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Short communication

The 1970 Clean Air Act and termination of rainfall suppression in a U.S. urban area

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HIGHLIGHTS

- There was a major decrease in particulate emissions after the passage of the Clean Air Act of 1970.
- The reduction in emissions caused a rapid rebound in summer rainfall in the Atlanta region in the late 1970s.
- There was a decrease in summer rainfall of at least 40 mm at affected locales prior to the passage of act.
- The rainfall suppression involved a decrease of heavy-rainfall days.

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ABSTRACT

The purpose of this paper is to determine the impact of reduced atmospheric particulate resulting from the Clean Air Act of 1970 on changes in summer rainfall in the Atlanta, Georgia USA region. In order to determine if rainfall at nine candidate stations in the metropolitan area was influenced by changes in particulate concentrations within the 1948–2009 period, predicted rainfall characteristics were derived from rainfall frequencies at nine reference stations located more than 80 km from downtown Atlanta. Both parametric and non-parametric tests were used to test for significant differences between observed values and predicted values within 34 overlapping 30-year periods. For the country as a whole, emissions of PM_{10} (i.e. particulates with a diameter less than or equal to 10 μm) decreased by approximately 40% from 1970 to 1975. The reduction in emissions caused a rapid rebound in summer rainfall in the Atlanta region. There was suppression of rainfall over and downwind of the Atlanta urbanized area during 30-yr periods that comprise all or portions of the decades of the 1950s, 1960s, and 1970s. This suppression occurred even while urban-related factors that promote rainfall enhancement were present. During the 1948–1977 suppression period, there was a decrease in rainfall of at least 40 mm at affected locales, which is substantial given that the mean seasonal rainfall was approximately 300 mm. The rainfall suppression involved a decrease of heavy-rainfall days. Atlanta is most likely not a unique case; therefore, particulate-induced rainfall suppression might have occurred over and downwind of other U.S. urban areas prior to the late 1970s.

1. Introduction

Increased atmospheric concentrations of particulates from urban and industrial sources have been implicated in precipitation suppression (Rosenfeld, 2000; Givati and Rosenfeld, 2004; Jirak and Cotton, 2006; Rosenfeld et al., 2007, 2008a, 2008b). In the United States, the passage of the Clean Air Act (CAA) of 1970 caused a dramatic decrease in particulate emissions; from 1970 to 1975, emissions of PM_{10} (i.e. particulates with a diameter less than or equal to 10 μm) decreased by approximately 40% (Fig. 1) (U.S. Environmental Protection Agency, 2012; Chay and Greenstone, 2003). Particulates serve as cloud condensation nuclei (CCN), and increased CCN from fossil-fuel combustion increases the number of cloud droplets while reducing droplet size (Gunn and Phillips, 1957; Coakley et al., 1987). This slows the conversion of cloud droplets into raindrops (Gunn and Phillips, 1957). For example, particulates from fossil-fuel combustion have been shown to suppress precipitation from shallow clouds (Rosenfeld, 2000; Givati and Rosenfeld, 2004; Jirak and Cotton, 2006; Rosenfeld et al., 2007, 2008a). Increased particulate concentrations also can increase the stability of the atmosphere, thereby inhibiting the development of convective clouds (Koren et al., 2004). Given the above information, it seems reasonable to surmise that precipitation suppression over and downwind

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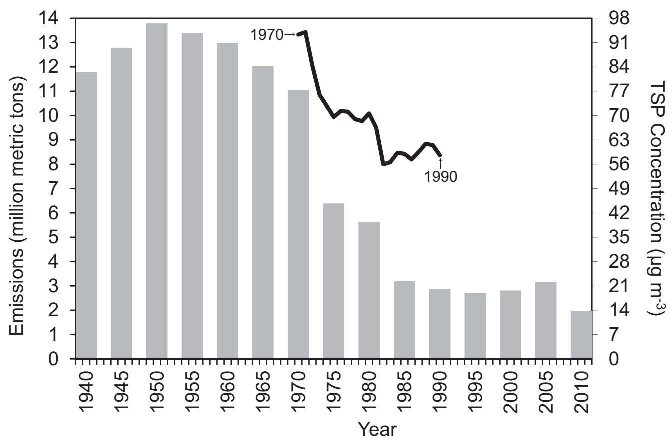

