Storm Precipitation in the United States. Part I: Meteorological Characteristics

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ABSTRACT

Climate studies of precipitation have generally focused on daily or longer time scales of precipitation accumulation. The main objective of this work was to identify the precipitation characteristics of storms based on 15-min precipitation data, including storm total precipitation, storm duration, mean storm intensity, and maximum 15-min intensity. A group of precipitation characteristics was subjected to a cluster analysis that identified nine regions of the conterminous United States with homogeneous seasonal cycles of mean storm precipitation characteristics. Both mean and extreme statistics were derived for each characteristic and season for each zone. Continuous probability density functions were generated that appropriately fit the empirical distributions of storm total precipitation and maximum 15-min intensity. The storm characteristics, in turn, were a function of seasonal water availability from source regions, atmospheric water vapor capacity, and storm precipitation mechanism. This is the first time that such an extensive climatology of storm precipitation characteristics has been produced. A preliminary trend analysis of the 1972–2002 storm characteristic data by zone showed substantial changes that tended to be geographically coherent, with noteworthy differences between the western and eastern United States. The western United States displayed a trend toward decreasing storm total precipitation and storm duration in most seasons, while storm intensity increased. The eastern United States experienced a general pattern of increasing storm total precipitation and storm duration during winter, as well as a tendency for maximum 15-min precipitation intensity to increase.

1. Introduction

The most common time scale for recording rainfall is daily accumulation. These daily accumulations are the basis for monthly, seasonal, and annual precipitation records. With record lengths exceeding 50 yr in many places, the spatial and temporal characteristics of these daily storms have been subject to extensive analysis (Dai et al. 1997; Karl and Knight 1998; Kunkel et al. 1999). Among others, the characteristics most often studied in climatology include total monthly, seasonal, and annual rainfall; the number of rain days in a period; and various categories of days with precipitation totals above certain levels. In regions where the climate is defined by rainy and dry seasons, the dates of onset, termination, and duration of the rainy season have been analyzed (Tarhule and Woo 1998).

These rainfall statistics provide valuable information regarding the general wetness or dryness of a location or region, and the identification of trends in regional rainfall (Fernandez and Garbrecht 1994; Adiku et al. 1997; De Luís et al. 2000; Campling et al. 2001; New et al. 2001; Ho et al. 2003). Groisman et al. (2004) have recently published an important compilation of changes in the hydrological cycle over the conterminous United States, based on daily precipitation data and other variables. On average, only 5% of precipitation days account for 15%–20% of annual precipitation totals. These heavy precipitation days are very significant for hydrological and soil erosion concerns. Further work in the soil erosion realm (Nearing et al. 2004) indicates that continuing increases in precipitation totals as projected by global climate models will lead to increases in soil erosion in the United States of about 1.7% for

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every 1% increase in rainfall. However, this research depends on the assumed continuity of existing relationships between daily precipitation totals and storm erosivity. While climatologies of heavy precipitation events exist, no existing modern climatology of all-storm precipitation characteristics has been presented prior to this work.

Details of the individual storms that produce the daily total rainfall are critical to understanding the hydrological and erosional consequences of storms (Brown and Foster 1987; Wilks 1989). While it is well known that rainfall depth is a determinate of the occurrence of floods, depth alone does not explain the occurrence or severity of flash flooding, erosion, or non-point-source pollution. To understand these phenomena, the rainfall intensity within a storm and the duration of a storm must be known. This information is available from hourly, 15-min, or more frequently measured rainfall accumulation data (Tattelman and Knight 1988; Polyak et al. 1994). Short-time-scale rainfall data are required for many hydrological applications such as modeling rainfall-runoff transformations (Zhang and Smith 2003), using time-dependent infiltration models (Ogden and Saghafian 1997), simulating wetland dynamics (Zhiquan et al. 1994), and modeling erosion (Wischmeier and Smith 1978).

Onof and Wheater (1993) describe the application of point rainfall time series models to important hydrological problems, such as the calibration of weather generators and the disaggregation of daily rainfall data for applications that are sensitive to short-term intensity behaviors. For example, the model they extended, the Bartlett–Lewis Rectangular Pulse Model, requires information on the length of time between storms, the number and time spacing of showers within a storm (storm cells), the duration of each of the cells, the mean depth of rainfall, and the storm duration (Onof and Wheater 1993). The data required to develop the probability distributions for these storm characteristics must come from rainfall records with temporal resolutions of less than an hour. Connolly et al. (1998) used high-temporal-resolution rainfall intensity data to simulate the number and characteristics of precipitation events on a rain day, including the starting time, duration, rainfall amount, time to peak intensity, and peak intensity of each event. In the United States, the National Climatic Data Center (NCDC) has time series of varying lengths for approximately 3700 fifteen-minute weighing-bucket rainfall stations (Hammer 1998). These 15-min rainfall data have not been utilized extensively on a national basis to fulfill the data needs of these point rainfall time series modeling efforts. This project will provide some of the statistics needed for these efforts.

The objective of this paper is to describe the storm precipitation characteristics defined by the storm total precipitation, storm duration, mean storm intensity, and maximum 15-min precipitation intensity. Precipitation characteristics for each of the four seasons (spring: March, April, May; summer: June, July, August; fall: September, October, November; winter: December, January, February) were generated as indicated in section 2. A companion paper (Angel et al. 2005, hereinafter Part II) examines other characteristics that are directly related to soil erosion. The basic statistics and distributions of the storm precipitation characteristics for each of nine spatial zones identified by a cluster analysis will be examined in section 3. By aggregating the seasonal storm statistics in each zone into annual time series, trends in storm precipitation characteristics based on 15-min precipitation data will be analyzed for the first time. The results are discussed in section 4.

2. Data and methods

Storm rainfall characteristics were computed using the NCDC 15-min rainfall database (Hammer 1998) for the period of 1971–2002. While approximately 3700 weighing-bucket rain gauge stations are included in the database, many stations had missing periods of record, and some had record lengths of less than 10 yr. The database was first screened to identify stations with a record length greater than 20 yr and less than 25% missing data, resulting in the selection of 1505 stations in the contiguous United States for inclusion in the study.

Each record of a 15-min data file contains 15-min-period precipitation observations for a single day when precipitation occurred. The records include quality control flags indicating missing data, accumulated data, and data flagged by NCDC for various reasons (Hammer 1998). The 15-min data were collected with Fischer–Porter weighing-bucket rain gauges that record rainfall in 0.1-in increments (2.54 mm). Thus, the smallest precipitation amount that would be defined as a storm in Système International d'unités (SI units) is 2.54 mm. This dataset is one of the most temporally homogenous in climatology, because each Fischer–Porter gauge is approximately the same throughout the network. This also means that potential drawbacks of using an unshielded, unheated weighing-bucket gauge are also present throughout the network. Although the gauges are winterized with antifreeze to liquify frozen precipitation in winter, cold climate locations still experience undercatch during the winter (Groisman and Legates 1994), which would affect some of the storm precipitation characteristics.

Utilizing a definition applied commonly in past studies of hydrology and soil erosion (Huff 1967; Wischmeier and Smith 1978; Renard et al. 1997), individual storms were defined as those periods with precipitation that were separated from preceding and succeeding precipitation by 6 h. Recent research has shown that the time between storms that is ideal for storm characterization varies with location (Bonta 2001, 2003). However, consistent with past practice, the use of a fixed 6 h between storms definition was important in calculating soil erosion characteristics in Part II of this study. With this definition, individual days can have multiple storms, and storms can occur over periods of time involving more than one calendar day. In computing the storm characteristics only precipitation observations that had no flags present and were separated from flagged or missing data by more than 6 h were used. Adjacent days also were examined to ensure the existence of a 6-h gap between storms and flagged or missing data, and to establish the beginning and end times of storms crossing from one day to the next. This storm definition and these data requirements ensured that individual storm statistics were not invalidated by incorporating missing or flagged data. However, this practice increased the percentage of data that were classified as missing.

