Interepochal Changes in Summer Precipitation in the Southeastern United States: Evidence of Possible Urban Effects near Atlanta, Georgia

Jeremy E. Diem

Department of Anthropology and Geography, Georgia State University, Atlanta, Georgia

Thomas L. Mote

Department of Geography, University of Georgia, Athens, Georgia

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ABSTRACT

Through modification of the planetary boundary layer, urbanization has the potential to have a significant impact on precipitation totals locally. Using daily summer-season precipitation data at 30 stations from 1953 to 2002, this study explores the possibility of urban effects as causes of spatial anomalies in precipitation in a zone within 180 km of Atlanta, Georgia. The time period is divided into consecutive epochs (e.g., 1953–77 and 1978–2002), and interepochal differences in precipitation totals, heavy-precipitation days, cumulative heavy precipitation, and atmospheric conditions are explored. The southern stations experienced significant decreases in precipitation, whereas significant precipitation increases occurred at central/west-central stations. The most striking increases occurred at Norcross, Georgia, which is ~30 km northeast of downtown Atlanta; Norcross had the third smallest number of heavy-precipitation days during 1953–77, but, during 1978–2002, it had the most heavy-precipitation days. Not only did the amount of urban land cover upwind of Norcross increase substantially from the earlier to the later epochs, but regionwide dewpoint temperatures also increased significantly. Therefore, it is suspected that the increased precipitation at Norcross was caused by urban effects, and these effects may have been enhanced by increased atmospheric humidity.

1. Introduction

Changes in land cover and land use can have a significant impact on land–atmosphere interactions. In turn, changes in those interactions can cause climatic changes, such as changes in precipitation. The initiation and enhancement of convective clouds—and, subsequently, precipitation modification—can occur in concert with other changes in landscape heterogeneity (Rabin et al. 1990), such as through the juxtaposition of crop lands and forest lands (Brown and Arnold 1998), irrigated lands and grasslands (Barnston and Schickedanz 1984), and urban lands and rural lands (e.g., Changnon 1981). Therefore, urbanization is one of the land-altering processes that can lead to changes in precipitation characteristics.

In theoretical terms, land cover and land use changes associated with urbanization have the potential to initiate and enhance precipitation, which, by way of thunderstorms, has deleterious impacts on society through increased flooding, soil erosion, and lightning strikes. Changnon et al. (1976) lists the major potential causes of precipitation enhancement as 1) increased cloud condensation nuclei (CCN) and ice nuclei; 2) increased surface roughness, which results in low-level convergence and upward vertical velocities; and 3) increased surface temperatures [i.e., urban heat island (UHI)]. Empirical work and modeling work suggest that precipitation enhancement is caused primarily by the heat island and increased surface roughness; the relatively deep urban planetary boundary layer (PBL) is advected downwind of the urban area (in Auer 1981; Hjelmfelt 1982). Using multiple numerical modeling simulations that only accounted for the UHI, Baik et al. (2001) demonstrated that UHI-forced convection can cause precipitation downwind of the UHI. In another precipitation-initiation study, however, Rozoff et al. (2003) concluded that the effects of increased surface roughness and the UHI may not be additive, because surface roughness may weaken the UHI. Regarding CCN, the positive effect of urban CCN on precipitation is not definite; in fact, Rosenfeld (2000) noted that particles emitted by industrial sources can cause small cloud droplets to form, which does not promote precipitation enhancement.

Corresponding author address: Dr. Jeremy E. Diem, Department of Anthropology and Geography, Georgia State University, Atlanta, GA 30303-3083.
E-mail: gegjed@langate.gsu.edu

The Metropolitan Meteorological Experiment (METROMEX) study, which was an intensive field campaign conducted in the St. Louis, Missouri, area from 1971 to 1975, mostly during June, July, and August, uncovered a strong relationship between urban land cover and precipitation enhancement [see Changnon (1981) for a review]. Rainfall downwind of St. Louis substantially exceeded rainfall upwind of the city. The rainfall difference was most pronounced for heavy-rainfall events—downwind locales had 2 times as many heavy-rainfall events as did upwind locales (Semonin 1981). Major conclusions from the 5-yr project were as follows: 1) urban convective clouds, when compared with rural clouds, generally reached greater heights, lasted longer, and were more likely to merge with other clouds (Braham 1981); 2) although precipitation enhancement occurred with a variety of storm systems, enhancement resulted primarily from heavy rains from a relatively small number of squall-line storms (Braham 1981); and 3) enhancement also occurred through the initiation of new storm cells over the city (Changnon et al. 1976). It was generally concluded that precipitation enhancement downwind of St. Louis resulted mostly from the modification of boundary layer dynamics from thermal and frictional forcing resulting from urban land cover (Braham 1981).

Over the past 40 yr, urban precipitation research in the United States has not been confined to the St. Louis area; however, research in other U.S. urban areas has not been as rigorous, and thus it has been more open to criticism. For example, research has been conducted in Chicago, Illinois; Cleveland, Ohio; Houston, Texas; Indianapolis, Indiana; New Orleans, Louisiana; Tulsa, Oklahoma; Washington, D.C. (Huff and Changnon 1973); Detroit, Michigan (Sanderson and Gorski 1978); and Pittsburgh, Pennsylvania (Rosenberger and Suckling 1989). Based on a thorough critique of urban precipitation studies, Lowry (1998) noted that the urban effects being sought usually cannot be distinguished from those of other influences, such as local topography and temporal changes in the relative frequencies of different synoptic weather types. Even the downwind increase in precipitation observed during METROMEX might be explained partially by increased topographic relief in the form of bluffs (Braham 1981).

Despite the aforementioned drawbacks of precipitation-enhancement studies that do not employ intensive field campaigns, it is those studies based on relatively long time periods and employing a relatively dense network of weather stations that provide the most convincing evidence of urban effects. Those climatological studies include Huff and Changnon (1972, 1973). Huff and Changnon (1972) found increased precipitation totals and increased precipitation days, including heavy-precipitation days, downwind of St. Louis from 1941 to 1968. Days and seasons were stratified, thereby leading to the following conclusions: the greatest enhancement occurred in conjunction with cold fronts; enhancement was most pronounced in relatively wet summers; and suppression may have occurred in the dry summers (Huff and Changnon 1972). Huff and Changnon (1973) used similar methods and determined that warm-season rainfall increased within and downwind of Chicago, Cleveland, Houston, New Orleans, St. Louis, and Washington during the 1955–70 period.

What appears to be the most serious deficiency of the urban-precipitation research is a lack of a climatological perspective when analyzing precipitation. Daily data from a robust number of sites within a geographic domain for multiple decades that span the development of an urban area should be employed in the detection of precipitation anomalies associated with urbanization. A long time period can be divided into consecutive epochs (e.g., Karl and Riebsame 1984), thereby enabling the diminution of topographic effects on precipitation for certain analyses in addition to the elucidation of atmospheric-circulation differences between epochs.

It needs to be noted as well that most precipitation-enhancement research has relied on isohyetal maps (i.e., precipitation surfaces created with spatial-interpolation techniques) with unknown accuracy as evidence of increased precipitation within and downwind of urban areas. As a consequence, it is difficult to attach a substantial amount of credibility to precipitation surfaces used by various authors in their attempts to verify precipitation enhancement.