Fig. 1. National PM_{10} emissions from 1940 to 2010 and the mean total suspended particulate (TSP) concentration from 1970 to 1990. PM_{10} emissions from 1940, 1950, 1960, 1970, 1975, 1980, 1985, 1990, 1995, 2000, 2005, and 2010 were obtained from the U.S. Environmental Protection Agency's National Emissions Inventory Air Pollutant Emissions Trends Data. Totals for 1945, 1955, and 1965 were calculated as means from decadal years listed above. TSP concentrations were obtained from Chay and Greenstone (2003), where mean annual TSP concentrations were calculated from data collected at 1000 to 1300 counties.

of U.S. cities occurred prior to the CAA and may have been moderated in the 1970s.

While also establishing standards for carbon monoxide, tropospheric ozone, and sulfur dioxide, the CAA also established a standard for total suspended particulates (TSPs), which are particles ranging in size from approximately 0.1 μm–30 μm in diameter. Standards for PM_{10}, which replaced the TSP standard, and $PM_{2.5}$ (i.e. particulates with a diameter less than or equal to 2.5 μm), were established in 1987 and 1997, respectively. The CAA resulted in a major improvement in particulate air quality from 1971 to 1975 (Chay and Greenstone, 2003) (Fig. 1). The 1950s and 1960s were decades with high particulate emissions and presumably high TSP, PM_{10}, and $PM_{2.5}$ concentrations; thus, clouds over and downwind of urban/industrial areas during those decades should have had more and smaller cloud droplets than did clouds during the past three decades.

Urban areas should affect precipitation, especially summer rainfall, even without any anthropogenic aerosol emissions. Urbanization causes an increase in surface roughness that can lead to convergence downwind of the urban area, and thus enhanced lifting of air needed for cloud formation and development (Hjelmfelt, 1982; Rozoff et al., 2003). Urbanization also results in one or more heat islands within a metropolitan area, and an urban heat island can enhance convection (Baik et al., 2001; Han et al., 2012).

The aim of this paper is to assess the impact of reduced particulate matter resulting from the CAA on changes in rainfall in the Atlanta region. The Atlanta region (Fig. 2) is an optimal region for the assessment. Firstly, the region had high TSP concentrations prior to the passage of the CAA: Fulton County, which is in the center in the center of the Atlanta region, did not meet federal standards for TSPs throughout the 1960 and into the early 1970s