The 15-min data were used to compute the storm total precipitation, storm duration, mean storm intensity, and the maximum 15-min precipitation intensity. Storm total precipitation (mm) is the total rainfall received from the first shower through the last shower. Storm duration (h) was defined as time from the beginning of the first shower of the storm to the end of the last shower of the storm. Storm mean intensity (mm h^{-1}) is the storm total precipitation divided by the storm duration. For each storm, the 15-min maximum intensity (mm h^{-1}) was computed by multiplying the greatest 15-min precipitation total by 4 to convert the units to hourly time rates. The characteristics of the Fisher–Porter rain gauge establish observational minima for precipitation variables. Storm total precipitation can be no less than 2.54 mm, storm duration can be no less than 15 min, 15-min precipitation intensity can be no lower than 10.16 mm h^{-1}, and the precision in determining storm durations, intensities, and totals is resolution limited. All values derived from these data will be confined to one decimal place, in response to the limitations of the measurement precision.

The four seasonal averages of the storm precipitation total, storm duration, storm intensity, storm 15-min maximum intensity, storm 30-min maximum intensity, storm precipitation kinetic energy (KE), and storm erosivity (EI) for each of the 1505 high-quality stations (four seasons × seven variables) were subjected to a cluster analysis using Ward's method. The latter three variables are described in detail in Part II. Ward's (1963) method is one of the most common approaches to clustering, and uses the metric of within-cluster sum-of-square minimization. Previous work indicates that Ward's method generates clusters of a similar size (Kalkstein et al. 1987), which is a desirable characteristic when using many variables to group large numbers of stations into spatially coherent regions. An agglomeration schedule listing the cluster-joining sequence and cluster-distance coefficient was used to determine the appropriate number of clusters to keep by finding a large local break in the progression of the coefficient value. There were two breaks in the between-group distance in the agglomeration schedule—one at five clusters and the other at eight clusters. Eight clusters divided the United States into reasonable climate zones. However, one cluster contained stations from both the West Coast and the northeastern states. Based on spatial congruence considerations, that cluster was broken into two clusters—one representing parts of the West Coast and the other the northern tier of states from Wisconsin to Maine. Thus, storm characteristics were analyzed for nine regional clusters (Fig. 1). A similar clustering approach with bimonthly averages and fewer variables yielded similar spatial regions, so the cluster analysis is quite robust. The geographical distribution of observation stations provides good coverage (dots in Fig. 1), and there is no significant geographical or temporal bias to the station dataset.

The storm precipitation characteristics observed for all valid storms at all stations in each of the nine clusters were pooled to generate empirical probability distributions and summary statistics for each characteristic type in each region. Two equation families were used for fitting analytical curves to empirical storm characteristic probabilities, forming probability density functions (PDFs). The PDF equations are potentially useful for constructing storm time series to be used in hydrologic or erosion modeling. The first equation used is the double exponential and is shown in (1). The coefficients a, b, c, and d are fit using nonlinear regression procedures in TableCurve 2D (SYSTAT 2002):

$$y = ae^{(-x/b)} + ce^{(-x/d)}. \tag{1}$$

The second equation family is a set of curves that can be derived from the transformed general natural logarithmic form shown in (2):

$$\ln y = a + bx^{\beta}(\ln x)^{\beta_1} + cx^{\gamma}(\ln x)^{\gamma_1}. \tag{2}$$

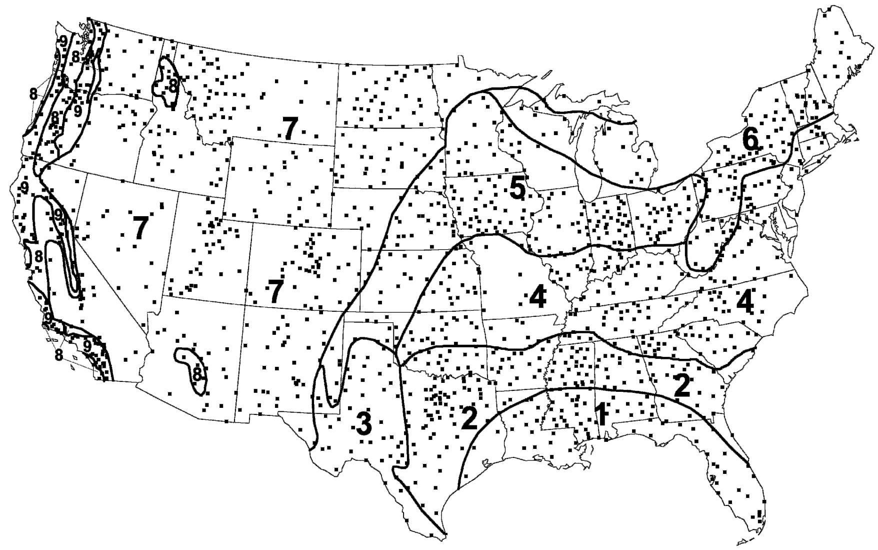

FIG. 1. Storm precipitation characteristic cluster zones. Squares indicate the locations of stations used in this study.

In (2), parameters, β, β_1, γ, and γ_1 define the general form of the equation and the coefficients *a*, *b*, and *c* are fit using linear regression procedures from TableCurve 2D (SYSTAT 2002). The Eq. (2) family tended to fit more of the observed large events further across the tail of the distribution, while still maintaining a good fit over the vast majority of the storm characteristic cases. For example, Fig. 2 illustrates a typical fit of the logarithmic family of curves to two different probability distributions of storm total precipitation for summer in zones 1 and 9. Each point represents the probability the precipitation in a storm event will be found within a given bin range. The curves each go through the most common cases, as well as the vast majority of the less common heavy cases. A few heavy cases are missed, but the amount of variance explained exceeds 99.9% for every variable and season, and often exceeds 99.99%. It is not recommended that these equations be applied beyond the point at which the curve deviates from the tail of the empirical distribution. In Fig. 2, that point is reached at 230 and 200 mm in summer for zones 1 and 9, respectively. The PDF curves described below will be truncated at the maximum limit of good fit. Because of the potential usefulness of these curves, an appendix has been created with the parameters and coefficients of the best-fit curve to each empirical probability distribution, along with the maximum limit of its application (see appendix; Table A1).

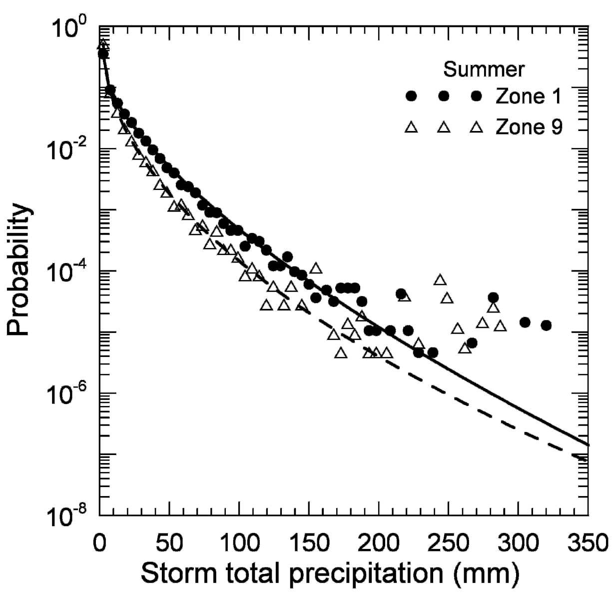

FIG. 2. Empirical probability density distributions of storm total precipitation during summer for zones 1 and 6, fit with curves from the natural logarithm family represented by Eq. (2).

