Urbanization alters rainfall extremes over the contiguous United States

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Abstract

Anthropogenic changes are likely to intensify rainfall extremes, posing a risk to human, environmental and urban systems. Understanding the impact of urbanization on rainfall extremes is critical for both reliable climate projections as well as sustainable urban development. This study presents the unexplored impacts of changes arising in urban areas on rainfall extremes over the Contiguous United States. The results show a 2.7-fold higher probability of exceeding a 25% change in 50 year rainfall events over urban areas than over rural areas. Spatially, the changes in rainfall extremes over the central, northeast central, southeast, and northwest central zones were more pronounced due to urbanization. Statistical analyses highlight a positive relationship between changes in rainfall extremes and urbanization within a set of concentric ring buffers around rain gauge stations. Here, we show that urbanization, even though a local feature, influences the mesoscale meteorological setting; and, is statistically associated with an intensification of rainfall extremes across the Contiguous United States.

1. Introduction

Rainfall extremes have caused severe disruption with widespread socio-economic impacts across the globe, and such events have been reported to become more frequent under warming conditions (Field et al 2012). However, future effects from such events can be minimized through adaptation and risk management efforts informed by an improved understanding of their response to climate change. Changes in extreme rainfall characteristics have been evident in the past (Goswami et al 2006, Allan and Soden 2008, Zou and Ren 2015), and were primarily believed to be governed and dominated by large-scale circulation or greenhouse driven climatic changes. In response to the trade-off between global climate changes and local changes, particularly due to urbanization, studies such as Pielke et al (2007) reported that regional land use land cover (LULC) changes significantly affect local circulation and alter rainfall patterns. Recently, anthropogenic changes over rainfall extremes in different parts of the globe, such as India (Kishtawal et al 2010, Vittal et al 2013, Shastri...
et al 2015, Singh et al 2016, Paul et al 2018), Europe (Brunetti et al 2004), China (Zhai et al 2005, Zou and Ren 2015), and the Contiguous US (Shepherd et al 2002, Diem and Brown 2003, Niyogi et al 2011, 2017).

A pioneering study by Horton (1921) reported the likelihood of occurrence of a thunderstorm modification over large cities compared to that in rural environments in the northeastern United States. Furthermore, many studies (Landsberg 1956, 1970, Atkinson 1968, Changnon 1968, Huff and Changnon 1972) then convinced the scientific community using case studies, climatological analysis around select cities, and field experiments that anthropogenic forces potentially alter the rainfall pattern over urban centers. Shephard (2005) carefully reviewed and documented the past efforts taken to understand the effect of the urban environment on rainfall. Additionally, Pielke et al (2011) presented detailed documentation from recent studies related to how changes in LULC affect local climate, including rainfall. Usually, LULC changes are driven by the transformation of natural land surfaces with anthropogenic surfaces that have different thermal properties (such as thermal fluxes, heat capacity, thermal inertia, surface albedo, pollution, and anthropogenic heat) (Bornstein and Lin 2000, Shepherd 2005), which further alter dynamic mesoscale processes, e.g. changes in atmospheric convergence zones and mesoscale convection (Rozoff et al 2003, Pielke et al 2007, 2011, Van den Heever and Cotton 2007). Additionally, urban structures through enhanced roughness and displacement dynamically modify atmospheric flow and cause micro-mesoscale convergence/divergence, which further modifies the urban rainfall (National Research Council 2012).

In the recent years, several studies have investigated the impact of urbanization on rainfall patterns at the city level (Niyogi et al 2011, Dou and Chen 2017, Liu and Niyogi 2019); however, very few have investigated regional-scale impacts over the contiguous US (Niyogi et al 2017). Surprisingly, no previous study has examined the effect on rainfall extremes that arise from urbanization for the Contiguous US. Also, no study has been performed on the identification of nonstationarity in rainfall extremes over the Contiguous US. Cheng and AghaKouchak (2014) presented nonstationary intensity-duration-frequency curves based on rainfall data from five rain gauge stations). Thus, in light of these research gaps, the present study seeks observational evidence of the unexplored impact of changes in rainfall extremes arising over urban areas across the entire Contiguous US. The present study also postulates a distinct link between urbanization and extreme rainfall changes and quantifies the impact of urbanization on inducing nonstationarity in rainfall extremes across the Contiguous US. This study identifies a set of fundamental research questions that can ensure that urban innovations yield the intended sustainability outcomes to benefit society at local, national, and global scales.

