INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2009)

(www.interscience.wiley.com) DOI: 10.1002/joc.2044

Urbanization signature in the observed heavy rainfall climatology over India

C. M. Kishtawal,[a,b] Dev Niyogi,[b]* Mukul Tewari,[c] Roger A. Pielke Sr[d] and J. Marshall Shepherd[e]

[a] *Space Application Center, Ahmedabad 380015, India*
[b] *Department of Earth and Atmospheric Sciences and Department of Agronomy, Purdue University, West Lafayette, IN 47906, USA*
[c] *National Center for Atmospheric Research, Boulder, CO 80303, USA*
[d] *University of Colorado, CIRES, Boulder, CO 80309, USA*
[e] *Department of Geography, University of Georgia, Athens, GA 30602, USA*

ABSTRACT: We assess the urbanization impacts on the heavy rainfall climatology during the Indian summer monsoon. While a number of studies have identified the impact of urbanization on local precipitation, a large-scale assessment has been lacking. This relation between urbanization and Indian monsoon rainfall changes is investigated by analyzing *in situ* and satellite-based precipitation and population datasets. Using a long-term daily rainfall dataset and high-resolution gridded analysis of human population, this study showed a significantly increasing trend in the frequency of heavy rainfall climatology over urban regions of India during the monsoon season. Urban regions experience less occurrences of light rainfall and significantly higher occurrences of intense precipitation compared to nonurban regions. Very heavy and extreme rainfall events showed increased trends over both urban and rural areas, but the trends over urban areas were larger and statistically more significant. Our analysis suggests that there is adequate statistical basis to conclude that the observed increasing trend in the frequency of heavy rainfall events over Indian monsoon region is more likely to be over regions where the pace of urbanization is faster. Moreover, rainfall measurements from satellites also indicate that urban areas are more (less) likely to experience heavier (lighter) precipitation rates compared to those in nonurban areas. While the mechanisms causing this enhancement in rainfall remain to be studied, the results provide the evidence that the increase in the heavy rainfall climatology over the Indian monsoon region is a signature of urban-induced rainfall anomaly. Copyright © 2009 Royal Meteorological Society

KEY WORDS land use land cover change; Indian monsoon; population growth; precipitation; urbanization; climate change

Received 26 February 2009; Revised 6 August 2009; Accepted 24 September 2009

1. Introduction

The Indian summer monsoon is a giant feedback system involving interactions between land, ocean, and the atmosphere. The Indian summer monsoon rainfall (ISMR), defined here as the cumulative rainfall over continental India during June–July–August–September (JJAS), also has important implications on the socioeconomic system of the subcontinent. For example, the domestic crop yield in India has traditionally been linked to the ISMR (Parthasarathy, 1984); the agricultural sector accounts for about a quarter of India's gross domestic product and 60% of the labor force. The initiation of the cross-equatorial flow off the Somalia coast of Africa during May in response to heating over the South Asian continent marks the beginning of the summer monsoon evolution process over the Arabian Sea.

The analysis of 100 years of surface rainfall observations over the Indian monsoon region suggests that the mean monsoon seasonal rainfall has not changed significantly (Goswami *et al*., 2006), but several locations across India show an increasing trend in heavy rainfall occurrence (>70 mm/day) during the summer monsoon season (Sinha Ray and Srivastava, 2000). The increase in extreme rainfall (>120 mm/day) events during the Indian monsoon has been particularly strong in the last 50 years (Goswami *et al*., 2006).

Parallel to these climatic changes, the Indian landscape has also been rapidly urbanizing. In the present study, we seek to assess if there is a relation between urbanization and the occurrence of heavy rainfall events during the Indian summer monsoon. This relation between urbanization and Indian monsoon rainfall changes is examined by analyzing satellite observations, surface-based precipitation data, and population datasets.

2. Background

With half the global population now living in cities and the urban infrastructure of the world expected to double over the next 35 years, urban environments are playing

---

* Correspondence to: Dev Niyogi, Department of Earth & Atmospheric Sciences and Department of Agronomy, Purdue University, West Lafayette, IN 47906, USA. E-mail: climate@purdue.edu

an increasingly important role in land-surface processes and climate change. Urban areas modify boundary layer processes through the creation of 'urban heat islands' (UHI). In cities, natural land surfaces are replaced by artificial surfaces that have very different thermal properties (e.g. heat capacity, specific heat, and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat resulting in urban air to be 2–10° warmer than that in surrounding nonurban areas (Oke, 1988). Urban areas are also regions of enhanced low-level convergence (via mechanical turbulence from rough surfaces), increased surface sensible heat flux, and elevated aerosol loading (Shepherd, 2005, Niyogi *et al.*, 2007).

Early investigations (Changnon, 1968; Landsberg, 1970; Huff and Changnon, 1972) noted evidence of warm seasonal rainfall increases of 9–17% downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was a landmark study that took place in the 1970s in the United States (Changnon *et al.*, 1981; Huff, 1986) to further investigate modification of rainfall by the urban environment. Results from METROMEX suggest that the urban effects lead to 5–25% increased precipitation, particularly 50–75 km downwind of the urban center during the summer months (Changnon *et al.*, 1991). There is increasing evidence that urbanization and changes in urban–rural boundaries can have a significant feedback on the spatiotemporal patterns of precipitation (Shepherd *et al.*, 2002; Shepherd and Burian, 2003; Niyogi *et al.*, 2006; Mote *et al.*, 2007; Lei *et al.*, 2008). Cotton and Pielke (2007, Chapter 5; Pielke *et al.*, 2007, Section 7) summarize numerous studies as to how urbanization alters rainfall patterns as a result of mesoscale circulations and through changes in convective available potential energy (CAPE). Moreover, recent research continues to show credible evidence that surface temperature increases (Kalnay and Cai, 2003), cloud enhancement (Inoue *et al.*, 2004), and precipitation anomalies (Hand and Shepherd, 2009; Shem and Shepherd, 2009; Shepherd *et al.*, 2009) may be linked to urban environments.

The alteration of this hydrometerological environment due to urbanization is one of the reasons that alterations in rainfall have been found in past studies. This would be expected to occur primarily with convective cloud rainfall.