The statistics computed for each variable and cluster of stations included the mean and standard deviation, and the means for all zones in each season and all seasons for each zone were checked for statistical independence. All but the most extreme storm event characteristics are analyzed here via the means and PDFs. To examine the extreme cases, the 100-yr return interval estimates for each variable and season were calculated for each station by fitting the two-parameter Gumbel distribution to the annual extreme series using *L*-moments software (Hosking 1991). The Gumbel distribution provided a robust fit to the available data (Wilks 1995), avoiding problems with overfitting that were present in several other distributions, including the three-parameter Gumbel. While longer time series would have provided a more complete record from which to derive the 100-yr storm statistics, the consistent application of a conservative methodology produces extreme value estimates that are comparable between zones and seasons.

Last, trends were determined by computing linear regressions between time series of years and seasonal mean storm characteristics in each zone and season. The Student's *t* test of the slope was used to determine the significance of the trend, and then the trend equation was evaluated to calculate the percentage change of the variable from 1972 to 2002. These statistics were used to compare the storm characteristics trends among the different variables, zones, and seasons.

3. Results and discussion

The 1505 high-quality 15-min rainfall stations were grouped into nine clusters (Fig. 1), hereinafter called zones, with similar storm precipitation characteristics. The storm characteristics, in turn, are a function of seasonal water availability from source regions (atmospheric circulation, distance to coastline, elevation, and barriers), the atmospheric water vapor capacity (temperature), and the precipitation mechanism associated with individual storms (either convective or stratiform). Zones 1, 2, 4, 5, and 6 extend predominantly west to east from the Great Plains to the Atlantic coast, with each further north than the last. These zones reflect the spatial gradient in storm characteristics because of the increasing distance from the Gulf of Mexico moisture source. Zone 6 has a substantial deviation to the south over the high altitudes of the central Appalachian Mountains, while zone 4 extends north along the Atlantic coast source of warmth and moisture all the way to New England.

In the Southwest, zone 3 incorporates the unique transitional aspects of west Texas, which is an area that is normally dry, but is subject to occasional incursions of Gulf moisture and tropical storms. Most of the interior West and parts of the northern Great Plains are in zone 7—the largest geographic area of all the zones and the one with the most stations (402). Zone 7 represents locations that are dry in all seasons, and have storm precipitation characteristics that reflect a lack of moisture, such as brief durations and small storm precipitation totals. There is a relative maximum in storm precipitation totals and other variables during the summer warm season, when moisture is more available. Given the statistical emphasis on seasonal cycle shape, and the coarse 3-month seasonal resolution of the analysis, it is not surprising that western locations with a wide range of annual precipitation amounts have similar storm characteristic seasonal cycles. For example, the Southwestern monsoon region in Arizona and New Mexico was not identified because the cluster analysis was conducted on seasonal rather than monthly data. Therefore, a shift of the peak in warm season precipitation from early to late summer would not be detected.

California and western Oregon and Washington contain parts of zones 7, 8, and 9. The drier areas in these states are grouped with zone 7, including the southern part of the Central Valley in California. Zones 8 and 9 at first appear to be intermingled, but, in fact, are clearly separable using topographic considerations (Daly et al. 2002). The stations making up zone 8 are located at lower elevations; the zone 8 mean elevation is 456 m, which is significantly lower than the 641-m mean for the zone 9 stations. Last, the zone 8 islands in Arizona and Idaho are caused by enhanced winter precipitation relative to the surrounding zone 7 stations. Increased winter storm duration and total precipitation in these islands resembles the seasonal cycle of the West Coast's zone 8.

The probability density distribution and 100-yr return interval statistics for each storm characteristic were calculated for the nine zones. These results are presented for each of the four seasons defined as winter (December–January–February), spring (March–April–May), summer (June–July–August), and fall (September–October–November).

a. Storm total precipitation

The average magnitude of storm total precipitation and its seasonal variations were both keys to the establishment of the zones chosen by cluster analysis. Therefore, it is not surprising to see the well-established pattern of decreasing mean storm totals from the Gulf of Mexico coastline to the northern border regions of the eastern United States (Table 1). In sequence, the mean storm total precipitation amount is larger in zone 1, and decreases through zones 2, 4, 5, and 6 in all seasons except winter. During the winter, zone 6 storms produce more precipitation than zone 5 storms do despite increased undercatch problems in a colder climate. Lake-effect snowbelts (Ellis and Leathers 1996) and mountainous terrain in zone 6 contributed more precipitation per storm than was lost through undercatch. In every storm characteristic table (e.g., Table 1), pairs of zones that are not significantly different during a season are marked with a superscript letter, while seasons that are not significantly different in a zone are marked with a superscript number. For instance, zones

TABLE 1. Storm total precipitation (mm) mean and 100-yr return interval estimate bounded by 2 times the standard error, for each zone and season. Zones with the same letter in a column are not significantly different at $\alpha = 0.05$, and zones with the same superscript number for a season in the same row are not significantly different at $\alpha = 0.05$.

	Mean				100 yr			
Zone	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1	15.8[1]	16.8	13.1[a]	15.7[a,1]	173.9 ± 6.8	196.0 ± 8.9	165.5 ± 6.5	207.9 ± 8.2
2	13.3	14.3	12.9[a]	15.6[a]	146.9 ± 5.2	158.3 ± 4.3	144.1 ± 4.5	180.5 ± 5.4
3	7.6	10.6	11.5[b,1]	11.8[1]	75.4 ± 7.8	110.6 ± 8.2	135.1 ± 8.4	137.1 ± 9.4
4	10.8	11.5	12.0	13.3	112.5 ± 3.5	127.1 ± 2.9	138.2 ± 2.8	153.2 ± 3.8
5	6.6	9.1	11.4[b]	9.8[b]	65.1 ± 3.2	98.5 ± 2.4	126.9 ± 2.3	109.5 ± 2.8
6	7.3	8.5	10.0	9.7	79.6 ± 2.6	90.5 ± 2.8	112.6 ± 3.1	115.9 ± 3.3
7	5.5	6.0	7.2	6.6	44.8 ± 3.2	64.5 ± 2.2	73.1 ± 2.6	66.6 ± 2.7
8	11.1	7.7	6.7	9.9[b]	160.9 ± 13.9	104.8 ± 8.0	58.7 ± 4.4	123.6 ± 9.7
9	17.5	11.0	7.9	14.9	246.1 ± 16.4	154.3 ± 10.0	71.8 ± 5.7	177.2 ± 11.8

1 and 2 share similar summer and fall storm total precipitation means.

In the interior and western United States, zone 3 displays a distinct seasonal cycle, with a low storm total precipitation mean during winter, when it is largely cut off from Gulf of Mexico moisture, and has relatively higher totals in the three remaining seasons. Zone 7 is the driest cluster, with all four seasons having the lowest mean storm total precipitation of all zones. Stations in two enclaves in northern Idaho and central Arizona behave in a similar manner to zone 8 (Fig. 1), which is the drier of two West Coast zones. Both zones 8 and 9 display a West Coast maritime climate pattern, with the largest storm precipitation totals during winter and the smallest during summer. Zone 9 encompasses locations at higher elevations on windward slopes located in the Coastal Range or Sierra Nevada. For this reason, zone 9 storm totals for each season exceed those of zone 8, located largely in interior valleys behind the Coastal Range.