2. Data and methods

We used the CPC US Unified gridded daily rainfall data (mm d$^{-1}$) with a 0.25° resolution from 1948 to 2006 provided by the NOAA <https://www.esrl.noaa.gov/psd/data/gridded/data.unified.daily.conus.html>. The CPC rainfall data is good quality and appropriate dataset for climate studies, and it has been used in prior studies (Mallakpour and Villarini 2015, 2017, Ashouri et al 2016, Collow et al 2016). Initially, the gridded fields of these daily rainfall data were generated using the inverse-distance interpolation technique (Shepard 1968) from a network of 8000 stations (Hou et al 2014). Furthermore, the CPC unified gauge-based analysis was built using a similar interpolation algorithm provided by Xie et al (2007) and Hou et al (2014). We also analyzed data about multiple demographic variables, including population density (POP), housing units (HU), low-income population (LOWI) and population living below the poverty line (POV) data for the year 1990 (Seirup and Yetman 2006) and 2000 (Seirup et al 2012). The data have a spatial resolution of 30 arc-seconds (~1 km$^2$). This dataset was produced by the Columbia University Center for International Earth Science Information Network (CIESIN). These four demographic variables were then converted to the same resolution as the 0.25° rainfall data using the interpolation technique to maintain a unique georeferenced framework. For the available rainfall data, the percentage difference between 1990 and 2000 demographic variables was used to assess the change in urban landscape and urbanization conditions for the decade. Generally, in the urbanization process, a dramatic form of land transformation occurs, which involves the replacement of the natural land cover with impervious surfaces, buildings, and other structures. For classifying the urban land transformation, the national land-cover datasets with a spatial resolution of 30 meters for the year 1992 (Vogelmann et al 2001), 2001 (Homer et al 2007), 2006 (Fry et al 2011) and 2011 (Homer et al 2015) were procured from the multi-resolution land characteristics consortium.

To further strengthen the analyses, we also included station-level data to understand the impact of urbanization on extreme rainfall events. The daily rainfall dataset was obtained from the National Centers for Environmental Information (NCEI) for 330 of the weather stations covering the entire Contiguous US from 1948 to 2015, which is widely used by several studies (Barrett et al 2012, Mishra et al 2015, Yin et al 2018). The stations considered in the present study have recorded a minimum of 40 years of data between 1948 and 2015, recorded until at least 2010, and contained no more than three consecutive years.
of missing data to maintain continuity and ensure the minimum required length (Mallakpour and Villarini 2015). Furthermore, to avoid confounding with topographical effects (e.g. Freitag et al 2018, Yang et al 2019), we considered only stations with elevations less than 500 m, as recommended by Niyogi et al (2017). Supplementary figure S1 (available online at stacks.iop.org/ERL/15/074033/mmedia) presents the location and elevation of the stations considered in this study.

3. Methods

We used block maxima for the delineation of extreme events, where the annual maximum (AM) value was considered for the entire analysis. We also used a diagnostic test to examine the changes in extreme events, following Kharin and Zwiers (2005). The same technique has been effectively used previously in many studies to identify the changes in rainfall extremes (Ghosh et al 2012, Vittal et al 2013, 2016). First, we divided the entire time series into two halves and performed the subsampling (with repetition) of AM extremes 1000 times because resampling methods, especially for extremes, may produce narrow confidence intervals and minimize the uncertainty in the analysis outputs (Dupuis and Field 1998). The mean values from those new samples were estimated further if the 90th (10th) percentile value (from a series of 1000 mean values) of the first half was less (higher) than the 10th (90th) percentile value (from a series of 1000 mean values) of the second half, respectively. Those grids were assigned positive (negative) changes at an approximately 10% statistical significance level (Vittal et al 2016). A graphical illustration of the bootstrap methodology is provided in the supplementary information and figure S2. The grids that satisfy these significance levels for changes in the mean values of rainfall extremes were considered further for nonstationary analyses (Rahmstorf and Coumou 2011). Our study further attempts to examine the possible association between the urbanization and rainfall extreme over these grids.

Further, a comprehensive nonstationary frequency analysis was performed for these grids using a cluster of 74 Generalized Additive Model for Location, Scale and Shape (GAMLSS) models, following Singh et al (2016). Refer to Rigby and Stasinopoulos (2005) for theoretical details of GAMLSS. A detailed description of the 74 models and methodology is provided in the supplementary information (table S1). Furthermore, we quantified the urbanization level based on demographic data for the decade between 1990 and 2000. We considered the percentage change in the POP, HU, LOWI, and POV from 1990 to 2000, which was further used to develop an urbanization index (UI) (figure S3). Here, we used multiple demographic variables to define urbanization, improving over past studies (Kishtawal et al 2010, Vittal et al 2013, Singh et al 2016, Niyogi et al 2017) that primarily considered the population density as a proxy for urbanization. We used Data Envelopment Analysis (DEA) to develop a UI for the entire Contiguous US. The DEA has been widely used in the field of operations research, but more recently, it has also been applied to natural disaster risk assessments (Wei et al 2004, Sherly et al 2015). Additional details regarding the urbanization index (UI) and Data Envelopment Analysis (DEA) are provided in the supplementary information.