Based on the need for a novel examination of urban effects on precipitation, this study presents a climatological analysis of spatial anomalies in precipitation. The major objectives of this study are 1) to determine whether spatial anomalies in precipitation characteristics have existed near Atlanta, Georgia; and 2) to explore changes in land cover and atmospheric conditions as causes of those anomalies.

2. Study region

The Atlanta region, which is located in the southeastern United States, has a humid subtropical climate. For this study, the Atlanta region is defined as a circle with a diameter of 360 km centered on downtown Atlanta (Fig. 1). The physiography within the region includes the Coastal Plain, Piedmont, Blue Ridge, and Valley and Ridge provinces. The Atlanta region is an excellent study region for the following reasons: precipitation is frequent and often intense during the summer months (Konrad and Meentemeyer 1994; Keim 1997); it contains a spatially extensive UHI (Quattrochi et al. 2000); and case-study convergence/precipitation research (Bornstein and Lin 2000) and multiyear precipitation-initiation research (Dixon and Mote 2003) have been conducted, and results from other precipitation studies have been debated in the literature (Shepherd et al. 2002; Diem et al. 2004; Shepherd 2004).

Metropolitan Atlanta has experienced tremendous

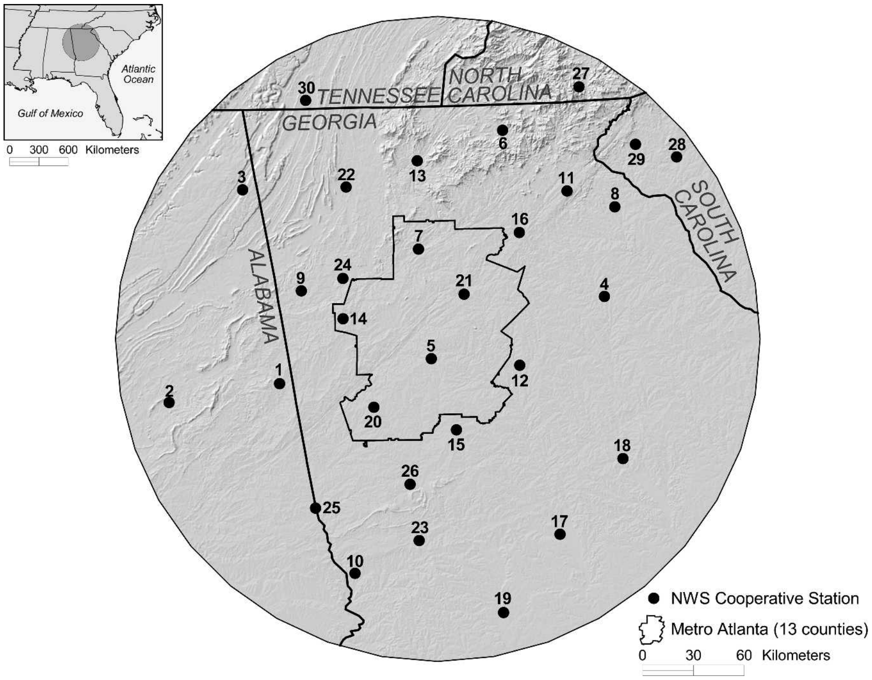

FIG. 1. Map of the study region showing locations of the 30 precipitation stations and the boundary of the Atlanta metropolitan area. Numbers denote the precipitation stations; station names and associated information are available in Table 1.

population growth and associated land cover and land use changes over the past 50 yr. Population in the innermost 13 counties of the Atlanta metropolitan statistical area (MSA) (see Fig. 1) grew from ~840 000 in 1950 to ~3 700 000 people in 2000, with the mean growth rate per decade over the 50 years exceeding 34% (U.S. Census Bureau 2001). From 1973 to 1998 for those 13 counties, Yang and Lo (2002) found a decrease in forest cover coincident with an increase in low-intensity urban cover. Urban land cover was 16% of the area in 1973; however, it had increased to 34% by 1998. Forest land decreased from 63% to 50%. The spread of high-intensity urban lands occurred along the major transportation routes (Yang and Lo 2002). As a result of the urbanization, Atlanta's UHI (Taha et al. 1999; Quattrochi et al. 2000) has presumably both increased in size and intensified over the past several decades.

Previous research investigating urban impacts on precipitation and precursor processes has been far from conclusive. For May through September of 1998–2000 using precipitation estimates from the Tropical Rainfall Measuring Mission satellite, Shepherd et al. (2002) concluded that precipitation enhancement occurred ~60 km south-southeast of Atlanta. In a critique of Shepherd et al. (2002), Diem et al. (2004) concluded that the perceived enhancement was most likely a bias of the satellite's sensor to tropical-system clouds, which were most prevalent to the south and southeast of Atlanta. Furthermore, based on lower-tropospheric airflow, Diem et al. (2004) stated that the "maximum impact area" should have been located to the east-northeast of Atlanta rather than to the south-southeast of Atlanta. For the same time period, Dixon and Mote (2003) found a majority of UHI-initiated precipitation events in the Atlanta metropolitan area to be located north of the city. However, Dixon and Mote (2003) focused on precipitation initiation as opposed to precipitation enhancement and only 37 events during May–September of 1996–2000 were considered. Last, based on case-study results from 26 July to 3 August 1996, Bornstein and Lin (2000) suggested that precipitation in the Atlanta area may be enhanced by the UHI. For the three case-study days, a front was located over the southeastern United States; therefore, the surface convergence that led to the precipitation may not have been caused entirely by the UHI.

3. Data

This research relied on summer-season (June, July, and August) data from 1953 to 2002 for ground-measured precipitation and lower-tropospheric conditions. In addition, historical land cover data were utilized. Data pertain to the summer season because the core of the METROMEX research occurred during the summer, and the summer climates of St. Louis and Atlanta are roughly similar.

Daily precipitation data from 30 stations within 180 km of Atlanta were extracted from the TD3200 and

TABLE 1. Characteristics of the 30 weather stations used in the study. "Percent missing" refers to the percent of days without valid daily precipitation totals. Latitude (N), longitude (W), slope, and aspect are reported in degrees. Elevation and relief are reported in meters. Identification number is indicated by "ID."

