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Review

Observed Spatiotemporal Trends in Intense Precipitation Events across United States: Applications for Stochastic Weather Generation

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Received: 31 January 2019; Accepted: 23 February 2019; Published: 27 February 2019

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Abstract: An increasing focus of climate change studies is the projection of storm events characterized by heavy, very heavy, extreme, and/or intense precipitation. Projected changes in the spatiotemporal distributions of such intense precipitation events remain uncertain due to large measures of variability in both the definition and evidence of increased intensity in the upper percentile range of observed daily precipitation distributions, particularly on a regional basis. As a result, projecting changes in future precipitation at the upper tail of the distribution (i.e., the heavy to heaviest events), such as through the use of stochastic weather generator programs, remains challenging. One approach to address this challenge is to better define what constitutes intense precipitation events and the degree of location-specific adjustment needed for the weather generator programs to appropriately account for potential increases in precipitation intensity due to climate change. In this study, we synthesized information on categories of intense precipitation events and assessed reported trends in the categories at national and regional scales within the context of applying this information to stochastic weather generation. Investigations of adjusting weather generation models to include long-term regional trends in intense precipitation events are limited, and modeling trends in site-specific future precipitation distributions forecasted by weather generator programs remains challenging. Probability exceedance curves and variations between simulated and observed distributions can help in modeling and assessment of trends in future extreme precipitation events that reflect changes in precipitation intensity due to climate change.

Keywords: precipitation intensification; precipitation distributions; extreme precipitation; stochastic weather generators

1. Introduction

Changes in the amount of precipitation, and the frequency and intensity of precipitation events are well-known phenomena occurring globally at multiple time scales [1,2]. Changes in these precipitation characteristics can adversely impact the environment by increasing storm water management problems [3,4], soil erosion [5], and runoff [6]; and by decreasing water quality [7,8] and agricultural productivity [9]. These changes have been studied worldwide, with many analyses focused on aggregated mean values of daily precipitation distributions, such as at monthly or annual time scales [10]. However, the events forming the upper tails of these daily distributions, commonly known as intense precipitation events [11–13], are frequently the primary drivers of adverse environmental impacts and need to be analyzed comprehensively in order to fully understand the implications of changing precipitation patterns as driven by global climate change.

Iwashima and Yamamoto [14], Karl et al. [11], and Karl and Knight [15] were among those who pioneered analyses of long-term changes in intense precipitation. Additional studies since have noted long-term increasing trends in intense precipitation, including at global (e.g., [16–19]), national (e.g., [15,20–22]), and regional scales (e.g., [23–25]). Some researchers who divided intense events into specific categories using numerical thresholds or relative percentiles have also found increasing trends in those categories [23,24,26]. Intense precipitation events have often been investigated for their responses to simulated warming scenarios (1.5 and 2 °C) [27], idealized increases in atmospheric CO_2 in 10 general circulation models (GCMs) produced under the Coupled Model Intercomparison Project Phase 5 (CMIP5) [28], and various degrees of artificial influences [29,30]. Fischer et al. [31] showed consistent projections of intense precipitation events despite large internal variability and irreducible uncertainties in climate model simulations. Fischer and Knutti [32] reported increases in intense precipitation based on an emerging climate change signal. Furthermore, Pfahl et al. [33] examined intense precipitation in climate model simulations across specific global regions by applying a physical scaling diagnostic.

These studies, which employed physical climate models based on thermodynamic and dynamic factors, greenhouse gas emissions, and/or representative concentration pathways in their assessments and analyses, provide a foundation both for ascertaining trends in intense precipitation and in defining thresholds by which such trends can be assessed. In general, however, there remains limited characterization and evidence of regional-scale trends in intense precipitation events [25]. This limitation may lead to inaccurate assessment of trends in site-specific future precipitation distributions forecasted by weather generator programs. In addition, weather generator estimates of intense precipitation for long-term future periods (e.g., ≥90 years) are typically based on available, observed daily precipitation distributions from shorter periods (e.g., ~20 years). These shorter observational windows are often too short for statistical characterization of trends in intense precipitation, which may bias future estimates of changes in precipitation intensity produced by weather generators. Inaccurate estimates can ultimately create flaws in soil erosion and runoff management plans that are predicated on future forecasted precipitation distributions.

One approach to address this challenge is to adjust the weather-generator-derived precipitation distributions such that precipitation estimates in their upper tails fall within giver error ranges of the corresponding estimates in the upper tails of observed precipitation distributions for the same location. Accurate simulation of changing precipitation intensity, based on an understanding of both critical thresholds of intensity and observational trends in intense precipitation events, can better predict the likelihood of future intense storms. The accuracy in simulation of precipitation intensity can also improve the assessments of intense precipitation impacts on local-scale soil erosion, infiltration, runoff, and plant productivity, with the ultimate goal of strengthening agricultural sustainability. However, ample ambiguity still exists in the scientific literature regarding the definition of intense precipitation events and procedure to simulate such events to highlight precipitation intensity changes.