To understand the possible mechanisms of urbanization impact on rainfall extreme over the Contiguous US, we considered two closest stations, one with a relatively high impervious fraction (0.54) and other with a low impervious fraction (0.09) within 50 km radius buffer. Further, we estimate the average Urban Heat Island (UHI) intensity [temperature difference over both station] during non-rainy days and 5–2 d before extreme rainfall event over the station with a higher impervious fraction (also shows a change in rainfall extremes). Further, we employ the KS test to understand if the distribution of UHI intensity is significantly different before extreme rainfall days compared to non-rainy days, which may further provide the evidence of UHI formation just before the occurrence of extreme rainfall events.

4. Results and discussion

The results obtained from the bootstrap approach indicate that almost 22% of the grids exhibit significant changes in AM rainfall, of which 12% and 10% show positive and negative changes, respectively, at the 10% significance level (figure 1(a)). We also have performed the similar analysis at a 5% significance level. Indeed, as expected for the F statistics, we found a slight decrease in the number of grids with positive (~10%) and negative (~9%) changes in rainfall at a 5% significance level, relative to the 10% significance level. However, we consider the analysis at a 10% significance level to achieve a relatively large sample size to gain more confidence in the findings. In the eastern US, notable positive changes in extreme rainfall were observed, while negative changes were clustered over the northwestern US (e.g. Montana, Oregon, Idaho, Wyoming, Utah, Colorado). These changes in rainfall extremes may be due to large-scale (synoptic) or local (urbanization-based) changes. The rainfall extremes also experience notable spatiotemporal changes (Min et al 2011, Ghosh et al 2012), due to aerosols (Rosenfeld 2000, Carrió et al 2010, Storer et al 2010, Schmid and Niyogi 2017), aerosol-land interactions (Niyogi et al 2007), and land-use changes such as agriculture (Niyogi et al 2009) and urbanization (Landsberg 1981, Pielke et al 2007).

Although changes in rainfall extremes are prominent in almost 22% of the grids, whether these changes are primarily due to local urbanization or
because of large-scale circulation feedbacks is not certain. To examine this further, we excluded ENSO and NAO years (NOAA, https://www.esrl.noaa.gov/psd/enso/past_events.html) from the analysis to potentially remove or reduce the influence of large-scale circulation on rainfall extremes, and analyzed for neutral years during the study period. We used 36 neutral years for further analysis after removing 23 ENSO years from the 59 years data. The ENSO years were determined based on the multivariate ENSO index (MEI). The MEI was constructed using multiple atmospheric-ocean variables (such as sea level pressure, zonal and meridional surface wind components, surface wind component, sea surface temperature (SST), near-surface temperature, and total cloudiness) fields in the tropical Pacific basin (Wolter and Timlin, 1998). The MEI provides a more complete and flexible description of the ENSO phenomenon than single variable ENSO indices such as the SOI or Nino-3.4 SST (Wolter and Timlin, 2011). Here, the results exhibit a similar pattern to those observed considering combined neutral and ENSO years, showing 12% and 7% grids with positive and negative changes, respectively (figure 1(b)). It is evident that when the confounding due to large-scale circulation pattern is considered, the changes in rainfall extremes are significant and are primarily associated with the influence of local changes such as urbanization.

To further understand the role of urbanization in changes in rainfall extremes, a comparative analysis between the grids with a high UI and the grids displaying changes in extremes was undertaken. As shown in figure S4(a), 63% (37%) of the grids with positive changes (out of 12% of total grids with positive changes) coincided with grids having a UI greater (less) than 0.4. On the other hand, 42% (58%) of the grids with negative changes (out of 10% of total grids with negative changes) coincided with grids with a UI greater (less) than 0.6 in the analysis, including all years (figure S4(a)). However, the overlap between the grids with positive changes and the grids with a UI greater than 0.4 increased to 72% in the analysis of the neutral years (figure S4(b)). These UI values (0.4, 0.5, and 0.6) are considered to compare the grids with lower to high UI values. These results highlight that the urbanization signature is detectable as an anthropogenic influence affecting extreme rainfall climatology. A relationship between negative changes in rainfall extremes and UI is also found. However, it is important to note that urbanization is not the sole reason responsible for the increase/decrease in rainfall extremes, and some regions may have different local feedbacks on regional climate due to synoptic conditions (Niyogi et al, 2017). For instance, Han et al (2014) explicitly highlighted that ‘many regions of the world urbanization act to increase precipitation over and/or downwind of cities, but in some regions, the precipitation reduction occurs.’ Hence, this relationship might be possible because some of the regions experienced a significant decrease in the magnitude of rainfall extreme due to large scale synoptic conditions, which may marginalize the effects of local-scale factors (such as urbanization) in intensifying the rainfall extremes. It is still a challenge to detect the urban rainfall signatures within the observational and modeling studies (Liu and Niyogi, 2019). As mentioned, getting a pure urban effect (with and without urban land cover) is perhaps possible in the models but not in observations. Further, in-depth modeling studies are necessary to find the causes and processes that lead to such differences.

