Comments on ''Rainfall Modification by Major Urban Areas: Observations from Spaceborne Rain Radar on the TRMM Satellite''

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1. Introduction

During the autumn semester of the 2002/03 academic year, the authors participated in a graduate-level geographical-climatology seminar (''Environmental Climatology'') at Georgia State University. The topics included climate variation and change, mesoscale climate modification, and atmospheric pollution. Peer-reviewed climatological research was critically discussed through a geographical lens, which embodies a holistic consideration of relevant processes as well as increased attention to spatial- and temporal-scale issues. Therefore, we eagerly anticipated the reading of Shepherd et al. (2002, hereinafter Shepherd et al.), because it presents recent research on our locale (i.e., Atlanta, Georgia), which on the surface appears to involve a geography-based methodology. In specific terms, Shepherd et al. examine the impacts of urbanization on precipitation totals in six regions (i.e., Atlanta; Montgomery, Alabama; Nashville, Tennessee; and San Antonio, Waco, and Dallas, Texas) during the May–September period of 1998–2000. Shepherd et al. hypothesize that the urban heat island (UHI) is responsible for precipitation enhancement downwind of the cities, and they assess this enhancement using a spatially continuous satellite-derived lower-tropospheric rainfall-rate database within an ensemble-averaging framework. The satellite data are affiliated with the Tropical Rainfall Measuring Mission (TRMM). For the above regions, Shepherd et al. conclude that their ''results validated previous ground-based and modeling studies that identified urban-induced rainfall maxima over and downwind of cities.'' Their results show an average increase of about 28% in monthly satellite-derived rainfall rates within 30–60 km downwind of the cities (Shepherd et al. 2002). For the Atlanta area, their study indicates that mean satellite-derived rainfall rates to the southeast of the city are 20% higher than rates to the northwest of the city, and the downwind distance from the center of the urban area to the maximum satellite-derived rainfall-rate value is $\sim$60 km (Shepherd et al. 2002).

The promising results presented in Shepherd et al. appear to prove that, by using data from radar-equipped satellites such as the TRMM satellite, one can possibly avoid the spatial deficiencies of point measurements (i.e., observations at weather stations). With spatially continuous data, spatial variations in rainfall rates can be discerned much more clearly; hence, downwind versus upwind comparisons can be improved. Nonetheless, Shepherd et al. do not fully adopt a geographical-climatology approach, and we consequently disagree with their conclusions.

In this comment, we not only discuss the major problems of the research presented in Shepherd et al. but also conduct independent evaluations of the paper's data and methods. The principal deficiencies of the research presented in Shepherd et al. stem from the spatial and temporal resolutions of the data. They use low-resolution data when high-resolution data are essential for yielding convincing results. Our attention is focused on the portions of the paper pertaining to the Atlanta area; nevertheless, we feel that many of our comments are applicable to the other cities. In the next section, the problems in Shepherd et al. are presented. Many of the points discussed in section 2 are expanded upon in appendix A.

2. Problems with the research

a. The accuracy of the satellite-derived rainfall rates is never reported

Shepherd et al. never note quantitatively the accuracy of the lower-tropospheric satellite-derived rainfall rates

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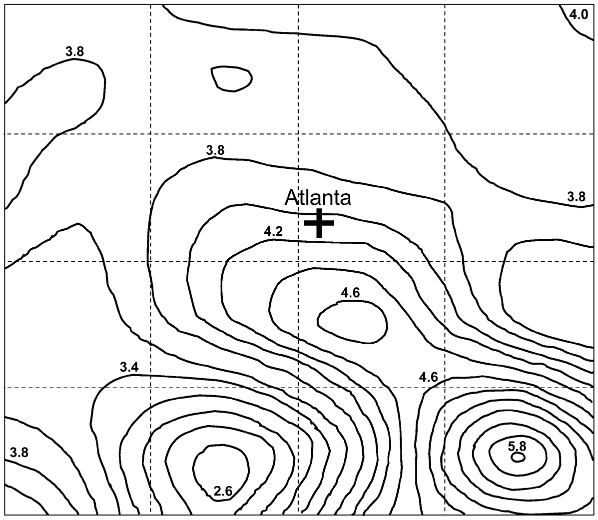

FIG. 1. Surface of TRMM-derived rainfall rates (mm h^{-1}) across the Atlanta area (after Shepherd et al. 2002). The spatial resolution appears to be ~3 km, the cells are 0.5° × 0.5° (dashed lines), and most of urbanized Atlanta exists within the cell containing downtown Atlanta (+).

derived from data recorded by the radar-equipped TRMM satellite. In addition, they do not report the spatial correlation between satellite-derived rainfall rates and ground-based precipitation totals. Shepherd et al. do state that ''to assess the accuracy of the spaceborne radar system, we refer to recent literature citing the performance of the [precipitation radar].'' Moreover, they note that ''the validation and calibration results indicate that the [precipitation radar] has been and will be sufficiently stable and accurate to assure quantitative rainfall estimates.'' Nevertheless, these are qualitative statements, and Shepherd et al. never prove that the satellite-derived rainfall rates are an appropriate proxy for ground-based precipitation totals in the Atlanta area. Further, we find no significant (confidence level α = 0.05) positive spatial correlation between the satellite-derived rainfall rates and ground-based precipitation totals (Figs. 1 and 2; also see points 1 and 2 in appendix A). Although the above incongruence between satellite-derived rainfall rates and ground-based precipitation totals may be caused by error-laden radar data, an unreliable rainfall-rate algorithm, and insufficient sampling density of ground-based stations, the dominant causes are probably the temporal sampling scheme of the TRMM satellite and the low spatial resolution of the radar-based data. The latter two causes are discussed in sections 2b and 2c.

b. The temporal sampling scheme of the TRMM satellite is not taken into account

The temporal sampling scheme of the TRMM satellite is conducive to a misrepresentation of mean rainfall rates in certain locales. During 1 month of coverage by TRMM, 2–4 clock hours remain poorly covered at all latitudes, with the number of poorly covered hours increasing with an increase in latitude above 25° (Kishtawal and Krishnamurti 2001). At the highest latitudes (~35°) accessible to TRMM, there is a 46-day return period between TRMM's overpass of a region and the next overpass at a similar hour (see Negri and Bell 2002). In theory, the precipitation radar should be most successful in capturing precipitation events that are not strongly linked to a particular hour or group of hours.