Convective rainfall is the typical precipitation regime in the warm seasons and in the tropics, including India. This rainfall is dependent on the vertical stratification of the temperature, water vapor, and winds that can be described by using a quantity called the CAPE, as discussed in Pielke (2001). CAPE depends on the flux of heat (sensible and latent) and moisture from the surface into the atmosphere along with the thermodynamic stratification of the overlying atmosphere. The realization of the CAPE as deep cumulus clouds depends on overcoming any inhibiting factors (i.e. convective inhibition, CIN), as saturation needs to occur in order for the potential convective energy to be released. If CIN can be overcome, the larger the CAPE, the more intense are the resulting cumulus clouds (and thus heavier rainfall rates are expected).

When urbanization occurs, the surface heat and moisture fluxes, and the overlying temperatures, humidity, and winds are significantly altered from what would occur if the region remained rural, as CAPE (and CIN) is altered. Spatial variations in the CAPE and CIN and in the mesoscale circulations that result from landscape heterogeneity, such as from urbanization, can focus on deep cumulus convection (Avissar and Liu 1996). Niyogi *et al.* (2006), Shem and Shepherd (2008) and Shepherd *et al.* (2009), using coupled atmosphereland models, quantified the relative changes in sensible and latent heat fluxes as a function of urban land cover for Oklahoma City, Atlanta and Houston respectively. Enhanced sensible heat flux was likely one factor related to the resolved urban-induced precipitation. These three studies also noted enhanced low-level convergence at the urban–rural interface. Low-level convergence from the urban-induced meso-circulation may serve as an initial or complementary source of lift required for convection, given other *a priori* conditions.

Despite the significant amount of research mentioned above, our understanding of how urban environment affects regional and global climate is far from complete. While a number of studies provide a detailed analysis of the impact of urbanization on the local precipitation climatology for urban areas of developed countries such as Atlanta (Mote *et al.*, 2007), Houston (Shepherd and Burian, 2003; Shepherd *et al.*, 2009), Tokyo (Kusaka *et al.*, 2000), Sydney (Gero and Pitman, 2006), Oklahoma City (Niyogi *et al.*, 2006), Indianapolis Beijing (Zhou *et al.*, 2004), and Mumbai (Lei *et al.*, 2008), the impact of urbanization on continental-scale rainfall changes and large-scale systems such as Indian summer monsoon system has not been analyzed in adequate detail, and is the focus of this paper.

According to the 2001 census, in India, out of the total population of 1027 million, about 285 million live in urban areas and 742 million in rural areas. Thus, around 29% of the population in India lives in urban areas. For every 100 persons living in rural areas of India, 39 live in urban areas, which is 4 more than the number in 1991. The percent urban population and urban–rural ratio (urban population per hundred rural population) is the commonly used measure of the degree of urbanization (Karl *et al.*, 1988). Figure 1 shows how the degree of urbanization has varied over India over the past century. It is interesting to see a dramatic shift in the rate of urbanization after India became independent in 1947. The average urban–rural ratio for India (39) is still significantly smaller compared to that for the world (89) and Asia (58). In coming decades, the urban–rural ratio for India is expected to increase more rapidly, and hence it is important to initiate the assessments of the climatic impacts of such urbanization, as undertaken in this study.

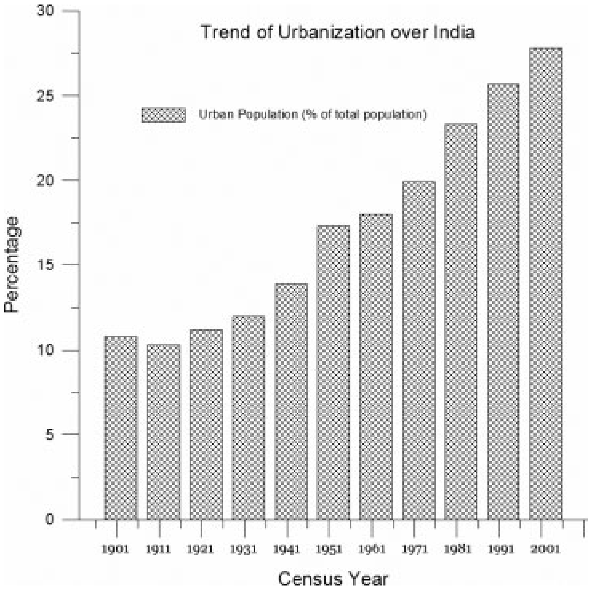

Figure 1. Growth of fraction of urban population for India during the past century.

2.1. Region of study

The study area is the Indian subcontinent that extends from 8.2 °N to 35.35 °N latitude and from 68.5 °E to 97 °E longitude. Summertime moisture availability over the Indian monsoon domain is significantly higher than that in the midlatitude regions. A preliminary analysis of National Center for Environmental Prediction (NCEP)-reanalysis data indicates that, during the summer season, the mean precipitable water (PW, the vertically integrated water vapor) over central India is 47.5 kg/m^2. In contrast, the PW values for the same season for the southwestern and the southeastern United States is 15.0–17.5 kg/m^2 and 37.5 kg/m^2 respectively. By May, most of interior India experiences mean temperatures over 305 K and maximum temperatures exceeding 313 K. Temperatures of 321 K and higher have been recorded in parts of India during this season. The Himalayas separate South Asia from the rest of Asia. The subcontinent has eight climatic zones that experience the monsoon, although it arrives in different parts of the country at different times (Pant and Rupa Kumar, 1997).

3. Data and methodology

3.1. Human population dataset

To analyze the patterns of human settlement and urbanization over the Indian summer monsoon region, we used Gridded Population of World (GPW, version-3, or GPW-V3) data from the Earth Institute at Columbia University. The GPW data is a large-scale spatial distribution of human population available at 2.5 arc min. Various census and statistical agencies have developed regionally relevant definitions of identifying urban region from population data. In order to define the boundaries of urban regions and the background rural regions, we performed a histogram analysis of the GPW-V3 data over the Indian region.

