.*, 1997], spatial variations in monsoonal activity have been illustrated

within the northern-periphery zone. Nevertheless, since lightning data have not been used in conjunction with other geospatial data, some large holes may exist in the understanding of the spatial complexity of monsoonal activity in the northern-periphery zone. Moreover, localized human impacts on lightning activity add to the complexity. For example, results based on analyses of NLDN data presented by Westcott [1995], Orville *et al.* [2001], Steiger *et al.* [2002], and Steiger and Orville [2003] suggest that increased cloud-to-ground lightning activity may occur over or downwind of urban areas or large pollution sources.

[4] Since Diem and Brown [2003] hypothesized that precipitation enhancement in central Arizona is most likely occurring north/northeast of Phoenix in the Lower Verde basin (Figure 1), the purpose of this paper is to test that hypothesis using lightning data instead of precipitation data. The objectives are (1) to determine if human activities in the Phoenix area may be responsible for enhanced monsoonal activity in central Arizona, and (2) to quantify the spatial relationship between lightning activity and rainfall.

2. Data

[5] The four types of data were (1) cloud-to-ground lightning data, (2) rainfall data, (3) lower-troposphere wind data, and (4) topographic data. The time period for the lightning and rainfall data was June 16–September 15 from 1996 through 2002 (see Diem [2005] for an explanation). The lightning data were part of a NLDN dataset acquired from Vaisala Inc., Tucson, Arizona, for a region within ~200 km of downtown Phoenix. The attributes of each lightning flash used in this study were date, time, latitude, and longitude. In central Arizona, the median location error of the flashes is ~500 m, and the flash-detection efficiency is >80% [see Cummins *et al.*, 1998]. The rainfall data were comprised of precipitation totals measured at Automated Local Evaluation in Real Time (ALERT), Arizona Meteorological Network (AZMET), and National Weather Service (NWS) stations within 95 km of downtown Phoenix (Figure 1). The total number of stations was 63; there were 50 ALERT stations, 12 NWS stations, and one AZMET station. Hourly rainfall totals were obtained for the ALERT and AZMET stations from the Flood Control District of Maricopa County and The University of Arizona Cooperative Extension, respectively. Daily rainfall totals were obtained for the NWS stations from the National Oceanic and Atmospheric Administration (NOAA). Complete details regarding procedures used to adjust the rainfall data are provided by Diem [2005]. Daily wind data at 850-mb and 700-mb over the Phoenix region were extracted from the NCEP/NCAR Reanalysis dataset [Kalnay *et al.*, 1996] of the Climate Diagnostics Center of the National Oceanic and Atmospheric Administration and the Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES

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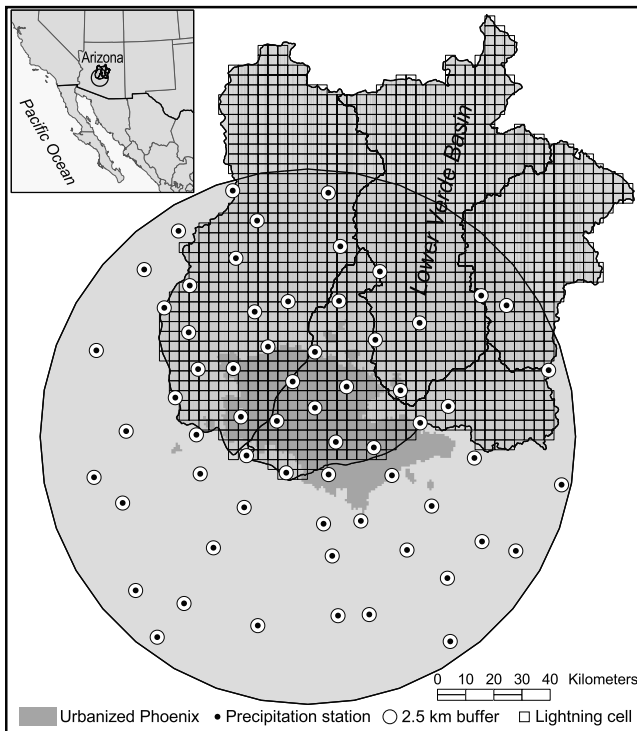


Figure 1. The four-basin region used for the lightning modeling and the circular region centered on Phoenix used for the lightning-rainfall correlation analysis.

CDC). Finally, a 30-m resolution digital elevation model (DEM), which is part of the National Elevation Dataset, was acquired from the United States Geological Survey.