Because Shepherd et al. do not account for the full impacts of the above sampling scheme, their mean monthly rainfall rates are biased. They are forced to assume that urbanization-enhanced precipitation has an equal probability of occurring during all hours of the day. This probability may not be applicable to the Atlanta area. For example, based on examinations of ground-based radar, Dixon and Mote (2003) note that a majority of UHI-induced precipitation events under conditions of weak synoptic flow during the May–September period of 1996–2000 occurred within the small temporal window of 2300–0300 next day LST. This temporal occurrence corresponds well to a peak in urban–rural temperature differences (Dixon and Mote 2003), which, in turn, can be used a proxy for UHI intensity (Oke 1987). If, in fact, there is a nocturnal bias for urbanization-induced precipitation events in the Atlanta area, which is at a latitude (34°N) that has multiple poorly covered hours per month, then the TRMM's precipitation radar may miss some of those events. In contrast, the precipitation radar has ample opportunity to capture synoptic-scale events, such as frontal systems and tropical systems (e.g., hurricanes), the presence of which should not be biased with respect to hour of occurrence.

c. The tenets of spatial scale are violated

Spatial scale is something that must be considered carefully in all geographical-climatology research. Spatial scale has several different meanings, two of which are geographic scale and measurement scale (Cao and Lam 1997). In most climatological research, especially that which pertains to the modification of climate at the mesoscale, one strives for a small measurement scale relative to the geographic scale. The satellite-derived rainfall-rate database used by Shepherd et al. ideally would have a spatial resolution of tens of meters. Because the spatial resolution of their database is approximately 50 km (0.5°), it is theoretically impossible to conduct proper comparisons of downwind versus upwind satellite-derived rainfall rates within a mesoscale context.

Spatial-scale problems also plague the original precipitation-radar data from which the 50-km data are derived. The spatial resolution of the original data is approximately 5 km, but this resolution may be too coarse for the detection of many convective storms. Heymsfield

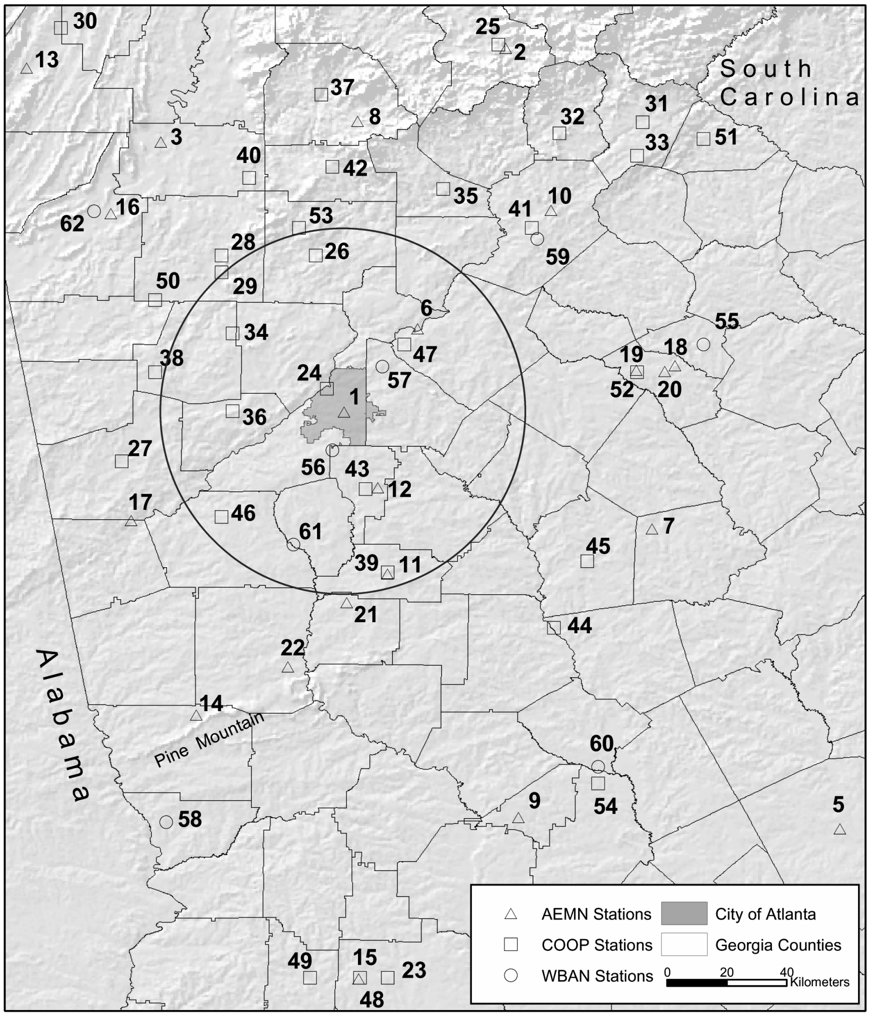

FIG. 2. Map of the greater-Atlanta area showing the location of the city of Atlanta, county boundaries, topographic features, and weather stations with precipitation data. Numbers denote the weather stations; station names and associated information are available in appendix B. AEMN: Georgia Automated Environment Network; NWS Coop: National Weather Service cooperative stations; NWS WBAN: National Weather Service WBAN stations (i.e., airport stations). All stations inside the circle are within 60 km of downtown Atlanta.