We considered the neutral (non-ENSO) years for further investigation. This is because the study aims to understand the relationship between the level of urbanization and nonstationarity (changes) in rainfall extremes. The 50 year and 100 year return levels were calculated for both stationary and nonstationary conditions, and the changes in the AM intensity between these scenarios were estimated. Figure S5(a) shows the spatial pattern of the 50 year events under the stationarity assumption. A similar analysis is carried out considering nonstationarity in rainfall extremes (figure S5(b)). The 50 year event in this scenario was obtained from the best-fit nonstationary model from a cluster of 74 models for only those grids showing significant changes in rainfall extremes. For the remaining grids where the assumption of stationarity remained valid, a stationary analysis was.
performed using a set of parametric and nonparametric models (Singh et al. 2015, Vittal et al. 2015). The changes in the 50 year events between stationary and nonstationary conditions were then calculated (figure S5(d-1)). The analysis was repeated, considering 100 years events (figures S5(c), (d), and (d-2)). The results indicate similar rainfall modification: an increase of up to 40% in the 50 year, and 100 year events under the nonstationary scenario across the eastern US, and a decrease of up to 40% in the northwestern part.

To confirm the urban impact on rainfall extreme, we divided the nonstationary grids into two categories based on their UI (namely, grids with a UI less than and greater than 0.5). Figures 2(a) and (b) show the probability of exceeding a 25% change in 50 year and 100 year rainfall events, respectively, when grids have a UI greater and less than 0.5. Figures 2(a) and (b) reveal that there is a 15% and 17% probability that grid with a UI less than 0.5 exceed a 25% change in 50 year and 100 year events, respectively. Remarkably, these probabilities increase by 41% and 40% (an almost 2.7-fold increase) for 50 year and 100 year events, respectively, when grids have a UI value greater than 0.5. That is, urbanization alters rainfall extremes across the Contiguous US domain. Although the UI developed using multiple socioeconomic variables can be considered a reliable proxy of urbanization (Kishtawal et al. 2010, Vittal et al. 2013, Singh et al. 2016), however, changes in LULC can also provide insightful information about anthropogenic modifications. It is also important to note that spatial variability in UI across the country is relatively low, and that may be the result of less spatial variation of the changes in demographic variables used for estimating UI. To supplement the result from UI based analysis, we performed a similar analysis based on the population density (figure S7), which has been widely used as a proxy of urbanization in previous studies (Kishtawal et al. 2010, Vittal et al. 2013, Singh et al. 2016, Niyogi et al. 2017). Figure S7 shows an almost 2-fold increase in the probability of exceeding 25% changes in 50 and 100 years events over grids with an increase in population density compare to grids with a decrease in population density between the years 1990 and 2000. These results again validate the role of urbanization (based on population density) in altering rainfall extreme over the Contiguous US.

In addition to the UI- and population density-based analyses, we considered grids with distinctively positive and negative changes in the built-up area from 1992 to 2006. Figures 2(c) and (d) indicate the PDFs of changes in 50 year and 100 year rainfall events, respectively, for the grids with a positive and negative change in impervious fraction. Similarly, the probability of exceeding a 25% change in 50 year (100 year) events was 2.2-fold higher in grids with a positive change in the impervious fraction than in those with a negative change in the impervious fraction, with a 43% (44%) and 20% (21%) probability, respectively.

It is also acknowledged that NAO plays a significant role in rainfall variability over the continental US (Durkee et al. 2008, Whan and Zwiers 2017). Hence, a set of analyses is performed, considering neutral years by excluding NAO years (figure S6). We observed a similar result except that the increase in the probability of exceeding 25% changes in extremes when comparing urban to rural grids is slightly decreased. The analysis does show the two-fold increase in the probability exceeding 25% changes in extremes when comparing urban to rural grids (figure S6). These results provide further evidence in support of the postulation regarding the influence of urbanization on rainfall extremes.

Furthermore, a quantitative relationship between changes in extreme events versus UI and built-up areas (or impervious fraction) was derived for exploring the role of urbanization and LULC changes in modulating extreme rainfall events and convection climatology over the Contiguous US. The linear regressions of changes in 50 year and 100 year events on the UI are shown in figures S8(a) and (b), respectively. In general, the mean and median values of changes exhibit a significant positive relationship at the 5% significance level, with increasing changes in 50 year and 100 year rainfall events with increasing UI. A linear regression analysis between changes in the built-up area from 1992 to 2006 and changes in 50 year (figure S8(c)) and 100 year (figure S8(d)) events was carried out to understand the influence of changes in LULC on extreme rainfall events. A statistically significant (at the 5% significance level) positive relationship was observed through linear regression. These findings further support our notion that the extent of urbanization impacts rainfall extremes over the Contiguous US.