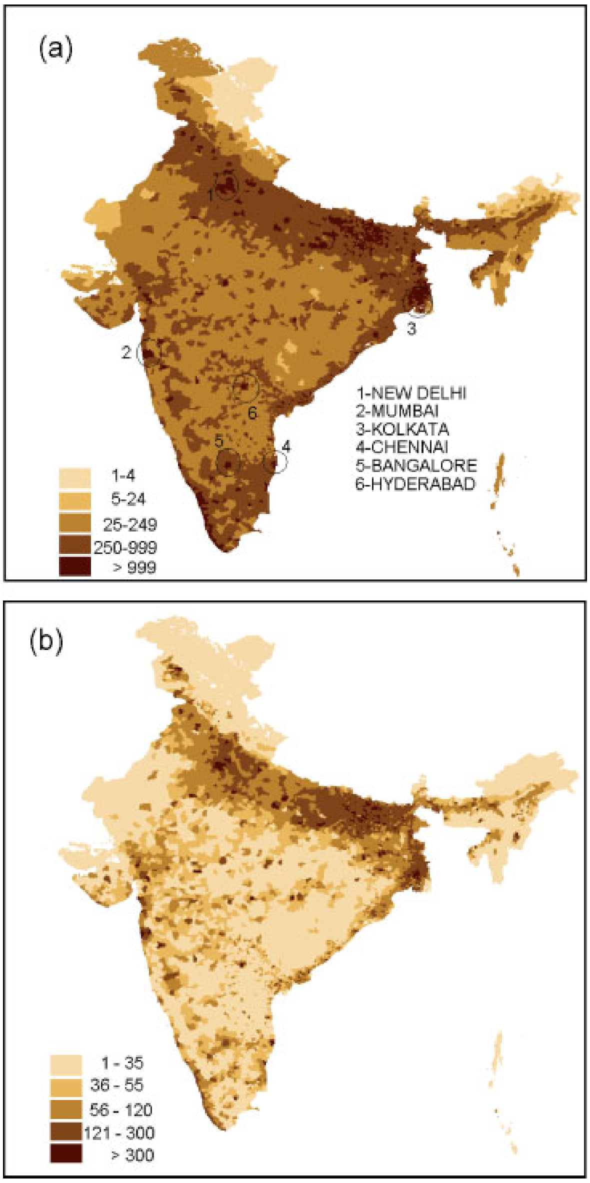

Figure 2. (a) Distribution of population density (P/km^2) over India in the year 2000 and (b) change of population density between the years 1990 and 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

Figure 2(a) shows the density of population of the Indian subcontinent for the year 2000 (persons/km^2, denoted as P/km^2 here onward). All of the major metropolitan cities of India are clearly visible in this figure. The cities marked in the image are New Delhi (estimated population 10.9 M), Mumbai (16.3 M), Kolkata (14.2 M), Chennai (7 M), and Bangalore (4.2 M). To evaluate the patterns of urbanization in India, we computed the difference of population density between 2000 and 1990 (Figure 2(b)). The difference in the population density indicates a pattern that is consistent with the recent economic growth across India where, during the past decade, the western part of India has experienced a significantly faster rate of urbanization

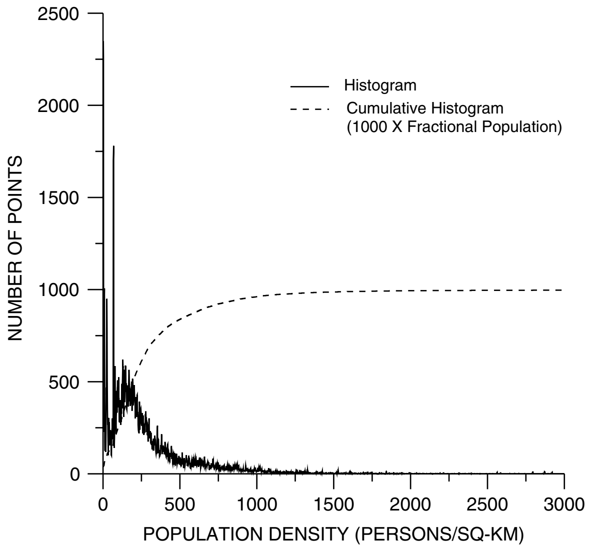

Figure 3. Histogram (solid line) and cumulative histogram of population density (P/km^2) for India. Cumulative histogram denotes the fractional population multiplied by 1000.

compared to the eastern part (Sachs *et al*., 2002). The most intense urbanization has occurred in the vicinity of existing large cities such as New Delhi, Mumbai, and Chennai and these new urban regions show the highest change (as large as 1000 P/km^2). Even though Figure 2(b) shows the patterns of urbanization and human settlement during a period of only 10 years, considering the fact that urbanization and sprawl is a slow and quasi-linear process, the trends shown by growth of population may be extrapolated for some decades into the past and the future. This assumption allows us to analyze long-term changes in precipitation in the context of urbanization indicated by the density of population.

To select proper thresholds for isolating the urban regions from the background, we performed the histogram analysis of the gridded population. Figure 3 shows the histogram of the population density over India. The cumulative histogram shows that the density of population is less than 600 P/km^2 for 90% of the study area, and we define this region as the background or the 'rural region'. A population density of 1600 P/km^2 defines the 99th percentile value for this region, and is treated as a threshold to define a grid point as urban. Only 0.3% grid points with population density larger than 3000 belong to intense urban regions such as large metropolitan cities.

3.2. Rainfall datasets

To assess the possible relationship between urbanization and the trends in heavy rainfall events, we adopted two widely used data sources available from the India Meteorological Department (IMD). The first dataset is the quality-controlled, rainfall climatology for 151 stations from 1901 to 1990 compiled by Sinha Ray and Srivastava (2000). The second dataset is the IMD 1° gridded analysis comprising over 1800 rainfall stations from 1950 to 2003 (Rajeevan *et al*., 2005). Goswami *et al.* (2006), for example, analyzed these gridded data in assessing the changes in the Indian monsoon climatology and concluded that the extreme rainfall events have an increasing trend over central India.

