Spatial and Temporal Characteristics of Heavy Hourly Rainfall in the United States

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ABSTRACT

The climatology of heavy rain events from hourly precipitation observations by Brooks and Stensrud is revisited in this study using two high-resolution precipitation datasets that incorporate both gauge observations and radar estimates. Analyses show a seasonal cycle of heavy rain events originating along the Gulf Coast and expanding across the eastern two-thirds of the United States by the summer, comparing well to previous findings. The frequency of extreme events is estimated, and may provide improvements over prior results due to both the increased spatial resolution of these data and improved techniques used in the estimation. The diurnal cycle of heavy rainfall is also examined, showing distinct differences in the strength of the cycle between seasons.

1. Introduction

Prior to the study by Brooks and Stensrud (2000, hereafter BS00) there had been little research on heavy rainfall at hourly time scales in the United States, let alone a climatology of such events. BS00 utilized the relatively long record length of the Hourly Precipitation Dataset (HPD) to construct a climatology of heavy rainfall events at 1–3-h durations, commenting on observed frequencies and estimating the frequencies of extreme events. The spatial and temporal information provided by this study serves as a valuable guide to forecasters on the flash flooding threat; however, the authors recognize the limitations of using data from the HPD, namely the coarse station spacing (approximately 50 km on average). This limitation is especially apparent when considering extreme precipitation events that are more likely to be undersampled, such as the 9 June 1972 Rapid City, South Dakota, flood (Maddox et al. 1978) noted by BS00. It was suggested that with the advent of the Weather Surveillance Radar-1988 Doppler (WSR-88D) network a climatology based on radar-estimated precipitation could be constructed, allowing for a refinement of the results presented in BS00.

The present study seeks to revisit the climatology of heavy and extreme rainfall in the United States developed by BS00 using high-resolution precipitation analyses that incorporate rainfall estimates from the WSR-88Ds. We first describe the datasets used in this study and compare them to the HPD in section 2. In sections 3 and 4, the monthly frequencies and distributions of hourly precipitation are examined, and the estimates of extreme rainfall rates from BS00 are reevaluated using high-resolution data. The diurnal cycle of heavy rainfall is presented in section 5. Finally, a discussion of the results and how they impact the findings of BS00 is presented in section 6.

2. Data and methods

This study uses two high-resolution datasets: the so-called stage IV precipitation dataset (ST4; Fulton et al. 1998), which is produced by the National Centers for Environmental Prediction (NCEP), and the next-generation quantitative precipitation estimate (QPE) (Q2; Vasiloff et al. 2007) hourly gauge-adjusted radar product, which is part of the National Mosaic and
Multisensor QPE System (Zhang et al. 2011). The ST4 is based on radar-derived precipitation estimates that are adjusted using rain gauge measurements; however, ST4 data also benefit from some manual quality control measures performed at National Weather Service River Forecast Centers. Although the manual quality control is regularly applied to 6- and 24-h accumulations in the ST4, the hourly analyses include a large number of spurious data points (e.g., Stevenson and Schumacher 2012). Additional quality control has been performed for this study to remove obvious spurious data, but these data should be used with caution for the investigation of heavy precipitation over the complex terrain of the western United States. The ST4 product is available on a 4 km × 4 km grid, but for the purposes of this study is converted to a latitude–longitude grid with 8.33-km gridpoint spacing using bilinear interpolation. This was found to help eliminate the identification of spurious events, although it may have also removed a few legitimate events that occurred at very small spatial scales. Data are available beginning in 2002, and the 10-yr period ending in 2011 is used for this study.

Hourly Q2 data are available beginning on 20 November 2008, but only data from 2009 to 2011 are used to allow for uniform comparisons between months. These data are plotted on a latitude–longitude grid with 1-km gridpoint spacing and a domain consisting of the contiguous United States. The gauge-adjusted radar Q2 product is constructed by taking the estimated precipitation for each radar location and applying a pixel-by-pixel correction based on a normalized error estimate from rain gauges within a radius of influence. If a gauge reports anomalously high (or low) rainfall, additional quality control measures are taken, removing values that strongly disagree with surrounding stations and recalculating the error estimates. Locations with sparse (or no) rain gauge coverage rely heavily (or solely) on the radar estimates. A full description of the entire Q2 processing procedure can be found in Zhang et al. (2011).