ID	Station	State	Coop ID[a]	Database	Percent missing	Lat	Lon	Elev[b]	Slope[b]	Aspect[b]	Relief[c]
1	Hightower	AL	13842	TD3200	3.0	33.53	85.40	335	7	126	67
2	Talladega	AL	18024	TD3200	0.2	33.44	86.10	187	3	264	44
3	Valley Head	AL	18469	TD3200	0.1	34.56	85.62	382	6	263	110
4	Athens	GA	90435	TD3210	0.1	33.95	83.32	223	3	334	54
5	Atlanta airport	GA	90451	TD3210	0.0	33.65	84.43	302	2	41	58
6	Blairsville	GA	90969	TD3200	0.0	34.85	83.94	617	10	195	76
7	Canton	GA	91585	TD3200	0.0	34.23	84.50	293	7	296	37
8	Carnesville	GA	91619	TD3200	0.6	34.42	83.23	231	4	52	38
9	Cedartown	GA	91732	TD3200	0.2	34.02	85.25	248	2	338	27
10	Columbus	GA	92166	TD3210	0.7	32.52	84.94	124	2	169	55
11	Cornelia	GA	92283	TD3200	0.1	34.52	83.53	446	6	292	208
12	Covington	GA	92318	TD3200	3.4	33.60	83.87	220	3	231	51
13	Ellijay	GA	93115	TD3200	0.7	34.70	84.49	437	10	173	82
14	Embry	GA	93147	TD3200	0.0	33.87	84.99	374	4	192	89
15	Experiment	GA	93271	TD3200	0.9	33.27	84.28	275	3	328	56
16	Gainesville	GA	93621	TD3200	0.2	34.30	83.85	359	5	306	52
17	Macon	GA	95443	TD3210	0.0	32.70	83.65	102	2	23	26
18	Milledgeville	GA	95874	TD3200	1.5	33.09	83.24	101	4	125	30
19	Montezuma	GA	95979	TD3200	0.1	32.29	84.02	107	3	243	32
20	Newnan	GA	96335	TD3200	0.2	33.40	84.80	273	4	278	54
21	Norcross	GA	96407	TD3200	0.0	33.99	84.21	294	4	294	31
22	Resaca	GA	97430	TD3200	0.1	34.57	84.95	201	3	11	21
23	Talbotton	GA	98535	TD3200	0.5	32.68	84.54	201	3	343	46
24	Taylorsville	GA	98600	TD3200	0.2	34.08	84.98	230	4	33	29
25	West Point	GA	99291	TD3200	1.0	32.87	85.18	184	3	113	20
26	Woodbury	GA	99506	TD3200	0.3	32.98	84.58	235	2	80	42
27	Coweeta	NC	312102	TD3200	0.0	35.07	83.43	833	19	102	217
28	Clemson	SC	381770	TD3200	0.1	34.68	82.82	227	4	265	42
29	Walhalla	SC	388887	TD3200	0.0	34.75	83.08	297	5	166	56
30	Chattanooga	TN	401656	TD3210	0.0	35.03	85.20	209	3	4	43

[a] Part of the National Weather Service's Cooperative Station Network.

[b] Calculated with a 30-m-resolution digital elevation model for a 28-km^2 circular region centered on the station.

[c] Calculated with a 30-m-resolution digital elevation model; mean elevation for a 28-km^2 circular region centered on the station minus mean elevation for a 113-km^2 circular region centered on the station.

TD3210 databases of the National Climatic Data Center (NCDC) (Table 1). The National Weather Service (NWS) cooperative stations fulfilled one or both of the following criteria: they did not have more than 20% of days missing for any month or they were locations that improved the spatial coverage of the station network. Those stations that did not fulfill the first criterion but satisfied the second criterion were Gainesville, Milledgeville, Talbotton, and Woodbury, Georgia. Less than 0.5% of the daily precipitation totals were missing (Table 1), and all 649 missing values were estimated based on an inverse-distance weighting scheme—which was found by Xia et al. (1999) to be just as accurate as other missing-value-estimation methods—involving data from at least two nearby stations. Any station having data for the selected missing-data day was a potential predictor station; all predictor stations are not shown in Fig. 1. The final database of daily precipitation totals is serially complete for all 30 stations.

Using hour-of-observation data obtained from monthly climatological data publications provided by the National Oceanic and Atmospheric Administration for all 50 yr, daily precipitation totals were associated with the day on which most of the precipitation probably occurred. Therefore, precipitation totals for morning observations were moved to the previous day. Afternoon/evening observations were made only at Cedartown (1994–2000), Georgia; Clemson (1957–63), South Carolina; Coweeta (1953–57), North Carolina; Experiment (1993), Georgia; and Talladega (1953–76, 1981–94), Alabama. Comparisons of precipitation totals at the evening-observation stations with precipitation totals at nearby stations with morning observation times indicated that only daily totals at Experiment in 1993 should be moved to the previous day.

Also concerning daily precipitation totals, the Automated Surface Observation System (ASOS) instrumentation was implemented at Athens, Georgia, in 1994, the Hartsfield-Jackson Atlanta International Airport (hereinafter Atlanta airport) in 1995, Chattanooga, Tennessee, in 1996, Columbus, Georgia, in 1994, and Macon, Georgia, in 1994. This system uses a tipping-bucket rain gauge; thus, for high rainfall rates, the undercatch resulting from the bucket tipping while the rain is falling could be substantial (Heinemann et al. 2002). Preliminary analyses of time series of seasonal precipitation totals indicated that there was an underestimate of precipitation totals during the employment of ASOS. By comparing daily precipitation totals at Georgia Automated Environmental Monitoring (GAEM) tipping-bucket stations (i.e., Blairsville, Griffin, Plains, and Watkinsville) with approximately collocated NWS cooperative stations (i.e., Blairsville, Experiment, Plains, and the University of Georgia Plant Sciences Farm), it was found that precipitation totals at GAEM stations were typically about 12% lower than totals at the cooperative stations. As a consequence, ASOS-measured precipitation values were multiplied by 1.12 to adjust for the suspected reduced precipitation totals associated with the tipping-bucket gauge. The above adjustment is probably conservative—comparisons of precipitation totals at ASOS stations near Gainesville and Rome, Georgia, with precipitation totals at nearby cooperative stations indicated that the adjustment factor might exceed 1.25.

Data pertaining to lower-tropospheric conditions above the region were composed of radiosonde measurements and modeled data. Wind measurements at 1200 UTC at 850 hPa above Athens for the 1962–93 period were acquired from the University Center for Atmospheric Research. Because soundings for north-central Georgia were made at Atlanta from 1953 to 1960 and at Peachtree City from 1995 to 2002, only those data measured at Athens were used. Also used were monthly data extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996), which was provided by the Climate Diagnostics Center of the National Oceanic and Atmospheric Administration and the Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES CDC). These data included geopotential height, air temperature, and dewpoint temperature at 1000, 925, 850, 700, and 500 hPa over the study region.

NCEP–NCAR reanalysis data also were used to construct the Bermuda high index (BHI) (Stahle and Cleaveland 1992) and a database of upper-level troughing days. The BHI is a measure of the slope of the sea level pressure gradient between Bermuda and New Orleans, Louisiana. Monthly sea level pressure (SLP) at grid points corresponding to Bermuda (32.33°N, 64.75°W) and New Orleans (29.95°N, 90.10°W) were used to construct the BHI. Standardized monthly SLP at New Orleans was subtracted from standardized monthly SLP at Bermuda (Stahle and Cleaveland 1992). Daily 500-hPa geopotential height surfaces were examined for troughs—which also included upper-level cyclones—directly over or to the immediate west of the study region.

Historical land cover data for the Atlanta metropolitan area were acquired from C. P. Lo (2004, personal communication) of the University of Georgia. The data consisted of spatially resolved classifications of land cover in 1973 and 1992. The classifications were composed of the following land cover classes: high-density urban land, low-density urban land, exposed/cultivated land, cropland/grassland, forest, and water. Information on the development of the land cover databases can be found in Yang and Lo (2002).