Additionally, we used 10 years of observations (1998–2007) from the Tropical Rainfall Measurement Mission (TRMM) combined rain rate product (3G68), which was obtained from the TRMM Science Data and Information System (TSDIS). Data are provided in 0.5° × 0.5° latitude–longitude grid boxes. The observation time for each grid box is recorded to the nearest minute. The data include retrievals from three different algorithms: the TRMM Microwave Imager (TMI, a passive microwave instrument), the Precipitation Radar (PR), and the COMB (the combination of TMI and PR instruments). In addition to the mean rain rate for the three algorithms, the 3G68 data set includes the numbers of rainy and total pixels observed by TMI, PR, and COMB, and the percentage of convective rain. It should be noted that rainfall products from each algorithm are available separately within the 3G68 dataset. The 3G68 data is an hourly gridded product, which includes 24 hourly grids in a single daily file. Generally, the TRMM satellite is able to observe a given location in the tropics about once per day, at different times each day, with a cycle of 42 days, the cycle of its orbital precession. Owing to the non-sun-synchronous orbit of TRMM, the rainfall observations are less likely to be influenced by diurnal biases. We have chosen to use the TRMM precipitation radar (TRMM-PR) observations from the TRMM 3G68 data set due to following reasons. PR is able to detect light rain rates down to about 0.7 mm/h and is able to separate out rain echoes for vertical sample sizes of about 250 m at nadir. Shepherd *et al.* (2002) also advocated the use of PR-derived rainfall rates rather than passive microwave or infrared datasets to study the impact of urbanization on rainfall climatology. Over land, the infrared or passive microwave-based rainfall estimates rely heavily on scattering signatures from ice in the upper portion of convective clouds. Often these signatures are not collocated with the actual surface rainfall location. The active PR is a more physically based measurement of rainfall and provides more certainty in the actual location of rainfall cells. PR measurements are subject to the satellite overpass time but these biases are minimized when a very large number of events are considered (as done in this study). One of the important points to note is that such biases are independent of the nature of the underlying surface (e.g. urban or rural).

4. Results

4.1. Urbanization and the trends in heavy precipitation events

The main focus of our analysis is to assess if the patterns of recent urbanization have affected the occurrence of heavy precipitation events during the monsoon season. According to the definition provided by IMD, a rainfall event is termed as 'heavy rainfall event' if the accumulated rainfall amount exceeds 70 mm in 24 h. Out of 154 surface locations that Sinha Ray and Srivastava (2000) analyzed, increasing trends in the frequency of heavy rainfall events were found at 23 stations, while 48 stations showed a decreasing trend. The remaining stations did not show a significant trend in the frequency of heavy precipitation events. To explore a link between these events and the trends of urbanization, we determined the average change of population density (between the years 1990 and 2000) within 0.25° radius from the location of each station. Areal mean difference in excess of 280 was considered as a measure of 'fast urbanization', while a value less than 55 was treated as 'slow' or no urbanization. The above thresholds represent the 99th percentile and 70th percentile of area-averaged differences of population density between the years 1990 and 2000.

Our analysis indicates that all the locations where the frequency of heavy precipitation has increased during the monsoon season show a significant increase in population density, which is an indicator of fast urbanization in their vicinity. Out of 23 such locations, 12 have experienced fast urbanization (change in population density >280 P/km^2) in their surrounding. On the other hand, out of the 48 stations that show a decreasing trend in heavy rainfall occurrences, 41 stations show slow or no urbanization while only 7 stations show intense urbanization. This statistical result is adequate to reject the null hypothesis with 99% confidence that the rainfall trends at the locations of fast urbanization are same as those at the locations of slow urbanization. Moreover, out of 15 largest cities (in terms of population) of India, 6 (Mumbai, New Delhi, Hyderabad, Ahmedabad, Pune, and Indore) show an increasing trend in the frequency of heavy precipitation, while only 1 (Nagpur in central India) shows a decreasing trend.

The gridded rainfall data were also categorized over urban and rural grids using the 1° averaged daily rainfall analysis. A cumulative histogram of all the gridded rainfall measurements during a 53-year period (1951–2003) indicates that 70 mm/day corresponds to 90th percentile value for grid-averaged rainfall also, and hence can be used as a threshold to define heavy rainfall events. This approach is conceptually similar to a method for defining heavy rain days applied by Hand and Shepherd (2009). To classify the nature of human settlement over the rainfall grid, we used maximum population density (MPD) within the grid cell. On the basis of the histogram analysis of population density discussed earlier, we define a rainfall grid as urban if MPD exceeds 3000 P/km^2 and rural if MPD is below 600 P/km^2. Figure 4 shows a summary of heavy rainfall (daily rainfall >70 mm) events aggregated over urban and rural grids. As the rural grids covered a larger area (62%) compared to urban grids (11%), aggregated events over the rural area were normalized such that they represented the same area as covered by the urban grids under consideration. The trend of heavy rainfall events over the urban area was about 18% per decade (significance level = 99%, correlation coefficient = 0.31, p-value = 0.0239), and very low for the rural area (significance level = 43%). Even though the rural area did not show any significant trends in heavy rainfall events, the rural area experienced a larger *frequency* of heavy rainfall events. For example, before the 1960s, the probability of a heavy rainfall event over a rural area was almost twice as large as that over an urban area of similar size. However, due to the increasing trend over the urban region, these probabilities appear to be equal in recent times.

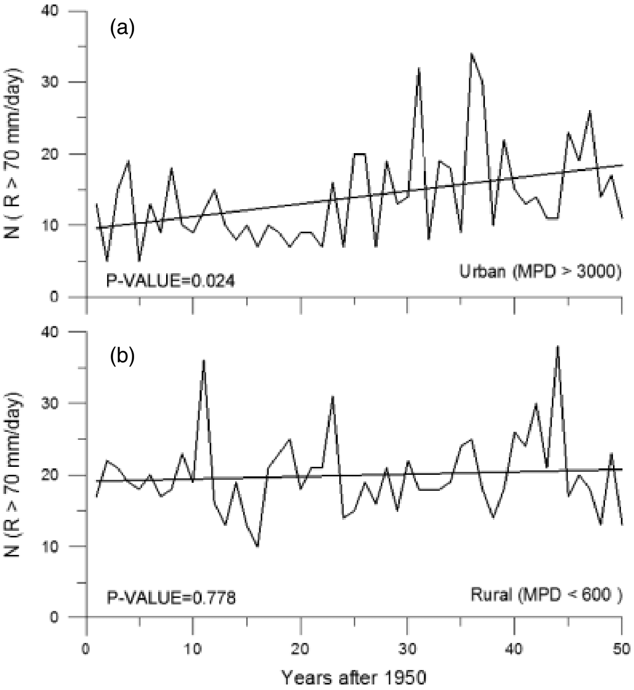

Figure 4. Upper panel shows the time series of the number of heavy rainfall (rain >70 mm/day) events over urban regions of study domain. Lower panel shows the same for the rural regions (number of rural events are normalized to equal the urban area). Lower/upper thresholds of MPD used to define a grid as urban/rural are indicated at the bottom of each figure.