While both the ST4 and Q2 products improve on the horizontal resolution issue inherent in the HPD, these datasets are not without errors and uncertainties. Since radar estimates are the primary source for these data, the typical issues related to radar measurements may impact the datasets: beam blockage, ground clutter, and the choice of radar reflectivity–rain rate (Z–R) relations (Vasiloff et al. 2007). More relevant to this study is the short 3-yr period of record of the Q2 dataset, an issue that is addressed by examining the same 3 yr of the ST4 and comparing those results to the full 10-yr period of record.

3. ST4 analysis
   a. 2002–11

Following BS00, we examine the seasonal distribution of heavy rainfall by computing monthly averages and plotting the distribution of these measures. The format of this analysis is constructed to offer direct comparisons to the key findings of BS00, as well as to provide additional insights afforded by the finer spatial resolution of the data.

For this study a heavy rainfall event is considered any hourly accumulation of at least 25 mm (~1 in.) at a grid point. In their Fig. 3, BS00 plotted rainfall between 1 and 1.5 in. (where 1 in. = ~25 mm), but in our Fig. 1 we show the annual frequency of all heavy rainfall events. Like BS00, the ST4 data show a maximum frequency of heavy rainfall in July, with this month accounting for 19.5% of all events. Additionally, the period of April–September accounts for 82.7% of all heavy rainfall from the ST4 dataset, falling just below the frequency found by BS00 (86%).

To directly compare the horizontal distribution of the frequency of heavy rainfall from the ST4 dataset to that from the HPD constructed by BS00, the same objective analysis technique is performed on all heavy hourly rainfall events of at least 25 mm. A one-pass Gaussian weight function scheme (Barnes 1964, 1973) is used, with the response function being

\[ R_o = \exp(-4\pi^2c/L^2), \]
where $L$ is the wavelength. To obtain results comparable to BS00, we use 1875 km$^2$ for the value of $c$, such that wavelengths less than 100 km are removed from the analysis.

A seasonal cycle of heavy rainfall is evident using the ST4 (Fig. 2), similar to that found by BS00, with a gradual increase in spatial extent and frequency originating from the Gulf Coast, peaking in July, and

Fig. 2. Frequency (events per year) of 25 mm (−1 in.) h$^{-1}$ or larger rainfall totals from the ST4 for each month objectively analyzed to the grid used in BS00.
retreating by winter. The maximum frequencies occurred in southern Florida during the 3-month period of June–August with values of 1.00, 0.97, and 1.04 events per year, respectively. The only other value to exceed 0.6 events per year occurred in October (0.68 events per year) along the Gulf Coast on the border of Texas and Louisiana. The relatively high resolution of the ST4 product allows for the identification of individual storm tracks from monthly maps of heavy rainfall frequency (Fig. 3). For example, traces of the path of what is likely an individual storm can be seen across Oklahoma in November. There are other examples of this during months in the late autumn and early spring due to fewer incidences of heavy rainfall, but such storm tracks are not as easily observed during months in which these events are more frequent.

Using their results from the HPD, BS00 estimated extreme event frequencies by utilizing the logarithmic decline of binned rainfall observations, adjusting for undersampling by multiplying their frequencies by 2500 (equivalent to 1-km grid spacing). They approximated that there should be 50,000 3 in. h⁻¹ and 25,000 6 in. h⁻¹ events per year. The finer grid spacing of the ST4 dataset allows for better estimation of the frequency of extreme precipitation events, with an adjustment made by multiplying by 69.4 to approximate the 1-km grid spacing. The approach of BS00, using logarithmic decline in annual rainfall frequencies to estimate values for extreme events, does not appear to model the frequency of rainfall events greater than 75 mm from ST4 data well (Fig. 4). To better represent the extreme rainfall, we use the Pareto (type II) distribution, which was found by Papalexiou et al. (2013) to best model the tail of so-called heavy-tailed distributions. Its probability density function (PDF) is defined as