4. Methods

Multidecadal data from a robust number of stations (i.e., 30) facilitated the use of statistical analyses to detect and explain spatial anomalies in precipitation. The methods involved 1) assessing spatiotemporal variations in precipitation in the context of consecutive epochs, 2) testing for significant changes in precipitation between consecutive epochs, 3) testing for differences in atmospheric conditions between consecutive epochs, and 4) explaining some of the changes in precipitation, including increases that may have been caused by urbanization. Attention was placed on dividing the 50-yr period into relatively long segments (i.e., 25 and 16 yr), because extreme events, such as tropical systems, can have a great impact on sample statistics if the time period is relatively short (Landsberg 1981).

To assess changes of a phenomenon over time, the period was divided into consecutive epochs. The two sets of consecutive epochs were as follows: 1953–77/1978–2002 and 1962–77/1978–93. The examination of the 1962–93 period is advantageous, because ASOS, which appears to be associated with noticeable precipitation inhomogeneities at some of the stations, was not in operation during this period at any of the 30 precipitation stations in the study region.

Enhanced cartographic analyses of spatiotemporal changes in precipitation were enabled by the standardization of precipitation values. The precipitation values were standardized with respect to the mean and standard deviation of the 30 values for each epoch. As a result, a consistent and minimally biased classification of relative precipitation values (i.e., z scores) at the 30 stations was produced. The following precipitation variables were analyzed: seasonal totals of all precipitation, seasonal totals of heavy-precipitation days (i.e., days with $\geq$25.4 mm of precipitation), and seasonal totals of cumulative heavy precipitation (i.e., total amount of precipitation occurring on heavy-precipitation days). Focus was placed on heavy-precipitation days, owing to the findings for St. Louis of major increases of high-intensity precipitation events, such as thunderstorms, downwind of the city (Semonin 1981). Moreover, between the two heavy-precipitation variables, the frequency of heavy-precipitation days should have been less affected by tropical systems than was cumulative heavy precipitation.

Interepochal changes in raw seasonal precipitation values, standardized seasonal precipitation values, and atmospheric conditions were tested for statistical significance. Seasonal precipitation values were standardized with respect to the mean and standard deviation of the 30 values for each year. The resulting seasonal *z* scores represented the relative magnitude of a precipitation value at a station in comparison with the entire suite of stations. The Mann–Whitney *U* test, rather than the parametric alternative, the Student's *t* test, was used to assess the significance of changes in precipitation and atmospheric conditions. Because the Mann–Whitney *U* test is less affected by extreme events (e.g., tropical systems), significant changes between epochs only could exist if either relatively high values or relatively low values were prevalent within an epoch.

Last, the likelihood of urban effects occurring at stations in the Atlanta metropolitan area was assessed. This procedure entailed an examination of relationships between precipitation and wind direction. Thus, precipitation values specific to wind direction sectors for the consecutive epochs of 1962–77 and 1978–93 were determined. Data from the 1962–93 period were used to avoid the possible impacts of the switch to ASOS instrumentation at the Atlanta airport station.

5. Results and discussion

a. Differences in precipitation between epochs

Temporal changes in epochal *z* scores reveal zones of increases and decreases in relative precipitation (Figs. 2 and 3). Although there is some consistency among the precipitation variables, the most abrupt changes occurred for the heavy-precipitation variables. Considering all of the variables, the spatially cohesive changes can be generalized as follows: there is decreased precipitation for southern stations, increased precipitation for central/west-central stations, decreased precipitation for northern/northwestern stations (excluding Chattanooga), and stable precipitation for northeastern stations. The southern zone of declining *z* scores encompasses, from south to north, Montezuma, Columbus, Talbotton, West Point, Woodbury, Milledgeville, and Experiment, Georgia. The central/west-central zone of increasing *z* scores comprises from west to east Talladega, Hightower, Cedartown, Embry, Taylorsville, Newnan, Canton, Atlanta airport, and Norcross, Georgia. Northern stations that experienced mostly *z*-score decreases include, from west to east, Valley Head, Alabama; Resaca, Georgia; Ellijay, Georgia; Blairsville; and Coweeta. The stable northeastern stations are, from west to east, Gainesville; Cornelia, Georgia; Carnesville, Georgia; Walhalla, South Carolina; and Clemson. Of the remaining stations, Athens and Covington, Georgia, appear to be transitions between the southern and stable zones, whereas Chattanooga and Macon are stations with spatially anomalous increases in *z* scores.

Several stations had extremely large changes in *z* scores between epochs. The most striking increases engendered abrupt moves from strongly negative *z* scores to strongly positive *z* scores. Those increases occurred at Atlanta airport and Norcross for the heavy-precipitation variable. For example, Norcross had the third-smallest number of heavy-precipitation days during 1953–77, but, during 1978–2002, it had the most heavy-precipitation days. Concerning shifts from positive to negative *z* scores, noteworthy decreases happened at several southern stations (i.e., Columbus, Experiment, Milledgeville, West Point, and Woodbury) as well as at a northern station (i.e., Ellijay).

During all epochs, standardized precipitation values in the southern zone were not at all congruent with values in the central/west-central zone. This is especially true when orographically affected stations (see Fig. 1 and Table 1), such as Canton and, possibly, Embry, are not considered. Because the transition between these two zones is most abrupt between Atlanta airport and Experiment, it is inferred that the southern zone of declining *z* scores ended just south of Atlanta airport.

A minority of the stations had *significant* changes in precipitation—both raw and standardized—between the epochs, and most of those stations had decreased precipitation (Tables 2 and 3). Columbus, Covington, Ellijay, Experiment, Milledgeville, Montezuma, Talbotton, West Point, and Woodbury had significant decreases in raw precipitation. Those same stations, except for Covington, also had significant decreases in standardized precipitation. Therefore, a significant decrease in precipitation occurred at nearly every southern station. The significant decrease at the northern station of Ellijay is not a major spatial anomaly, because the two closest stations (Resaca and Blairsville) did not experience significant increases.

Significant increases in precipitation occurred primarily in the central/west-central zone. Those stations included Atlanta airport, Cedartown, Embry, Norcross, Talladega, and Taylorsville. Chattanooga and Talladega also had significant increases; however, those stations were not only on the fringe of the study region but they also did not have increases in raw precipitation. Thus, increases at those stations are considered to be less important than changes at Atlanta airport, Cedartown, Embry, Norcross, and Taylorsville. Of all of the stations, Norcross experienced the most significant increase in precipitation intensity. Both Norcross and Taylorsville had significant increases in raw heavy-precipitation days from 1953–77 to 1978–2002, but the percent increase in heavy precipitation days at Norcross in comparison with Taylorsville increased from 8% in 1953–77 to 18% in 1978–2002. Furthermore, only Norcross had significant increases in raw heavy-precipitation days and standardized heavy-precipitation days for both sets of consecutive epochs.