A detailed analysis of different homogeneous climate zones was carried out to understand the regional differences in rainfall changes and the regional feedback from anthropogenic changes on extreme rainfall. The analysis was done because sub-regions are known to provide different local feedback on regional climate due to synoptic conditions (Niyogi et al. 2017, Liu and Niyogi 2019). Figure S9 represents the nine homogeneous climate zones considered in this study (Ganguli et al. 2017). Figure 3 shows the PDF for the nine climate regions across the Contiguous US, which further confirms the findings for the broader region and also shows the regional details. The shape of the PDFs indicates that grids with a bigger change in the built-up area exhibit a greater change in 50 year events than grids with a smaller change in the built-up area. From the nonparametric K-S test, four major climatic zones: central, northeast central, southeast, and northwest central, stand out. These zones exhibit a PDF of 50 year changes in grids with low changes in the built-up area that lies above the PDF of grids with
Figure 2. Probabilities that urbanization caused changes in extreme events. Parametric conditional probability density functions (PDFs) for changes in extreme events given a certain threshold. (a) and (b) show the probability of exceeding a 25% change in 50 year and 100 year events, respectively, when grids have a UI greater and less than 0.5. (c) and (d) show the probability of exceeding a 25% change in 50 year and 100 year events, respectively, when grids have changes in impervious fraction (or built-up area) greater and less than 0. Grids with a high UI or change in impervious fraction show a remarkable increase in the probability of exceeding a 25% change in extremes, confirming a significant impact of urbanization on intensifying rainfall extremes. (Refer to figure S7 for solely population-based analysis.)

significant changes in the built-up area (figure 3). Even with urbanization at a larger scale, the northeast region shows an insignificant bias in changes for 50 year events under two different categories of grids. This finding aligns with that reported in Niyogi et al (2017), which highlighted that the northeast consists of more urban influence than rural grids. As a result, increasing rainfall near urban-rural boundaries also contributes to rural areas and confounds the results (Paul et al 2018).

The analysis from gridded rainfall datasets is complemented with station data. This is because the gridded datasets may have inherent errors due to spatiotemporal variability and measurement/sampling errors (Hofstra et al 2009, Schneider et al 2014, Prein and Gobiet 2017). Typical error sources include regional orography, the density of rain gauge stations, the temporal resolution of the grid cell, type of rainfall (Schneider et al 2014), and homogeneity of an entire area in a gridded dataset (Hofstra et al 2009). Accordingly, station-level rainfall from 1948 to 2015 was further analyzed. Figure S1 shows the location of the 330 rainfall stations used in this study. Notably, we only considered neutral years for the remaining analyses. Overall, 13% and 9% of the total stations exhibit positive and negative changes, respectively, across the Contiguous US (figure S10). The stations with positive changes tend to be located in the Contiguous eastern US and along the west coast of the country. More precisely, a stronger tendency of positive changes in AM rainfall events is evident over urban clusters. Indeed, this station-level analysis also provides satisfactory evidence of the influence of urbanization on rainfall extremes. Furthermore, given the influence of urbanization, the areal fraction of impervious surfaces within the three concentric circles that have a radius of 5, 10, and 20 km around the station (only for those stations that show significant changes, as shown in figure S10) was calculated based on the latest LULC data as of the year 2011. Figure S11 shows the LULC around the 5 km, 10 km, and 20 km concentric ring buffers for three representative rain gauge stations as an example.

A set of quantitative relationships between the change in 50 year and 100 year events and the fraction of built-up surfaces within the concentric ring buffer of 5 km, 10 km, and 20 km was established (figure 4). The observations indicate a significant positive relationship at the 5% significance level, with increasing changes in extreme events with increases in the built-up area around the station within each of the three concentric ring buffers. We undertook similar analyses for gridded level data for ‘without NAO’ years (figure S12). Results indicate a significant positive
Figure 3. Probability distribution function for grids with positive (red) and negative (green) changes in impervious fractions (built-up area) over different climate regions. The p-values from the K–S test (given in inset) indicate that the distribution of changes in 50 year events from the grids with positive changes in the impervious fraction is significantly different (shift towards right at 5% significance level) than the distribution obtained from the grids with negative changes in impervious fraction, over four major climatic zones: central, northeast central, southeast, and northwest central. The asterisk indicates a statistically significant p-value at 5% significance level. Refer to figure S9 for more detail about these homogeneous climate zones.

relationship between the changes in 50 year (figures S12(a)–(c)) and 100 year events (figures S12(d)–(f)), and the impervious built-up area (indicative of urbanization) around the stations. These results provide additional statistically meaningful empirical evidence of the influence of urbanization on extreme rainfall events.