3. Methods

[6] Spatially anomalous zones of lightning activity were identified through the minimization of topographic effects on lightning flashes within a four-basin region in central Arizona (Figure 1). With topography having a major influence on lightning activity throughout the study region [Watson *et al.*, 1994b], it was imperative that topographic influences be made as small as possible in order for human-influenced spatial anomalies to be identified. The lightning database was gridded at a spatial resolution of 3.5 km, which was the smallest resolution that ensured the majority of the flashes inside the cell actually occurred inside the cell. There were 1425 cells in the four-basin region. Multiple linear regression (MLR) models were developed, with elevation, slope, and relief as the principal predictor variables. The initial elevation and slope variables were the mean elevation and mean slope within a grid cell. To account for larger-scale influences, neighborhood values of elevation and slope were calculated by applying 3-cell by 3-cell, 5-cell by 5-cell, 7-cell by 7-cell, and 9-cell by 9-cell moving-mean filters. Therefore, the additional elevation and slope values were similar to mean values within 5.3 km, 8.7 km, 12.3 km, and 15.8 km of the center of a cell. Four relief variables were calculated by subtracting the four neighborhood elevations from the mean elevation of a cell. The 14 potential predictor variables (i.e. five elevation variables, five slope variables, and four relief variables)

were subjected to a standardized principal components analysis (PCA), and components with eigenvalues ≥ 1 were extracted and orthogonally rotated (i.e. VARIMAX). Therefore, PCA was used to screen the variables [see Kachigan, 1991]. Backward-stepwise MLR models were developed using a high loading variable from each component; only predictor variables having slope coefficients significantly ($\alpha = 0.01$) different from zero were retained. A separate model was created for each combination of independent predictor variables, and the model with the largest coefficient of determination was used to produce the predicted totals of lightning flashes for the cells. The resultant residuals represented the amount of lightning activity that was related more to geographic position than to local topographic characteristics [e.g., Diem, 2005].

[7] Anomalous lightning-flash cells had either extremely large positive residuals or extremely large negative residuals. In order to better identify zones of anomalous-lightning activity, the residuals were smoothed using a 3-cell by 3-cell moving-mean filter. The smoothed residuals were checked for significant ($\alpha = 0.01$) positive spatial autocorrelation using the Moran's I test, and if significant spatial autocorrelation existed, continuous surfaces of residuals were created using the spline spatial-interpolation technique. Anomalous-lightning zones were those zones with interpolated residuals at least two standard deviations from the mean residual value.

[8] Lightning-flash characteristics were summarized within the lightning-anomaly zones. The percent difference from predicted flash frequency from the MLR model was calculated. In addition, the percentage of days with lightning activity, the spatial uniqueness of flash days, and the hourly occurrences of lightning were determined. Finally, the typical lower-troposphere wind flow on flash days was calculated.

[9] The four-basin region had an insufficient density of precipitation stations in order to assess the spatial correlation between lightning flashes and rainfall during the monsoon season; therefore, the 63 dispersed precipitation stations in the Phoenix region were used instead (Figure 1). The total number of lightning flashes within 2.5 km of each station was calculated; 2.5 km is equivalent to the location accuracy of the NWS stations as provided in the station metadata. The Pearson product-moment correlation test was used to test for a significant ($\alpha = 0.01$) positive correlation between lightning and rainfall.

4. Results and Discussion

[10] One-hundred MLR models were developed, and the selected model had a coefficient of determination of 0.85. Regarding the PCA, three components containing 96% of the variation in the dataset were extracted, and those components represented elevation, slope, and relief. Therefore, each MLR model had three initial predictor variables. The final model was as follows:

$$\hat{Y} = 5.924963 + (0.004957 * E_{5 \times 5}) + (0.172057 * S_{9 \times 9}) + (0.008953 * R_{3 \times 3}),$$

where \hat{Y} is the square root of total number of lightning flashes, $E_{5 \times 5}$ is the mean elevation within a 5-cell by 5-cell

neighborhood, $S_{9 \times 9}$ is the mean slope within a 9-cell by 9-cell neighborhood, and $R_{3 \times 3}$ is mean elevation within the 3.5-km cell minus the mean elevation within a 3-cell by 3-cell neighborhood. Elevation values were in meters above sea level, relief values were in meters, and slope values were in degrees.

