Reply

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ABSTRACT

Diem et al. have responded with critical comments as to whether urbanization-enhanced precipitation is maximized in the south-southeast of Atlanta, Georgia, as was recently documented by Shepherd et al. The reply herein offers both general and specific responses to the issues raised by Diem et al.

1. Introduction

The literature continues to indicate that the signature of the ''urban heat island (UHI) effect'' may be resolvable in rainfall patterns over and downwind of metropolitan areas. However, a recent U.S. Weather Research Program panel concluded that more observational and modeling research is needed in this area (Dabberdt et al. 2000). Rapid population growth in the last few decades has made Atlanta, Georgia, one of the fastest growing metropolitan areas in the United States. Because Atlanta is a model of rapid transition from forest/agriculture land use to urbanization, the National Aeronautics and Space Administration (NASA) and other agencies have initiated programs such as the Atlanta Land Use Analysis: Temperature and Air Quality Project (Project ATLANTA; Quattrochi et al. 1998).

2. Motivation and previous work

Such focus has led to a wealth of information on Atlanta's UHI environment. Atlanta's UHI may also affect the global water cycle by inadvertent forcing of precipitating cloud systems. Bornstein and Lin (2000) used data from Project ATLANTA's 27 mesonet sites and eight National Weather Service sites to investigate interactions of the Atlanta UHI, its convergence zone, and convective storm initiation. Shepherd et al. (2002, hereinafter Shepherd et al.) recently found evidence that Atlanta and other urban areas may modify cloud and precipitation development. Dixon and Mote (2003) recently investigated the patterns and causes of Atlanta's UHI-initiated precipitation. Many results of recent studies are consistent with previous work. For example, early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972) found evidence of warm-season rainfall increases of 9%–17% over and downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was an extensive study that took place in the 1970s in the United States (Changnon 1978; Huff 1986) to investigate modification of mesoscale and convective rainfall by major cities. In general, results from METROMEX have shown that urban effects lead to increased precipitation during the summer months. Increased precipitation was typically observed within and 50–75 km downwind of the city, reflecting increases of 5%–25% over background values (Huff and Vogel 1978; Changnon 1979; Changnon et al. 1981, 1991). More recent studies have continued to validate and extend the findings from pre-METROMEX and post-METROMEX investigations (Balling and Brazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000; Thielen et al. 2000; Baik et al. 2001; Ohashi and Kida 2002; Changnon and Westcott 2002).

Diem et al. (2004, hereinafter Diem et al.) have offered a critical response to Shepherd et al. We are delighted that Shepherd et al. garnered the interest of our colleagues in the community and initiated a critical response. The response was well posed and thought provoking. The response that we offer stands by our initial findings; however, Diem et al. raise some issues of which we were keenly aware. The response herein offers both general and specific responses to those issues raised.

3. General comments in response to Diem et al.

a. *Intent of Shepherd et al.*

Shepherd et al. (2002) was written with the intention of demonstrating the feasibility of the Tropical Rainfall

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Measuring Mission (TRMM) precipitation radar for identifying potential urban-induced rainfall signatures. As stated in section 3 of Shepherd et al., one of the novelties of the study was the application of satellite data to the problem of urban-induced precipitation. The authors always recognized that the TRMM dataset is not the optimal dataset for this type of study. In fact, we stated that TRMM is in a low-inclination orbit and is particularly suited and designed for capturing rainfall events at temporal scales of 1 month or greater. The study was not intended to utilize TRMM to identify

1) individual urban-induced storms,
2) seasonally stratified events, or
3) synoptic-regime events.

These approaches are ideal but do not lend themselves to the 0.5° climate-focused datasets of TRMM. For this reason, we employed a more general approach in which climatological wind regimes (with variance around a mean vector) were correlated with climatological values offered by the TRMM data. For the more detailed approaches listed above, a more focused and appropriate dataset (gauges and ground-based radar) are required. To this end, we are conducting the 2003–04 Studies of Precipitation Anomalies from Widespread Urban Land Use (SPRAWL) field campaign. SPRAWL evolved because of our own skepticism of the satellite results presented in Shepherd et al.