We explored the possible physical mechanism behind the associations identified between urbanization and rainfall intensification. We considered a pair of nearest urban and rural stations, shown in figure S13. The urban and rural stations had high (0.54) and low (0.09) impervious fractions within a 50 km radius buffer zone. The urban station recorded a significant change in rainfall extreme, which was not seen in the rural stations. Since urban heat island (UHI) is one well-known indicator of the urban impact on the atmosphere, the occurrence of UHI before the extreme rain days is explored following (Liu and Niyogi 2019). Figure 5 shows the average UHI during non-rainy days and 5–2 d before the extreme rainfall events. It is observed that the average UHI 5, 3, and 2 d before the extreme events are significantly higher (at a 5% significance level) than the UHI during the non-rainy days. The impervious surface around the station aids heat retention and leads to higher urban air temperature, and intensified UHI, which often can lead to a mesoscale convection environment just before the extreme rainfall events. The UHI—urban rainfall intensification mechanism is discussed in a number of studies such as Dou et al (2015), and synthesis of multiple studies is presented in Liu and Niyogi (2019). The increased urban heat can promote updraft/downdrafts and alter the urban/periurban meteorological setting through shear, and low-level moisture convergence, which can via feedback affect the rainfall characteristics. Indeed, UHI is only one of the possible mechanisms, and urban-rural roughness changes, aerosols, urban terrain, and anthropogenic activities all can interactively modify the mesoscale environment and the rain over and around the urban region (Niyogi et al 2011). As a result, the results noted for UHI and extreme rains over the urban region provide a proof of concept and not the complete mechanism (which can be explored in a future study).
Figure 4. The linear relationship between the impervious fraction (indicative of increasing urbanization) and changes in 50 year events estimated through the stationary and nonstationary analysis in the (a) 5 km, (b) 10 km and (c) 20 km buffer zones for stations that showed a significant change in AM events. Similarly, figures (d)–(f) in the second row exhibit a positive relationship between the impervious fraction and change in 100 year events at 5 km, 10 km, and 20 km, respectively. The slope and p-value are shown above each figure. The changes in extreme events are noted to be positively related to the impervious fraction at the 5% significance level. Here, we considered only neutral years (non-ENSO years) in this analysis.

Furthermore, a nonstationary analysis was performed for those stations that show significant changes in AM events at a 10% significance level (figure 6). The changes in the 50 year events from nonstationary analysis varied from −50% to 50% compared to that from the stationary analysis. Additionally, more positive changes were found to be clustered over urban centers across the east and west coast of the Contiguous US, i.e. the magnitude of 50 year events from the nonstationary analysis was higher than those from the stationary analysis (figure 6). In other words, if the analysis were done without considering nonstationarity (as is the case with many assessments), the resulting magnitude would be under-reported.

Three exemplary stations were also considered for the comparison of the 50 year and 100 year return level obtained from stationary and nonstationary analyses, and to visualize the dynamic behavior of the return level throughout the study period. Here, we consider the three stations from each scenario, showing positive change (figure S14(a)), no change (figure S14(b)), and negative change (figure S14(c)). The results highlight that extreme events occurring under nonstationary conditions may exhibit positive changes over urban regions, especially when compared with estimations from the stationary analysis.

In the broader context, these results highlight that designing an urban infrastructure with the stationarity assumption will lead to higher risk or the overestimation/underestimation of structural measures. Accordingly, this study proposed and adopted a methodology to understand the changing characteristics of rainfall extremes. The findings from this study are relevant to engineers, policy/decision-makers, economists, climate scientists for the development of an adaptive design framework. Globally, cities have witnessed an increasing threat of severe and frequent extremes and raise a concern about the preparedness of our infrastructure, and human health as well as safety (Baklanov et al. 2018, Gupta et al. 2018).

5. Conclusions

The study analyzed the impact of urbanization on rainfall extremes. This analysis was conducted using both gridded and station-level long-term rainfall data through a comprehensive nonstationary framework. The study results indicate an association between the extent of urbanization and intensification of
rainfall extremes over the Contiguous US. The study also highlights the spatial variability of nonstationarity in rainfall extremes with strong regional patterns across the Contiguous US. Almost 18% of total grids from neutral years (non-ENSO year) analysis display nonstationary (significant changes in mean values) behavior, out of which the positive changes are clustered across the urbanized east and west coasts of the Contiguous US. In contrast, the negative changes are clustered across the northwest region. The results of the nonstationary analysis indicate the intensification of rainfall, up to a 40% increase in the 50 year and 100 year events under the nonstationary scenario, particularly across the Contiguous eastern US, and up to a 40% decrease in the Contiguous northwestern US (e.g. Montana, Oregon, Idaho, Wyoming, Utah, Colorado).