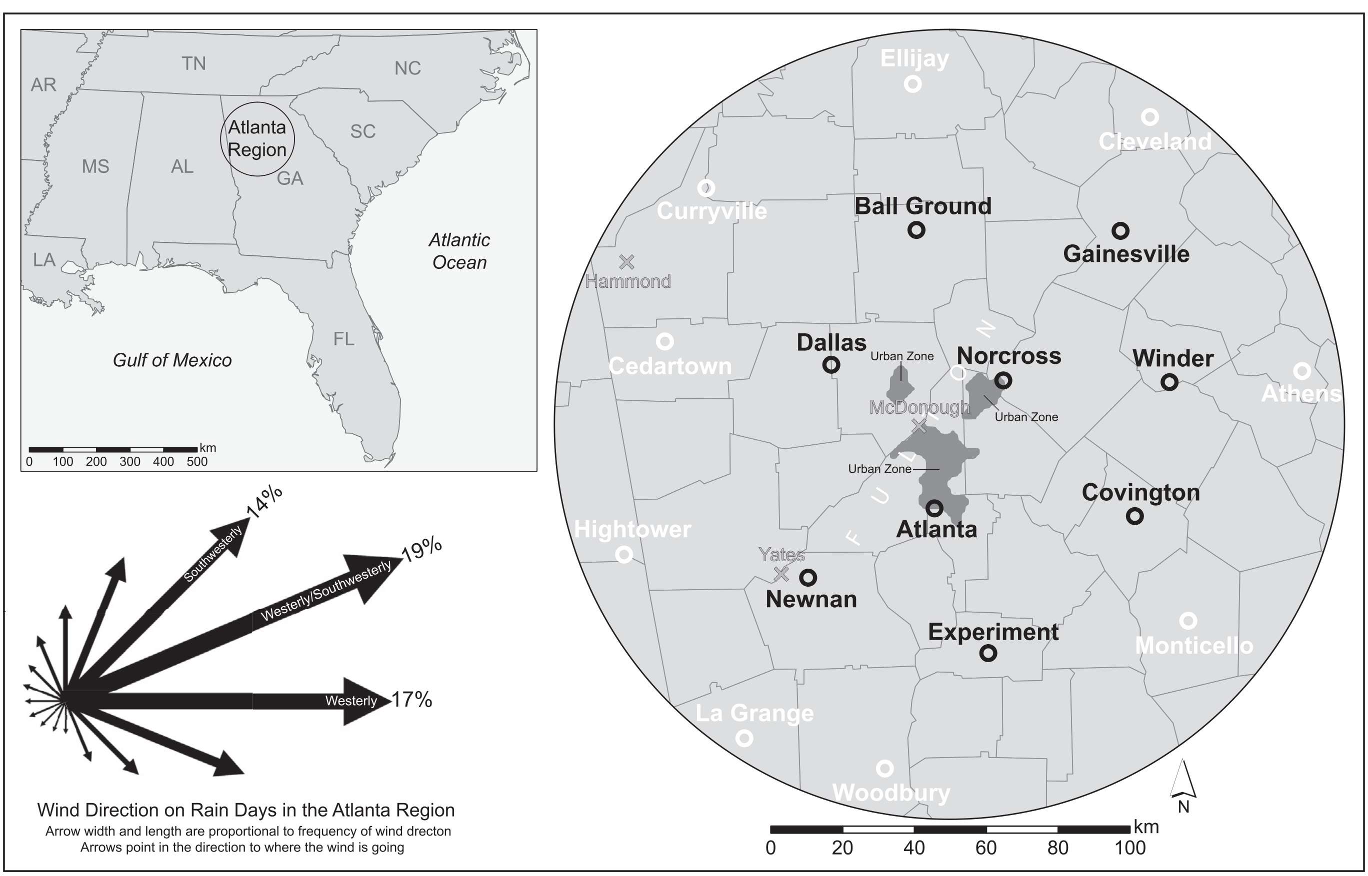

Fig. 2. Location of the study region within the southeastern United States and locations of the nine candidate precipitation stations (black circles), the nine reference precipitation stations (white circles), the three power plants (Hammond, McDonough, and Yates) in operation prior to 1970, and the urban zones of metropolitan Atlanta circa 1973. Also shown are lower-troposphere wind directions on rainfall days at the 18 precipitation stations during the 1948–1977 period. Daily wind data at 850 hPa, 700 hPa, and 500 hPa for grid cells corresponding to the Atlanta region were extracted from the NCEP/NCAR Reanalysis dataset of the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (Kalnay et al., 1996).

(U.S. Environmental Protection Agency, 1973). Secondly, there are many long-term precipitation stations in the Atlanta region that have similar rainfall totals (Diem, 2013). Thirdly, there is climatological evidence for the enhancement of heavy rainfall downwind of the urban area during the past several decades (Diem and Mote, 2005; Diem, 2008). Finally, multiple studies have examined the effects of the Atlanta urban area on rainfall and lightning enhancement (Dixon and Mote, 2003; Diem and Mote, 2005; Mote et al., 2007; Diem, 2008; Rose et al., 2008; Shem and Shepherd, 2009; Bentley et al., 2010; Ashley et al., 2012; Bentley et al., 2012; Stallins et al., 2013), but no studies have focused on the potential impacts of changes in particulate concentrations on rainfall.