[11] A single zone of large positive residuals dominated the residuals landscape (Figure 2). The smoothed residuals had significant positive spatial autocorrelation: the Moran's I value was 0.28 and its associated P value was less than 0.001. The spatial interpolation yielded eight zones having residuals at least two standard deviations from the mean (i.e. zero). Six of the zones were too small to be considered further. The largest and most intense positive-anomaly zone comprised $\sim 770 \text{ km}^2$ spanning the Lower Verde and Aqua Fria basins (i.e. between 40 km and 100 km north/northeast of urbanized Phoenix), while the largest and most intense negative-anomaly zone comprised $\sim 150 \text{ km}^2$ in the north-eastern portion of the Lower Verde basin. The negative-anomaly zone was topographically unique: only two other cells had values for $E_{5 \times 5}$, $S_{9 \times 9}$, and $R_{3 \times 3}$ that were within the ranges of values for the cells in the negative-anomaly zone. Therefore, the relatively low number of lightning strikes within the negative-anomaly zone can be explained by the fact that the zone was the only part of the four-basin region that was essentially located on the Mogollon Rim (i.e. the southwestern edge of the Colorado Plateau). The positive-anomaly zone definitely was not topographically unique: over 20% of the remaining cells in the four-basin region had values for $E_{5 \times 5}$, $S_{9 \times 9}$, and $R_{3 \times 3}$ that were within the ranges of values for cells in the positive-anomaly zone. The relatively high number of lightning flashes within the positive-anomaly zone cannot be explained by the topographic setting of the zone.

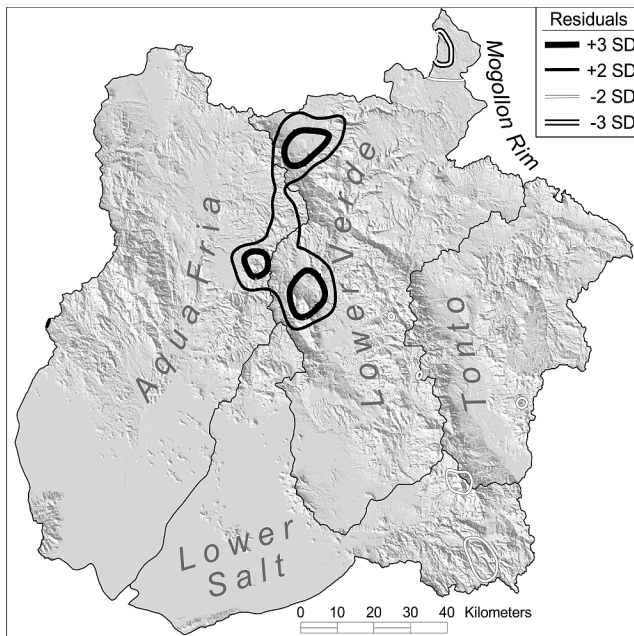


Figure 2. Lightning-flash anomaly zones in the four-basin region. Isolines show residuals that are two and three standard deviations from the mean.

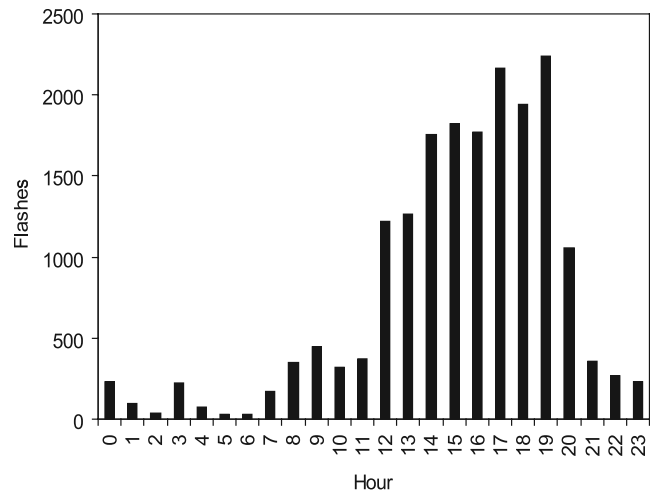


Figure 3. Hourly occurrence of lightning flashes within the positive-anomaly zone.

[12] Lightning enhancement in the positive-anomaly zone was substantial, and it is possible that rainfall also may have been enhanced. With 18,467 lightning flashes occurring in the positive-anomaly over the seven seasons, flashes in the zone were $\sim 40\%$ more frequent than expected based on topographic position. Lightning activity in the positive-anomaly zone occurred on 39 days per monsoon season (i.e. 42% of monsoon-season days). None of the flash days were unique to the positive-anomaly zone, and only one day had more flashes inside the zone than in the rest of the four-basin region. Lightning activity in the positive-anomaly zone was a predominantly daytime phenomenon, for over 75% of the flashes occurred between 12 P.M. and 8 P.M. (Figure 3). Within the Phoenix region, there was a strong significant correlation ($r = 0.92$) between lightning and rainfall (Figure 4), thus it is possible that the positive-anomaly zone also received enhanced rainfall. Unfortunately, absolutely no precipitation stations existed in the zone during the period of study.