et al. (2000) report that various studies suggest that less than one-quarter of rain cells have diameters that are larger than approximately 4 km. TRMM-derived rainfall-rate estimates become increasingly reduced as the size of the storm cell decreases; the effects of beam filtering and limited sensitivity compound to make cells that are either small or weak entirely or partly undetectable by the precipitation radar (Heymsfield et al. 2000). As a consequence, in addition to possibly having an undersampling of urbanization-induced precipitation events over time, the radar should have difficulty detecting urban-induced clouds even if the overpass occurs near or at the suspected peak period (i.e. ~0000 LST).

Owing to the above spatial-scale problem of the TRMM data, the satellite-derived rainfall rates for the Atlanta area should be considerably biased toward tropical systems. We find that tropical systems were responsible for much more precipitation south-southeast of Atlanta than in other parts of the extended metropolitan area during Shepherd et al.'s study period (Fig. 3; also see point 3 in appendix A). For example, Americus, Georgia, (473 mm) received approximately 7 times as much tropical-system precipitation as did Chickamauga Park, Georgia, (69 mm; see appendix-A point 3). For the greater Atlanta area, tropical systems appear to have a disproportionate impact on the estimates of rainfall rates derived from the TRMM satellite. Therefore, Shepherd et al.'s 50-km rainfall-rate data, especially the cells south-southeast of Atlanta, are more likely to be evidence of tropical systems rather than evidence of urbanization-induced convective events.

Also, Shepherd et al. magnify the problems of the

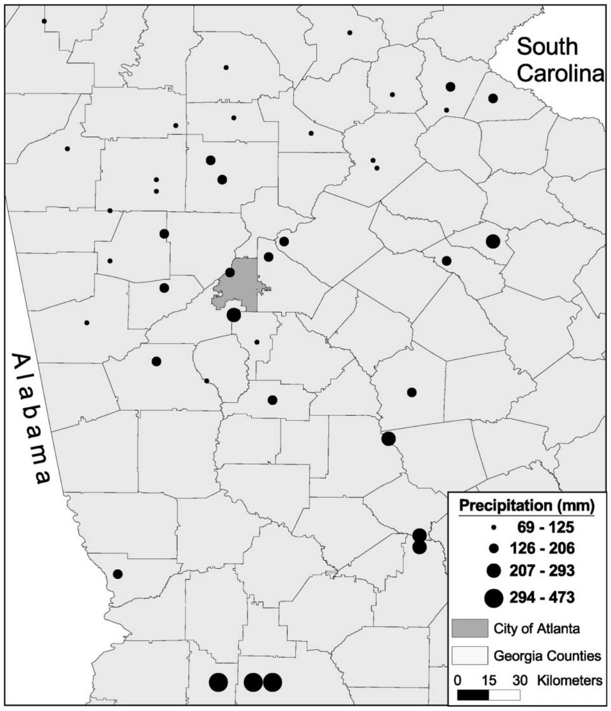

FIG. 3. Proportional-symbol map of cumulative tropical-system precipitation totals at NWS stations in the greater-Atlanta area. The time period is May–Sep of 1998–2000.

satellite-derived rainfall-rate data by producing a rainfall-rate surface with falsely high spatial resolution. By doing so, they encounter another scale issue, ecological fallacy, which, defined broadly, is the inappropriate inference of individual-level relationships from areal-unit results (Wrigley 1995). Ecological fallacy also involves the production of a surface having a resolution finer than that of the data from which it is directly derived. Shepherd et al. commit ecological fallacy by using a dataset with a resolution of less than 3 km that was created from a 50-km dataset (Fig. 1). They never report the spatial-interpolation technique used to create the high-resolution surface, but we suspect that inverse-distance weighting or a similar technique was used. The final cell size of the satellite-derived rainfall-rate data is at least 280 times as small as the original cell size; however, it appears that Shepherd et al. made no steps to ensure a proper downscaling. A valid high-resolution surface cannot be created by simply interpolating from a surface with a coarser resolution. As should be expected when spatial scale is not regarded, Shepherd et al.'s interpolated rainfall-rate surface is not reliable. Last, we find those rainfall-rate estimates not to have a significant positive correlation with precipitation totals measured at the ground (see point 4 in appendix A).

Although probably not foreseen by Shepherd et al., their inappropriately downscaled rainfall rates are positively correlated ($\alpha = 0.05$) with tropical-system precipitation totals measured at the ground (see point 5 in appendix A). Thus, the data on which Shepherd et al. conduct their analyses reflect tropical-system precipitation totals as opposed to total summer-season precipitation totals. In addition to focusing on spatial-scale issues, Shepherd et al. could have minimized the tropical-system problem had they also considered several temporal-scale issues more carefully.

TABLE 1. Atlanta-area wind directions at 850, 700, and 500 hPa during the study period for the following types of days: all days, all precipitation days at Griffin, and all synoptically quiescent precipitation days at Griffin.