In this study, we review the existing literature regarding definitions of intense precipitation events and changes in their distribution due to current and projected future climate change for their specific application to stochastic weather generators and their associated site-specific and management-scale questions relevant to agricultural productivity. The specific objectives of this study include (1) synthesizing the state of knowledge regarding definitions (categories) of intense precipitation and techniques used to derive thresholds for such categories; and (2) assessing categorical, observational trends of intense precipitation at both regional and national scales. This review will further serve as the foundation for subsequent case study analyses where approaches for adjusting forecasted precipitation distributions at a specific location can be tested and evaluated with the aim of applying such adjustments to agricultural productivity models.

2. Definition and Categorical Classifications of Intense Precipitation Events

2.1. Categorization of Intense Precipitation Events: Definition and Thresholds

Several studies have defined intense precipitation events as all events in the upper tail of daily precipitation distribution above either 50.8 mm [11–13,22] or the 90th percentile [15]. Groisman et al. [26] referred to the former approach as fixed numerical thresholds and the latter as percentile-defined thresholds. Groisman et al. [22] were among the first to categorize intense precipitation events. They divided the events across the contiguous United States into two categories (heavy and very heavy events) and distinguished both categories by fixed numerical (above 50.8 and 101.6 mm, respectively) as well as percentile-defined (above 90th and 99th percentiles, respectively) thresholds.

Later studies led by Groisman divided the events into three categories: heavy, very heavy, and extreme events [23,24,26]. Groisman et al. [23,24] used percentile-defined thresholds to distinguish these three categories as follows:

- Heavy: 90th to 95th percentile reported in [23]; 95th percentile reported in [24].
- Very heavy: 99th to 99.7th percentile reported in [23]; 99th percentile reported in [24].
- Extreme: 99.9th percentile reported in [23,24]

However, Groisman et al. [26] used fixed numerical thresholds to distinguish them (heavy: 25.4 to 76.2 mm; very heavy: 76.2 to 154.9 mm; and extreme: >154.9 mm). The percentile-defined thresholds given by Groisman et al. [23] had discontinuous thresholds ranging from heavy to extreme precipitation events; the study did not articulate the reason for using discontinuous thresholds. Intense precipitation categories and their numerical and percentile thresholds are summarized in Table 1.

Table 1. Categories of intense precipitation reported by various studies (as mentioned) based on either fixed numerical [numerical values (with units "mm/day")] or percentile-defined [values followed by percent sign (%)] thresholds.

Study	Precipitation Category			Period
	Heavy	Very Heavy	Extreme	
Karl et al. [11]	>50.8	N/A	N/A	1910–1995
Easterling et al. [13]	>50.8	N/A	N/A	1910–1996
Karl and Knight [15]	10%	N/A	N/A	1910–1995
Groisman et al. [22]	50.8–101.6	>101.6	N/A	1961–1990
Groisman et al. [22]	10%	1%	N/A	1961–1990
Groisman et al. [23] (a)	10%–5%	1%–0.3%	0.1%	1908–2000
Groisman et al. [23] (b)	15–20	35–45	>55	1908–2000
Groisman et al. [23] (c)	30–40	75–105	>130	1908–2000
Groisman et al. [23] (d)	30–45	75–105	>130	1908–2000
Groisman et al. [24]	5%	1%	0.1%	1910–1999
Groisman et al. [26]	25.4–76.2	76.2–154.9	>154.9	N/A

* Note: N/A means not available. Also, in Groisman et al. [23], (a) denotes the percentile thresholds for precipitation categories across the contagious United States, while (b), (c), and (d) denote the numerical thresholds (derived from percentiles) for the categories in southwest, south, and southeast regions of United States, respectively.

A few studies have also investigated thresholds for intense precipitation categories regionally within the United States. Groisman et al. [23] used an area-averaging method to quantify numerical thresholds for each category in nine regions of the US. They argued that the area-averaging method reduces spatial variability in precipitation distributions. Among their results, they estimated numerical thresholds as follows (Table 1):

- 15–20 mm, 35–45 mm, and >55 mm, respectively, for heavy, very heavy, and extreme precipitation categories in the southwest.
- 30–40 mm, 75–105 mm, and >130 mm, respectively, for heavy, very heavy, and extreme precipitation categories in the south.

- 30–45 mm, 75–105 mm, and >130 mm, respectively, for heavy, very heavy, and extreme precipitation categories in the southeast.