Some of the factors affecting the heavy rain climatology might have been the region's local topography and proximity to the coast. Moreover, a fraction of extreme rainfall events could also be triggered by transient monsoon systems such as monsoon lows and monsoon depressions. To access the contribution of these transient systems on heavy rainfall events, we performed a combined analysis using the IMD's rainfall dataset and the track of monsoon lows/depressions. Using an approach similar to Shepherd *et al.* (2007) a heavy rainfall event was considered to be associated with a monsoon low or depression if both the events occurred within 24 h and within a 5° spatial separation from each other. This simplified analysis suggests that the transient systems could account for only less than 10% of heavy rainfall events. Thus, an important deduction is that most of the heavy rainfall events are not associated with the transient monsoon systems, and they are potentially modulated by the mesoscale convective instabilities. We infer therefore that these heavy rainfall events are more susceptible to modifications in the local environment such as from urbanization.

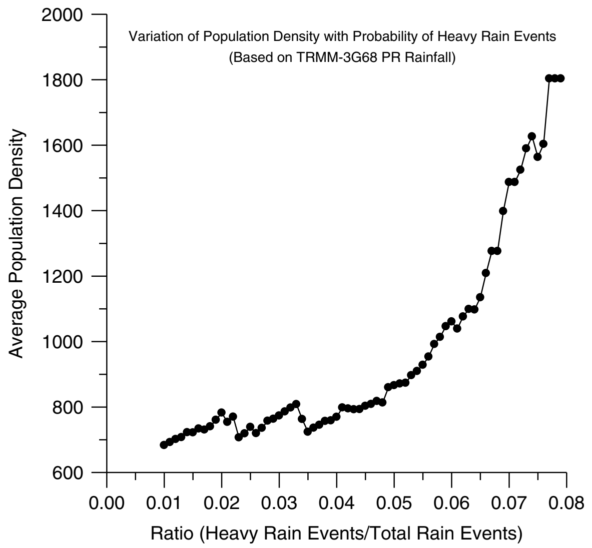

Figure 5. Variation of average population density for grid cells with varying probabilities of heavy rainfall. The graph is based on the analysis of PR near-surface rainfall from TRMM 3G-68 data for 10 monsoon seasons (1998–2007).

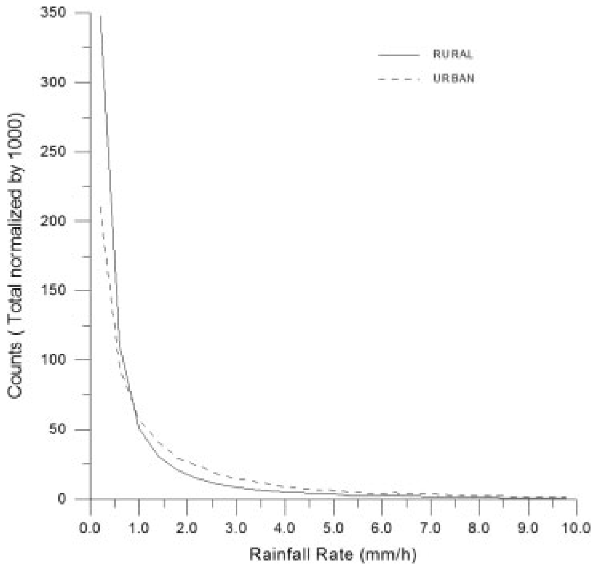

Figure 6. Normalized histogram of PR rain rates for urban and rural grids. The histogram is based on the analysis of ten monsoon seasons (1998–2007). Urban areas denote the grid points where population density exceeds 99th percentile value.

4.2. Rainfall distribution over urban and nonurban regions: Analysis using TRMM observations

We further analyzed 10 years of TRMM-PR data (from 1998 to 2007) to investigate the effect of urban areas on rainfall modification. It should be noted that the TRMM-PR rainfall rates are only ‘conditional’ in nature because these denote the rainfall that occurred only during the satellite overpass.

To assess whether there is some link between human settlement and the rainfall processes, we analyzed the TRMM-PR rainfall from 3G68 dataset and tried to relate it to the average population density. Using the gridded PR observations, we identified all the rain events (with near-surface rain rate >0.0 mm/h) and all the heavy rain events (with near-surface rain rate >5.0 mm/h). The threshold 5 mm/h indicates the 90th percentile of all the PR near-surface rain rate data over Indian region covering the monsoon months (June–September) for the 10-year period (1998–2007). We then computed the ratio of heavy rainfall events to all the rain events (termed as ‘heavy rainfall probability’ here onward) at each 0.5° grid cell. Similarly, the high-resolution data of population density was resampled onto the 0.5° grid cells by taking the average of all the high-resolution points within a grid cell. Figure 5 shows the variation of average population density with different thresholds of heavy rainfall probability. It should be noted that the ‘y-axis’ shows the average population of all the grid points for which the heavy rainfall probability is larger than the thresholds shown in the ‘x-axis’. Figure 5 shows a nonlinear enhancement of heavy rainfall events for more densely populated regions, clearly indicating the influence of human settlements on the processes leading to heavy rainfall events. Figure 6 shows the probability distribution function (PDF) of PR rain rate for urban and nonurban regions. Because of the large difference of population of urban and rural pixels, the PR pixel population is normalized in such a way that the total count is 1000 for both urban and rural areas. This figure shows that, on average, urban regions experience less occurrences of light rainfall (rain rate ≤2 mm/h) and significantly higher occurrences of intense precipitation (rain rate >2 mm/h) compared to nonurban regions. An urban grid is about 30–40% more likely to experience a rain rate between 2 and 5 mm/h compared to a nonurban grid during monsoon season. When all the raining PR pixels were averaged, the urban regions show a mean rainfall rate of 1.67 mm/h compared to 1.12 mm/h for nonurban regions. When only the high rain rate pixels (rain rates >5 mm/h) are averaged, the urban grids show a mean rainfall of 8.24 mm/h compared to 6.17 mm/h for nonurban regions. To test the statistical significance of these results, we estimated the normalized population of grid-averaged PR rainfall in 29 bins between 0.5 and 15 mm/h with an interval of 0.5 mm/h. A nonparametric Chi-square test indicates that the difference in rainfall distributions over urban and nonurban regions is significant at the 99% confidence level.