The extreme interannual variability of summer precipitation, especially heavy-precipitation days and cumulative heavy precipitation, in the southeastern

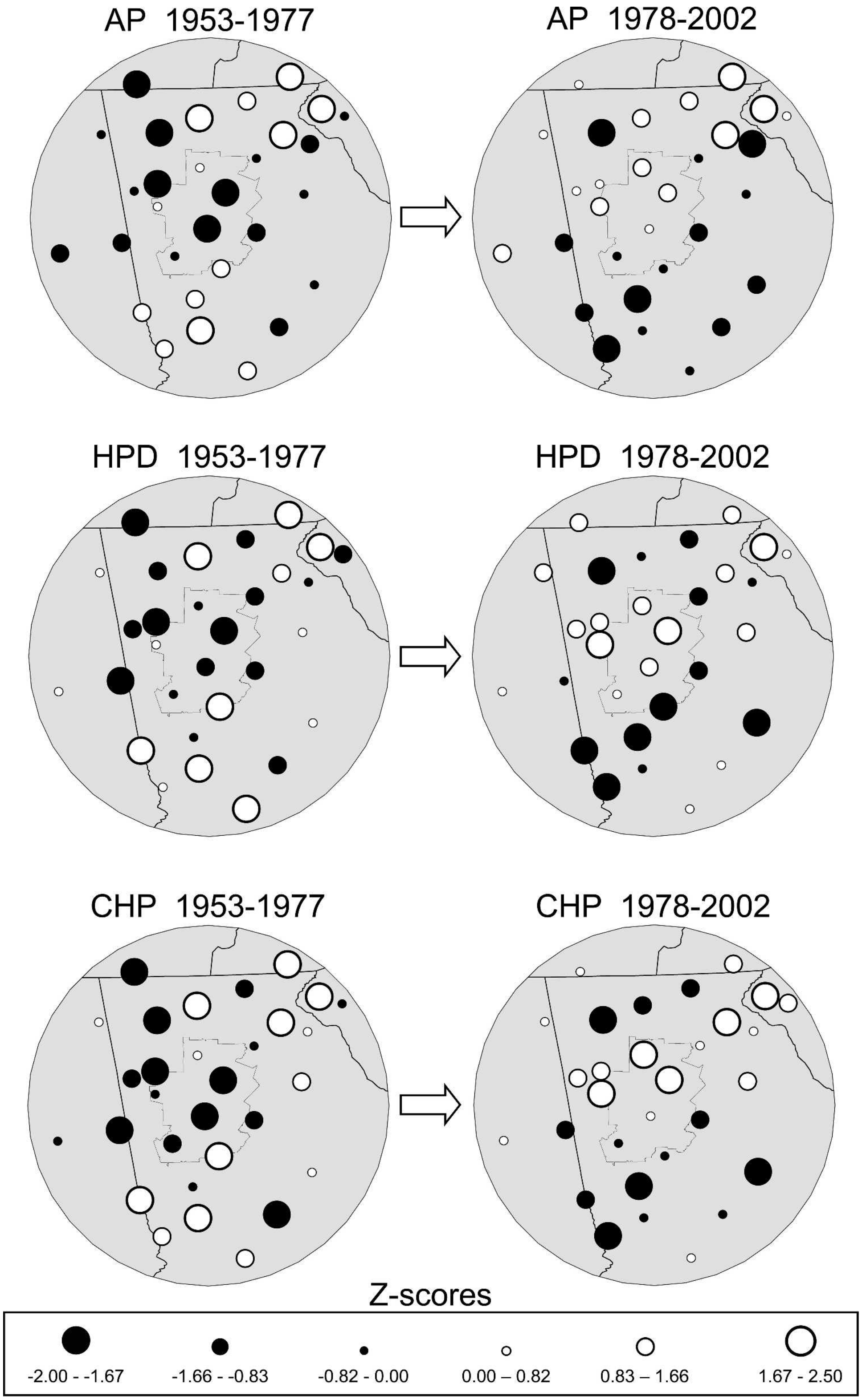

FIG. 2. Changes in *z* scores between 1953–77 and 1978–2002 for all precipitation (AP), heavy-precipitation days (HPD), and cumulative heavy precipitation (CHP). The *z* scores were calculated separately for each epoch using the mean and std dev of the 30 stations.

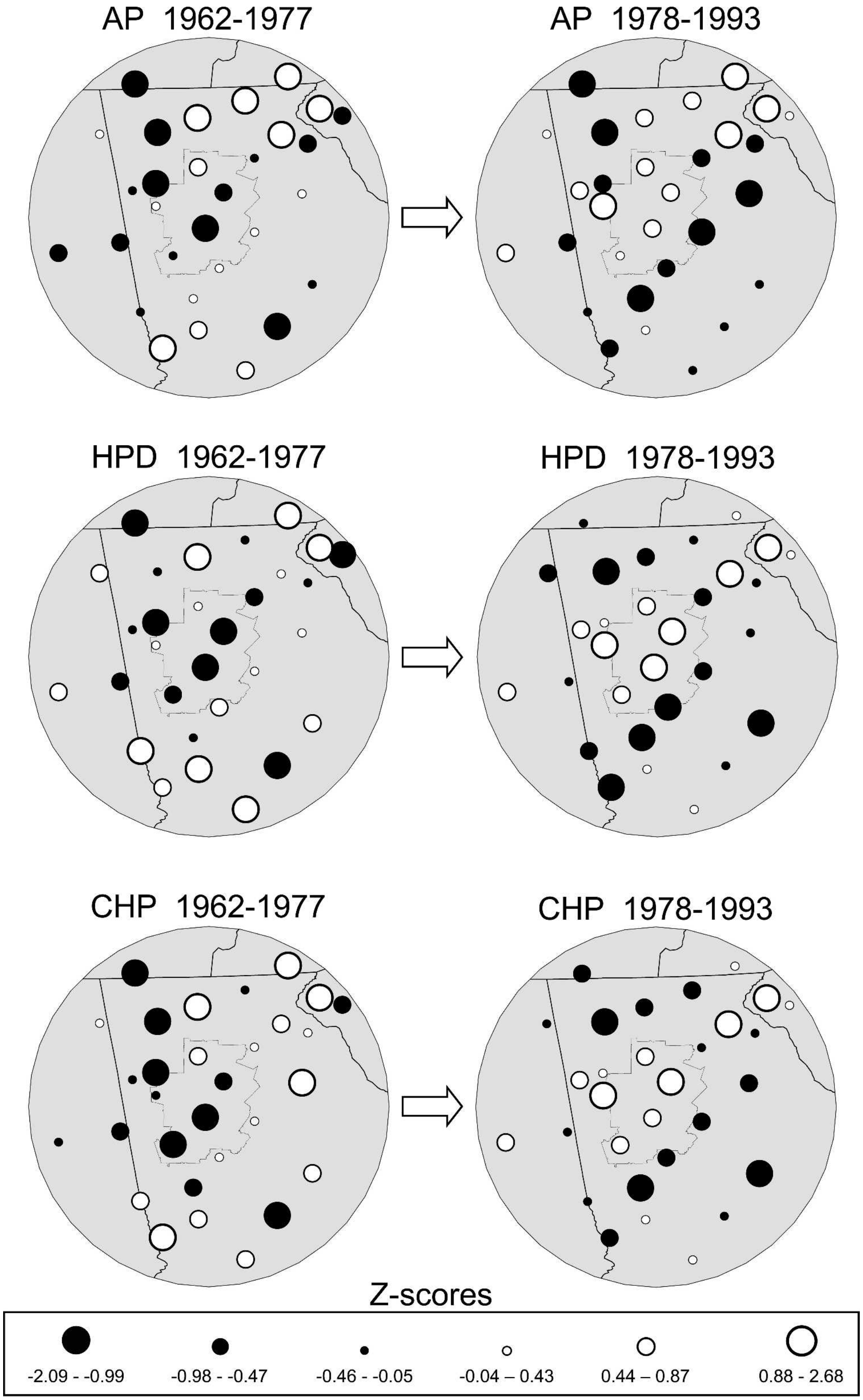

FIG. 3. As in Fig. 2 but showing changes in z scores between 1962–77 and 1978–93.

