Hurricane Florence in September 2018.

Extreme Precipitation and Climate Change: Observations and Projections

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Abstract

Many research studies have documented a historical increase in extreme precipitation in the United States over the past 40 years. Recent global warming is very likely to have been the primary cause, through increases in greenhouse gas concentrations due largely to fossil fuel combustion. The probable specific mechanism is through the warming of ocean surface waters which, likely, has caused the observed increase in atmospheric water vapor concentration. This increase in water vapor is one important factor in the historical extreme precipitation increases, and future changes in extreme precipitation will be subject to this same mechanism. If greenhouse gas concentrations continue to rise due to human activity it is virtually certain that global warming will continue, resulting in increased atmospheric water vapor concentrations. While the magnitude of future changes is uncertain for several reasons, the direction of change is not. Because moisture maximization is one of the central methods used in its estimation, Probable Maximum Precipitation values will increase.

Introduction

Notable extreme precipitation events have occurred in recent years. Hurricane Harvey, in southeast Texas, produced up to 60 inches of rain over a one week period in late August 2017. Hurricane Florence produced up to 38 inches of rain over southeast North Carolina in September 2018. A recent analysis, covering the contiguous United States for 1949-2018 (Kunkel & Champion, 2019), found that Harvey and Florence were the 1st and 7th ranked events, respectively, for total rainfall averaged over 20,000 mi^2 and for a four-day duration. They also found an upward trend in the number of four-day events with very heavy precipitation accumulation averaged over 20,000 mi^2.

Global temperature has risen about 1.8°F since the 1970s. This increase has been attributed to increases in atmospheric greenhouse gas concentrations (GHGs) due to human activities, most importantly the combustion of fossil fuels (IPCC, 2014). Carbon dioxide concentrations have risen about 45% since the beginning of the Industrial Revolution around 1760, primarily from fossil fuel combustion. Continued use of fossil fuels will lead to further increases in CO2 concentrations while other human activities are likely to lead to increases in the concentration of other greenhouse gas concentrations, such as methane and nitrous oxide. This is projected to result in additional global warming. This paper reviews the observational evidence for historical increases in extreme precipitation and describes the basis for potential future changes in Probable Maximum Precipitation (PMP).

Historical Trends

Many studies have found increases in heavy precipitation over the contiguous U.S. The Fourth National Climate Assessment (NCA4) reviews many of these and presents examples of historical trends. One analysis shown in the NCA4 (Easterling et al., 2017) used a network of 766 long-term stations from the Global Historical Climatology Network-Daily (GHCN-D, Menne et al., 2012). These stations were selected because they have minimal (less than 10%) missing daily precipitation data over the period 1900-2016. The stations are from the National Weather Service's Cooperative Observer Network which uses common instrumentation and observational methodology. Over this entire period, the observational instrumentation (eight-inch bucket) and methodology have remained essentially the same. The spatial density of these 766 stations varied regionally, with more stations in the eastern and central U.S. and fewer in the western U.S. However, the data analysis procedures included several steps to ensure that all areas of the U.S. were approximately equally weighted. The purpose of the station selection and data analysis