Day	850-hPa wind direction (°)	700-hPa wind direction (°)	500-hPa wind direction (°)
All days	270	282	289
All precipitation days	256	261	269
Synoptically quiescent precipitation days	259	268	275

d. Ensemble averaging is used inappropriately

Multiple synoptic-scale circulations are present over the southeastern United States during the summer season. Therefore, it is often necessary to stratify days by ‘‘synoptic weather types’’ when conducting precipitation-enhancement research (Lowry 1998). Synoptic types can be determined using meteorological data with daily resolution, and only a few of those types should be associated with urban enhancement of precipitation totals. Instead of performing a synoptic typing, Shepherd et al. create a summer-season ensemble from monthly data. They consequently commit the following errors.

First, Shepherd et al. assume that all precipitation events during the time period were synoptically quiescent in nature. This assumption is critically important, because they note that ‘‘synoptic forcing such as frontal systems tends to mask mesoscale circulations.’’ We have found frontal systems and tropical systems to have major impacts on precipitation totals in the Atlanta area from May to September of 1998–2000. Approximately 25% of precipitation days were associated with frontal activity and tropical storms, and those days contributed at least 20% of the precipitation total (see points 3, 6, 7, and 8 in appendix A). The same percentage of strong-flow days was found by Dixon and Mote (2003) for the May–September period of 1996–2000. Substantial masking by synoptic-scale systems has diluted the results of Shepherd et al.'s study.

Second, Shepherd et al. assume that precipitation in the Atlanta area occurred continuously from May to September of 1998–2000. Precipitation, however, is not a continuous process, and wind direction may be expected to differ between precipitation days and nonprecipitation days. Using an overall-average 700-hPa wind direction of 273°—which is based on a 19-yr dataset

TABLE 2. Characteristics of synoptically quiescent precipitation days at Griffin and Williamson. For each station, the precipitation totals for the two scenarios are not significantly ($\alpha = 0.05$) different.

Station	Mean daily prescription total (mm) when Atlanta was upwind	Mean daily precipitation total (mm) when Atlanta was *not* upwind	Percent of total precipitation that occurred on days when Atlanta was upwind	Percent of total precipitation that occurred on days when Atlanta was *not* upwind	Compass direction (°) to Atlanta	Distance (km) to Atlanta
Griffin	9.5	7.3	41	59	348	60
Williamson	6.7	7.3	27	73	355	65

rather than just the 1998–2000 period—Shepherd et al. conclude that the maximum satellite-derived rainfall-rate value was approximately 60 km to the *southeast* of the center of the urban area. In addition to the fact that based on their wind direction the maximum value should have occurred to the *east* of the urban area, it is impossible to produce a 60-km estimate with data (i.e., TRMM monthly rainfall-rate product) that have a spatial resolution of approximately 50 km.

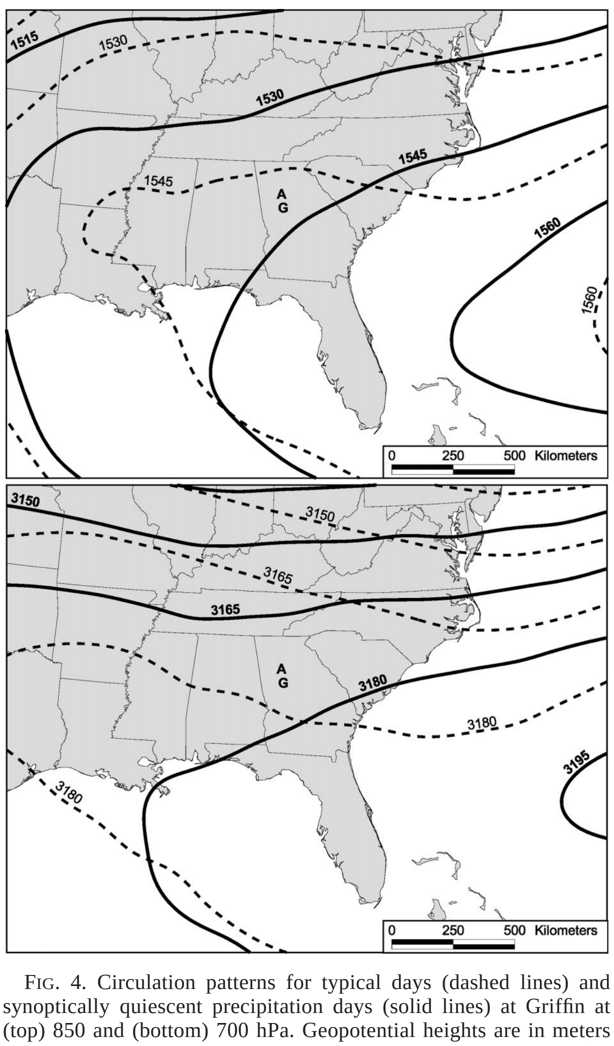

FIG. 4. Circulation patterns for typical days (dashed lines) and synoptically quiescent precipitation days (solid lines) at Griffin at (top) 850 and (bottom) 700 hPa. Geopotential heights are in meters above sea level. Here ''A'' refers to Atlanta and ''G'' refers to Griffin. The time period is May–Sep of 1998–2000.

