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Short Communication

Detecting summer rainfall enhancement within metropolitan Atlanta, Georgia USA

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ABSTRACT: This paper presents a methodology for detecting summer rainfall enhancement within a metropolitan area. The chosen study domain is the Atlanta, Georgia USA metropolitan area, and the time period covers summer (i.e. June–August) seasons from 1949 to 2005. In order to determine if observed heavy-rainfall frequencies at nine candidate stations in the metropolitan area are enhanced, predicted frequencies are derived from heavy-rainfall frequencies at seven reference stations located more than 50 km from downtown Atlanta. Both parametric and non-parametric tests are used to test for significant differences between observed frequencies and predicted frequencies within 29 overlapping 30 year periods (i.e. climatological periods). Norcross, which was ~30 km northeast of downtown Atlanta and thus was typically downwind of urbanized Atlanta on heavy-rainfall days at all candidate stations, was the only station to exhibit significant rainfall enhancement. The final ten climatological periods exhibited enhancement, with observed frequencies of ≥30 mm days for those periods being at least 20% larger than predicted frequencies. It is hoped the methods employed in this paper can be used in other metropolitan areas. Copyright © 2007 Royal Meteorological Society

KEY WORDS precipitation; rainfall; urban heat island; Atlanta

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1. Introduction

Urban enhancement of summer precipitation is thought to be caused by increases in surface roughness or surface temperatures (i.e. urban heat island (UHI)) or both (Changnon *et al.*, 1976; Baik *et al.*, 2001; Rozoff *et al.*, 2003). Results from most empirical urban-effects studies suggest that heavy-rainfall may be enhanced over and downwind of urban areas (Huff and Changnon, 1972; Huff and Changnon, 1973; Huff, 1975; Dettwiller and Changnon, 1976; Changnon, 1978; Huff and Vogel, 1978; Changnon, 1980; Changnon *et al.*, 1991; Jauregui and Romales, 1996; Changnon and Westcott, 2002; Diem and Mote, 2005). Nevertheless, it has been argued that urban effects on precipitation – which are confounded with other factors (i.e. topographic relief and proximity to water bodies) – have not yet been assessed with a sound scientific methodology; methods used have been either two-point differences (i.e. urban minus rural) and associated time series, isohyetal mapping, graphical correlation, or numerical modelling (Lowry, 1998).

The 28-county Atlanta, Georgia metropolitan area, which is located in the interior portion of the southeastern United States, is an excellent geographical domain for a climatological examination of rainfall enhancement during the summer season (Figure 1). Since Atlanta has a humid subtropical climate, it is characterized by the usual absence of summer droughts (Trewartha and Horn, 1980). The region receives ~320 mm of rainfall from June through August (Diem, 2006). Long-term precipitation stations in metropolitan Atlanta are neither in areas of large topographic relief nor proximate to large water bodies; thus, any detected rainfall enhancement in the metropolitan area should not be linked to orographic lifting or mesoscale circulations associated with land–water contrasts. Finally, the population of metropolitan Atlanta quadrupled from 1950 to 2000, with the 2000 population exceeding 4 million persons (US Census Bureau, 2001). Therefore, one can assume that the potential for urban phenomena, such as the UHI, to impact rainfall increased substantially over the past half-century. In fact, the present-day UHI of Atlanta also may initiate precipitation events (Bornstein and Lin, 2000; Dixon and Mote, 2003).

Strong climatological evidence of rainfall enhancement within metropolitan Atlanta does not exist. Diem and Mote (2005) note that Norcross – which is ~30 km northeast of downtown Atlanta – had the largest increase in summer season heavy-rainfall days between two consecutive epochs (i.e. 1953–1977 and 1978–2002) among 30 dispersed stations within 180 km of downtown Atlanta (Figure 1). Nevertheless, the Diem and Mote (2005) study has the following deficiencies with respect to