TABLE 2. Statistically significant increases (POS) and decreases (NEG) in raw values of all precipitation (AP), heavy-precipitation days (HPD), and cumulative heavy precipitation (CHP) from 1953–77 to 1978–2002 and from 1962–77 to 1978–93.

	AP		HPD		CHP	
Station	1953–77 to 1978–2002	1962–77 to 1978–1993	1953–77 to 1978–2002	1962–77 to 1978–1993	1953–77 to 1978–2002	1962–77 to 1978–1993
Hightower	—	—	—	—	—	—
Talladega	—	—	—	—	—	—
Valley Head	—	—	—	—	—	—
Athens	—	—	—	—	—	—
Atlanta airport	—	—	—	—	—	—
Blairsville	—	—	—	—	—	—
Canton	—	—	—	—	—	—
Carnesville	—	—	—	—	—	—
Cedartown	—	—	—	—	—	—
Columbus	NEG**	NEG**	NEG**	NEG**	NEG**	NEG**
Cornelia	—	—	—	—	—	—
Covington	—	NEG*	—	—	—	—
Ellijay	—	—	NEG**	NEG**	NEG**	NEG**
Embry	—	—	—	—	—	—
Experiment	NEG**	NEG*	NEG**	NEG*	NEG**	—
Gainesville	—	—	—	—	—	—
Macon	—	—	—	—	—	—
Milledgeville	—	—	NEG**	NEG**	NEG*	NEG**
Montezuma	NEG**	—	—	—	—	—
Newnan	—	—	—	—	—	—
Norcross	—	—	POS**	POS**	POS**	—
Resaca	—	—	—	—	—	—
Talbotton	NEG**	NEG*	NEG**	NEG*	NEG*	—
Taylorsville	POS**	—	POS**	—	POS**	—
West Point	—	—	NEG**	NEG*	NEG**	—
Woodbury	NEG**	NEG**	—	—	NEG**	NEG**
Coweeta	—	—	—	—	—	—
Clemson	—	—	—	—	—	—
Walhalla	—	—	—	—	—	—
Chattanooga	—	—	—	—	—	—

* Significance level $\alpha = 0.10$.
** Significance level $\alpha = 0.05$.

United States actually makes the aforementioned significant increases and decreases—which are determined with nonparametric tests—even more impressive. The mean coefficients of variation for all precipitation, heavy precipitation, and cumulative heavy precipitation for the 50-yr period were 0.34, 0.57, and 0.63, respectively. Precipitation values within an epoch for any given station are far from uniform.

b. *Changes in synoptic-scale atmospheric conditions between epochs*

Coincident with the precipitation changes were major changes in the temperature and pressure of the lower troposphere between the two sets of epochs. Geopotential heights and temperatures increased significantly at nearly all pressure levels while temperature lapse rates decreased significantly (Table 4). In addition, the BHI decreased significantly while going from positive median values during the earlier epochs to negative median values during the later epochs. Negative BHI values—which can be caused by the westward expansion of the Bermuda high (i.e. North Atlantic subtropical anticyclone)—typically indicate reduced atmospheric instability over the southeastern United States (Henderson and Vega 1996). There also was a decrease in troughing days: median seasonal frequencies of troughing days decreased by 10%–20% for the two sets of consecutive epochs, with the decrease within the 1962–93 period being statistically significant (Table 4). The decline in troughing days is critically important, because heavy precipitation and associated phenomena during the warm season in the southeastern United States have been linked strongly to troughing events and associated surface fronts (Weisman 1990; Easterling 1991; Keim 1996; Gamble and Meentemeyer 1997; Konrad 1997). Because troughs are more prevalent in the northern portion of the study region rather than in the southern portion, the decline in troughing days probably was most severe in the vicinity of the southern stations. As a consequence, although it is beyond the scope of this paper to provide the exact causes of all precipitation changes, the suspected cause of the significant decrease in precipitation at the southern stations was the switch to a more anticyclonic atmospheric circulation.

Dewpoint temperatures throughout the lower tropo-

TABLE 3. As in Table 2, but for standardized values.

	AP		HPD		CHP	
Station	1953–77 to 1978–2002	1962–77 to 1978–1993	1953–77 to 1978–2002	1962–77 to 1978–1993	1953–77 to 1978–2002	1962–77 to 1978–1993
Hightower	—	—	—	—	—	—
Talladega	POS**	POS**	—	—	—	—
Valley Head	—	—	—	—	—	—
Athens	—	—	—	—	—	—
Atlanta airport	POS*	POS**	—	POS*	—	POS*
Blairsville	—	—	—	—	—	—
Canton	—	—	—	—	—	—
Carnesville	—	—	—	—	—	—
Cedartown	—	—	POS*	—	—	—
Columbus	NEG**	NEG*	NEG**	NEG**	NEG**	—
Cornelia	—	—	—	—	—	—
Covington	—	—	—	—	—	—
Ellijay	—	—	NEG**	NEG**	NEG**	NEG**
Embry	—	—	—	—	POS**	POS**
Experiment	—	—	NEG**	—	NEG*	—
Gainesville	—	—	—	—	—	—
Macon	—	—	—	—	—	—
Milledgeville	—	—	NEG*	NEG*	NEG*	—
Montezuma	NEG*	—	—	—	—	—
Newnan	—	—	—	—	—	—
Norcross	POS**	POS**	POS**	POS**	POS**	POS**
Resaca	—	—	—	—	—	—
Talbotton	—	—	NEG**	—	—	—
Taylorsville	POS**	—	POS**	POS*	POS**	—
West Point	—	—	NEG**	—	NEG**	—
Woodbury	NEG**	NEG**	—	—	NEG*	—
Coweeta	—	—	—	—	—	—
Clemson	—	—	—	—	—	—
Walhalla	—	—	—	—	—	—
Chattanooga	POS*	—	POS*	—	—	—

* Significance level $\alpha = 0.10$.
** Significance level $\alpha = 0.05$.

sphere also increased significantly between the epochs (Table 4). Thus, the southern-station precipitation decrease occurred despite an increase in atmospheric humidity. In fact, the amount of precipitable water over the study region probably increased over time: Ross and Elliott (2001) detected a significant increase [i.e. 1.09 mm $(10\ \mathrm{yr})^{-1}$] in summertime lower-tropospheric precipitable water over the eastern United States from 1973 to 1995. As will be discussed in the following section, the increased atmospheric moisture may have enabled urban effects on precipitation.

c. *Urbanization as a possible cause of positive changes in precipitation between epochs*

Interepochal changes in precipitation per wind direction sector indicate that urban effects on precipitation were most likely at Norcross and Atlanta airport, which are located within and to the northeast of urbanized Atlanta, respectively. Westerly 850-hPa flow dominated on average, but the largest precipitation totals and the largest interepochal increases in precipitation values at Atlanta airport, Embry, Norcross, and Taylorsville were linked to days with southwesterly flow (Tables 5, 6, and 7). This is not unusual, because Konrad and Meentemeyer (1994) determined that most warm-season heavy rainfall events in the southeastern United States occur during southwesterly flow. Because there was not a major interepochal increase in precipitation at Embry and Taylorsville—which are located approximately 70 km west of Atlanta—uring periods of easterly/southeasterly flow, urban effects originating from Atlanta probably were insignificant at those stations. Moreover, one could also argue that if Embry and Taylorsville received urban-enhanced precipitation, then Canton and Gainesville—which were more often downwind of Atlanta—also should have experienced significant increases in precipitation.