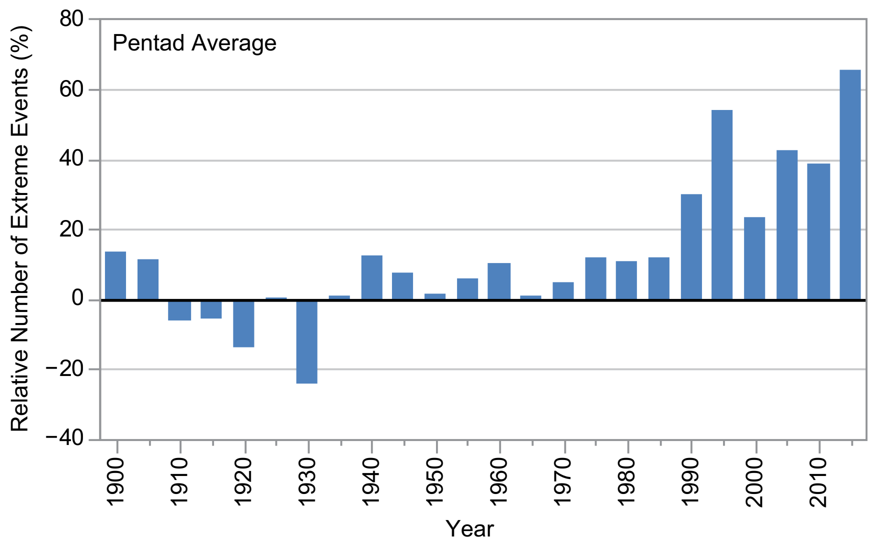

Figure 1. Two-day precipitation event time series

Note. Events exceed the threshold for a 1-in-5yr recurrence interval for the contiguous United States averaged over pentads. The index is calculated from 766 observing stations with minimal missing data. Values are anomalies (%) with respect to the base period of 1901-1960 (updated from Easterling et al. 2017, Figure 7.3).

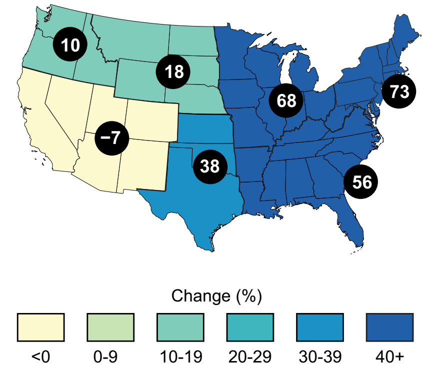

Figure 2. Regional changes over 1900-2019 in the number of 2-day precipitation events exceeding the threshold for a 1-in-5yr recurrence interval

Note. Updated from Easterling et al. 2017, Figure 7.4.

methods is to maximize the influence of real climate changes on the results and minimize the effects of non-climatic factors. I updated this analysis through 2019. This updated analysis shows that the number of heavy precipitation events of two-day accumulations exceeding a five-year recurrence interval exhibits an upward trend since the 1970s (Fig. 1). The number of events was about 52% above average for the period 2010-2019. Regional trend values (Fig. 2) are higher in the eastern half of the contiguous U.S. than the western half with the highest values in the northeast U.S.

Kunkel et al. (2020a) analyzed trends over 1949-2016 for a range of metrics of extreme precipitation, including durations of one, two, three, five, 10, 20, and 30 days and recurrence intervals of one, two, five, 10, and 20 years for a network of 3,104 GHCN-D stations. This analysis used similar methods as in Figs. 1 and 2. Due to the shorter period of analysis, more stations met the criterion of less than 10% missing daily precipitation data. They found upward trends in nationally averaged values for all metrics. The magnitudes of the trends were higher for the longer recurrence intervals, i.e., the rarer events. They also found upward trends in all metrics in all regions, except for two regions representing the far western U.S. In these regions, there was a mix of upward and downward trends.

The range of recurrence intervals explored in the above studies (one to 20 years) is much shorter than the extreme levels that are of typical interest for dam safety. While trend analysis of more extreme events is desirable, there is a tradeoff as analysis of trends for the most extreme events is hampered by reduced statistical robustness arising from small sample sizes. For very long recurrence intervals (>1000 years) with more direct relevance to PMP, the historical record of precipitation observations measured in a consistent manner (about 120-130 years at most) is simply not long enough to achieve the sample sizes necessary for traditional statistical trend detection methods. As an alternative, the analysis in Fig. 1 was extended by identifying the single largest daily and three-day duration events at each of the 766 stations over the 125-year period of 1895-2019; these events might nominally be considered on average 100 to 200-year recurrence interval events. The temporal distribution of these events (Fig. 3) indicates that there is an upward trend for both durations. From 1990 onward, the number of stations with their largest daily events is 53% above the long-term average while the number of three-days events is 35% above average. The highest fraction of stations with their largest events occurred in the most recent five-year period (2015-2019). Thus, the upward trend in moderately extreme precipitation events, displayed in Figs. 1 and 2, extends to the largest events as well.