2. Materials and methods

2.1. Rainfall data

Daily rainfall totals for summer (i.e. June–August) seasons from 1948 to 2009 for 18 National Weather Service cooperative stations (Athens, Atlanta, Ball Ground, Cedartown, Cleveland, Covington, Curryville, Dallas, Ellijay, Experiment, Gainesville, Hightower, La Grange, Monticello, Newnan, Norcross, Winder, and Woodbury) were obtained from the National Oceanic and Atmospheric Administration (Table 1) (Diem, 2013). The stations comprised nine candidate stations (Atlanta, Ball Ground, Covington, Dallas, Experiment, Gainesville, Newnan, Norcross, and Winder), which were the stations closest to the urban zones (i.e. large patches of urban land cover) of the Atlanta region, and nine reference stations (Athens, Cedartown, Cleveland, Curryville, Ellijay, Hightower, La Grange, Monticello, and Woodbury), which were at least 80 km from downtown Atlanta and assumed to have been affected negligibly by particulate matter originating from urban Atlanta (Fig. 2). Urban land was determined from a 1973 land-cover database of the Atlanta region (Yang and Lo, 2002). Automated Surface Observing Stations (ASOS) instrumentation, which includes tipping-bucket raingages, was implemented at Athens in 1994 and Atlanta in 1995. Diem and Mote (2005) compared rainfall totals from manual raingages and tipping-bucket raingages in the Atlanta region and found that precipitation totals at tipping-bucket stations were typically about 12% lower than precipitation totals at manual raingages. Therefore, ASOS-measured rainfall totals at Athens and Atlanta used in this study were multiplied by 1.12. Using hour-of-observation data obtained from monthly climatological data publications provided by the National Climatic Data Center for all applicable years, daily precipitation totals were associated with the day on which most of the precipitation most likely occurred. For example, precipitation totals associated with an 8 A.M. observation time have been shifted to the previous day. The entire dataset was missing 4.2% of the daily precipitation totals (Table 1). Missing values at all stations were replaced with precipitation estimates based on an inverse-distance weighting (IDW) scheme involving data from nearby stations (Diem, 2013; Xia et al., 1999).

2.2. Predicted rainfall values

Summer rainfall totals at the nine candidate stations (Atlanta, Ball Ground, Covington, Dallas, Experiment, Gainesville, Newnan, Norcross, and Winder) were predicted for each of the 62 years using weighted totals at the reference stations (Athens, Cedartown, Cleveland, Curryville, Ellijay, Hightower, La Grange, Monticello, and Woodbury) (Fig. 2). In addition, quartile-specific values of rainfall days and seasonal rainfall were predicted for Atlanta, Covington, Norcross, and Winder for the 1948–1977 period. All rainfall days at the 18 stations during the period were used in the determination of quartile thresholds for the rainfall days. Inverse-distance weighting was used as the weighting procedure; thus, the closest reference station had the largest influence on the predicted total at a candidate station. A candidate station had an observed and predicted rainfall value for each year.

2.3. Discontinuity testing

Identifying potential discontinuities in rainfall totals was performed using a regression-based technique (Solow, 1987; Easterling and Peterson, 1995). The prediction procedure described in the previous section minimizes the impact of interannual variability in synoptic circulation on discontinuities; therefore, the discontinuities would reflect mostly changes in the urban boundary layer relative to the rural boundary layer. Differences between observed and predicted rainfall totals from the nine candidate stations were summed for each year. Pooling differences from nine stations reduced the chances of a discontinuity caused by station-specific inhomogeneities (i.e. changes in instruments, observing practices, station locations, or station environment) in any of the nine time series. Therefore, the identified discontinuities would have been caused by atmospheric variations. Both *F* tests of likelihood ratio

Table 1
The 18 precipitation stations used in the study along with the National Weather Service identification number and the percentage of days with missing daily rainfall totals for each station.