Here, we proposed a gridded Urbanization Index (UI) for the Contiguous US based on multiple demographic variables in place of the population density based conventional proxy for urbanization. We observed an increase in the probability of exceeding a 25% change in 50 year events from 15% to 41% (an almost 2.7 times increase) when comparing the grids with low to those with high UI values. Spatially, the extreme rainfall changes over the central, northeast central, southeast, and northwest central climate zones across the Contiguous US were more pronounced than those over other regions, and these changes are attributed to the changes in anthropogenic activities. Furthermore, the results obtained from the station-level analysis show that rain gauge stations located over urban clusters experienced positive changes in annual maxima (AM) rainfall, conforming with the results obtained from the gridded data analysis. A significant positive linear relationship between the impervious fraction within a concentric ring buffer of 5 km, 10 km, and 20 km around the station and the change in extreme rainfall events distinctly highlighted the influence of urbanization (built-up or impervious areas) on rainfall extremes.

Thus, we found urbanization to be one of the local influences related to changes in rainfall extremes across the country. Urbanization may also lead to an intensification of extreme rainfall, and this suggests there are more extremes likely in the future and need to be considered in infrastructure design (Yang et al. 2015). These results further suggest that designing an urban infrastructure with the assumption of stationarity may lead to higher risk or the overestimation/underestimation of structural measures. This information will be useful in understanding the possible implications of local changes in rainfall extremes and in projecting these changes into the future by considering the feedback of urbanization in climate change projections. This study identifies a set of fundamental research questions that can ensure that urban innovations yield the intended sustainability outcomes to benefit society at local, national, and global scales.

The present study is a first-of-its-kind to develop a quantitative relationship between the level of urbanization and changes in rainfall extremes, to assess the influence of urbanization on rainfall extremes over entire Contiguous US. Also, we show that even though urbanization has a local footprint, statistical evidence highlights its influence and association with the intensification of rainfall extremes across the country.