The PDF for the storm total precipitation was determined by fitting a form of Eq. (1) or (2) to the empirical probability bins for each season and zone (Fig. 3). The PDF equations fit more than 99.9% of the variance of the empirical probability distribution, missing only a few extremely heavy events; these heavy events are examined in the context of the mean 100-yr storm for each zone and season. In the eastern United States, events with larger storm total precipitation amounts are more common in zones 1 and 2, and the distribution becomes more skewed to low-precipitation storms as distance increases from the Gulf northward through zones 4, 5, 6, and 7. There is also a greater seasonal change in the storm precipitation total PDFs in the eastern United States in the more continental zone 5, where larger storm total precipitation amounts are more common in summer than winter. Interestingly, the season with the lowest probability of large storms in the dry western interior zone 7 is spring. The greatest seasonal change in storm total precipitation was found on the West Coast in zones 8 and 9. These zones show the reversal of the eastern seasonal pattern, with low-precipitation storms dominating in summer and more substantial probabilities of larger storm events evident during fall and winter.

Because of the large number of independent station determinations of the 100-yr-return interval storm total precipitation values, and the conservative nature of the two-parameter Gumbel distribution, the two standard error uncertainty ranges are quite small in each zone (Table 1). Where the uncertainty bands of two zones or two seasons overlap, the 100-yr levels are not different in a statistically significant manner. Storms of a very long duration along the West Coast ensure that zone 9 has the largest mean 100-yr storm precipitation totals during the winter (246.1 mm), while extratropical cyclones, onshore flow into stationary systems, and tropical cyclones (Robinson and Henderson 1992; Keim and Faiers 1996) cause zone 1 to lead during the spring, summer, and fall, respectively (165.5–207.9 mm, Table 1). At the low end, zone 7 in the West has the smallest mean 100-yr storm total precipitation values in almost all seasons (44.8 mm in winter), except for the West Coast summer climates of zones 8 and 9.

b. Storm duration

The duration of storms tends to vary significantly across zones and seasons (Table 2). The longest mean storm duration is 7.8 h during winter in West Coast zone 9, and the shortest mean storm duration is 1.9 h during summer in the western interior zone 7. Zones 8 and 9 have the longest-duration storms in winter, spring, and fall because of the steady influx of Pacific moisture when the flow is onshore. Even during sum-

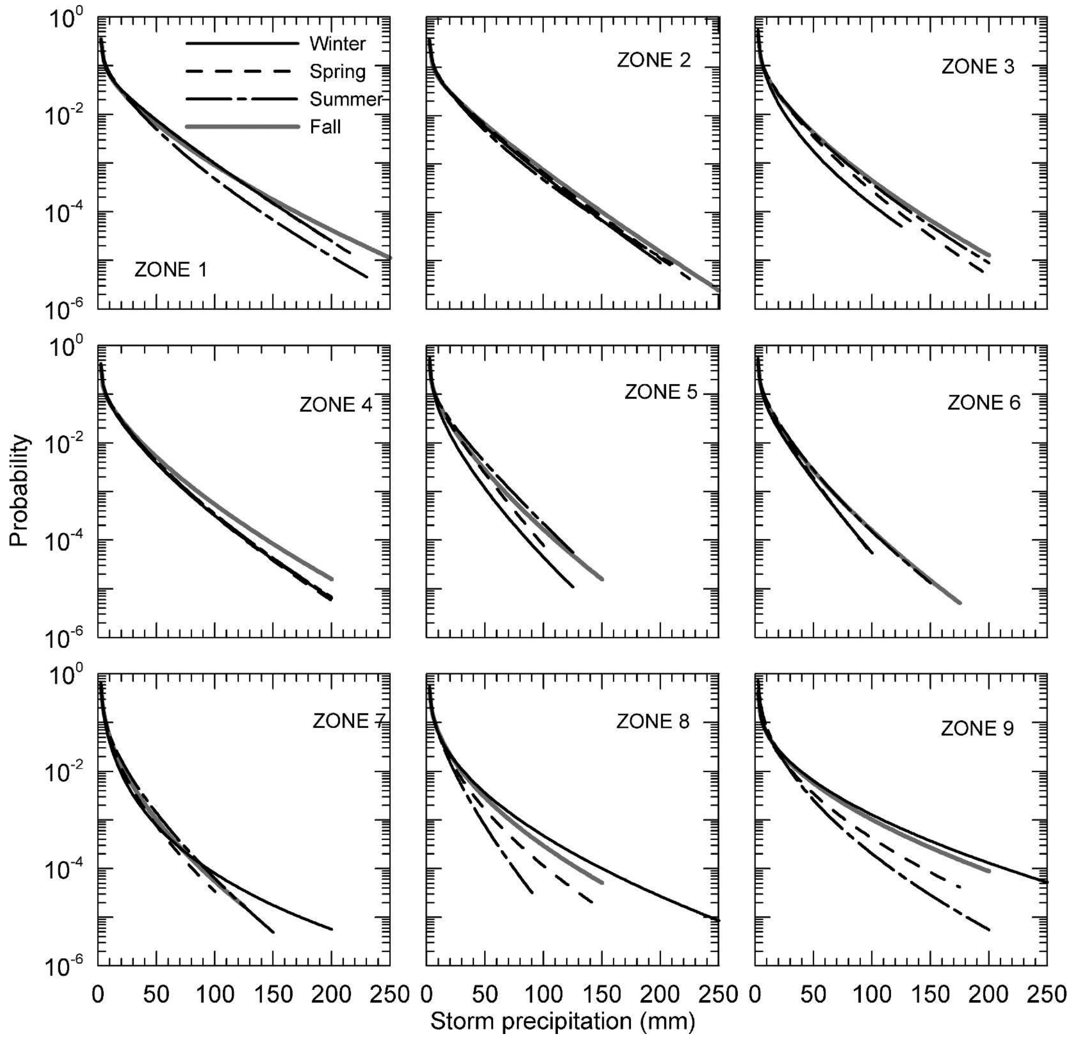

FIG. 3. Storm total precipitation (mm) probability density distributions for all nine zones and four seasons.

mer, zone 9 has the longest mean storm duration, but zone 6 has the second longest mean duration because of the summer extratropical storm track occasionally affecting New England (Zishka and Smith 1980). The mean duration of storms is shortest in dry interior zone 7, except during spring, when zone 3 storms have the shortest duration. Generally, across all regions, the mean storm duration is least during the summer convective rain season and longest in fall, winter, or spring, when the effects of extratropical low pressure systems and frontal boundaries are responsible for most rain events.

The mean 100-yr storm duration ranges from 26.5 h in zone 3 during summer to 84.2 h in zone 9 during the winter. These 100-yr storm durations may seem brief but reflect the necessity of at least 2.54 mm of precipitation falling every 6 h to meet the minimum rain gauge sensitivity and storm requirements. Longer duration precipitation events composed of very light drizzle would not be detected in this analysis.

c. *Storm intensity*

In all nine zones, mean storm precipitation intensity is greatest in summer. Storm intensity is least in all seasons in West Coast zones 8 and 9, although zone 9 has significantly less storm intensity on average than zone 8 (Table 3). During winter, zone 9 has the minimum mean storm intensity in all zones of 5.3 mm h^{-1}. During the summer, the Gulf Coast zones achieve the highest storm precipitation intensity means, with zone 1 averaging 11.4 mm h^{-1}.

The mean 100-yr storm intensity ranges from 16.3 mm h^{-1} in cool and dry interior zone 7 during the winter to 87.3 mm h^{-1} in the warm and humid Gulf Coast zone 1 during the summer. In all zones the 100-yr storm

TABLE 2. Storm duration (h) mean and 100-yr return interval estimate bounded by 2 times the standard error, for each zone and season. Zones with the same letter in a column are not significantly different at $\alpha = 0.05$, and zones with the same superscript number for a season in the same row are not significantly different at $\alpha = 0.05$.