Station	ID	% missing
Athens	90435	0.1
Atlanta	90451	0.0
Ball Ground	90603	1.5
Cedartown	91732	0.8
Cleveland	92006	1.7
Covington	92318	3.9
Curryville	92429	1.5
Dallas	92485	1.8
Ellijay	93115	0.6
Experiment	93271	9.9
Gainesville	93621	0.2
Hightower	13842	2.9
La Grange	94949	11.9
Monticello	95988	8.0
Newnan	96335	3.9
Norcross	96407	7.0
Winder	99466	19.8
Woodbury	99506	0.3

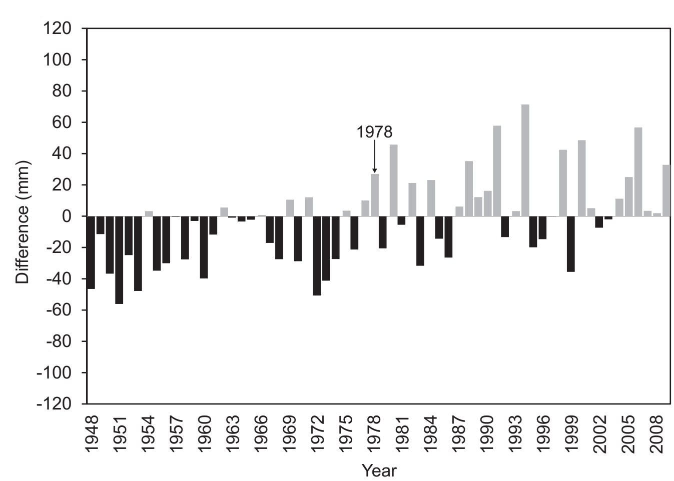

Fig. 3. Mean differences between observed and predicted seasonal rainfall totals for the nine candidate stations. The only significant discontinuity occurred in 1978.

statistics and Student's t tests were used to test for significant discontinuities (Easterling and Peterson, 1995); the t tests involved testing for differences between the twelve years prior and the twelve years after a potential discontinuity. The chosen significance levels for the one-tailed F tests and one-tailed t tests were 0.05 and 0.01, respectively.

2.4. Difference testing

The entire period, 1948–2009, was divided into 34 over-lapping 30-yr periods (i.e. 1948–1977, 1949–1978, …, 1980–2009), and both Student's t tests and Mann–Whitney U tests were used to test for significant differences between the observed and predicted values at each candidate station for each period. One-tailed tests with significance levels of 0.01 were used. To minimize the probability of stating incorrectly that either suppression or enhancement occurred, only the larger of the two P-values was considered.

3. Results and discussion

The Atlanta urban region underwent a rapid rebound in rainfall in the late 1970s (Fig. 3). The only significant discontinuity in the time series occurred in 1978. This discontinuity does not represent changes in instruments, observing practices, station locations, or station environment. It also is minimally affected by interannual variations in synoptic conditions.

Significant rainfall suppression occurred over and downwind (i.e. east to northeast) of urbanized Atlanta during 30-yr periods that comprise all or portions of the decades of the 1950s, 1960s, and 1970s (Fig. 4). Conversely, there was no significant rainfall