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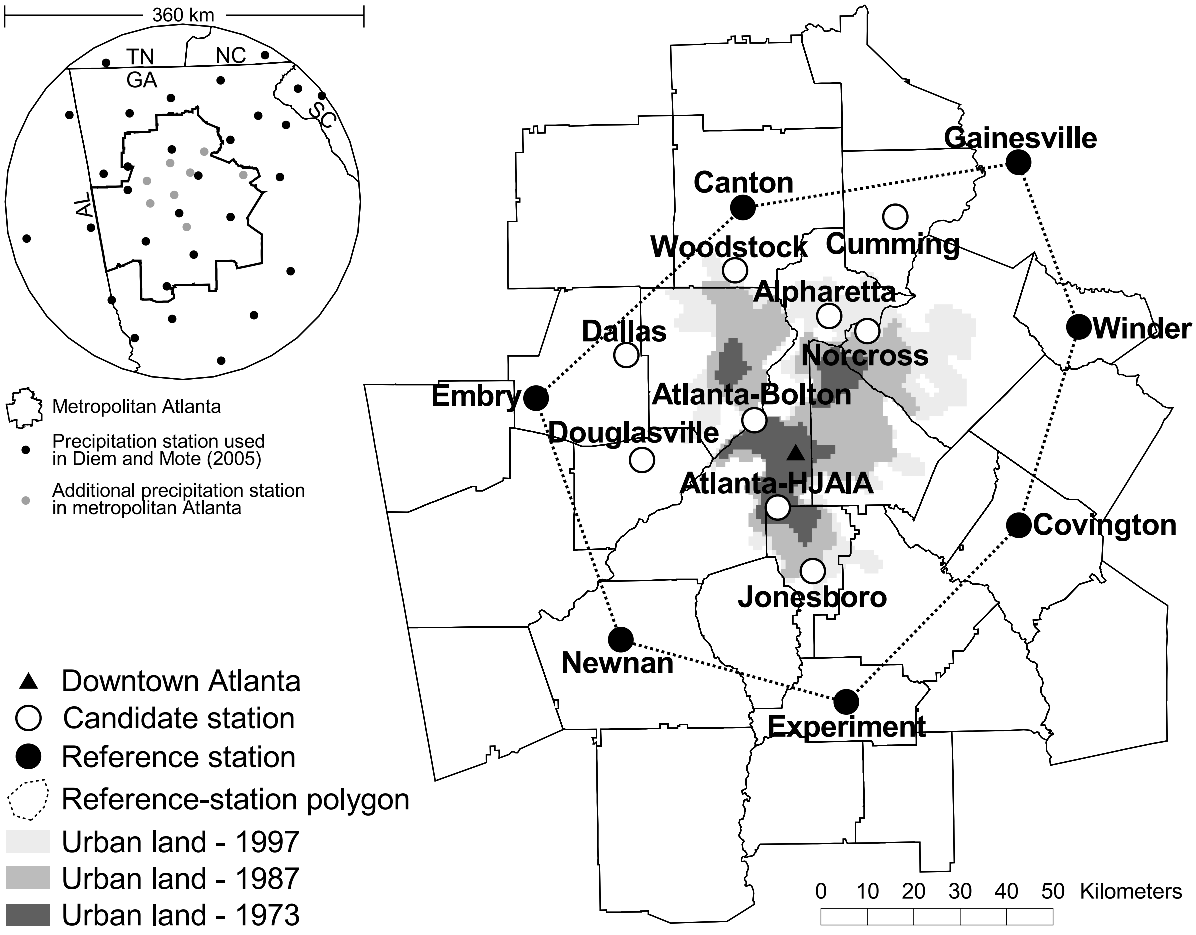

Figure 1. Locations of 38 precipitation stations within 180 km of downtown Atlanta, the Atlanta metropolitan area, the nine candidate stations, the seven reference stations, the reference station polygon, and urban land in 1973, 1987, and 1997. Urban land was determined from 1973, 1987, and 1997 land-cover databases of the Atlanta region (Yang and Lo 2002). The gridded databases were converted into binary images (i.e. urban and non-urban), before being coarsened to 1-km resolution using a majority filter and nearest-neighbour resampling. For 1987 and 1997, only urban land connected to the 1973 urban patches are shown. 'HJAIA' is Hartsfield–Jackson Atlanta International Airport.

the examination of rainfall enhancement: (1) due to its design, it was unable to estimate the amount of rainfall enhancement at Norcross; (2) it only considered two 25 year periods, rather than a series of longer climatological periods; and (3) since few precipitation stations within metropolitan Atlanta were examined, it may have missed some important spatial anomalies. Consequently, the purpose of this paper is to examine possible urban effects on summer season heavy-rainfall frequencies at stations within metropolitan Atlanta for climatological periods that existed between 1949 and 2005. Examining potential urban impacts on heavy rainfall is important, because heavy rainfall – which often is associated with lightning and flash floods – has some extreme negative impacts on public welfare; moreover, urban-impacted weather stations can contaminate results in regional and global climate change studies.