The definition of urbanization may be one potential limitation of this study. As discussed in Niyogi et al. (2017), urbanization is more than landform changes, and capturing human influence continues to be an area of active research (Blumenfeld-Lieberthal et al. 2018, Luqman et al. 2019, Wan et al. 2019). Notably, the change in the nonurban landscape, such as agricultural intensification, may also influence the rainfall extremes (Douglas et al. 2006, Niyogi et al. 2006, Pielke et al. 2011, 2016), and is an area of ongoing research. The impact and scale of influence of urban aerosols on the rainfall changes are not well known (Storer et al. 2010, Schmid and Niyogi 2017), and not explicitly considering them is an additional uncertainty and limitation of the present analyses.
Figure 6. Map showing the changes in 50 year events for the stations that exhibited significant change at a 10% significance level. Here, the changes are estimated as $\frac{\text{RP}_{50}^{\text{Nonstationary}} - \text{RP}_{50}^{\text{Stationary}}}{\text{RP}_{50}^{\text{Stationary}}} \times 100$.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Advisory Committee for Environmental Research and Education 2018 Sustainable urban systems: articulating a long-term convergence research agenda. a report from the NSF Advisory Committee for Environmental Research and Education Prepared by the Sustainable Urban Systems Subcommittee (www.nsf.gov/ere/ereweb/ac-ere/sustainable-urban-systems.pdf)
Allan R P and Soden B J 2008 Atmospheric warming and the amplification of precipitation extremes Science 321 1481–4
Ashouri H et al 2016 Evaluation of NASA’s MERRA precipitation product in reproducing the observed trend and distribution of extreme precipitation events in the United States J. Hydrometeor. 17 693–711
Atkinson B W 1968 A preliminary investigation of the possible effect of London’s urban area on the distribution of thunder rainfall, 1951–1960 Trans. Inst. Br. Geogr. 44 97–118
Paul S et al 2018 Increased spatial variability and intensification of extreme monsoon rainfall due to urbanization Sci. Rep. 8 3918
Pielke R A et al 2007 An overview of regional land-use and land-cover impacts on rainfall Tellus B 59 587–601
Pielke R A et al 2011 Land use/land cover changes and climate: modeling analysis and observational evidence Wiley Interdiscip. Rev.: Clim. Change 2 828–50
Pielke R A, Mahmood R and Mcalpine C 2016 Land’s complex role in climate change Phys. Today 69 40–46
Prein A F and Gobiet A 2017 Impacts of uncertainties in European gridded precipitation observations on regional climate analysis Int. J. Climatol. 37 305–27
Rahnstorf S and Coumou D 2011 Increase of extreme events in a warming world Proc. Natl Acad. Sci. 108 17905–9
Ramaswami A, Russell A G, Culligan P J, Sharma K R and Kumar E 2016 Meta-principles for developing smart, sustainable, and healthy cities Science 352 940–3
Rigby R A and Stasinopoulos D M 2005 Generalized additive models for location, scale and shape J. R. Stat. Soc. 54 507–54
Rosenfeld D 2000 Suppression of rain and snow by urban and industrial air pollution Science 287 1795–6
Rozoff C M et al 2003 Simulation of St. Louis, Missouri, land use impacts on thunderstorms J. Appl. Meteor. 42 716–38
Schmid P F and Niyogi D 2017 Modeling urban precipitation modification by spatially heterogeneous aerosols J. Appl. Meteorol. Clim. 56 2141–53
Schneider U et al 2014 GPCC’s new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle Theor. Appl. Climatol. 115 15–40
Seirup L, Yetman G and Razafindrazay L 2012 U.S. Census Grids (Summary File 3), 1990 (Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC))
Seirup L and Yetman G 2006 U.S. Census Grids (Summary File 3), 2000 (Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC))
Shastri H, Paul S, Ghosh S and Karmakar S 2015 Impact of urbanization on Indian summer monsoon rainfall extremes J. Geophys. Res. Atmos. 120 406–516
Shepard D 1968 A two-dimensional interpolation function for irregularly-spaced data Proc. 1968 23rd ACM National Conf. (New York: ACM) pp 517–24
Shepherd J M, Pierce H, Negri A J and Systems S 2002 Rainfall modification by major urban areas: observations from space borne rain radar on the TRMM satellite J. Appl. Meteorol. 41 689–701
Shepherd J M 2005 A review of current investigations of urban-induced rainfall and recommendations for the future Earth Interact. 9 1–27
Shery M A, Karmakar S, Parthasarathy D, Chan T and Rau C 2015 Disaster vulnerability mapping for a densely populated coastal urban area: an application to Mumbai, India Ann. Am. Assoc. Geogr. 105 1198–220
Singh J, Vittal H, Singh T, Karmakar S and Ghosh S 2015 A framework for investigating the diagnostic trend in stationary and nonstationary flood frequency analysis under changing climate J. Clim., Change 1 47–65
Singh J, Vittal H, Karmakar S, Ghosh S and Niyogi D 2016 Urbanization causes nonstationarity in Indian summer monsoon rainfall extremes Geophys. Res. Lett. 43 11269–77
Storer R L et al 2010 Modeling aerosol impacts on convective storms in different environments J. Atmospheric Sci. 67 3904–15
Van den Heever S C and Cotton W R 2007 Urban aerosol impacts on downwind convective storms J. Appl. Meteorol. Climatol. 46 828–50
Vittal H, Ghosh S, Karmakar S, Pathak A and Murtygudde R 2016 Lack of dependence of Indian summer monsoon rainfall extremes on temperature: an observational evidence Sci. Rep. 6 31039
Vittal H, Karmakar S and Ghosh S 2013 Diometric changes in trends and patterns of extreme rainfall over India from pre-1950 to post-1950 Geophys. Res. Lett. 40 3253–8
Vittal H, Singh J, Kumar P and Karmakar S 2015 A framework for multivariate data-based at-site flood frequency analysis: essentiality of the conjugal application of parametric and nonparametric approaches J. Hydrod. 525 658–75
Vogelmann J E et al 2001 Completion of the 1990’s National Land Cover Data Set for the conterminous United States Photogramm. Eng. Remote Sens. 67 650–62
Wan H, Shao Y, Campbell J B and Deng X 2019 Mapping annual urban change using time series landsat and NLCID Photogramm. Eng. Remote Sens. 85 715–24
Wei Y M, Fan Y, Lu C and Tsai H T 2004 The assessment of vulnerability to natural disasters in China by using the DEA method Environ. Impact Assess. Rev. 24 427–39
Whan K and Zwiers F 2017 The impact of ENSO and the NAO on extreme winter precipitation in North America in observations and regional climate models Clim. Dyn. 48 1401–11
Wolter K and Timlin M S 1998 Measuring the strength of ENSO events: how does 1997/98 rank? Weather 53 315–24
Wolter K and Timlin M S 2011 El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI ext) Int. J. Climatol. 31 1074–47
Xie P et al 2007 A gauge-based analysis of daily precipitation over East Asia J. Hydrometeor. 8 607–26
Yang L, Tian F and Niyogi D 2015 A need to revisit hydrologic responses to urbanization by incorporating the feedback on spatial rainfall patterns Urban Clim. 12 128–40
Yang L, Smith J and Niyogi D 2019 Urban impacts on extreme monsoon rainfall and flooding in complex terrain Geophys. Res. Lett. 46 3918–27
Yin J et al 2018 Large increase in global storm runoff extremes driven by climate and anthropogenic changes Nat. Commun. 9 4389
Zhai P, Zhang X, Wan H and Pan X 2005 Trends in total precipitation and frequency of daily precipitation extremes over China J. Clim. 18 1096–108
Zou X and Ren F 2015 Changes in regional heavy rainfall events in China during 1961–2012 Adv. Atmos. Sci. 32 704–14