Shepherd et al. demonstrated that the University of Georgia (UGA) Automated Environmental Monitoring Network (AEMN; Hoogenboom 1996) might not be sufficiently dense to capture the convective- to meso-gamma-scale rainfall anomalies associated with the urban heat island. This fact could be deleterious to any effort to identify convective-scale precipitation anomalies in an urban area and could lead to possible biases or gaps in the data. It is important in any spatiotemporal sampling to set the spacing between recorded samples at a maximum of one-half of the wavelength of the spatial variation/periodicity of the process. Gridded TRMM precipitation radar (PR) data used in Shepherd et al. are typically 0.5° (∼50 km) in spatial resolution. This point illustrates the need for *a higher-density network* (∼25 km or less) near Atlanta to validate the TRMM satellite-indicated rainfall anomalies.

NASA has deployed the NASA–Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN). NCURN is operated in conjunction with faculty and students at CAU and supplements AEMN and National Weather Service sites. The network consists of 25–30 gauges spaced approximately 25.0 km apart and is centered on the geographic center of the Atlanta metropolitan area. Figure 1 is the emerging NCURN configuration. The NCURN was implemented as a long-term observation system and to support SPRAWL. The specific objectives of SPRAWL are

1) to conduct an intensive ground validation campaign of TRMM PR findings during the summer of 2003 (July–August) using the dense NCURN network in Atlanta and surrounding areas,
2) to utilize ground- and space-based datasets to identify and quantify ''urban induced'' rainfall events over a 1-month intensive observation period (IOP),
3) to develop a ''case study'' validation dataset for comparison with simulations using the NASA Goddard Space Flight Center's version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1994) coupled to the Parameterization for Land–Atmosphere–Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995),
4) to develop a prototype continental urban rainfall validation site for TRMM and future precipitation missions (e.g., Global Precipitation Measurement) to mitigate the problem of insufficient continental validation sites (Kummerow et al. 2000), and
5) to provide a high-spatial-resolution, long-term rainfall monitoring capability around Atlanta.

SPRAWL will occur during the summer of 2003 and 2004 in the Atlanta area in conjunction with NASA, the National Weather Service, CAU, and the UGA AEMN network. We have placed a dense rain gauge network around the city of Atlanta to fill gaps in the UGA AEMN network. During selected IOPs we will collect rainfall, upper-level meteorological, and surface meteorological data. The purpose of this dataset is to establish a 2-yr database of information that will allow us to address whether urban-induced rainfall occurs around Atlanta, what wind regimes are prevalent, what diurnal time period is preferred, and other relevant questions. The author emphasizes here that *SPRAWL was being planned as Shepherd et al. (2002) was being written*, because it was known and anticipated that the TRMM data could not be considered to be a conclusive dataset to approach thoroughly the urban rainfall problem. Shepherd et al. (2004) describes the NCURN network and SPRAWL.

b. ''Apples and oranges''

Concerns about the accuracy of TRMM data may illustrate a possible unfamiliarity by Diem et al. with the space-based radar. Kummerow et al. (2000) reported that comparisons of PR-measured radar reflectivities with those measured by ground-based radar at NASA's Florida ground validation site show good agreement (differences within about 1 dB, on average). Schumacher and Houze (2000) compared the PR rainfall estimates with an S-band ground-based radar in the Kwajalein Atoll and also found good agreement. They found that the PR only misses 2.3% of near-surface rainfall relative to the ground-based radar and gauges. Similar