Interepochal changes in urban land coverage also supports the notion that Norcross and, to a lesser degree, Atlanta airport were the most likely stations to have experienced urban effects on precipitation. Precipitation increases at those stations occurred over a relatively large wind direction range, and this range may reflect the spatial extent of urbanized lands relative to those stations (Tables 6 and 7). In 1973 most of the urban lands were southwest of Norcross and north of Atlanta, but by 1992 both stations had become

TABLE 4. Significant increases (POS) and decreases (NEG) in atmospheric conditions from 1953–77 to 1978–2002 and from 1962–77 to 1978–93. The variables are as follows: Bermuda high index (BHI); geopotential height, temperature, and dewpoint temperature at 1000 (H_{1000}, T_{1000}, DPT_{1000}), 925 (H_{925}, T_{925}, DPT_{925}), 850 (H_{850}, T_{850}, DPT_{850}), 700 (H_{700}, T_{700}, DPT_{700}), and 500 hPa (H_{500}, T_{500}, DPT_{500}); and temperature differences between pressure levels ($T_{1000–500}$, $T_{1000–700}$, $T_{1000–850}$, $T_{1000–925}$).

Variable	1953–77 to 1978–2002	1962–1977 to 1978–93
BHI	NEG*	NEG*
H_{1000}	—	—
H_{925}	—	—
H_{850}	POS*	POS*
H_{700}	POS**	POS**
H_{500}	POS**	POS**
T_{1000}	—	—
T_{925}	—	—
T_{850}	POS**	POS**
T_{700}	POS**	POS**
T_{500}	POS**	POS**
$T_{1000–500}$	NEG**	NEG**
$T_{1000–700}$	NEG**	NEG**
$T_{1000–850}$	NEG**	NEG**
$T_{1000–925}$	—	NEG**
DPT_{1000}	POS**	POS**
DPT_{925}	POS**	POS**
DPT_{850}	POS**	POS**
DPT_{700}	POS**	POS**
DPT_{500}	—	POS*

* Significance level $\alpha = 0.10$.
** Significance level $\alpha = 0.05$.

nearly enveloped by urban lands (Fig. 4). In fact, there was a 75% increase from 1973 to 1992 in urban land area within a 30-km wedge extending upwind (i.e., southwest) of Norcross. And, under generally southwesterly flow (136°–315°), Norcross went from having 39 heavy-precipitation days during 1962–77 to having 67 heavy-precipitation days during 1978–93 (Fig. 4). The total in the later epoch was the largest of the 30 stations in the entire study region.

Urban boundary layer modifications coupled with increased atmospheric moisture may explain the precipitation increase at Norcross. Because urban PBLs tend to have lower amounts of atmospheric moisture than upwind rural areas (Dirks 1974; Auer 1981; Semonin 1981), the lower equivalent potential temperatures θ_e in the lowest part of the PBL (Braham 1981) diminish the convective-cloud-enhancement potential of urban areas. Therefore, an increase in atmospheric moisture should lessen this effect. Coupled with increased moisture leading to more instability over urban areas is the urban PBL typically being several hundred meters higher than the upwind rural PBL (in Auer 1981; Rozoff et al. 2003). As noted previously, clouds have a greater potential for merger within a deepened PBL; thus intensified thunderstorms become more likely over and downwind of urban areas.

It also is possible that the relatively low θ_e of the urban PBL actually caused increased precipitation. Boatman (1974) suggested that air with relatively low θ_e can cause a decrease in updraft buoyancy. As a consequence, if the increase in urban land cover from 1953 to 2002 upwind of Norcross caused a decrease in θ_e, then precipitation rates may have increased because of the premature weakening of passing storms.

Last, despite the evidence presented above for urban effects on precipitation within and downwind of urbanized Atlanta, one must not disregard the fact that the increased precipitation may have been completely independent of urban effects. Precipitation increases did occur approximately 70 km west of Atlanta, and those increases were not linked to an urban-modified PBL. Therefore, regional-scale climatic variability may have masked—rather than controlled—precipitation enhancement within and downwind of Atlanta. Furthermore, four relocations of the Norcross station across the 50-yr period may have caused increased precipitation at the station. The relocations were 1) a move of ~5 km from 1972 to 1973, 2) a move of ~5 km from 1977 to 1978 back to its previous location, 3) a move of ~4 km from 1991 to 1992, and 4) a move of several kilometers or less from 1992 to 1993. The relocations changed the local setting of the rain gauge (e.g., changes in the amount of wind shielding), which may have affected the amounts of measured precipitation. Nevertheless, the local topographic setting of the Norcross rain gauge remained relatively constant, and—

TABLE 5. The 850-hPa wind direction occurrences and precipitation totals (mm) at Atlanta airport and Norcross per wind direction sector during 1962–77 and 1978–93. Here WD refers to wind direction (°) above Athens.

WD sector	Percent 1962–77	Percent 1978–93	Atlanta airport, 1962–77	Atlanta airport, 1978–93	Norcross, 1962–77	Norcross, 1978–93
1–45	6	6	12	5	18	7
46–90	11	10	15	5	18	10
91–135	9	8	28	23	24	25
136–180	7	7	31	41	39	48
181–225	11	11	53	78	63	76
226–270	24	27	97	114	101	112
271–315	22	21	58	56	48	51
316–360	10	9	16	7	11	11
Sum	100	100	310	329	321	339

TABLE 6. Number of heavy-precipitation days at Atlanta airport, Norcross, and Taylorsville per 850-hPa wind direction sector during 1962–77 and 1978–93. Here, WD refers to wind direction (°) above Athens.

WD sector	Atlanta airport, 1962–77	Atlanta airport, 1978–93	Norcross, 1962–77	Norcross, 1978–93	Taylorsville, 1962–77	Taylorsville, 1978–93
1–45	1	0	2	1	3	2
46–90	2	0	4	2	1	3
91–135	4	4	4	4	3	4
136–180	7	10	5	12	8	9
181–225	10	18	11	19	10	12
226–270	17	19	17	23	11	13
271–315	8	12	5	12	7	8
316–360	2	1	1	2	2	5
Sum	51	64	50	76	46	58

most important—the times series of summer precipitation totals does not contain noticeable inhomogeneities caused by station relocations (Fig. 5).