	Mean				100 yr			
Zone	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1	4.3	3.4[a,1]	2.0	3.3[1]	41.5 ± 1.3	36.8 ± 1.2	30.9 ± 1.3	45.2 ± 1.6
2	4.6	3.4[a]	2.3	3.8[a]	46.9 ± 1.5	36.1 ± 0.9	28.8 ± 0.9	43.3 ± 1.0
3	3.0[a,1]	2.3	2.1	3.1[1]	33.5 ± 2.5	26.7 ± 1.5	26.5 ± 1.3	40.4 ± 2.1
4	4.4	3.7	2.5	4.1	43.5 ± 1.0	41.9 ± 0.8	31.1 ± 0.7	44.2 ± 0.8
5	3.0[a]	3.3	2.4	3.4	34.3 ± 1.0	39.0 ± 0.7	28.0 ± 0.5	39.2 ± 0.8
6	3.8[1]	3.8[b,1]	2.8	3.9[a]	43.0 ± 1.2	45.8 ± 1.3	34.4 ± 0.8	43.3 ± 0.9
7	2.7[1]	2.6[1]	1.9	2.8	31.0 ± 1.3	35.8 ± 1.0	26.9 ± 0.7	34.6 ± 0.9
8	5.3	3.8[b]	2.6	4.6	65.8 ± 3.2	51.2 ± 2.8	28.9 ± 2.1	51.5 ± 2.9
9	7.8	5.5	3.4	6.5	84.2 ± 4.3	63.3 ± 3.2	32.9 ± 2.3	64.4 ± 3.8

intensity is greatest in the summer, indicative of the effects of convective storms during that season, even in places with few storms, such as the West Coast. The seasonal cycle of mean 100-yr storm intensity is quite large in all regions except zones 8 and 9 and is much more pronounced in relative amplitude than the seasonal cycle of mean storm intensity.

d. Maximum 15-min intensity

The smallest maximum 15-min precipitation intensity that can be measured in the NCDC observational system is 10.16 mm h^{-1}. This intensity reflects one 2.54-mm precipitation increment in one time period, multiplied by 4 to quantify the value as an hourly rate. In the case of zones 6 and 7 in winter, a maximum 15-min intensity mean of 10.2 mm h^{-1} indicates the existence of very few 15-min periods with more than one 2.54-mm increment of precipitation measured (Table 4). This is to be expected in a cold, dry winter climate. In other eastern zones close to the Gulf of Mexico, there are many more cases in which precipitation rates reach and exceed 20 mm h^{-1} for a 15-min period, and so the maximum 15-min intensity means are larger. The greatest maximum 15-min intensity means occur during the summer in all zones. The smallest maximum 15-min intensity means in most zones occur in winter, except for the West Coast zones.

The PDFs of the maximum 15-min precipitation intensity for all seasons and zones clearly show the tendency for lower intensities during the winter and higher intensities during the summer in most zones (Fig. 4). Colder storms tend to be stratiform, while warmer storms tend to be convective, thus, explaining the seasonal cycle illustrated by the PDFs. The only exception to this rule occurs in the West Coast zones 8 and 9, where spring maximum 15-min intensities tend to be slightly lower than in fall and winter. During late fall and winter the stratiform storms have more moisture and stronger westerlies pushing the moisture up the slopes, and produce higher maximum rain rates than during the spring.

The mean 100-yr maximum 15-min storm intensity ranges from 22.9 mm h^{-1} in zone 7 during the winter to 180.8 mm h^{-1} in zone 1 during the summer. With the

TABLE 3. Storm intensity (mm h^{-1}) mean and 100-yr return interval estimate bounded by 2 times the standard error, for each zone and season. Zones with the same letter in a column are not significantly different at $\alpha = 0.05$, and zones with the same superscript number for a season in the same row are not significantly different at $\alpha = 0.05$.

	Mean				100-yr			
Zone	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1	7.0[a]	8.8	11.4	9.0	41.5 ± 2.1	66.0 ± 3.7	87.3 ± 2.9	66.7 ± 2.6
2	6.3	8.0	10.3	7.9	30.8 ± 1.3	59.0 ± 1.9	72.2 ± 2.5	53.9 ± 1.8
3	7.1[a]	9.0	9.7	8.3	23.2 ± 2.2	57.2 ± 4.0	63.3 ± 3.7	50.2 ± 3.7
4	6.0	7.0[a,1]	9.5	7.0[a,1]	22.3 ± 0.8	48.9 ± 1.5	72.3 ± 1.4	45.2 ± 1.2
5	6.9[1]	7.0[a,1]	9.1	7.0[a,1]	19.2 ± 0.7	42.2 ± 1.2	69.3 ± 1.2	40.2 ± 1.2
6	6.4[1]	6.4[b]	8.1	6.5[1]	19.4 ± 1.0	33.4 ± 1.4	62.2 ± 1.5	35.2 ± 1.5
7	7.4	7.3	8.7	7.2	16.3 ± 0.6	25.5 ± 0.9	49.0 ± 1.5	25.7 ± 0.9
8	5.9	6.4[b]	7.5	6.1	21.1 ± 1.5	22.1 ± 1.4	27.5 ± 2.0	22.8 ± 1.3
9	5.3	5.8	7.0	5.6	23.5 ± 1.6	20.7 ± 1.4	24.8 ± 1.8	21.9 ± 1.4

TABLE 4. Storm 15-min maximum precipitation intensity (mm h^{-1}) mean and 100-yr return interval estimate bounded by 2 times the standard error, for each zone and season. Zones with the same letter in a column are not significantly different at $\alpha = 0.05$, and zones with the same superscript number for a season in the same row are not significantly different at $\alpha = 0.05$.

	Mean				100 yr			
Zone	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
1	16.8	21.4	23.9	20.8	121.5 ± 4.0	166.0 ± 4.7	180.8 ± 4.3	158.5 ± 4.7
2	13.6	18.7[1]	22.0	18.7[1]	90.3 ± 3.1	145.2 ± 3.1	161.0 ± 3.3	141.7 ± 3.4
3	11.4[a]	17.3	19.5	16.6	51.7 ± 5.9	134.4 ± 7.0	153.2 ± 6.3	127.4 ± 6.9
4	11.4[a]	14.3	19.8	15.0	59.3 ± 2.1	111.1 ± 2.6	151.1 ± 2.3	113.6 ± 2.3
5	10.5	12.8	18.8	13.2	34.8 ± 1.6	98.9 ± 2.2	147.6 ± 2.0	99.5 ± 2.0
6	10.2[b]	11.2	15.7	11.9	36.9 ± 1.8	73.4 ± 2.4	122.4 ± 2.6	81.2 ± 2.2
7	10.2[b]	10.8[a]	13.9	11.0	22.9 ± 1.2	49.5 ± 1.9	96.6 ± 3.3	51.7 ± 2.2
8	10.8	10.6	11.7	11.0	51.2 ± 3.5	44.3 ± 2.4	54.2 ± 4.5	49.3 ± 2.7
9	11.3[a,1]	10.7[a]	11.5	11.4[1]	61.7 ± 3.8	49.0 ± 2.7	46.6 ± 4.9	56.0 ± 3.5

exception of West Coast zones, larger mean zonal 100-yr maximum 15-min intensities occur during the summer season, and smaller mean zonal 100-yr maximum 15-min intensities occur during the winter in all of the other zones.

e. *Trends in storm characteristics*

A variety of regional mean storm characteristics have undergone substantial trends since the advent of digitized 15-min precipitation observations. The trends in Table 5 are presented as the percent change between the 1972 and 2002 mean storm characteristic values. To calculate these trends, all stations in each zone were pooled to create time series of seasonal mean characteristics by year. Following this, linear regressions were performed over the 1972–2002 period, and significance was established for trends representing each characteristic and season. Last, the percent change during the period for each season and characteristic was calculated as the difference between the 2002 and 1972 mean values derived from the regression equation, divided by the 1972 value, and multiplied by 100. In general, mean changes of less than 2% were not significantly different from 0. Because the digital 15-min precipitation data exist only for a 31-yr period, these trends may not be representative of longer periods during the twentieth century.