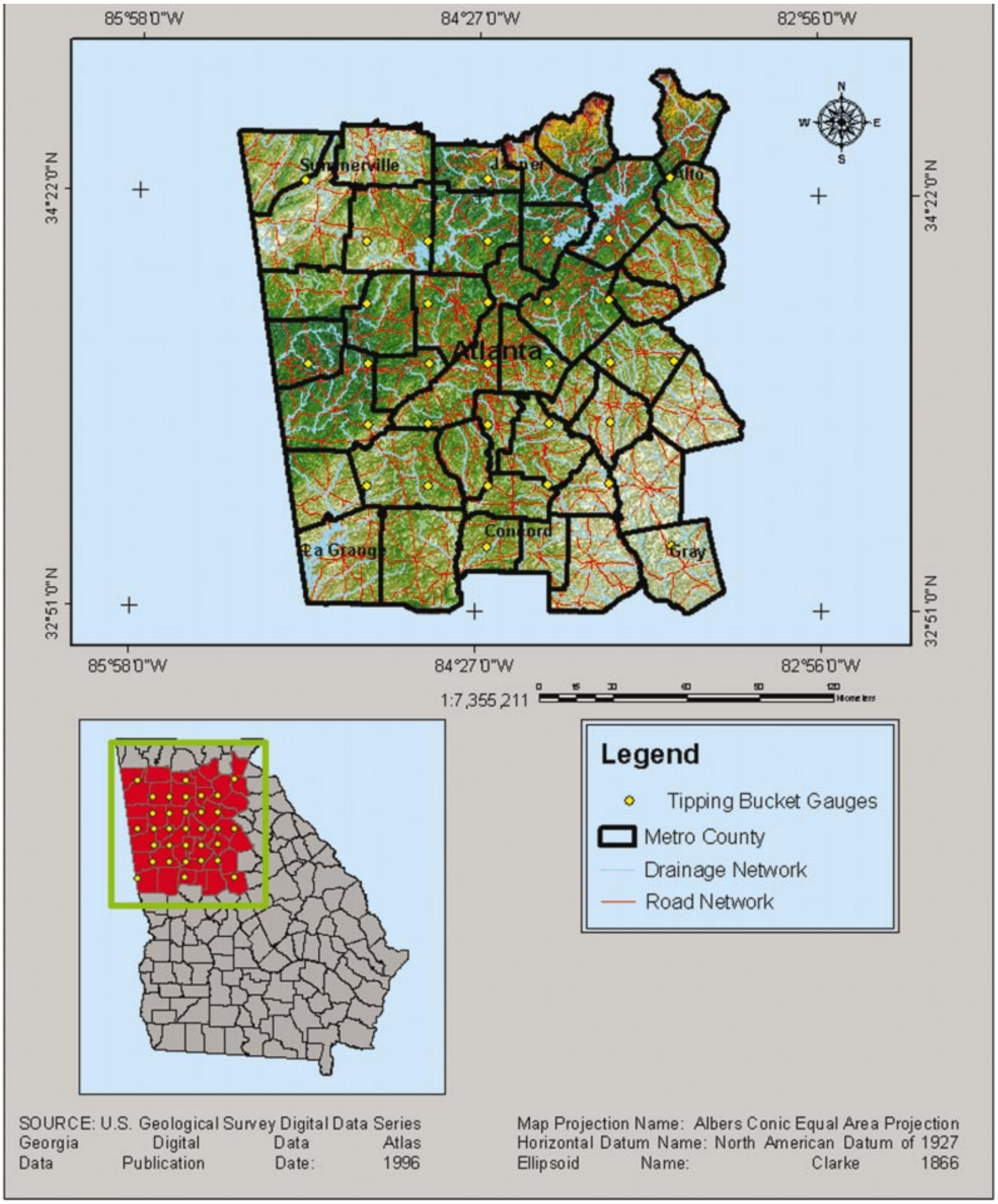

FIG. 1. NASA–CAU Urban Rain Gauge Network.

calibration and validation studies corroborate these results (Bolen and Chandrasekar 2000; Heymsfield et al. 2000). The validation and calibration results indicate that the PR has been and will be sufficiently stable and accurate to assure quantitative rainfall estimates. In fact, operational agencies are considering the possibility of using the PR as a calibration constant to ground-based radars that are calibrated independently and rarely to the 1-dB*Z* standards of the PR (Kummerow et al. 2000).