Moisture maximization is one of the methods utilized in the estimation of PMP values. A question I explored was whether the magnitude of historical precipitation extremes was closely related to coincident atmospheric water vapor content. I analyzed this relationship by identifying the maximum three-hour precipitable water (PW) value during the day of the event and at

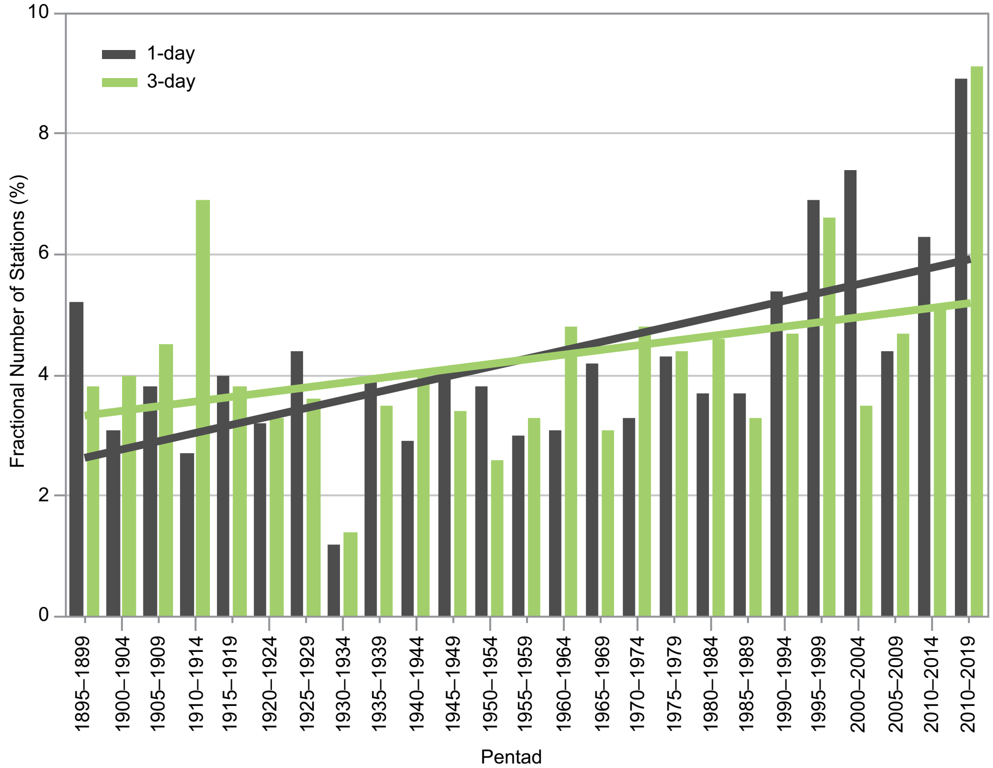

Figure 3. Timeseries of largest station events

Note. Time series (1895-2019) of an index of the year of occurrence of the largest 1-day and 3-day duration events at each individual station in the network of 766 observing stations with minimal missing data used in Fig. 1. Values are the sum of annual counts over 5-yr periods adjusted for spatial differences in station density and expressed as the fractional percent of all stations. Upward trends are statistically significant density and expressed as the fractional percent of all stations. Upward trends are statistically significant.

the event location for events of one-day duration exceeding the one-year recurrence interval threshold for the same set of 3,104 stations noted above and used in Kunkel et al. (2020a). PW is the integrated amount of water vapor in the atmosphere from the surface to the top of the troposphere. A composite of all 3,104 stations showed that the mean and various quantiles of the one-year, one-day extreme precipitation event magnitudes increased monotonically with PW (Kunkel et al. 2020b).