$$f(x) = \frac{\gamma}{\beta} \left(1 + \frac{x}{\beta}\right)^{-\left[\frac{\gamma}{\beta}\right]-1},$$  (2)

where $\beta$ is the scale parameter and $\gamma$ is the shape parameter. Each dataset is fit to both the log-linear model and the Pareto distribution using a least squares fit, with parameter values listed for each in Table 1. This approach results in estimates of 1651 events of 76 mm ($\sim$3 in.) h⁻¹ and 228 events of 152 mm ($\sim$6 in.) h⁻¹ yr⁻¹. Compared to these results, the approximations made by BS00 are an order of magnitude too high for the 3 in. h⁻¹ events and an order of magnitude too low for the 6 in. h⁻¹ events. A likely reason for the overestimate of the former is a lack of adequate sampling of extreme rainfall events due in part to the coarse grid spacing of the HPD, while the reason for underestimating the latter is in part owed to the choice of distribution used (not heavy tailed).

b. 2009–11

Since the period of record of the Q2 data used in this study is only three years (2009–11), a subset of the ST4 data composed of the same three years is compared to the full 10 years of ST4 data to determine whether those three years are representative. The parameters for both the
log-linear model and the Pareto distribution are provided in Table 1 for the three sets of data, and a comparison between the full ST4 dataset and the 3-yr subset is shown in Fig. 4. The parameter values of the two ST4 datasets are nearly identical for the log-linear model, and are in close agreement for the Pareto distribution, while the parameter values of the Q2 dataset, especially in the case of the Pareto distribution, differ more substantially from those of the ST4. The similarities between the 10-yr ST4 dataset and its 3-yr subset suggest that differences

FIG. 3. As in Fig. 2, but plotted using the 8.33-km ST4 grid.
between the results obtained from the ST4 and Q2 datasets are due primarily to differences in grid spacing, processing, and quality control rather than the characteristics of heavy rainfall during the 2009–11 period.

4. Q2 analysis

Examining hourly rainfall of at least 25 mm h\(^{-1}\), the frequency of heavy rainfall events reaches a maximum in July (19.6%) and the other frequencies are nearly symmetric about that month (Fig. 5). Unlike the results from BS00 and the ST4 analysis, the frequencies of April, May, and June are all higher (by ~2%) than their counterparts in the 3 months following July. This is likely a result of the Q2’s short period of record rather than better detection of heavy rainfall in those months. The period of April–September accounts for 84.4% of heavy rainfall events from the Q2, agreeing well with the results from both BS00 (86%) and the ST4 analysis (82.7%).

An evident seasonal cycle of heavy rainfall events is shown in Fig. 6, with persistent frequencies of at least 0.1 yr\(^{-1}\) each month in the Gulf Coast region. The frequency of heavy rainfall events expands month by month from an areal minimum in February, encompassing the majority of the eastern two-thirds of the contiguous United States by July, and gradually decreasing in areal extent through the remainder of the year. The maximum frequency of events (1.39 yr\(^{-1}\)) among all months occurs in July in South Carolina, with the June maximum of 1.33 yr\(^{-1}\) located in southern Florida a close second. During the period beginning in March and ending in November the maximum frequency of heavy rainfall events during each month exceeds 1.00 yr\(^{-1}\), with the exception of September (0.99 yr\(^{-1}\)).

The spatial distribution of heavy rainfall for each month compares well with the findings of BS00 (their Fig. 5). As expected, the maximum frequencies by month in this study are significantly higher than those previously observed since the frequencies are calculated from only three years of data. Both studies also show a shift in maxima from the Gulf Coast region to the Great Plains from the beginning of the year to June, but the July maximum in this study is located in South Carolina rather than closer to the central United States, and high frequencies persist there into August. It should be noted, however, that differences such as these may be a consequence of the short record length of the Q2 dataset rather than climatological signals. Other similarities between the spatial frequencies observed in BS00 and the present study include the local minima over the Appalachian Mountains during the summer and in southern Texas in July and August. Another local feature of interest is the appearance of the North American monsoon (Douglas et al. 1993) in Arizona from July through September.