We do not exhaustively discuss the accuracy of the TRMM radar in detail because the remote sensing community and those accustomed to the data generally accept that the TRMM PR is an accurate system [within 1 dB*Z* of ground systems such as the Weather Surveillance Radar-1988 Doppler (WSR-88D)] and has a more rigorous calibration standard than most ground-based radars. Liao et al. (2001) provides more insight into the calibration and validation of the TRMM PR. Therefore, we stand by the statement that ''the PR has been . . . sufficiently stable and accurate to assure quantitative rainfall estimates.'' There obviously will be errors associated with the radar reflectivity–rainfall rate conversion and assumptions, but we do not feel that these errors are any more problematic than other rain-measuring systems.

In addition, we emphasize that space–time-averaged PR data are utilized. The analysis was conducted on mean monthly ''conditional'' rainfall rates. Conditional rain rates account for events only where rainfall is detected in the grid box. Shepherd and Burian (2003) emphasized that because of the limitations of the TRMM conditional rain-rate approach ''TRMM PR rainfall rates are not the ideal dataset for detecting specific urban-induced events.'' Yet, it is important for Diem et al. to note that our data present a climatological snapshot of the mean rainfall rates in the study area when rain occurs. So, in essence our results show, for example, that when it does rain the rates tend to be higher in the southeast quadrant of our area. We acknowledge that one of the biggest deficiencies with the Shepherd et al. study is that in using conditional rainfall rates, we are likely working with a sample size in each grid box that is smaller than we would like and is also location variant. We address this to some degree in the approaches of Shepherd and Burian (2003), but we recognize this approach as a limitation. As a reminder, when we reported these results we were somewhat skeptical also. For this reason, we planned and are conducting the SPRAWL campaign.

In many of the analyses presented in Diem et al., the authors display monthly rainfall amounts. This is an apples and oranges comparison with the conditional rainfall rates of Shepherd et al. (2002). We state this fact in the paper. In fact, what our results really say is that urban-induced rainfall is generally convective in nature and has preferred regions. Comments in section 4 further address some of these issues.

4. Response to specific comments by Diem et al.

a. Diurnal bias

We disagree with the assertion that our data are biased. TRMM is in a precessing, low-inclination (35°), low-altitude orbit, and because of the non-sun-synchronous orbit strategy, the equatorial crossing time gradually shifts. For this reason, it is unlikely that results reflect any biases from diurnal forcing. Because of the nature of the TRMM conditional rain rates, it is true that the values for a given grid box may be contributed from an array of systems and diurnal times. The authors are aware of the nice work by Dixon and Mote (2003) but have some fundamental disagreement with some of their findings. Typically the peak in the urban–rural surface temperature difference is in the late evening time window, as stated by Diem et al. However, the urban heat island circulation, boundary layer destabilization, and associated low-level convergence (e.g., all of which are more important for convective development than the simple UHI surface temperature gradient) are most evident during the daytime. This fact is due to the greater urban–rural pressure gradient and vertical mixing during daytime hours (Shreffler 1978; Fujibe and Asai 1980; Kusaka et al. 2000; Ohashi and Kida 2002). Recent modeling results from using a mesoscale model support these findings that daytime dynamic forcing is the dominant forcing mechanism for the UHI rainfall. During the summer, moisture is generally sufficient in Atlanta, and so the authors are not convinced that moisture is the ''smoking gun'' as Dixon and Mote (2003) seem to suggest.

Furthermore, we would hypothesize that Dixon and Mote's (2003) decision to exclude widespread ''daytime heating'' convection from their database may represent a deficiency. These storms are likely characteristic of what would be considered ''urban heat'' island–generated storms because we know that daytime-heating thunderstorms are likely forced by something other than simply daytime heating (e.g., UHI convergence, outflow boundaries). In general, Dixon and Mote's (2003) criteria may be too restrictive and thereby may bias the diurnal tendency of UHI-induced convection.

b. Mesoscale or not?