An examination of the precipitation–wind direction relationship at a station in Shepherd et al.'s ''maximum impact area'' reveals the need for proper ensemble averaging. Because their 60-km radius nearly intersects weather stations located at Griffin and Williamson, Georgia (stations 11 and 21 in Fig. 2), we select those stations for further analyses. We find the Griffin station to be infrequently downwind of the Atlanta area, especially on precipitation days (Table 1). On synoptically quiescent precipitation days at Griffin during the study period, the average 850-, 700-, and 500-hPa wind directions were 259°, 268°, and 275°, respectively (see points 8 and 9 in appendix A). None of these wind directions represents northwesterly–northerly flow, which, based on Shepherd et al.'s logic, is needed for anthropogenic activities in the Atlanta area to have an impact on precipitation totals at Griffin more so than at locales from west to northwest of Atlanta. Moreover, most of the synoptically quiescent precipitation at Griffin occurred when the station was not downwind of Atlanta, and there was no significant difference in precipitation totals between days when Atlanta was upwind of Griffin and days when Atlanta was not upwind of Griffin (Table 2; also see point 10 of appendix A). Williamson, which is a nearby station, has similar results (Table 2; also see points 11 and 12 of appendix A). Overall, urbanized Atlanta does not appear to increase precipitation totals at Griffin and Williamson on synoptically quiescent days, which are the types of days when urbanization-induced storms should be most abundant (Dixon and Mote 2003).

As opposed to urbanized Atlanta being the dominant control, the occurrence of synoptically quiescent precipitation days at Griffin is linked to the contraction of the Bermuda high (Fig. 4; also see point 13 of appendix A). The Bermuda high is a quasi-stationary subtropical anticyclone located in the North Atlantic Ocean. When the Bermuda high contracts, an increase in southerly flow can increase precipitation because of increased moisture advection, which is confined to the lowest layers of the atmosphere (Henderson and Vega 1996; Schubert et al. 1998). In converse, expansion of the Bermuda high facilitates drought, because low-level moisture advection is displaced westward and higher pressures aloft limit convection over the Southeast (Stahle and Cleaveland 1992; Henderson and Vega 1996; Schubert et al. 1998).

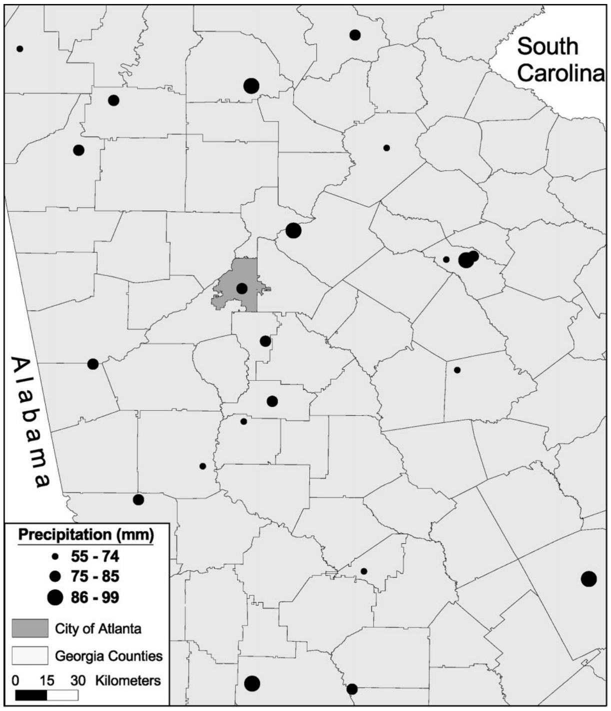

FIG. 5. Proportional-symbol map of mean monthly precipitation totals at Georgia AEMN stations in the greater Atlanta area. The time period is May–Sep of 1998–2000.

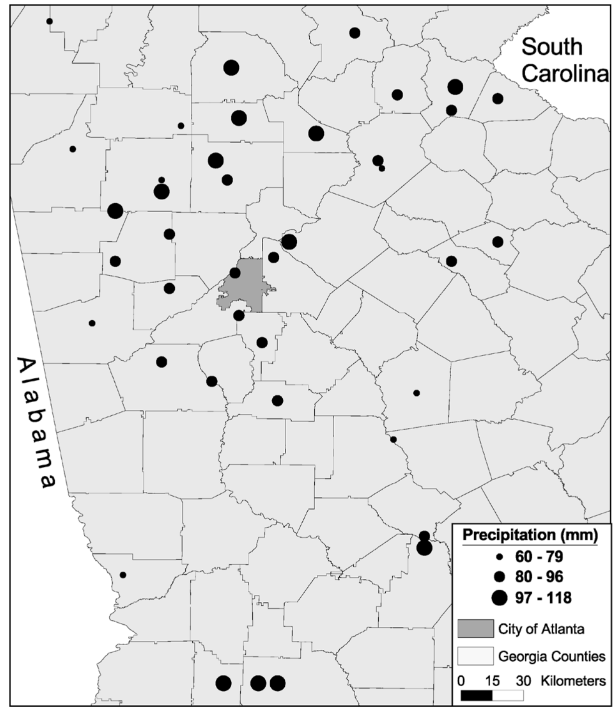

FIG. 6. Proportional-symbol map of mean monthly precipitation totals at NWS stations in the greater Atlanta area. The time period is May–Sep of 1998–2000.

e. The precipitation map is misleading

Shepherd et al. present a questionable surface of ground-based precipitation totals to corroborate their findings from analyses based on the satellite-derived rainfall rates. They state that the precipitation surface ''illustrates a broad maximum south-southeast of the city during the May–September period,'' and they conclude that ''the consistency of the relative maxima locations provides encouraging validation for the [precipitation radar].'' Shepherd et al. fail to report the actual stations in the Georgia Automated Environmental Monitoring Network (AEMN) used to produce the surface. We suspect that data from several stations located within or proximate to urbanized Atlanta as well as stations located 10s of kilometers east of Atlanta were not used by Shepherd et al. in the surface-generation procedure. We determine that the surface is not accurate enough for a ''broad maximum [of rainfall totals] south-southeast of the city. . .'' to be inferred (see point 14 of appendix A). The accuracy of the surface is only slightly better than what would have been achieved had the surface been created by randomly assigning precipitation totals to all locales (see point 15 of appendix A).