4.3. Alternate remote-sensing data for analysis of human settlement and urbanization

Although the analysis for the present study is based on the gridded population density, the observations from remote-sensing satellites can provide useful information about the human settlements. For example, night-light observations by satellite instruments such as Operational Linescan System (OLS) can provide details of human settlements, which are arguably more linked to industrialization and urbanization than the population. The OLS instrument onboard the Defense Meteorological Satellite Program (DMSP) satellite is an oscillating scan radiometer designed for cloud imaging with two spectral bands [visible (VIS) and thermal infrared (TIR)] and a swath of ~3000 km. OLS has a unique low light imaging capability developed for the detection of clouds using moonlight. In addition to moonlit clouds, the OLS also detects lights from human settlements. By analyzing the location, frequency, and appearance of lights observed in an image time series, it is possible to distinguish human settlements at a spatial footprint of about 1 km. The nighttime satellite data provided by the DMSP/OLS has been successfully used for global/continental urban mapping, showing linear relations with other socioeconomic variables such as population, gross domestic product, and electrical power consumption (Elvidge *et al.*, 1997; Imhoff *et al.*, 1997; Sutton *et al.*, 1997). In the context of the present study, the OLS data not only captures the patterns of human settlement but also the growth of the settlement (Figure 7). For this reason, the analysis of rainfall variability yields similar results for population density and OLS data (Figure 8). Remote-sensing data provides a significant advantage of mapping those areas, which are inaccessible to humans (e.g. deserts and high mountainous regions).

5. Discussion and conclusion

A number of urban rainfall anomaly studies (*cf* Shepherd and Burian, 2003; Cotton and Pielke, 2007; Shepherd *et al.*, 2009) have argued that one of the dominant mechanisms that can explain the pronounced urban effects on rainfall during the warm season is the UHI-induced mesoscale convergence (which can significantly alter the boundary layer) and its interaction with the other local circulations. Lei *et al.* (2008)'s analysis of a record heavy rain event over Mumbai revealed that localized convection and heavy rainfall in and around Mumbai may be enhanced by convergence associated with the urban circulation. Similar results were reported by Niyogi *et al.* (2006), Shem and Shepherd (2008), and Shepherd *et al.* (2009) for warm season convection and rainfall over Oklahoma City, Oklahoma; Atlanta, Georgia and Houston Texas, respectively. These results are relevant in this study because they suggest that preexisting or large-scale forced (e.g. frontal or monsoonal) convection might be enhanced by urban forcing.

Urban locations over the monsoon region also show prominent UHIs. Figure 9 shows the observed land-surface temperatures over two major Indian cities during summer. As expected, the UHI intensity is greater at night, although studies have indicated that the actual urban circulation and boundary layer response can be more apparent during the daytime (Oke, 1988). Interestingly, many of the locations that have experienced increase in the frequency of heavy precipitation events are not coastal in nature. This is particularly true for the stations situated in the northern part of India. It can be argued that the enhanced rainfall can be a result of (1) the interaction between the monsoon and UHI-induced low-level convergence (Braham *et al.*, 1981) and (2) urban aerosol interactions with clouds (van den Heever and Cotton, 2007).

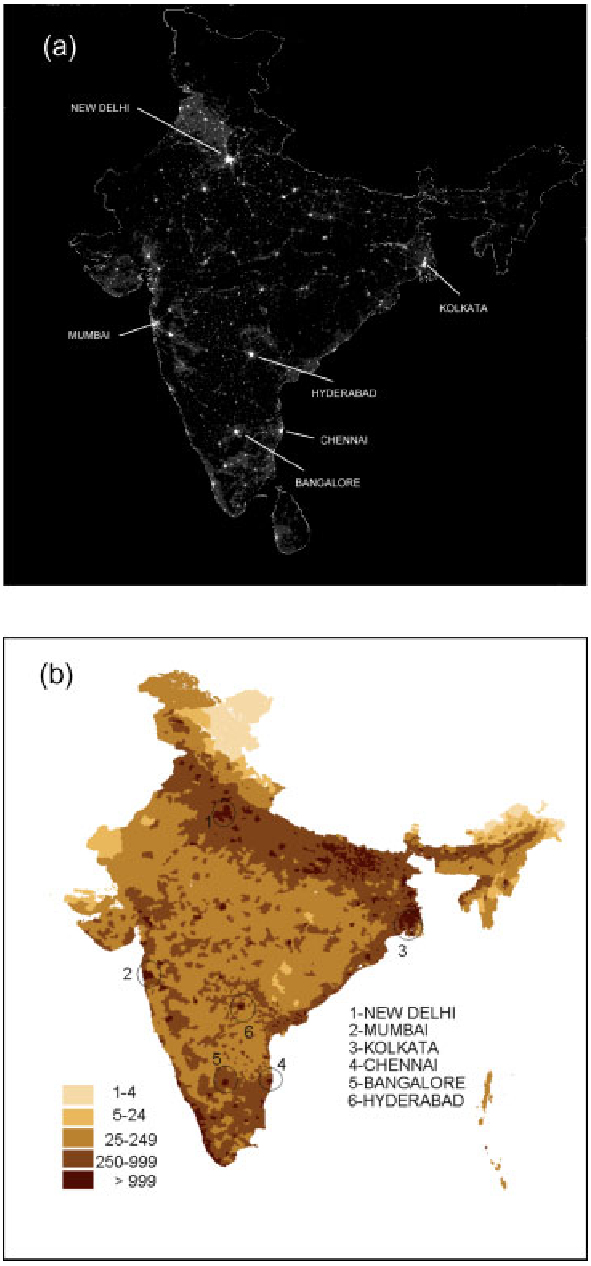

Figure 7. (a) Enhanced OLS image showing the patterns of human settlement during the year 2000 (b) Gridded population density for the year 2000. Location of six metropolitan cities are shown in both the figures. This figure is available in colour online at www.interscience.wiley.com/ijoc