2. Data and methods

The principal data were daily precipitation totals for summer (i.e. June–August) seasons from 1949 to 2005 for 38 National Weather Service cooperative stations in the extended Atlanta region (Figure 1). The earliest possible starting year for the analyses was 1941; however, prior to 1949, a substantial number of days at multiple stations had an estimated – rather than a reported – precipitation total. Data for the 38 stations – which consisted of the 30 stations examined in Diem and Mote (2005) along with eight additional stations in metropolitan Atlanta – were extracted from the TD3200 and TD3210 databases of the National Climatic Data Center (NCDC). Extensive metadata for those stations enabled intensive quality assurance/quality control procedures to be conducted. The entire data set was missing 1.3% of the daily precipitation totals. Using hour of observation data obtained from monthly climatological data publications provided by the NCDC for all applicable years, daily precipitation totals were associated with the day on which most of the precipitation most likely occurred. This procedure was needed to make estimated daily precipitation totals as accurate as possible. Missing values were replaced with precipitation estimates based on an inverse distance weighting (IDW) scheme involving data from nearby stations. Automated surface observing stations (ASOS) instrumentation was implemented at Athens in 1994, Columbus in 1994, Macon in 1994, Atlanta- i.e. Hartsfield–Jackson Atlanta International Airport (HJAIA) in 1995, and Chattanooga in 1996; as a result, ASOS-measured precipitation values were multiplied by 1.12 to adjust for the reduced precipitation totals associated with the tipping-bucket raingage (see Diem and Mote (2005) for an explanation).

A network of reference stations, which were stations assumed to be devoid of urban effects, was needed to detect possible urban effects on rainfall within metropolitan Atlanta. Since previous studies (Changnon, 1978; Huff and Vogel, 1978) associated with the Metropolitan Meteorological Experiment (METROMEX) project in St Louis, Missouri USA indicate that summer rainfall enhancement probably existed no farther than ∼50 km downwind of the city centre, reference stations used in this study were at least 50 km from downtown Atlanta. The reference station network consisted of seven stations (Canton, Covington, Embry, Experiment, Gainesville, Newnan, and Winder) that when viewed as vertices produced a polygon centred on downtown Atlanta (Figure 1). The vertices (i.e. reference stations) were relatively evenly spaced, with the distances between the vertices ranging from 38 to 61 km.

Heavy-rainfall values were determined from the frequency distribution of rainfall totals on rainfall days (i.e. days with $\geq$0.254 mm of rainfall) over the 57-year period at the seven reference stations. A log transformation made the distribution approximately normally distributed. The initial heavy-rainfall threshold was the value at one standard deviation above the mean, while subsequent heavy-rainfall values were assigned to approximately the 90th percentile.

Using annual frequencies of heavy-rainfall days at the reference stations, frequencies were predicted for nine candidate stations (Alpharetta, Atlanta-Bolton, Atlanta-HJAIA, Cumming, Dallas, Douglasville, Jonesboro, Norcross, and Woodstock) located within the reference station polygon (Figure 1). Frequencies of heavy-rainfall days for the candidate stations were estimated using weighted and non-weighted values at the reference stations. The weighting procedure was IDW, while the non-weighting procedure used the mean of the reference stations as the predicted value for each of the candidate stations. With IDW, the closest reference station had the largest influence on the predicted values at a candidate station.

Testing for significantly ($\alpha = 0.05$) larger observed values than predicted values for the 29 overlapping 30-year periods was performed. A typical climatological period is 30 years; thus, the use of 30-year periods ensured that the climate – rather than smaller-scale patterns – of a location was being assessed. It was assumed that if rainfall enhancement did not occur, then none of the 30-year periods would have observed values significantly larger than predicted values. For each year, a candidate station had a single observed value and two predicted values for each heavy-rainfall variable. Both the Student's t-test, a parametric test, and the Mann–Whitney U-test, a non-parametric test, were used to test for differences between the observed and predicted values. The testing produced four P-values (i.e. two values for the Student's t-test and two values for the Mann–Whitney U-test) for each station/variable/period combination. In order to minimize the probability of stating incorrectly that enhancement occurred, the P-value used in this study was the largest of the four P-values.