For storm total precipitation, zones 6, 7, 8, and 9 in the western and northern United States showed reductions in winter mean storm total precipitation, and zones 2, 3, 4, and 5 showed increases (Table 5). The larger trends carry substantive information, but interannual variability is sufficiently large in many cases to prevent statistical significance from being achieved. For example, zone 7 displays a highly statistically significant downward trend at $p = 0.01$, zone 3 shows an upward trend significant at $p = 0.06$, and zone 9 has a large downward trend, but with a nonsignificant $p = 0.24$ (Fig. 5). The latter two trends are potentially important, even without a high degree of statistical significance, because they are fully representative of the data and are not dominated by beginning and end of the year positions of the time series.

During the spring, both the Gulf Coast zones 1 and 2 and the West Coast zones 8 and 9 experienced substantial declines in mean storm total precipitation, from 5% to 13%. Only zone 9 demonstrated a substantial trend in the summer, with storm total precipitation decreasing more than 12%, as it did during winter and spring. Last, during autumn, there was a significant increase in storm total precipitation in zone 1 along the Gulf Coast, while the interior west zone 7 and adjacent west Texas zone 3 showed declines in storm total precipitation of more than 10%.

Trends in central U.S. storm total precipitation are of special interest, because recent studies (Groisman et al. 2004; Kunkel et al. 1999) have shown that heavy precipitation event frequency and total precipitation are increasing. In this study, Table 5 indicates that zones 3 and 5 have significant upward trends in winter storm total precipitation. Comparable zones in the Groisman et al. (2004) study (the west-central part of region 7 and most of region 8, respectively) display increasing trends in heavy precipitation events on an annual basis. However, trends are much smaller for all storms in the other three seasons in the current study. An examination of the characteristics of large storms is beyond the scope of this study.

The trends in mean storm duration explain most of the trends in mean storm total precipitation (Table 5). In all of the cases discussed above, the storm durations trend in the same direction as the storm precipitation totals. Logically, the length of storms is important to

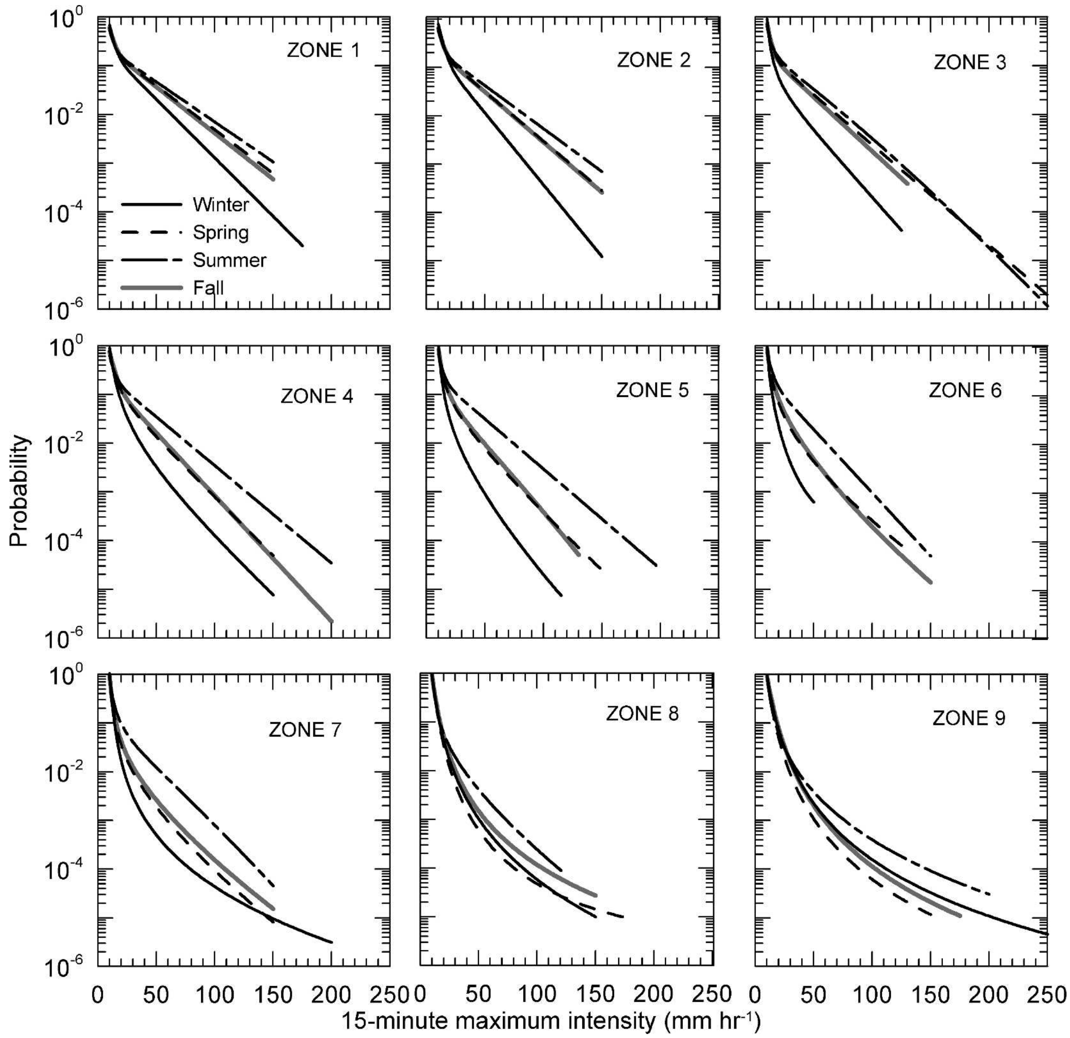

FIG. 4. Storm 15-min maximum precipitation intensity (mm h^{-1}) probability density distributions for all nine zones and four seasons.

the precipitation totals produced by storms. There are only a few cases where substantial trends in storm duration are not matched by changes in storm total precipitation, and these seem to correspond to large changes of the opposite sign in mean storm intensity (Table 5). Examples of this behavior would include spring in zone 3 and summer in zone 2, where increases in storm duration of more than 12% coincide with significant decreases in storm intensity of 7%–9%. Zone 1 in winter showed the opposite behavior, with a substantial decrease in mean storm duration of 8.7%, while experiencing a highly significant increase in storm intensity of 9.6%.

The mean storm maximum 15-min intensity trends (Table 5) do not necessarily follow the trends of overall storm intensity, because maximum 15-min intensity is a function of the precipitation dynamics and thermodynamics (stratiform, convective, or mixed precipitation formations), and moisture availability. During winter, substantial increases in mean storm maximum 15-min intensity are observed in the eastern United States, except in the colder zones 6 and 7. Spring indicates a dissimilar pattern, with substantial declines in maximum 15-min intensity in southern zone 1 and 2, and weak increases elsewhere in the east and interior west. Summer 15-min maximum intensity changes show little spatial pattern, with a significant decline in zone 2 and a significant increase in zone 7. In fall, the pattern of predominant increases in mean storm maximum 15-min intensity returns to the warmer zones of the eastern United States. Zone 9 displayed the most consistent results, with decreases in maximum 15-min intensity during all seasons at higher altitudes along the West Coast.