The validity of the different mechanisms and processes needs to be tested through extensive observational analysis. A recent observational analysis by Jin and Shepherd (2008) used satellite-derived aerosol, cloud, and rainfall parameters to study the problem. Their analysis suggests that aerosols do affect cloud microphysics but were not the dominant forcing at the monthly scale for precipitation anomalies around the Beijing area. They hypothesized that urban dynamic forcing might play a larger role in urban convection, at least initially. Nonetheless, our analysis provides the evidence that the increase

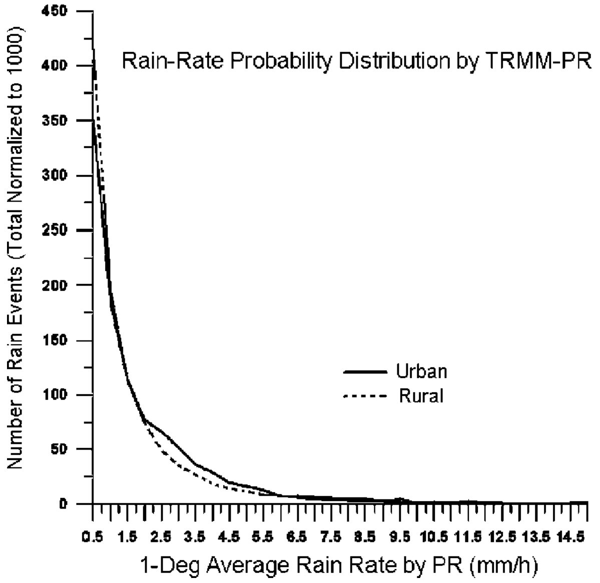

Figure 8. Same as Figure 6, except the fact that discrimination of urban and rural areas is based on OLS data.

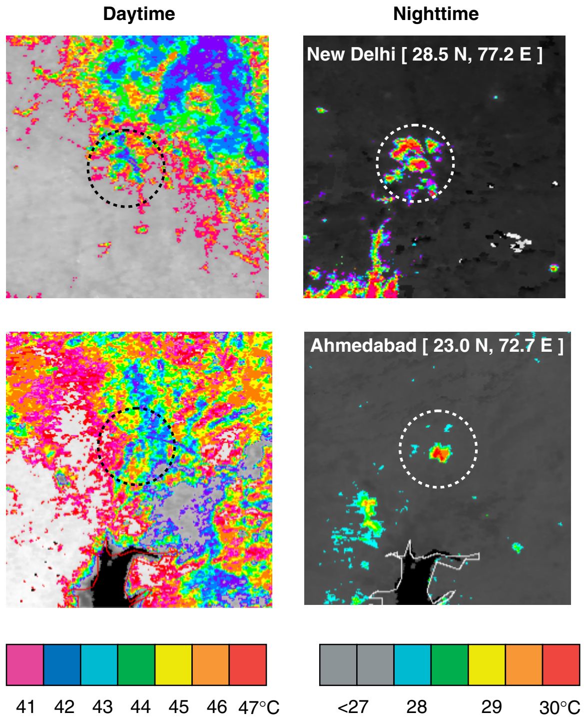

Figure 9. MODIS-retrieved land-surface temperature for two major cities of India during summer. Center of the circles denote approximate location of the city. This figure is available in colour online at www.interscience.wiley.com/ijoc

in the heavy rainfall climatology over the Indian monsoon region is a signature of urban-induced rainfall anomaly, and future studies need to extract the mechanisms causing this increased heavy rainfall.

In conclusion, the present study has tried to establish a link between the trends of urbanization as detected by the remote-sensing data and the patterns of precipitation over the Indian summer monsoon region. Our analysis suggests that there is adequate statistical basis to conclude that the observed increasing trend in the frequency of heavy rainfall events over the Indian monsoon region is more likely to be over the regions where the pace of land use/land cover change through urbanization is faster. Moreover, rainfall measurements from satellites also indicate that urban areas are more (less) likely to experience heavier (lighter) precipitation rates compared to nonurban areas. How exactly the urbanization impact alters the regional rainfall patterns through UHIs, mesoscale convergences, and urban aerosol interactions in a humid and convectively unstable environment of monsoon is still an active area of research.

Acknowledgements

Authors are thankful to Dr K. C. Sinha Ray for useful discussions and for providing the locations over India where heavy rainfall frequency shows significant trends. We also thank Physical Oceanography Distributed Active Archive Center (PO-DAAC) of NASA for providing valuable TRMM observations for this study, and DMSP for providing the OLS data. The study benefitted in part from ATM- NSF-0847472 (Dr Liming Zhou and Dr J. Fein) and NASA NNX07AF39G (Dr Ramesh Kakar), and CIRES/ATOC at the University of Colorado at Boulder.

References

Avissar R, Liu Y. 1996. Three-dimensional numerical study of shallow convective clouds and precipitation induced by land surface forcing. *Journal of Geophysical Research* **101**(D3): 7499–7518.

Braham RR, Semonin RG, Auer AH, Changnon SA, Hales JM. 1981. Summary of urban effects on clouds and rain. In *METROMEX: A Review and Summary*, Meteorological Monograph 18, Changnon SA (ed). American Meteorological Society: Boston, MA, 141–152.

Changnon SA. 1968. The LaPorte weather anomaly – fact or fiction?. *Bulletin of the American Meteorological Society* **49**: 4–11.

Changnon SA, Semonin RG, Auer AH, Braham RR, Hales J. American Meteorological Society. 1981. *METROMEX: A Review and Summary*. Meteorological Monograph No. 40, 81 pp.

Changnon SA, Shealy RT, Scott RW. 1991. Precipitation changes in fall, winter, and spring caused by St. Louis. *Journal of Applied Meteorology* **30**: 126–134.

Cotton W, Pielke RA Sr. 2007. *Human Impacts on Weather and Climate*, Chap 5, 2nd edn, Cambridge University Press: Cambridge.