The original AEMN data do not support Shepherd et al.'s conclusion that a broad maximum exists to the south-southeast of the city. For example, Griffin received about 15% less precipitation than did Ellijay, Georgia, which is located north of the city (Fig. 5; appendix B). Through their mapping, Shepherd et al. also misinterpret the precipitation totals in the vicinity of Cordele and Fort Valley, Georgia, which are located over 140 km southeast of Atlanta, as being high. The average monthly precipitation totals at Cordele (~77 mm) and Fort Valley (~70 mm) were actually less than the average for all AEMN stations (~78 mm, appendix B).

Precipitation totals also were not maximized at National Weather Service (NWS) stations southeast of Atlanta (Fig. 6). We assume that precipitation totals at the NWS stations are more accurate than totals at the AEMN stations owing to the AEMN network's tipping-bucket method. For high rainfall rates, the undercatch resulting from the bucket tipping while the rain is falling can be substantial (Heinemann et al. 2002). Data from the NWS stations indicate that the largest precipitation totals actually existed north of Atlanta and over 150 km south-southeast of Atlanta, rather than approximately 60 km south-southeast of the city as inferred by Shepherd et al.

Shepherd et al.'s precipitation map, although inaccurate, does reflect qualitatively the spatial variations in satellite-derived rainfall rates, which appear to be influenced heavily by tropical systems. As a result, we surmise that their satellite-derived rainfall-rate and ground-based precipitation maps are reflections of tropical-system precipitation instead of urbanization-enhanced precipitation.

f. Topographic impacts on precipitation totals are not explored

Shepherd et al. disregard the impact of topography on precipitation totals in the Atlanta area, because they state that the Atlanta area is ''relatively flat'' and is ''not located near major topography.'' On the contrary, substantial relief exists within the greater Atlanta area, and it is probably enough to cause enhanced lifting of air parcels. For instance, Pine Mountain, which is located approximately 110 km south of Atlanta, has a typical relief exceeding 150 m and extends nearly 60 km across west-central Georgia, and a mountainous area with up to 2 times as much relief is located approximately 75 km north of Atlanta near the Jasper, Georgia, station (Fig. 2). In fact, over the May–September period of 1998–2000 the largest precipitation totals were measured near Jasper (Fig. 6). This relationship between precipitation and relief is congruent with findings presented in Huff (1975) and Huff and Vogel (1978), where topographic effects in southern Missouri, which has less relief than that at Pine Mountain, increased warm-season precipitation totals by 15%. Therefore, it can be reasonably assumed that topographic effects in certain parts of the Atlanta area could have increased precipitation totals by that amount.

3. Conclusions

Some major problems with the research presented in Shepherd et al. (2002) have been discussed in this paper, and those problems derive mainly from a misuse of the data. Primarily through the examination of a satellite-derived rainfall-rate dataset having a 50-km spatial resolution and a seasonal temporal resolution, Shepherd et al. conclude that precipitation enhancement occurred to the southeast of Atlanta during the May–September period of 1998–2000. We feel that the above conclusion is likely to be invalidated by one or more of the following deficiencies of their research: 1) the accuracy of the satellite-derived rainfall rates is never reported, 2) the temporal sampling scheme of the TRMM satellite is not taken into account, 3) the tenets of spatial scale are violated, 4) ensemble averaging is used inappropriately, 5) the precipitation map is misleading, and 6) topographic impacts on precipitation totals are not explored.

The rainfall-rate data from the TRMM satellite embody spatial- and temporal-scale problems. By using the satellite-derived rainfall-rate data, Shepherd et al. assume for the Atlanta area that hourly variations in precipitation are negligible, the spatial extent of a precipitation event has no bearing on its detection by the precipitation radar, and the eventual 50-km data are fine enough to determine spatial variations in precipitation totals at the mesoscale. First, the TRMM satellite was designed to capture the daily cycle; thus, its precipitation radar should undersample precipitation events that tend to occur at particular times of the day. UHI-induced precipitation events in the Atlanta area may have a propensity for nocturnal occurrences (Dixon and Mote 2003), whereas synoptic-scale systems, such as midlatitude cyclones and tropical systems, do not have an hourly bias. Second, the low spatial resolution (~5 km) and low sensitivity of the precipitation radar should compromise its suitability for detecting urbanization-induced convective clouds. Third, the eventual 50-km resolution of the satellite-derived rainfall-rates is entirely too coarse to make inferences about spatial variations in precipitation enhancement within the greater Atlanta area.

Despite the shortcomings of the precipitation radar in the context of urbanization-enhanced precipitation research, Shepherd et al. (2002) use the derived rainfall rates and attempt to increase the spatial resolution of the database through contouring. They do not downscale properly; thus, the new rainfall-rates values are not valid. As we have shown, the resulting satellite-derived rainfall-rate estimates are not correlated with precipitation totals measured at the ground. Instead, the satellite-derived rainfall-rate estimates are correlated with *tropical-system precipitation totals* measured at the ground. The rainfall-rate database upon which Shepherd et al.'s results and conclusions were based is most likely depicting tropical-system precipitation rather than total precipitation.

Had Shepherd et al. (2002) properly used ensemble averaging, the tropical-system problem could have been avoided. They needed to identify various synoptic types and then perform ensemble averaging on those types rather than averaging over the entire summer season. Shepherd et al. only had access to a monthly-resolution satellite-derived rainfall-rate product, however, and monthly data are not amenable to appropriate ensemble averaging because of the heterogeneity of atmospheric conditions at that temporal resolution. The monthly data should not have been used.