TABLE 5. Trends in storm total characteristics for each zone and season expressed in percent change from 1972 to 2002. Entries marked with ** are significant at the $p = 0.05$ level, and those marked with * are significant at the $p = 0.10$ level.

Season	Zone 1	2	3	4	5	6	7	8	9
Storm total precipitation									
Winter	−0.9	7.7	28.0*	9.6	16.5*	−11.2	−12.4**	−1.4	−12.3
Spring	−10.3	−10.2*	2.5	1.1	4.4	2.2	−3.4	−5.2	−12.9*
Summer	1.3	−2.5	−3.3	1.5	0.2	−2.9	2.4	−1.1	−12.8
Fall	22.2**	−1.8	−10.9	2.7	−2.3	−3.0	−10.6**	4.9	−2.2
Storm duration									
Winter	−8.7	7.1	30.2	7.3	13.8	−8.3	−15.7**	−3.7	−10.0
Spring	−5.8	−1.1	18.7	3.2	1.1	2.3	−8.2	−9.2	−11.3*
Summer	4.9	12.3*	−3.7	2.9	−5.3	−6.3	−6.1	−1.3	−7.6
Fall	18.6	−2.0	−24.6**	1.3	−3.8	−5.3	−14.7**	1.1	−4.0
Storm intensity									
Winter	9.6**	1.3	−0.8	−1.2	−1.8	0.4	3.5	1.0	3.8
Spring	−3.5	−3.5	−7.1*	−1.3	0.1	−1.8	2.6	3.1	2.1
Summer	−3.0	−9.1**	0.6	−4.5*	1.9	0.2	2.2**	1.0	−2.3
Fall	−1.2	−2.4	1.5	−1.6	0.9	1.4	4.8*	1.2	3.1
15-min maximum intensity									
Winter	3.7	4.9	9.0**	3.5	2.5	−1.3	−0.4	2.0	−0.8
Spring	−7.0	−5.9	−0.8	1.1	1.5	1.3	0.7	0.8	−1.7
Summer	0.2	−6.3**	−0.7	−0.9	2.5	0.3	4.4**	−0.5	−4.1**
Fall	6.9*	0.2	3.0	0.4	−1.0	−0.4	−0.3	0.1	−1.7

4. Conclusions

Storm precipitation characteristics in the United States are integral to the understanding of the impacts of precipitation on society and the environment. It is the cumulative effects of storm segments on the natural and human environments that lead to runoff, soil erosion, and flooding, as well as infiltration, crop growth, and aquifer recharge. Storm characteristics are needed for the parameterization of hydrological and soil models that help quantify these processes. Yet analyses of this type are quite difficult for an individual location, because of the brief time series of data, the limitations of its 15-min, 2.54-mm resolution, and its quality.

By engaging a cluster analysis to group the stations, a more precise delineation of the storm precipitation characteristics can be done for the regions. Nine regions were identified through clustering seven variable types and four seasons simultaneously. The large number of individual storms that were available at the observation stations in each region were pooled to identify basic and distributional statistics. The storm characteristics were related to seasonal water availability from source regions, atmospheric water vapor capacity, and the storm precipitation mechanism. The regional pools of storm values also contained enough storm data to generate stable annual time series for each storm

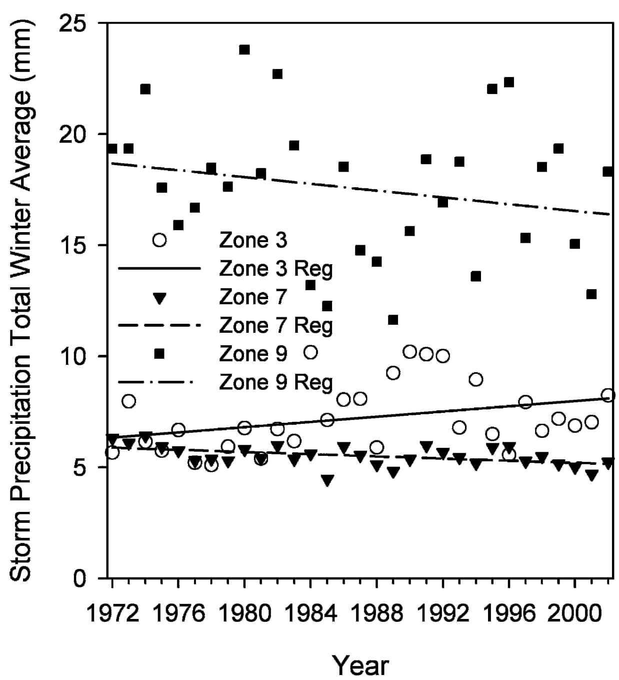

FIG. 5. Trend regressions for winter storm total precipitation from 1972 to 2002 for zone 7 ($p = 0.01$), zone 3 ($p = 0.06$), and zone 9 ($p = 0.24$).

TABLE A1. Storm total precipitation (mm), equations valid for 2.54 mm ≤ X ≤ X max.

Zone	Season	Equation No.	a	b	c	d	β	β_1	γ	γ_1	X Max
1	Winter	(2)	−1.9723	−0.2284	6.1444	—	1.0	−1.0	−1.5	0.0	200
1	Spring	(2)	−1.9679	−0.2292	6.0332	—	1.0	−1.0	−1.5	0.0	225
1	Summer	(2)	−1.7665	−0.1277	5.9025	—	0.5	1.0	−2.0	0.0	230
1	Fall	(2)	−2.1329	−0.1061	5.0436	—	0.5	1.0	−1.5	0.0	250
2	Winter	(2)	−1.8267	−0.2592	6.3157	—	1.0	−1.0	−1.5	0.0	200
2	Spring	(2)	−1.8011	−0.2542	5.8209	—	1.0	−1.0	−1.5	0.0	225
2	Summer	(2)	−1.7871	−0.1273	6.1549	—	0.5	1.0	−2.0	0.0	210
2	Fall	(2)	−1.9119	−0.2431	6.2088	—	1.0	−1.0	−1.5	0.0	250
3	Winter	(2)	−0.2517	−0.8620	6.5934	—	0.5	0.0	−2.0	0.0	125
3	Spring	(2)	−1.8141	−0.1390	7.7483	—	0.5	1.0	−2.0	0.0	200
3	Summer	(2)	−1.9324	−0.1295	4.9803	—	0.5	1.0	−1.5	0.0	200
3	Fall	(2)	−2.0839	−0.1227	5.7807	—	0.5	1.0	−1.5	0.0	200
4	Winter	(2)	−1.8261	−0.1352	7.6267	—	0.5	1.0	−2.0	0.0	200
4	Spring	(2)	−1.6892	−0.1384	5.9998	—	0.5	1.0	−2.0	0.0	200
4	Summer	(2)	−1.6930	−0.1363	5.7769	—	0.5	1.0	−2.0	0.0	200
4	Fall	(2)	−1.8842	−0.1223	7.0029	—	0.5	1.0	−2.0	0.0	200
5	Winter	(2)	−1.9105	−0.1761	6.6357	—	0.5	1.0	−1.5	0.0	125
5	Spring	(2)	−1.2276	−0.3792	5.8684	—	1.0	−1.0	−1.5	0.0	105
5	Summer	(2)	−1.4131	−0.3231	5.3654	—	1.0	−1.0	−1.5	0.0	125
5	Fall	(2)	−1.6550	−0.1532	6.8540	—	0.5	1.0	−2.0	0.0	150
6	Winter	(2)	−1.4827	−0.3837	7.8101	—	1.0	−1.0	−1.5	0.0	100
6	Spring	(2)	−1.1520	−0.4022	5.9930	—	1.0	−1.0	−1.5	0.0	100
6	Summer	(2)	−1.4978	−0.1585	5.2444	—	0.511	1.0	−2.0	0.0	150
6	Fall	(2)	−1.6679	−0.1538	7.0564	—	0.5	1.0	−2.0	0.0	175
7	Winter	(2)	−1.2662	−0.3853	7.6817	—	0.0	2.0	−2.0	0.0	200
7	Spring	(2)	0.3088	−1.0586	5.5198	—	0.5	0.0	−2.0	0.0	100
7	Summer	(2)	−2.0609	−0.1660	4.2396	—	0.5	1.0	−1.0	0.0	150
7	Fall	(2)	0.1569	−0.9964	5.6289	—	0.5	0.0	−2.0	0.0	125
8	Winter	(2)	−0.7580	−0.6900	4.2939	—	0.5	0.0	−1.5	0.0	250
8	Spring	(2)	0.0253	−0.9104	4.8766	—	0.5	0.0	−2.0	0.0	150
8	Summer	(2)	−1.3877	−0.2097	7.1287	—	0.5	1.0	−2.0	0.0	90
8	Fall	(2)	−0.3325	−0.7794	5.0644	—	0.5	0.0	−2.0	0.0	150
9	Winter	(2)	−1.1624	−0.5501	6.8532	—	0.5	0.0	−2.0	0.0	400
9	Spring	(2)	−0.5810	−0.7186	6.0118	—	0.5	0.0	−2.0	0.0	175
9	Summer	(2)	−0.1701	−0.8672	5.8261	—	0.5	0.0	−2.0	0.0	200
9	Fall	(2)	−0.9994	−0.5892	6.4643	—	0.5	0.0	−2.0	0.0	200