For candidate stations with significantly larger observed values than predicted values, residuals were analysed for temporal discontinuities. Station relocations, changes in instrumentation, problems with instrumentation, changes in the nearby environment (e.g. buildings and trees), and changes in observers and observer practices can produce an inhomogeneous precipitation record, which contains discontinuities caused by non-climatic factors (Peterson *et al.*, 1998). A regression-based approach was used to find the largest discontinuity for each station/variable combination (Easterling and Peterson, 1995). Only if the largest discontinuity coincided with a station relocation, was that relocation considered a viable cause of significant differences between observed and predicted heavy-rainfall frequencies. In addition, if a station was at the same location during different non-contiguous time periods, a one-tailed Mann–Whitney U-test was used to test for significant differences in residuals.

Finally, mean lower troposphere wind directions on heavy-rainfall days at all candidate stations were calculated. This information was needed to determine if heavy-rainfall days coincided with a station being downwind of urbanized Atlanta. Daily zonal and meridional flow at 925, 850, and 700 hPa over metropolitan Atlanta were extracted from the NCEP/NCAR Reanalysis data set (Kalnay *et al.*, 1996) provided by the National Oceanic and Atmospheric Administration via the Earth System Research Laboratory.

3. Results and discussion

Heavy-rainfall days had $\geq$20, $\geq$25, or $\geq$30 mm of rainfall. One standard deviation above the mean of the transformed distribution of daily rainfall totals occurred at 20 mm. The percentiles for 25 and 30 mm were 88 and 92%, respectively. Consequently, both heavy-rainfall values were used instead of a single heavy-rainfall value that corresponded exactly with the 90th percentile.

Enhancement of heavy-rainfall frequency occurred only at the Norcross station. Norcross had significantly ($\alpha = 0.05$) larger observed frequencies of $\geq$30 mm days than the predicted frequencies for the final ten climatological periods (i.e. 1967–2005), while significant enhancement of frequencies of $\geq$25 mm days was restricted to several of the most recent climatological periods (i.e. 1970–1999, 1975–2004, and 1976–2005) (Table I). Significant enhancement did not occur for $\geq$20 mm days. The observed frequencies of $\geq$30 mm days for the final ten periods were 20% to 25% larger than the predicted frequencies; the typical number of observed $\geq$30 mm

Table I. The 30 smallest one-tailed P-values for situations where observed frequencies were larger than predicted frequencies. Only P-values ≤ 0.05 represent a significant difference between frequencies.

Station	Variable (mm)	Period	P
Norcross	≥30	1970–1999	0.015
Norcross	≥30	1974–2003	0.017
Norcross	≥30	1972–2001	0.017
Norcross	≥30	1969–1998	0.017
Norcross	≥30	1968–1997	0.020
Norcross	≥30	1975–2004	0.020
Norcross	≥30	1973–2002	0.025
Norcross	≥30	1971–2000	0.025
Norcross	≥30	1976–2005	0.032
Norcross	≥25	1970–1999	0.036
Norcross	≥30	1967–1996	0.044
Norcross	≥25	1976–2005	0.046
Norcross	≥25	1975–2004	0.050
Norcross	≥30	1966–1995	0.052
Norcross	≥25	1972–2001	0.053
Norcross	≥25	1974–2003	0.060
Norcross	≥25	1971–2000	0.067
Norcross	≥30	1964–1993	0.072
Norcross	≥30	1962–1991	0.073
Norcross	≥25	1973–2002	0.073
Norcross	≥30	1961–1990	0.074
Norcross	≥30	1965–1994	0.090
Norcross	≥25	1969–1998	0.096
Norcross	≥30	1960–1989	0.101
Norcross	≥30	1959–1988	0.104
Alpharetta	≥30	1964–1993	0.110
Alpharetta	≥30	1962–1991	0.114
Woodstock	≥30	1969–1998	0.115
Norcross	≥25	1968–1997	0.126
Alpharetta	≥30	1965–1994	0.127

days for a climatological period was 99. The final ten climatological periods shared 21 years (i.e. 1976–1996), and the observed frequency of ≥30 mm days for those years was 34% larger than the predicted frequencies. The observed frequencies of ≥25 mm days for the final two periods were 24% larger than the predicted frequencies. Finally, Norcross had the most ≥25 mm and ≥30 mm days among all the precipitation stations within 180 km of Atlanta for the final seven and nine climatological periods, respectively.