I then explored whether the precipitation magnitudes scaled directly with water vapor by dividing the precipitation amounts by PW values. Over a range of moderate to high values of PW (one to two inches), the average ratio is nearly constant with a value around two. This nearly constant ratio at moderate to high PW values indicates that, on average, extreme precipitation magnitude is directly proportional to water vapor. At very high values of PW (two to three or more inches), the average ratio increases slightly with PW, indicating that extreme precipitation magnitude increases at a faster rate than the increase in water vapor. This is indicative of what is known as a super-Clausius-Clapeyron ("super-CC") effect, which will be addressed in the following section. Some historical extreme events occurred with low PW (<0.5 inches) when there were very strong atmospheric dynamics and consequently high or unusually sustained upward vertical motion. For example, on April 16, 2007, Morgan, GA (one of the 766 long-term stations) recorded rainfall of 3.97 inches with PW = 0.45 inches. Other nearby stations recorded heavy amounts up to 5.4 inches. This occurred with the passage of a strong upper level low and accompanying cold front that triggered thunderstorms.

Future Trends

An assessment of future trends in extreme precipitation begins with consideration of the potential effects of global warming. The recent rapid increases in greenhouse gas concentrations have increased the amount of energy in the infrared part of the electromagnetic spectrum emitted by the atmosphere to the earth's surface. Most of this excess energy is being absorbed by oceans, raising the temperature of ocean surface waters. My analysis of historical sea surface temperatures indicates that Northern Hemisphere oceans have warmed by about 1.6°F since 1970 (Fig. 4). The maximum amount of water vapor in the atmosphere is exponentially dependent on temperature according to the Clausius-Clapeyron (CC) relationship, increasing by nearly 3.5% per °F. Global atmospheric water vapor content has increased since 1973 (Wuebbles et al., 2017). Since the amount of water vapor in the atmosphere near the ocean surface is near saturation, the historical increase in ocean surface temperature may be contributing to the overall increase in atmospheric water vapor.

Precipitation (P) in a single meteorological event can be approximated by

$$P \cong PW\ \Omega \qquad (1)$$

where Ω is a metric of the upward motion of air in the atmosphere. PW can be interpreted as the capacity of the