characteristic and season, allowing an analysis of trends in these characteristics to be performed.

The climatology of mean storm precipitation characteristics provides the basis for understanding trends. A preliminary trend analysis of the 1972–2002 mean storm characteristic data by zone showed changes that tended to be geographically linked, with noteworthy similarities within the western and eastern United States. The western United States displayed a tendency toward decreasing mean storm total precipitation and mean storm duration in most seasons, while mean storm intensity increased. The eastern United States experienced a general pattern of increasing mean storm total precipitation and storm duration during winter, but did not reveal spatially coherent trends in the other seasons. There were some significant trends in winter storm total precipitation in zones 3 and 5, where previous studies (Groisman et al. 2004; Kunkel et al. 1999) identified annual increases in heavy precipitation events. The mean maximum 15-min precipitation intensity also increased predominantly in the eastern U.S. zones during winter. These promising preliminary results will be expanded in future work to examine the spatial patterns of trends based on individual stations rather than zones, and by separating larger storms from the total distribution. A further examination of the impacts of climate system variability on storm characteristics is presently under way, including the influence of El Niño–Southern Oscillation events on the interannual variability of storm precipitation characteristics. Many of the changes discussed in this paper could have an influence on hydrological systems and soil erosion; the storm characteristics related to soil erosion are the topic of Part II.

TABLE A2. Maximum 15-min precipitation rate (mm h^{-1}), equations valid for 10.16 mm h^{-1} ≤ X ≤ X max.

Zone	Season	Equation No.	a	b	c	d	β	β_1	γ	γ_1	X Max
1	Winter	(1)	0.3667	18.0614	12.9683	3.1115	—	—	—	—	175
1	Spring	(1)	0.3068	24.1689	9.1803	3.2347	—	—	—	—	150
1	Summer	(1)	0.3108	26.4199	9.5379	3.0189	—	—	—	—	150
1	Fall	(1)	0.3285	22.8956	9.2410	3.2237	—	—	—	—	150
2	Winter	(1)	0.3496	14.6347	12.9282	3.3452	—	—	—	—	150
2	Spring	(1)	0.3293	21.3057	10.1162	3.2483	—	—	—	—	150
2	Summer	(1)	0.3270	24.4305	9.1810	3.1247	—	—	—	—	150
2	Fall	(1)	0.3392	20.9468	10.6365	3.1880	—	—	—	—	150
3	Winter	(2)	−2.3397	−0.0620	296.4414	—	1.0	0.0	−2.0	0.0	125
3	Spring	(1)	0.2748	21.0970	17.7207	2.9081	—	—	—	—	250
3	Summer	(2)	−1.7898	−0.0086	159.4769	—	1.0	1.0	−2.0	0.0	250
3	Fall	(1)	0.2942	19.5702	19.8120	2.8357	—	—	—	—	130
4	Winter	(2)	−8.6295	−0.0488	20.9118	—	1.0	0.0	0.0	−1.0	150
4	Spring	(2)	−1.6854	−0.0550	89.0486	—	1.0	0.0	−2.0	1.0	150
4	Summer	(1)	0.3494	21.6722	9.9377	3.1639	—	—	—	—	200
4	Fall	(1)	0.3180	16.8316	11.0341	3.4554	—	—	—	—	200
5	Winter	(2)	−1.5595	−0.2018	310.8555	—	0.5	1.0	−2.0	0.0	115
5	Spring	(2)	−0.7230	−0.3306	207.6000	—	1.0	−1.0	−2.0	0.0	150
5	Summer	(1)	0.3313	21.1672	11.8397	3.1006	—	—	—	—	200
5	Fall	(2)	−2.6596	−0.0115	89.0467	—	1.0	1.0	−1.5	0.0	130
6	Winter	(2)	−10.7051	3803.3322	−4753.4915	—	−1.5	0.0	−2.0	1.0	50
6	Spring	(2)	−1.6235	−0.1542	119.4122	—	0.5	1.0	−2.0	1.0	125
6	Summer	(1)	0.3843	16.6909	11.0276	3.3188	—	—	—	—	150
6	Fall	(2)	−0.7054	−0.1708	190.0026	—	0.5	1.0	−2.0	0.0	150
7	Winter	(2)	−2.3098	−0.3711	140.7097	—	0.0	2.0	−1.5	0.0	200
7	Spring	(2)	−2.0231	−0.1580	324.0197	—	0.5	1.0	−2.0	0.0	150
7	Summer	(2)	−2.7475	−0.0097	89.7930	—	1.0	1.0	−1.5	0.0	150
7	Fall	(2)	−1.9124	−0.1496	304.7464	—	0.5	1.0	−2.0	0.0	150
8	Winter	(2)	−5.8109	−0.3695	17.9511	—	0.0	2.0	0.0	−1.0	150
8	Spring	(2)	12.00017	0.5354	−5.9300	—	0.5	0.0	0.0	1.0	175
8	Summer	(2)	−1.4350	−0.1503	252.8451	—	0.5	1.0	−2.0	0.0	125
8	Fall	(2)	6.9912	−3.5075	10.9248	—	0.0	1.0	−1.0	0.0	150
9	Winter	(2)	8.9959	−3.8547	−7.0270	—	0.0	1.0	−2.0	1.0	250
9	Spring	(2)	9.2646	−4.1158	22.3724	—	0.0	1.0	−2.0	0.0	150
9	Summer	(2)	0.1078	−0.3745	186.7279	—	0.0	2.0	−2.0	0.0	200
9	Fall	(2)	10.2071	−4.1846	−27.1398	—	0.0	1.0	−2.0	1.0	175

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APPENDIX

Coefficients of PDF Curves by Zone and Season

In Tables A1 and A2, the equations that best fit the probability distribution for each variable, season, and zone are identified as Eq. (1) or Eq. (2) (see section 2). The appropriate parameters are identified for cases utilizing Eq. (2), and the regression coefficients for the best fit of an analytic curve to the empirical PDF are given for all of the equations.

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