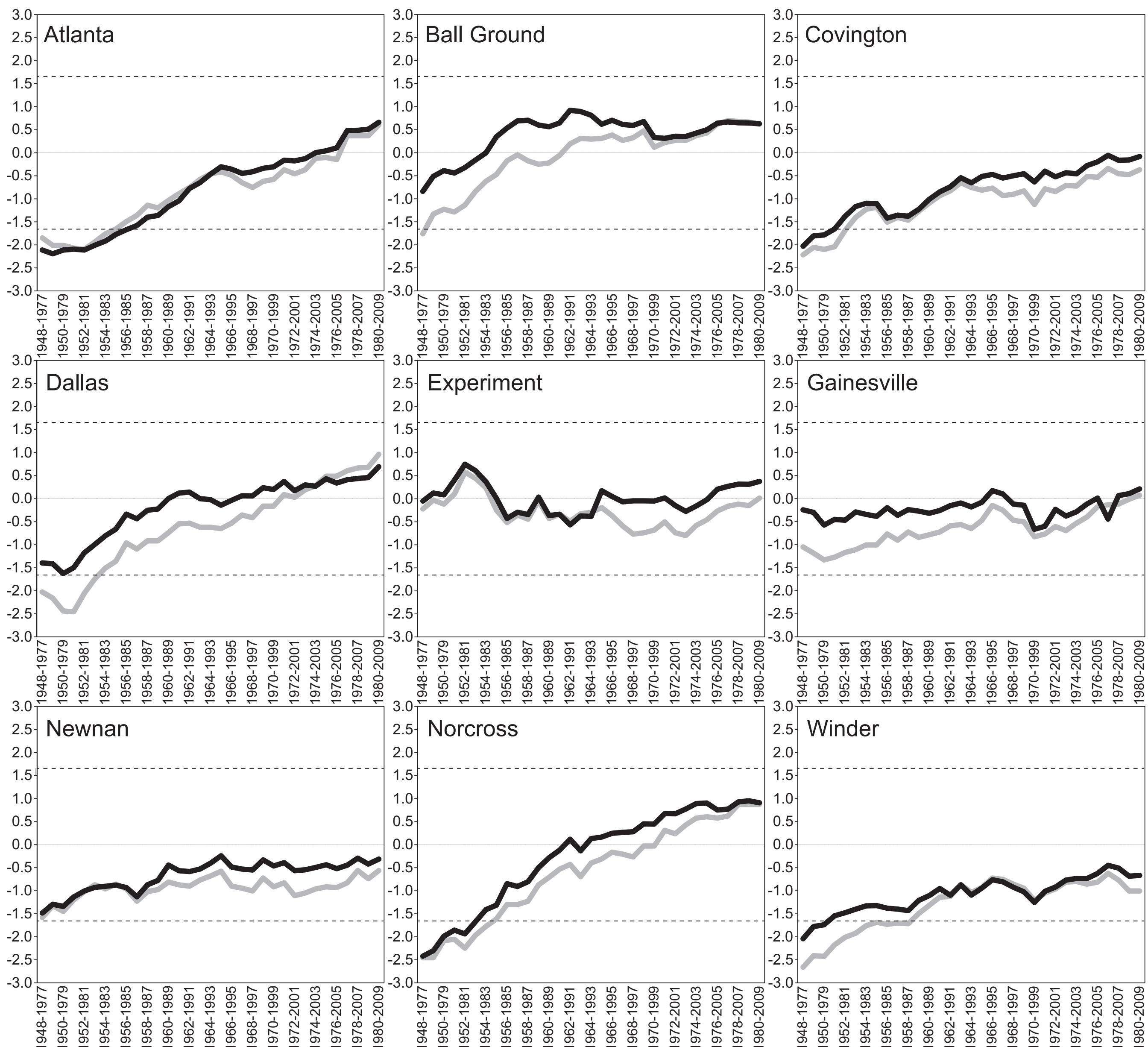

Fig. 4. Temporal variations in difference statistics for 34 over-lapping climate periods. Each of the 34 periods has a t statistic from a Student's t test and a z statistic from a Mann–Whitney U test. Black (gray) lines show changes in t (z) statistics. Significant positive differences (i.e. observed > predicted) are above the upper horizontal line and significant negative differences (i.e. observed < predicted) are below the lower horizontal line. The significance level is 0.01 for a one-tailed test.

Table 2
Observed (O), predicted (P), and difference (Δ) values for the 1948–1977 period for frequencies of rainfall days and rainfall totals (in mm). The quartiles were based on daily rainfall totals and the bounds were as follows: ≥ 0.254 mm and <2 mm, ≥2 mm and <6 mm, ≥6 mm and <15 mm, and ≥15 mm.