Groisman et al. [24] further applied an area-averaging method to the distributions used by Groisman et al. [23] to estimate numerical thresholds of very heavy precipitation events, both regionally and seasonally. They estimated thresholds for very heavy events in the southwest, south, and southeast during winter, spring, summer, and autumn as 30, 35, 45, and 45 mm; 65, 95, 100, and 110 mm; and 85, 100, 100, and 110 mm, respectively.

2.2. Fixed Numerical versus Percentile-Defined Thresholds: Pros and Cons

The selection of a threshold to define intense precipitation categories is based on type, scale, and intensity of daily precipitation distributions [26,34]. Fixed numerical thresholds in intense precipitation categories can be reliable for representing various regions with homogenous precipitation events [34]. For example, Klein and Konnen [35] used a fixed numerical approach to represent a coherent picture of standardized extremes for intense precipitation across Europe utilizing precipitation data from over 100 stations distributed approximately equally across the study region. On the other hand, percentile-defined thresholds are derived from specific precipitation distributions for a given location [34]. These thresholds can provide a better spatial reference for analyzing intense categories of forecasted precipitation distributions for a specific location, and can help to derive numerical thresholds of the categories in distributions representing the location.

3. Categorical Trends in Intense Precipitation

Historical trends in heavy, very heavy, and extreme precipitation events from previous key studies are summarized in Table 2. Karl and Knight [15] noted an approximately 10% increase in total precipitation across the contiguous United States for the period 1910–1995. They attributed around 53% of this increase to a statistically significant upward trend in the 90th percentile of the precipitation distribution. Furthermore, they also reported a 7% national increase in daily precipitation above the 95th percentile, which they named as the extreme highest 1-day events. Kunkel et al. [20] analyzed trends for extreme precipitation events with a recurrence interval of one year or longer and concluded that the events were increasing at the rate of 3% per decade in the United States for the period 1931–1996. Groisman et al. [22] found that the frequency of intense precipitation ($P > 50.8$ mm, including heavy, very heavy, and extreme precipitation) had a significant increasing trend of approximately 32% (at $p = 0.01$) nationally across the United States and approximately 38% per 100 years regionally across the southern United States for the period 1901–1996. Kunkel et al. [21] concluded that intense precipitation events (heavy or higher precipitation) had higher frequencies during the late 19th/early 20th century (1890s to 1910s), which decreased to a minimum in the 1920s and 1930s and later increased again in the 1990s to a level approximating the frequencies of the 1890s to 1910s.

Table 2. Trends (negative for decreasing and positive for increasing) in intense precipitation categories quantified by the mentioned studies.

Study	% Change in Precipitation Category			Period	Study Region
	Heavy	Very Heavy	Extreme		
Karl and Knight [15]	N/A	N/A	7	1910–1995	All of US
Karl and Knight [15]	N/A	N/A	12	1910–1995	Southern Great Plains
Kunkel et al. [21]	N/A	N/A	3	1931–1996	All of US
Groisman et al. [23]	14	20	21	1908–2002	All of US
Groisman et al. [23]	N/A	N/A	30	1908–2002	Southwest
Groisman et al. [24]	−0.1	0.9	1.5	1910–1970	All of US
Groisman et al. [24]	4.6	7.2	14.1	1970–1999	All of US
Groisman et al. [24]	N/A	20	N/A	1893–2002	Central US
Groisman et al. [24]	N/A	26	N/A	1970–2002	Central US
Karl et al. [25]	15	N/A	N/A	1958–2007	Great Plains

* Note: Karl and Knight [15] and Kunkel et al. [21] analyzed the events above the 95th percentile and named them as extreme. Groisman et al. [23,24] analyzed trends per 100 and 10 years, respectively, at 0.05 level of significance. Karl et al. [25] analyzed highest 1% of all daily events and termed them as intense precipitation events. N/A means not available.

Some studies have also examined long-term trends in specific categories of intense precipitation. In this regard, Groisman et al. [23] reported increases of 14%, 20%, and 21% per 100 years in heavy (upper 5%), very heavy (upper 1%), and extreme (upper 0.1%) events over the contiguous United States during the period 1908–2000. They specifically found that extreme events did not increase significantly before 1970 but increased by 26% per 30 years after 1970 for the same period (1908–2000). Groisman et al. [24] found insignificant national-scale trends in heavy, very heavy, and extreme precipitation events for the period 1910–1970; however, the events significantly increased by 4.6%, 7.2%, and 14.1%, respectively, for 1970–1999. Groisman et al. [26] updated the daily precipitation time series used by Groisman et al. [23,24] to the end of 2010 and found results of similar statistical significance in the three intense precipitation categories.