Elvidge CD, Baugh KE, Kihn EA, Kroehl HW, Davis ER. 1997. Mapping city Imagery and Population Density for the Continental United States. *Photogrammetric Engineering and Remote Sensing* **63**: 727–734.

Gero AF, Pitman AJ. 2006. The Impact of Land Cover Change on a Simulated Storm Event in the Sydney Basin. *Journal of Applied Meteorology and Climatology* **45**: 283–300.

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan MS, Xavier PK. 2006. Increasing trend of Extreme Rain Events over India in a Warming Environment. *Science* **314**: 1442–1445.

Hand L, Shepherd JM. 2009. An investigation of warm season spatial rainfall variability in Oklahoma City: Possible linkages to urbanization and prevailing wind. *Journal of Applied Meteorology and Climatology* **48**: 251–269.

Huff FA. 1986. Urban hydrological review. *Bulletin of American Meteorological Society* **67**: 703–712.

Huff FA, Changnon SA. 1972. Climatological assessment of urban effects on precipitation at St. Louis. *Journal of Applied Meteorology* **11**: 823–842.

Imhoff ML, Lawrence WT, Elvidge CD, Paul T, Levine E, Privalsky MV, Brown V. 1997. Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the United States. *Remote Sensing of the Environment* **59**: 105–117.

Inoue T, Kimura F. 2004. Urban effects on low level clouds around the Tokyo metropolitan area on clear summer days. *Geophysical Research Letters* **31**: L05103, DOI:10.1029/2003GL018908.

Jin M, Shepherd JM. 2008. Aerosol relationships to warm season clouds and rainfall at monthly scales over east China: Urban land versus ocean. *Journal of Geophysical Research* **113**: D24S90, DOI:10.1029/2008JD010276.

Kalnay E, Cai M. 2003. Impact of urbanization and land use on climate change. *Nature* **423**: 528–531.

Karl T, Diaz HF, Kukla G. 1988. Urbanization: Its detection and effect in the United States climate record. *Journal of Climate* **1**: 1099–1123.

Kusaka H, Kimura F, Hirakuchi H, Mizutori M. 2000. The effects of land-use alteration on the sea breeze and daytime heat island in the Tokyo metropolitan area. *Journal of the Meteorological Society of Japan* **78**: 405–420.

Landsberg HE. 1970. Man-made climate changes. *Science* **170**: 1265–1274.

Lei M, Niyogi D, Kishtawal C, Pielke R Sr, Beltrán-Przekurat A, Nobis T, Vaidya S. 2008. Effect of explicit urban land surface representation on the simulation of the 26 July 2005 heavy rain event over Mumbai, India. *Atmospheric Chemistry and Physics* **8**: 5975–5995.

Mote TL, Lacke MC, Shepherd JM. 2007. Radar signatures of the urban effect on precipitation distribution: a case study for Atlanta, Georgia. *Geophysical Research Letters* **34**: L20710, DOI:10.1029/2007GL031903.

Niyogi D, Holt T, Zhong S, Pyle PC, Basara J. 2006. Urban and land surface effects on the 30 July 2003 mesoscale convective system event observed in the Southern Great Plains. *Journal of Geophysical Research* **111**: D19107, DOI:10.1029/2005JD006746.

Niyogi D, Chang H, Chen F, Gu L, Kumar A, Menon S, Pielke RA Sr. 2007. Potential impacts of aerosol-land-atmosphere interaction on the Indian monsoonal rainfall characteristics. *Natural Hazards* Monsoon Special Issue, DOI:10.1007/s11069-006-9085-y.

Oke T. 1988. The urban energy balance. *Progress in Physical Geography* **12**: 471–508.

Parthasarathy B. 1984. Interannual and long-term variability of Indian summer monsoon rainfall. *Proceedings of the Indian Academy of Sciences (Earth Planet Science)* **93**: 371–385.

Pant GB, Rupa Kumar K. 1997. *Climates of South Asia*. John Wiley & Sons: Chichester, 320 pp.

Pielke RA Sr. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* **39**: 151–177.

Pielke RA Sr, Adegoke J, Beltran-Przekurat A, Hiemstra CA, Lin J, Nair US, Niyogi D, Nobis TE. 2007. An overview of regional land use and land cover impacts on rainfall. *Tellus B* **59**: 587–601.

Rajeevan M, Bhate J, Kale JD, Lal B. 2005. *Development of a High Resolution Daily Gridded Rainfall Data for the Indian Region*. (Met Monograph Climatology, 22/2005, 26 pp, available from India Meteorological Department, Pune, India).

Sachs JD, Bajpai N, Ramiah A. 2002. Understanding regional economic growth in India. *Asian Economic Papers* **1**: 32–62.

Shem W, Shepherd JM. 2008. On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Atmospheric Research* **92**: 172–189.

Shem W, Shepherd M. 2009. On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Atmospheric Research* **92**: 172–189.

Shepherd JM. 2005. A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions* **9**: 9–26.

Shepherd JM, Burian SJ. 2003. Detection of urban-induced rainfall anomalies in a major coastal city. *Earth Interactions* **7**: 1–17.

Shepherd JM, Grundstein A, Mote TL. 2007. Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States. *Geophysical Research Letters* **34**: L23810–, DOI:10.1029/2007GL031694.

Shepherd JM, Pierce HF, Negri AJ. 2002. Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology* **41**: 689–701.

Shepherd JM, Carter WM, Manyin M, Messen D, Burian S. 2009. The impact of urbanization on current and future coastal convection: A case study for Houston. *Environment And Planning B* (In Press).

Sinha Ray KC, Srivastava AK. 2000. Is there any change in extreme events like heavy rainfall ?. *Current Science* **79**(2): 155–158.

Sutton P, Roberts D, Elvidge CD, Meij H. 1997. A comparison of Nighttime Satellite lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing* **63**: 1303–1317.

van den Heever SC, Cotton WR. 2007. Urban aerosol impacts on downwind convective storms. *Journal of Applied Meteorology and Climatology* **46**: 828–850.

Zhou L, Dickinson RE, Tian Y, Fang J, Li Q, Kaufmann RK, Tucker CJ, Myneni RB. 2004. Evidence for a significant urbanization effect on climate in China. *Proceedings of the National Academy Science* **101**: 9540–9544.