	Total			1st quartile			2nd quartile			3rd quartile			4th quartile		
	O	P	Δ	O	P	Δ	O	P	Δ	O	P	Δ	O	P	Δ
Rainfall Days															
Atlanta	31.4	30.0	+1.4	9.3	6.4	+2.7[a]	7.7	7.8	−0.1	7.8	8.0	−0.2	6.7	7.8	−1.1[a]
Covington	29.6	29.6	0.0	7.5	6.0	+1.5[a]	8.2	7.8	+0.4	7.5	8.0	−0.5	6.4	7.7	−1.3[a]
Norcross	28.8	29.5	−0.7	7.2	6.2	+1.0	7.0	7.7	−0.7	8.3	8.0	+0.3	6.4	7.6	−1.2[a]
Winder	28.9	29.1	−0.2	6.9	5.8	+1.1	7.5	7.7	−0.2	8.0	8.0	0.0	6.5	7.6	−1.1[a]
Rainfall Totals															
Atlanta	308	349	−41[a]	7.8	6.2	+1.6[a]	29	29	0	78	79	−1	194	235 -	41[a]
Covington	305	346	−41[a]	7.3	6.0	+1.3[a]	31	29	+2	74	79	−5	192	231	−39[a]
Norcross	294	343	−49[a]	6.3	6.0	+0.3	26	29	−3	81	79	+2	181	229	−48[a]
Winder	298	340	−42[a]	6.4	5.8	+0.6	29	29	0	78	79	−1	185	226 -	41[a]

[a] Significant at $\alpha = 0.01$.

enhancement at any station during any time period. Suppression of summer rainfall occurred at Atlanta, Covington, Norcross, and Winder for the following periods: 1948–1977, 1949–1978, and 1950–1979. Both Atlanta and Norcross shared three additional suppression periods (1951–1980, 1952–1981, and 1953–1982), with Atlanta having still two more periods (1954–1983 and 1955–1984). The suppression over and downwind of Atlanta occurred even while urban-related factors that promote rainfall enhancement were present.

Rainfall suppression from 1948 to 1977 (i.e. the first period) at Atlanta, Covington, Norcross, and Winder involved a shift from heavy-rainfall days to light-rainfall days (Table 2). The total amount of observed rainfall was between 40 and 50 mm less than the predicted rainfall. At all four stations, there was suppression of both the seasonal frequencies of fourth-quartile rainfall days and the seasonal rainfall totals for fourth-quartile days. There was enhancement of both seasonal frequencies of first-quartile rainfall days and the seasonal rainfall totals for first-quartile days at Atlanta and Covington. Consequently, rainfall suppression involved a decrease of heavy-rainfall days, and, to a lesser degree, an increase in light-rainfall days.

Historical suppression of summer rainfall in the Atlanta region was much more intense than is the recent and present-day enhancement of rainfall. Much research has gone into examining either urban-induced initiation or enhancement of rainfall or lightning or both, and a fair amount of that research has involved the Atlanta region (Dixon and Mote, 2003; Diem and Mote, 2005; Mote et al., 2007; Diem, 2008; Rose et al., 2008; Shem and Shepherd, 2009; Bentley et al., 2010; Ashley et al., 2012; Bentley et al., 2012; Stallins et al., 2013). This is the first study to examine the possibility of rainfall suppression in Atlanta. Seasonal rainfall at Atlanta, Covington, Norcross, and Winder was suppressed by up to at least 40 mm, which is substantial given that the mean seasonal rainfall was approximately 300 mm. Significant enhancements of seasonal rainfall totals have never been discovered in the Atlanta region; rather, enhancement appears to be limited to an increased frequency of heavy-rainfall days (Diem, 2008).

4. Conclusions

The reduction in particulate emissions in the 1970s caused a rapid rebound in summer rainfall in the Atlanta region. There was suppression of rainfall over and downwind of the Atlanta urbanized area during 30-yr periods that comprise all or portions of the decades of the 1950s, 1960s, and 1970s. This suppression occurred even while urban-related factors that promote rainfall enhancement were present. Atlanta is most likely not a unique case; therefore, particulate-induced rainfall suppression might have occurred over and downwind of other U.S. urban areas prior to the late 1970s. It is hoped this study will spur research on rainfall suppression by particulates prior to the middle to late 1970s in other U.S. urban areas.

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