The higher resolution of the Q2 dataset (1-km grid spacing) allows for the impact of individual storm systems to be identified in the heavy rainfall frequencies for each month (Fig. 7), however, the appearance of repeated storm tracks in these analyses is most likely another result of the short record length of the Q2 dataset, and not...
indicative of preferential storm tracks. Individual storm tracks are most easily observed in months with fewer heavy rainfall events, for instance during the month of February across Indiana and Ohio, or in November across Oklahoma. Areas of repeated storm paths are seen in Arkansas and Mississippi during April and from Arkansas to Tennessee in May, exhibiting a linear pattern of higher frequencies. These same repeated storm paths are also evident in the objectively analyzed plots (Fig. 6) as quasi-linear areas of higher frequencies.

Using the same approach for estimating extremes as with the ST4 data, the logarithmic decline of binned Q2 rainfall is approximated well for amounts less than 125 mm, but for larger amounts the Pareto distribution better fits the data (Fig. 8). This approach results in 4633 events of 76 mm (~3 in.) h\(^{-1}\) yr\(^{-1}\) and 5.3 events of 152 mm (~6 in.) h\(^{-1}\) yr\(^{-1}\). The estimation of 3 in. h\(^{-1}\) events is more than 2.5 times as large as that of the ST4, but still an order of magnitude less than that of BS00, while the estimation of 6 in. h\(^{-1}\) events is an order of magnitude less than in BS00, and two orders of magnitude less than in ST4. As with the discrepancies between the extreme rainfall estimations of BS00 and the ST4, the overestimation of extreme events by these two datasets compared to the Q2 is likely a result of the approximation of 1-km grid spacing. At larger precipitation values these

![Table 1: Distribution parameters for the ST4 data from 2002 to 2011 and from 2009 to 2011, and for the Q2 data from 2009 to 2011. The log-linear model was fit using data from 25 to 50 mm, and the Pareto distribution was fit using data from 75 to 200 mm for ST4 data and from 125 to 200 mm for Q2 data.](image)

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![Figure 5: As in Fig. 1, but for Q2 data.](image)
errors are somewhat lessened with the ST4 by using the Pareto distribution, but the coarser grid spacing of the ST4 dataset gives the appearance of heavy rainfall over a larger area than in reality, which is then further exasperated by scaling to approximate the grid spacing of 1 km. Therefore, we believe the estimations using the Q2 are superior due to both the use of a heavy-tailed distribution for large precipitation values and the

FIG. 6. Frequency (events per year) of 25 mm (−1 in.) h⁻¹ or larger rainfall totals from the Q2 for each month objectively analyzed to the grid used in BS00.
dataset’s finer grid spacing, which precludes the need to scale the data.

5. Diurnal cycle

An aspect of heavy rainfall that was not explored by BS00 is the diurnal cycle of these events. In his study of the diurnal variations of precipitation and thunderstorm frequency, Wallace (1975) observed seasonal maxima in the frequency of “heavy” precipitation from late afternoon through the overnight hours (local standard time) for various locations in the eastern two-thirds of the United States. Wallace’s definition of heavy was significantly less than ours (>0.10 in. h⁻¹), and was based on rain gauge measurements from observing stations with an effective grid spacing coarser than that of BS00. Winkler et al. (1988) examined the seasonal variations of the diurnal cycle of heavy hourly rainfall, dividing hourly rainfall accumulations into four categories. Although they deemed rainfall of at least 5 mm h⁻¹ to be heavy, their highest category (≈25.4 mm h⁻¹) most closely matched the definition used in the present study (≈25.0 mm h⁻¹). They found that the diurnal cycle was weaker during the winter and stronger during the summer, and that heavier rainfall usually occurred later in the day compared to lighter rainfall. While this study also used rain gauge data, they fit it to a 75-km grid, slightly coarser than that of BS00.