Diem et al. state that at scales of roughly 50 km, it is impossible to conduct comparisons within a mesoscale context. On one hand, we would love to have finer-resolution data (hence, SPRAWL) but our intent was to demonstrate the ability for TRMM 0.5° PR data to identify mesoscale signatures. In fact, the study was motivated by analyses of the 0.5° data that continued to illustrate clearly defined rainfall signatures associated with sea-breeze fronts and orography, both of which are mesoscale forcing mechanisms. It is also worth reminding Diem et al. that the mesoscale spans from meso gamma (~2 km) to meso alpha (~2000 km), based on Orlanski (1975). Other definitions presented in (Ray 1986) are also consistent with Orlanski (1975).

c. Tropical-system bias

The discussion of whether tropical systems biased our data is valid. We were generally concerned also that our data might be biased by tropical activity, although our preliminary analysis could not justify why the tropical contribution would be so concentrated in the southeast quadrant when most of the systems during this period produced fairly widespread rainfall over the entire Atlanta area. However, this uncertainty is another reason why we are conducting the SPRAWL campaign.

d. Ecological fallacy

Shepherd et al. chose to plot contours of the 0.5° data for presentation clarity but recognized that the Barnes-type analysis utilized in the General Meteorology Package (GEMPAK) may have overly smoothed the data. In

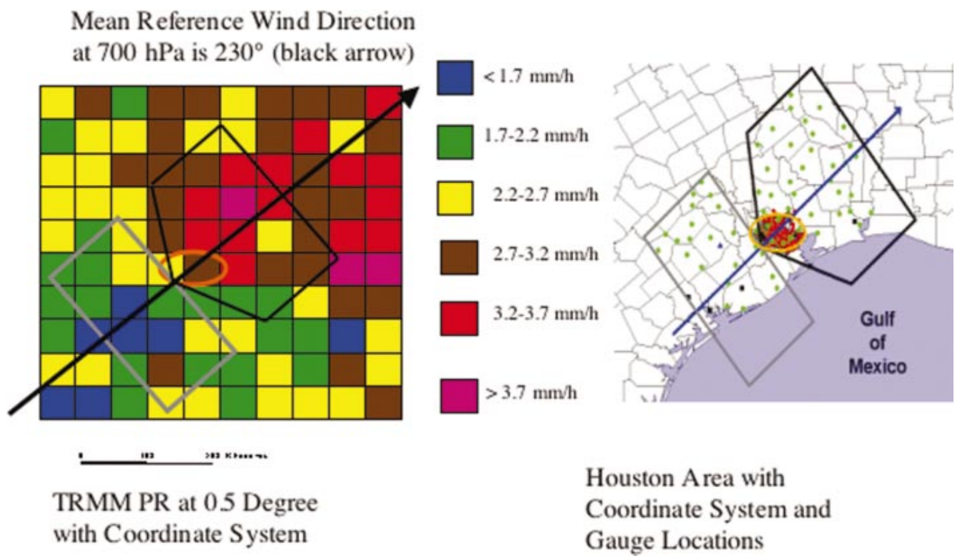

FIG. 2. The ''theoretical study coordinate system'' with mean annual distribution of TRMM-derived rainfall rates from Jan 1998 to May 2002 (excluding Aug 2001). The orange oval is the approximate Houston urban zone and is centered on (29.75°N, 95.75°W) and (29.75°N, 95.25°W), respectively. The black vector represents the mean annual 700-hPa steering direction. The pentagon-shaped box is the ''downwind urban impacted region (DUIR),'' and the rectangular box is the ''upwind control region (UCR).''

Shepherd and Burian (2003), we have chosen to plot the data in grid boxes of native resolution (Fig. 2). Had we done this in Shepherd et al., a distinct anomalously high region would still be evident in southeast of the metropolitan area. We acknowledge that the objective-analysis treatment presented in Shepherd et al. was probably not the optimal treatment. We were not trying to ''downscale,'' we simply wanted a cleaner presentation using contouring.

e. Ensemble averaging

As stated previously, we did not intend to try to stratify synoptic regimes or individual cases because the satellite's climate-centric dataset did not lend itself to this more detailed (and preferred) analysis. To investigate the capabilities of satellite-based measurements for identifying urban effects on rainfall, a working hypothesis was established, similar in philosophy to Huff and Changnon (1972). In their framework, hypothesized areas of urban effect and no effect on a climatological time scale were determined. Their study identified the most frequent lower-tropospheric wind flow for each city and defined the hypothesized ''downwind-affected region'' and upwind control regions. Our working hypothesis is a variation of this approach:

1) Areas within a 25-km radius of the city (e.g., the central urban area) will exhibit some level of enhanced precipitation caused by the UHI effects.
2) Areas within 25–75 km downwind of the central urban area and within a 125° sector will exhibit the maximum impact of UHI effects.
3) Areas within 25–75 km upwind of the central urban area are defined as the ''upwind control area.''
4) Areas within ~50 km^2 orthogonal to the mean wind vector are considered to be regions of minimal to no impact.