With the mean wind direction on heavy-rainfall days at candidate stations being southwesterly (i.e. the range in mean wind directions involving all three lower troposphere levels was 199°–248°), it is possible that rainfall enhancement occurred at other places besides Norcross located northeast of Atlanta. For the 30-year analyses, only Norcross had P-values smaller than those for Alpharetta, which was ~10 km northwest of Norcross (Table I). Unfortunately, the Alpharetta station was discontinued too early (i.e. 1994) for significant enhancement to be detected using the statistical techniques presented in this paper.

The rainfall anomalies at Norcross most likely were not caused by non-climatic factors. Potential discontinuities in the heavy-rainfall time series were associated with either an extremely large positive residual (i.e. 1985) or an extremely large negative residual (i.e. 1992), rather than an abrupt shift from a series of small residuals to a series of large residuals (Figure 2). While the station moved 5 times over the 57-year period, only the large discontinuity in 1992 was caused by a change in location or observer or both. Fortunately, the station was at that location and had that observer for only a single year. If an abrupt shift from a series of small residuals to a series of large residuals would have occurred, then the enhancement may have been due to a non-climatic factor. Furthermore, the Norcross station was at the same location during 1949–1972 and 1978–1991, and P-values <0.01 resulted when testing for differences between 1978–1991 residuals and 1949–1972 residuals for ≥25 mm and ≥30 mm days. Nevertheless, since there is insufficient historical local environment information for the Norcross station, changes in the local environment at a particular location cannot be eliminated completely as

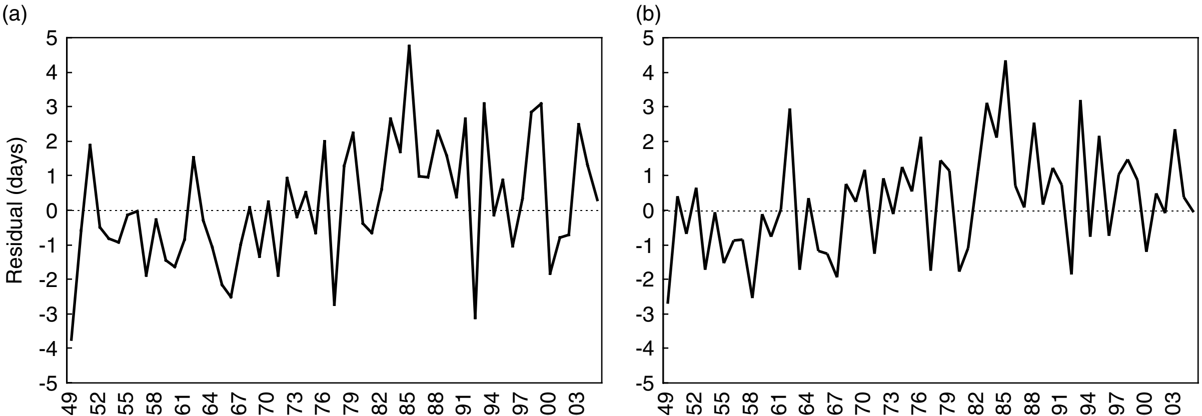

Figure 2. Time series of annual residuals for (a) ≥25 mm days and (b) ≥30 mm days at Norcross. The residuals shown are the mean of the two sets of residuals resulting from the two weighting schemes used to produce the predicted frequencies of heavy-rainfall days.

partial causes of rainfall enhancement at the Norcross station.

4. Conclusions

The purpose of this paper was to examine possible urban effects on summer rainfall within metropolitan Atlanta for climatological periods from 1949 to 2005. Heavy-rainfall frequencies were predicted for nine candidate stations, using heavy-rainfall frequencies at seven reference stations. Both the Student's t-test and the Mann–Whitney U-test were used to test for significant differences between observed frequencies and predicted frequencies within overlapping climatological periods. Urban effects were assumed to be the principal cause of observed frequencies that were significantly larger than predicted frequencies. Enhancement of heavy-rainfall frequency occurred northeast of Atlanta at the Norcross station; the observed frequencies of heavy-rainfall days were at least 20% larger than the predicted frequencies for the final ten climatological periods. It was well beyond the scope of this paper to uncover and explain the exact physical mechanisms responsible for the rainfall enhancement at Norcross. The methodology presented in this paper has not only verified rainfall enhancement downwind of Atlanta but also provided a conservative estimate of the enhancement magnitude. If a metropolitan area has sufficient precipitation data and is suspected of having summer rainfall enhancement, then it is hoped this methodology can be used for that metropolitan area.

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