In addition to the overlooking of tropical systems, the inappropriate ensemble averaging also led to another problematic conclusion by Shepherd et al. (2002). They assume that the lower-tropospheric wind direction does not change substantially between nonprecipitation days and precipitation days. They determine that the mean 700-hPa wind direction for all days was 273°, and they use this direction to establish the zone downwind of Atlanta (i.e., the maximum impact area). Because the typical wind direction *on precipitation days* was less than 270° (i.e., as compared with 282° for all days), the maximum impact area should have been located to the *east-northeast* of Atlanta rather than to the south-southeast of Atlanta. Our results partially confirm this speculation, because urbanized Atlanta does not appear to increase precipitation totals to the south-southeast of the city. The largest precipitation totals occur to the north of the city, but orographic lifting rather than urban effects may be responsible for the increased precipitation in that area.

Shepherd et al. also use an inaccurate precipitation surface to corroborate their findings from the rainfall-rate analyses. Precipitation totals from several ground-based monitoring networks, including the network used by Shepherd et al., do not support their conclusion that a broad maximum in precipitation totals existed approximately 60 km south-southeast of the city. A maximum in tropical-system precipitation rather than total precipitation existed more than 100 km south-southeast of Atlanta. As noted above, a maximum in precipitation totals occurred north of the city. A precipitation surface should have been used only if it were reasonably accurate.

In conclusion, we feel that given the problems in Shepherd et al. (2002) much additional research is necessary to validate urbanization-enhanced precipitation in the Atlanta area and other urban areas. Future research must explicitly consider both spatial- and temporal-scale factors. Because of hindrances resulting from low spatial resolution and varying sampling times, TRMM data should be used with caution. In addition, it must be verified that the satellite data are capable of containing signals associated with urbanization-induced convective cells. Proper ensemble averaging must be conducted to separate synoptic-scale events from mesoscale events. Determining the relative impact of topography on cloud development and precipitation totals is also needed. Future research should explore long-term variations in precipitation totals, especially in the context of spatial, topographical, and synoptic-climatological factors.

APPENDIX A

Notes on Section 2

1) Daily precipitation data for 62 stations located in north-central Georgia were obtained from the Georgia Automated Environmental Network and the National Climatic Data Center (NCDC). The NCDC provided data for the U.S. Weather Bureau–Air Force–Navy (WBAN) and cooperative stations of the National Weather Service. The AEMN and NWS networks included 22 and 40 stations, respectively. None of the stations had missing data. The locations and affiliations of the stations are provided in Fig. 2 and in appendix B.
2) Ground-based precipitation totals were averaged for all stations that were located within each of the 16 rainfall-rate cells in the Atlanta area (Fig. 1). This was done separately for the following sets of stations: all stations, only AEMN stations, and only NWS stations. The number of rainfall-rate–precipitation pairs for the above sets were 15, 11, and 13, respectively. The strength of the association between the satellite-derived rainfall-rate estimates and the precipitation totals was tested using the Kendall's tau test. The resulting correlation coefficients for the three sets of pairs were 0.18, −0.34, and 0.32, respectively. None of the correlation coefficients were significantly ($\alpha = 0.05$) different from 0.
3) Daily tropical-system data specific to the southeastern United States was provided by the Southeast Regional Climate Center (more information was available at the time of writing at http://www.dnr.state.sc.us/climate/sercc/climateinfo/tropical/tropical.html). The tropical systems included the following tropical storms and hurricanes in chronological order: Bonnie, Earl, Georges, Dennis, Floyd, Harvey, Debby, Gordon, and Helene.
4) The strength of the association between the interpolated satellite-derived rainfall-rate estimates and the precipitation totals was tested using the Kendall's tau test. This test was conducted using all stations, only AEMN stations, and only NWS stations. The number of rainfall-rate–precipitation pairs for the above sets was 61, 21, and 40, respectively. The resulting correlation coefficients for the three sets of pairs were 0.10, −0.14, and 0.14, respectively. None of the correlation coefficients were significantly ($\alpha = 0.05$) different from 0.
5) The strength of the association between the interpolated satellite-derived rainfall-rate estimates and the tropical-system precipitation totals was tested using the Kendall's tau test. This test was conducted using only the 40 NWS stations. The resulting correlation coefficient (0.36) was significantly ($\alpha = 0.05$) greater than 0.
6) Daily 500-hPa pressure maps were examined for tropical systems, troughing events, and upper-level lows for all 459 days of the period. The data were extracted from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis dataset (Kalnay et al. 1996), which was provided by the National Oceanic and Atmospheric Administration Climate Diagnostics Center.
7) Daily precipitation totals at Hartsfield–Jackson Atlanta International Airport, DeKalb–Peachtree Airport, and Peachtree City were used in the analysis.
8) The 850-, 700-, and 500-hPa wind data at 1200 UTC were acquired for Peachtree City from the National Oceanic and Atmospheric Administration Forecast Systems Laboratory.
9) The number of synoptically quiescent precipitation days at Griffin for which corresponding 700-hPa wind data existed was 74, and the number of those days on which Atlanta was upwind was 26.
10) If advection were to occur directly from Atlanta to Griffin, the meteorological wind direction would be $\sim 348°$. If one assumes a 125° sector just as Shepherd et al. (2002) did, then, for Atlanta to affect precipitation totals at Griffin, the 700-hPa wind direction would range from 286° to 51°. A Mann–

Whitney U test was employed to test for significant ($\alpha = 0.05$) differences in daily precipitation totals between days on which Atlanta was upwind of Griffin and days on which Atlanta was not upwind of Griffin.