Both high-resolution precipitation datasets, Q2 and ST4, are used to analyze the diurnal cycle of heavy rainfall in the contiguous United States. Both datasets show afternoon maxima and morning minima for the spring, summer, and autumn (Fig. 9), while the Q2 shows peaks in the winter later at night and in the morning, with an early afternoon minimum. The seasonal variations from the Q2 reflect the findings of Winkler et al. (1988) with a strong diurnal cycle evident during the summer due to convective systems providing much of the heavy precipitation during this season, and a much weaker diurnal cycle during the winter as a result of the predominance of synoptic-scale rainfall during these months. Differences in the magnitude of the diurnal cycle by season are a result of there being more synoptic-scale precipitation during the winter and convective precipitation being more frequent during the summer. The seasonal diurnal cycles from the ST4 show similar behavior for the spring, summer, and autumn, but the winter shows a greater amount of variation with maxima in the early afternoon and later at night. The slightly larger degree of variation observed during all four seasons using ST4 data compared to that from the Q2 is most likely a result of differences in sample size; despite the shorter period of record, the Q2 has approximately 69 times as many grid points as the ST4, allowing for detection of multiple grid points with heavy rainfall in the Q2 that would be identified as a single grid point in the ST4. In this circumstance the short period of record of the Q2 is overcome by its finer gridpoint spacing. Despite the differences in diurnal cycle by season of these two datasets, their annual diurnal cycles compare very well (Fig. 9), providing a high amount of confidence in the late afternoon maximum and morning minimum frequencies of heavy rainfall.
6. Discussion

The climatology of heavy rain events constructed by Brooks and Stensrud (2000) is revisited, this time using two hourly precipitation datasets with improved horizontal resolution. These data show an annual cycle of the frequency of hourly heavy rainfall events that peaks in July, and decreases logarithmically between 25 and 50 mm, but is better characterized with a heavy-tailed distribution at larger precipitation values. The spatial distribution of the heavy rainfall events also shows an annual cycle, originating along the Gulf Coast and

**FIG. 7.** As in Fig. 6, but plotted using the 1-km Q2 grid.
expanding across the eastern two-thirds of the United States by the summer.

Because of the short length of record of the Q2 dataset, a subset of the ST4 covering the same period of time as the Q2 was compared to the full ST4 dataset. The results of this comparison supported the assertion that differences between the Q2 and ST4 datasets are due to factors such as the length of record and grid spacing of these datasets, with the particular years composing the Q2 not displaying more

FIG. 8. Annual average number of rainfall events in the United States from ST4 data (black circles and lines) and Q2 data (gray squares and lines). Events are binned at 1-mm intervals and displayed at 10-mm intervals for clarity. ST4 data are from the full 10-yr period of record (2002–11). The solid lines are log-linear fits to the binned data from 25 to 50 mm, and the dashed lines are fit to the Pareto distribution (type II) using data from 75 to 200 mm for ST4 data and 125 to 200 mm for Q2 data. The dotted line is an approximation of the estimate made by BS00.

or fewer heavy precipitation events. It was found that the Q2’s length of record was somewhat problematic when evaluating spatial frequencies, but was sufficient when calculating frequencies for the entire contiguous United

FIG. 9. Diurnal cycle of 25 mm (≈1 in.) h⁻¹ or larger rainfall in the United States for (a) ST4 and (b) Q2 data. Seasonal frequency values are calculated based on the total number of events that occurred during each 3-month period (e.g., December–February, DJF). The total numbers of events from the ST4 for each season (beginning with DJF) are 46,908, 197,131, 474,607, and 172,453. From the Q2 the total numbers of events from each season are 1,744,438, 9,564,713, 22,049,806, and 7,673,456.
States. In fact, even with a short period of record, it could be argued that the Q2 provides better estimates of extreme precipitation due to its finer grid spacing.

Results found in this study compare well with previous findings, and in the case of extreme precipitation frequencies our findings improve upon them. Although only three full years of Q2 data exist at this time, we feel there is sufficient data to begin making comparisons with results from past studies that were based on data collected from rain gauges. At such a time as the record length of the Q2 dataset reaches a more substantial length it will be worthwhile to construct a complete climatology of hourly heavy rainfall events, and perhaps at time scales as small as 15 or even 5 min.

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