The 700-hPa level was chosen arbitrarily as a representative level for the mean steering flow for convective storms and is supported by previous work in the literature (Hagemeyer 1991). The National Centers for Environmental Prediction–NCAR reanalysis dataset (Kalnay et al. 1996) and published work by Hagemeyer (1991) were used to determine the mean warm-season ''prevailing'' flow at 700 hPa for the selected cities. For each city, the horizontal reference axis is oriented according to the mean prevailing wind direction. The 125° sector accounts for the ''steering'' directions representing means that include values greater or less than the mean value; therefore, the mean affected area accounts for the spread of values that encompass the mean (e.g., the deviation). We are still comfortable with this approach for the TRMM dataset but recognize it as limited. SPRAWL will allow for more robust stratification based on case-by-case wind regimes and system classification (e.g., frontal, weak forcing).

At this point, we reemphasize that Diem et al. should not misconstrue that this study was meant to be a ''robust'' analysis of Atlanta's urban-induced rainfall tendencies. Instead, it was trying to establish that a unique space-based rain radar was detecting rainfall-rate signatures that might be linked to urban-induced rainfall. This study offered a preliminary assessment for the more in-depth field and modeling work that SPRAWL will enable.

f. Rainfall map comparisons

The map that we presented for amount was used as a qualitative tool to illustrate broadly the rainfall distribution. We stand by the accuracy of our analysis. Furthermore, Shepherd et al. did not go into a detailed analysis because it is a case of apples and oranges, and there is no way to provide a meaningful comparison between gauge amounts and TRMM conditional rainfall rates (conditional rainfall rates previously defined).

g. Topography

The author of this reply is from Cherokee County, Georgia, and is very familiar with the topography in Georgia. In fact, we state that the Atlanta area is ''relatively'' flat. This was in comparison with cities like Phoenix, Arizona, or Denver, Colorado, that have substantial surrounding relief (defined as greater than 500 m above sea level). In fact, Shepherd et al. (2002) acknowledged that the Atlanta area was not flat by listing its altitude in Table 1 of that paper. However, we emphasize that we do not believe that the relief is a primary factor in this study. Substantial evidence of topography-induced signatures in the mountainous South Carolina, North Carolina, and Georgia regions was observed when we examined annual data from TRMM.

h. Distance

Diem et al. are correct in noting that gauging a downwind distance is not possible from this dataset. For this reason, we chose to give a distance range. Guided by our recent model results and SPRAWL results, we hope to quantify a distance with more conclusiveness in the future.

5. Conclusions

Diem et al. have encouraged the authors by expressing a keen interest in Shepherd et al. (2002). Recent work by this author and several colleagues in the community continues to show evidence that urban areas are causing discernible anomalies in precipitation. Diem et al. raise some valid issues in their paper, but most of them do not ultimately negate the value and intent of Shepherd et al. (2002). Their comments suggest that they did not fully understand that Shepherd et al.'s intent was to offer a new ''prototype'' approach for studying urban rainfall anomalies. Recent urban sessions at the 2003 Fall American Geophysical Union Meeting and the 2004 American Meteorological Society Annual Meeting illustrate the renewed interest in the subject matter. Our approach in Shepherd et al. used a satellite-based technique to study the problem but was never intended to suggest that its results were conclusive or thoroughly studied. Instead, the goal was to stimulate new ground-based efforts like SPRAWL, additional satellite observations, and modeling studies. Over the next decade, more research will be required to answer firmly the questions that have arisen over the last few decades concerning urbanization and precipitation variability.

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