[13] If the positive-anomaly zone did receive increased lightning through human impacts, then the three possible causes of lightning enhancement were (1) the intensification of existing convective storms, (2) the initiation of new convective storms, and (3) the alteration of microphysical processes within storm clouds. The development of the Phoenix area through irrigation-intensive land uses (i.e. crops, residential areas, and golf courses) has caused the Phoenix area to become a substantial source of water vapor: heavily irrigated lands in the Phoenix area emit at least seven times more water vapor into the atmosphere than do equal-sized desert areas nearby, thus the amount of evapotranspiration in the Phoenix area has been calculated to equal that from a hypothetical 2000 km^2 lake [Diem and Brown, 2003]. Within the Phoenix metropolitan area, $>5.5 \text{ Gg}$ of particulate matter are emitted annually into the atmosphere by way of fossil-fuel combustion (AirData: Access to air pollution data, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, available at <http://www.epa.gov/air/data/>, 2006), thereby leading to increased levels of cloud-condensation nuclei (CCN). Winds throughout the lower troposphere should transport Phoenix-

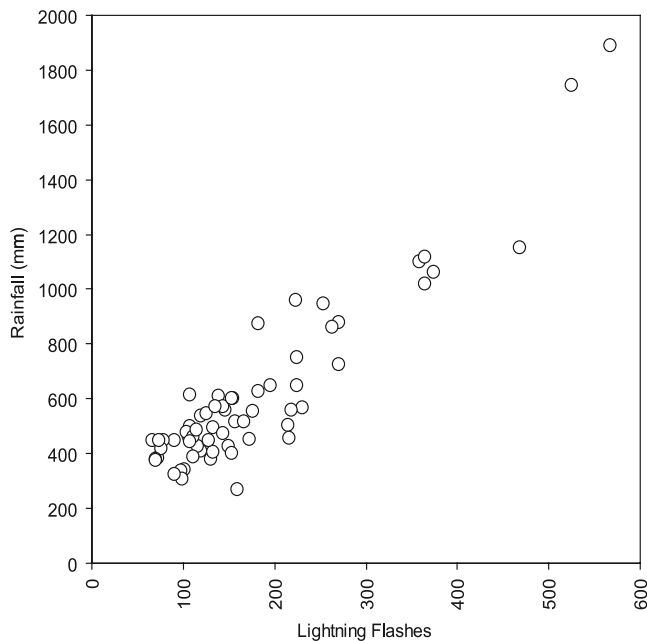


Figure 4. Scatterplot of rainfall totals vs. lightning flashes in the Phoenix region during the 1996–2002 monsoon seasons.

derived water vapor and CCN to the Aqua Fria and Lower Verde basins: [Stewart *et al.*, 2002] show daytime southerly winds at the surface over both Phoenix and mountainous areas to the north, and the typical synoptic-scale lower-troposphere flow over southwestern Arizona on flash days is southerly to southwesterly. The addition of Phoenix-derived water vapor to the atmosphere over the positive-anomaly zone may have either intensified existing convective storms or initiated new convective storms or both over the zone. It is much more likely that storm intensification rather than the storm initiation occurred, because all the flash days in the positive-anomaly were flash days somewhere else in the four-basin region. The addition of Phoenix-derived CCN to the zone may have increased charge separation and thus increased the frequency of lightning flashes [Sherwood *et al.*, 2006]. Finally, it needs to be noted that increased convection and convergence associated with the urban heat island were not responsible for the lightning enhancement, since – unlike most other urban areas in the United States – the Phoenix area is not a daytime heat island [Brazel *et al.*, 2000].

5. Conclusions

[14] This paper presented an examination of cloud-to-ground lightning activity in central Arizona during the monsoon season in order to determine if human activities in the Phoenix area may have caused lightning enhancement and possibly rainfall enhancement. Based on data from 63 stations within 95 km of Phoenix, a strong positive correlation between rainfall and lightning flashes in central Arizona was revealed. Using lightning-flash totals from seven monsoon seasons as the predictand, MLR models with topographic variables as predictors yielded predicted flash totals for 1425 grid cells in a four-basin region in

central Arizona. The chosen model – which had elevation, slope, and relief as predictor variables – explained 85% of the variance in lightning-flash totals. Anomalous zones of lightning-activity were determined from groups of residuals that were at least two standard deviations from the mean of residuals.

[15] The largest and most intense anomaly zone was a group of positive residuals covering ~ 770 km² north/northeast of Phoenix in the Lower Verde and Aqua Fria basins. Observed lightning flashes in this zone were $\sim 40\%$ more frequent than lightning flashes predicted by the MLR model, and nearly all lightning activity occurred in the afternoon and early evening. The two most likely Phoenix-based contributions responsible for the lightning enhancement were increased atmospheric humidity and increased particulate-matter levels. In order to confirm the presence of a human-induced spatial anomaly in monsoonal rainfall in central Arizona, multiple rain gages are needed in the lightning-anomaly zone north/northeast of Phoenix.

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