6. Conclusions

Urbanization is one process that can modify land–atmosphere interactions, thereby resulting in alterations of the hydrologic cycle. Results from a climatological examination of summer-season daily precipitation data from 1953 to 2002 for a network of 30 stations in the southeastern United States indicate that precipitation within and downwind of urbanized Atlanta may have been enhanced by urban effects. Dividing the 50-yr period into consecutive epochs enabled the discernment of differences in raw precipitation, standardized precipitation, and atmospheric conditions between epochs. Norcross, a station ~30 km northeast of downtown Atlanta, was the only station to have experienced significant increases in heavy-precipitation days both from 1953–77 to 1978–2002 and from 1962–77 to 1978–93. In fact, although Norcross had some of the smallest numbers of heavy-precipitation days for the earlier epochs, it had the most heavy-precipitation days for the later epochs.

It is suspected that the increased precipitation at Norcross was caused by urban effects. The increased depth of the urban PBL is conducive to cloud merger and thunderstorm intensification. The relatively low θ_e near the surface of an urban PBL can reduce updraft buoyancy; however, increased atmospheric humidity—which did occur from 1953 to 2002—can increase θ_e. It is also possible that the low θ_e of the urban PBL caused increased precipitation rates at Norcross through the weakening of passing storms. Nevertheless, stations west of Norcross and thus upwind of urbanized Atlanta also experienced significant increases in precipitation. Therefore, it is possible that the precipitation increase at Norcross may have occurred without the presence of any urban lands proximate to or upwind of Norcross.

The background interannual variability in precipitation across the domain reduces the credibility of precipitation-enhancement claims at Norcross. It is true that Norcross had the most significant change in precipitation between the epochs; however, other stations had nearly as significant increases and decreases in precipitation. If under the "control" situation, there existed both negligible interannual variability and no significant secular trends, then detection of urban effects on precipitation would be straightforward. This paper has shown that this is definitely not the case; much noise exists and major precipitation changes were independent of urban impacts.

Another major deficiency of the urban-impacts aspect of this study is the scarcity of stations within and proximate to Atlanta. Confidence in the results is jeopardized by the fact that Norcross is the only station immediately downwind of Atlanta on days with south-

TABLE 7. Cumulative heavy precipitation (mm) at Atlanta airport, Embry, and Norcross per 850-hPa wind direction sector during 1962–77 and 1978–93. Here, WD refers to wind direction (°) above Athens, GA.

WD sector	Atlanta airport, 1962–77	Atlanta airport, 1978–93	Embry, 1962–77	Embry, 1978–93	Norcross, 1962–77	Norcross, 1978–93
1–45	36	0	85	75	140	50
46–90	66	0	64	81	147	82
91–135	189	128	144	220	171	123
136–180	284	447	390	561	292	544
181–225	399	751	768	810	500	744
226–270	590	734	383	856	719	845
271–315	282	404	399	409	163	472
316–360	55	34	171	25	75	85
Sum	1900	2499	2405	3038	2207	2946

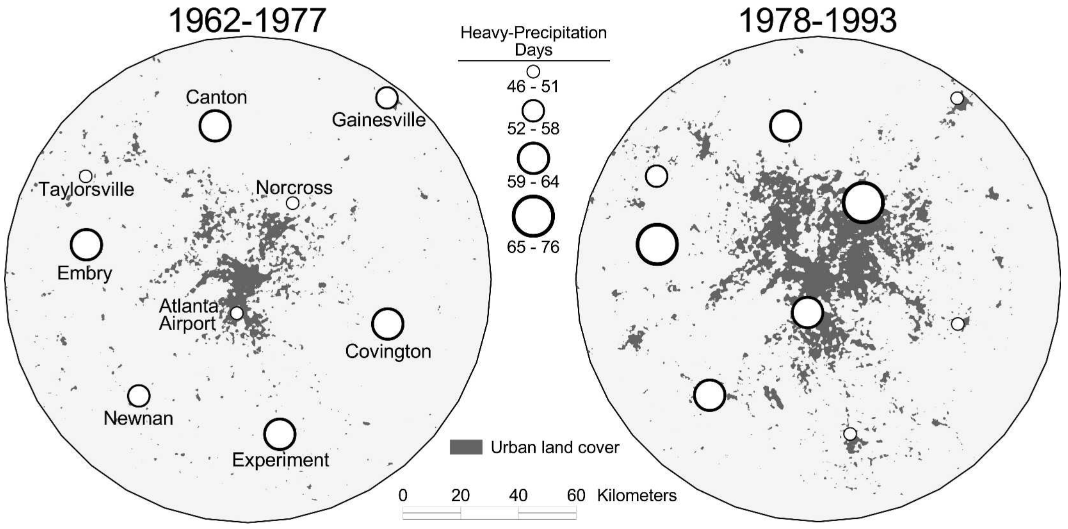

FIG. 4. Frequencies of heavy-precipitation days during predominantly southwesterly flow at stations within and near the Atlanta metropolitan area. Southwesterly flow is defined as 850-hPa winds having wind directions between 135° and 315°. Urban land cover was determined from 1973 and 1992 land cover classifications.

erly/southwesterly flow. Because an increase in heavy-precipitation days at Norcross could have been caused by station relocation, more stations north/northeast of Atlanta are needed to verify fully the enhancement of precipitation by urban factors. To obtain a denser network of stations, shorter epochs are needed; however, extreme events having a strong stochastic nature are more likely to contaminate results from shorter epochs than from longer epochs.

Future research is needed to confirm further urban effects on precipitation as well as to determine the exact causes of the increased precipitation. An ideal scenario for this study would have been for the consecutive epochs to have statistically similar atmospheric conditions but drastically different amounts of urban land cover (e.g., preurban to heavily urbanized). And if the only increases in precipitation had occurred within and slightly downwind of urbanized Atlanta, then urban effects could have been targeted as the dominant control of the increased precipitation. Although the above scenario did not exist for this study, additional climatological studies, such as time series analysis and precipitation regionalization, can be used to find additional evidence of urban precipitation enhancement. Yet to determine the exact causes of the precipitation increases, detailed case studies involving modeling simulations are required.

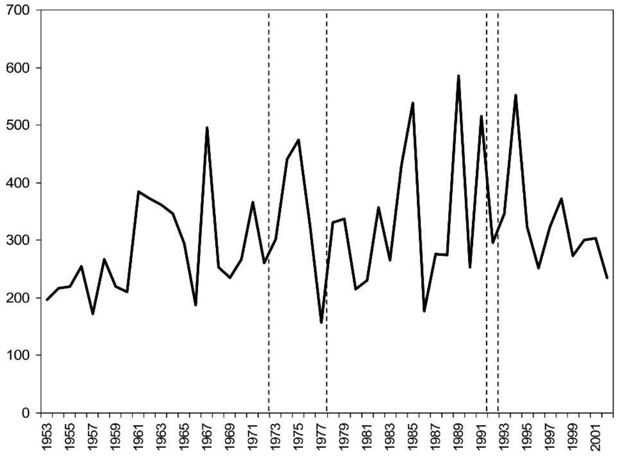

FIG. 5. Time series of summer precipitation totals at Norcross. The dashed vertical lines indicate station relocations. Year is on the *x* axis, and precipitation (mm) is on the *y* axis.

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