11) The number of synoptically quiescent precipitation days at Williamson for which corresponding 700-hPa wind data existed was 81, and the number of those days on which Atlanta was upwind was 23.
12) If advection were to occur directly from Atlanta to Williamson, the meteorological wind direction would be ~355°. If one assumes a 125° sector just as Shepherd et al. (2002) did, then, for Atlanta to affect precipitation totals at Williamson, the 700-hPa wind direction would range from 293° to 58°. A Mann–Whitney U test was employed to test for significant ($\alpha = 0.05$) differences in daily precipitation totals between days on which Atlanta was upwind of Williamson and days on which Atlanta was not upwind of Williamson.
13) Geopotential height composites were created using an online program (http://www.cdc.noaa.gov/Composites/Day) provided by the National Oceanic and Atmospheric Administration Climate Diagnostics Center. The 800- and 700-hPa geopotential heights were extracted from the NCEP–NCAR reanalysis dataset (Kalnay et al. 1996).
14) Because the exact surface-generating technique is not reported by Shepherd et al. (2002), the approximate accuracy of the map was determined using a jackknifing approach with the 22 AEMN stations located within and proximate to the domain. Three popular surface-generating techniques (contouring, inverse-distance weighting, and kriging) were employed. The relative errors of those surfaces were approximately 13%. The relative error of the precipitation surface presented in Shepherd et al. (2002) was definitely larger, because that surface was created with data from fewer stations.
15) To produce a random surface, a random value was assigned to each station, with the minimum value corresponding to the minimum observed precipitation total and the maximum value corresponding to the maximum observed precipitation total. The predicted precipitation totals at each of the 22 stations were the random values. This procedure was performed 100 times, and the relative error was determined from the 100 trials (i.e., each trial resulted in a relative error). The average relative error for the random surfaces was 17%.

APPENDIX B

Weather Stations

Listing of weather stations in the greater Atlanta area and their corresponding numbers, mean monthly precipitation totals, and type as shown on Fig. 2.

No.	Station	Mean monthly precipitation (mm)	Type
1	Atlanta	75	AEMN
2	Blairsville	80	AEMN
3	Calhoun	78	AEMN
4	Cordele	77	AEMN
5	Dublin	99	AEMN
6	Duluth	86	AEMN
7	Eatonton	69	AEMN
8	Ellijay	94	AEMN
9	Fort Valley	70	AEMN
10	Gainesville	67	AEMN
11	Griffin	80	AEMN
12	Jonesboro	78	AEMN
13	Lafayette	55	AEMN
14	Pine Mountain	79	AEMN
15	Plains	88	AEMN
16	Rome	75	AEMN
17	Roopville	78	AEMN
18	Watkinsville (Horticulture Research Farm)	91	AEMN
19	Watkinsville (Plant Sciences Research Farm)	71	AEMN
20	Watkinsville (J.P. Campbell Sr. Natural Resource Conservation Center)	82	AEMN
21	Williamson	69	AEMN
22	Woodbury	74	AEMN
23	Americus 3 SW	97	NWS Cooperative
24	Atlanta Bolton	96	NWS Cooperative
25	Blairsville Experiment Station	92	NWS Cooperative
26	Canton	96	NWS Cooperative
27	Carrollton	76	NWS Cooperative

APPENDIX B

Weather Stations

(*Continued*)

No.	Station	Mean monthly precipitation (mm)	Type
28	Cartersville	73	NWS Cooperative
29	Cartersville No. 2	100	NWS Cooperative
30	Chickamauga Park	64	NWS Cooperative
31	Clarkesville	104	NWS Cooperative
32	Cleveland	87	NWS Cooperative
33	Cornelia	89	NWS Cooperative
34	Dallas 7 NE	88	NWS Cooperative
35	Dawsonville	103	NWS Cooperative
36	Douglasville	90	NWS Cooperative
37	Ellijay	99	NWS Cooperative
38	Embry	82	NWS Cooperative
39	Experiment	95	NWS Cooperative
40	Fairmount	78	NWS Cooperative
41	Gainesville	96	NWS Cooperative
42	Jasper 1 NNW	118	NWS Cooperative
43	Jonesboro	90	NWS Cooperative
44	Juliette	76	NWS Cooperative
45	Monticello	78	NWS Cooperative
46	Newnan 4 NE	91	NWS Cooperative
47	Norcross 4 N	97	NWS Cooperative
48	Plains southwest Georgia experiment station	98	NWS Cooperative
49	Preston	106	NWS Cooperative
50	Taylorsville	104	NWS Cooperative
51	Toccoa	83	NWS Cooperative
52	University of Georgia Plant Science Farm	85	NWS Cooperative
53	Waleska	98	NWS Cooperative
54	Warner Robins	100	NWS Cooperative
55	Athens (Athens–Ben Epps Airport)	84	NWS WBAN
56	Atlanta (Hartsfield–Jackson Atlanta International Airport)	87	NWS WBAN
57	Atlanta (DeKalb–Peachtree Airport)	94	NWS WBAN
58	Columbus (Columbus Metropolitan Airport)	60	NWS WBAN
59	Gainesville (Lee Gilmer Memorial Airport)	77	NWS WBAN
60	Macon (Middle Georgia Regional Airport)	92	NWS WBAN
61	Peachtree City (Falcon Field)	81	NWS WBAN
62	Rome (R. B. Russell Airport)	72	NWS WBAN

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