Only a few studies have investigated regional trends in intense precipitation categories. These investigations examined trends in either very heavy or extreme events specifically. Karl and Knight [15] noted a 12% increase in extreme highest 1-day events (above the 95th percentile) in the southern Great Plains for the period 1910–1995. Groisman et al. [23] noted that extreme precipitation (above the 99th percentile) experienced a 30% increase in the southwest United States for the period 1908–2000. Groisman et al. [24] noted increasing linear trends of 20% (per 110 years) for the period 1893–2002 and 26% (per 30 years) for 1970–2002 in the Central United States. Karl et al. [25] observed an increase of approximately 15% in very heavy precipitation (highest 1% of all daily events) for the broader Great Plains region for the period 1958–2007. The spatial and temporal trends noted in the aforementioned studies suggest that increases in intense precipitation events prevailed during recent decades (30–40 years), both regionally and nationally.

The primary data sets for a majority of studies noted in Tables 1 and 2 belong to over 100 stations across the United States, most of which are part of the Historical Climate Network (HCN) [36]. Groisman et al. [23,24,26] used the digital archives of approximately 6000 stations maintained by the National Climatic Data Center (NCDC) all over the United States. Some studies mentioned that the size of standard precipitation gauges (8 inches) used in the stations remained unchanged, even for longer periods of measurements [11,15]. Kunkel et al. [20] noted that wind shields were added to about 3% of the gauges in the 1940s, which had negligible effects on the observations. Some other studies, however, did not reveal their source of the data sets clearly [13,22,25].

4. Precipitation Projections Using Stochastic Weather Generators

Stochastic weather generators use a statistical approach to simulate random series of atmospheric variables, such as temperature, precipitation, solar radiation, and wind [37,38]. They predict long-term changes in future climate conditions in special circumstances when historical climate data are available only for limited periods [39,40]. Weather generators are different from numerical global climate models because they focus on small spatial scales to provide numerous alternative random simulations based on observed climate data, while the climate models include global-scale future analysis of Earth's atmosphere and its interaction with other components in the system [38]. Several weather generators noteworthy of their concurrent use in climate studies include WGEN [41,42], USCLIMATE [43], CLIMGEN [44], CLIGEN [45], WeaGETS [46], LARS-WG [47], and SYNTOR [48].

Projection of site-specific future precipitation based on the location's historically observed precipitation distribution is one of the most significant goals for weather generators. The generators generally simulate precipitation on a biweekly to monthly time scale [39]; however, a few of them can also generate daily precipitation estimates [48,49]. Due to the stochastic approach, weather generators do not reflect trends in the projected precipitation distributions. Instead, they reflect a change in baseline steady-state conditions at a future date. Therefore, comprehensive understanding of the observed distributions is essential for analysis of trends in the projected distributions.

5. Need for Adjustments in Precipitation Projections

Increases in intense precipitation projected by global climate models (e.g., [50–53]), and consistent with the observed increasing trends noted in the aforementioned studies, may not be accurately reflected in location-specific estimates of future precipitation. This is because precipitation distributions forecasted for a specific location using weather generators, such as SYNTOR [48,49], may underestimate the intense events because of a disproportionate observed-to-modeled data ratio. For example, SYNTOR can generate hundreds of years of simulated daily precipitation for a given location using a minimum of only 20 years of observed daily precipitation data. A comparison of probability exceedance curves of forecasted and observed distributions at a given location can provide a useful starting point for identifying and quantifying adjustments of intense precipitation needed to generate more representative precipitation distributions.

6. Conclusions

In this study, we synthesized the literature regarding categories, thresholds, and long-term trends in intense precipitation (P > 90th percentile) distributions regionally and nationally for the United States. Intense precipitation events have been widely divided into three categories: heavy, very heavy, and extreme events. The thresholds for these categories are determined using either the fixed numerical or percentile defined approach. National trends have been reported well for these categories. However, a clear distinction in regional precipitation trends is lacking. Ambiguity in regional trends in intense events of observed precipitation distributions can lead to inaccurate assessment of site-specific trends in the intense events of forecasted precipitation distributions. Analysis of probability exceedance curves of observed and forecasted distributions may help in formulating approaches to rectify intense events of forecasted distributions such that they lie within the error range of the corresponding intense events in observed distributions. Furthermore, improvements in site-specific intense events of future precipitation distributions could be used to address several regional issues adversely impacting agricultural sustainability, such as increased soil erosion and runoff, decreased infiltration and crop productivity, and uncertain future water availability.

Author Contributions: J.G., D.B. and S.J. conceived and designed the study; S.J. performed literature review and wrote the first draft of the manuscript; all authors revised and proofread the manuscript for publication.

Funding: This research received no external funding.

Acknowledgments: The authors thank Phil Busteed for providing useful insights during the course of designing the study. The authors also thank two anonymous reviewers for their critical reviews on an earlier version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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