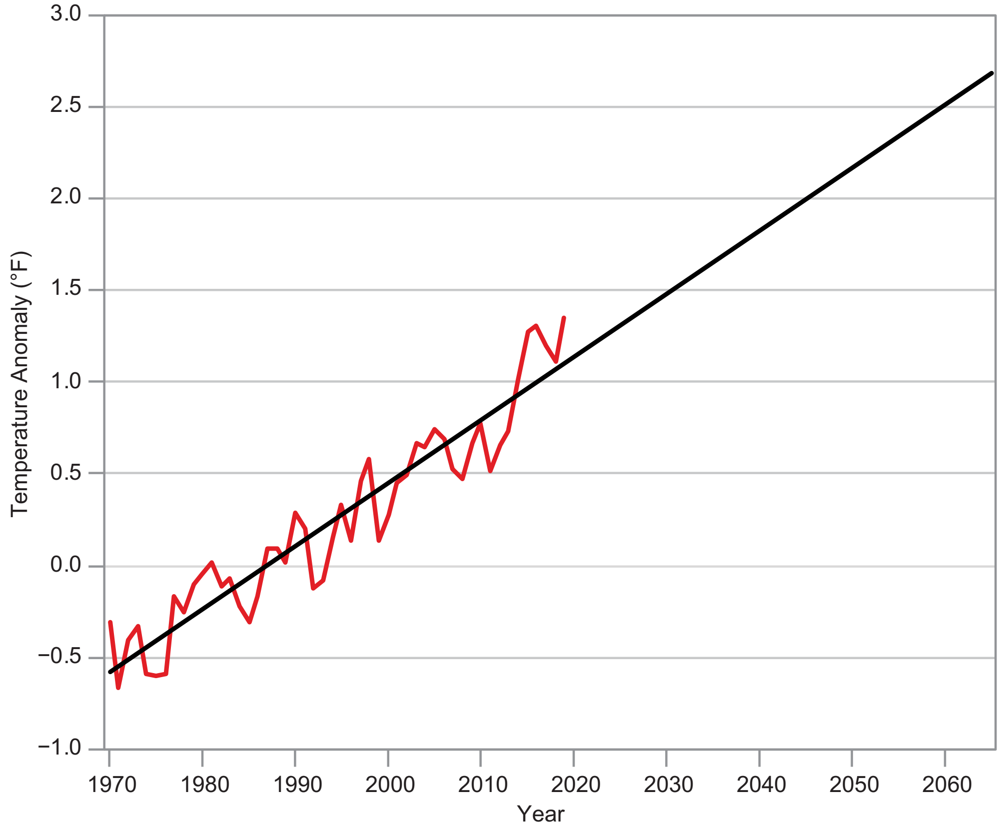

Figure 4. Northern Hemisphere Sea Surface Temperature

Note. Time series (red) of sea surface temperature (SSTs) anomalies for 1970-2019 averaged over Northern Hemisphere oceans. The reference period is 1901-2000. Trend line (black) is extrapolated to 2065.

atmosphere to produce extreme precipitation while Ω represents the opportunity through the occurrence of weather systems. Probable Maximum Precipitation (PMP) can be expressed as

$$PMP \cong PW_{max}\,\Omega_{max} \qquad (2)$$

where the "max" subscript represents maximum values for a specific region and season.

Under a scenario of continued increases of greenhouse gas concentrations in the future, global temperatures, including sea surface temperatures (SSTs), will continue to increase. This will increase atmospheric water vapor concentrations and, mostly likely, PW_{max} values as well.

General Circulation Models (GCMs) are tools that are used by scientists to investigate a range of atmospheric processes, including the effects of different levels of GHGs on climate conditions. These models are complex computer programs that represent the physics of the climate system. Dozens of climate modeling groups exist, representing many countries. These modeling groups have run coordinated experiments to investigate potential future climate conditions with higher GHG concentrations.

In Kunkel et al. (2013), our research group performed an analysis of metrics approximating PW_{max} and Ω_{max} for data from 14 GCMs. These metrics are the highest daily values of PW and Ω in a 30-year period. The analysis compared a historical period (1971-2000) with a future period (2070-2099) under a scenario in which GHGs increase to more than 900 ppm by the end of the 21st Century--current values are around 410 ppm. We found PW_{max} increases of more than 20% almost everywhere across the globe. In most areas of the contiguous United States, PW_{max} values are projected to increase by 25-40% under that scenario. These increases are generally around or greater than the change in saturation water vapor pressure calculated from local changes in temperature from the CC relationship (Kunkel et al., 2013).

Future changes of Ω, and specifically Ω_{max}, in heavy precipitation-producing weather systems due to global warming are less obvious from basic principles. The weather systems that can produce PMP levels of precipitation are likely to change in frequency and intensity, but those changes are likely to vary regionally and in complex ways. For example, future changes in the number of extratropical cyclones (ETCs) and their associated fronts (responsible for many extreme precipitation events in the U.S.) show large model-to-model differences and thus large uncertainties (Kossin et al., 2017). Similarly, there is uncertainty whether the number of landfalling hurricanes will change, but the number of the strongest hurricanes is projected to increase (Knutson et al., 2019). My analysis of 14 GCMs found that the future changes to Ω_{max} varied regionally and were much smaller (based on percentage) than the changes in water vapor.

The historical relationship between extreme precipitation magnitude and PW suggests that future changes in extreme precipitation magnitude are likely to be at least at the CC rate and perhaps could exceed CC rates. A linear extrapolation of recent trends indicate that SSTs could be more than 2.5°F warmer than late 20th Century levels (Fig. 4) by the middle of the 21st Century. This translates to increases of about 9% in atmospheric water vapor concentrations.

Conclusions

There is a direct relationship between atmospheric water vapor and the magnitude of extreme precipitation. Historical observations confirm that this relationship is a primary one that modulates extreme precipitation. The other major determining factor of extreme precipitation is the intensity and duration of upward motion in the atmosphere caused by various types of weather systems and processes.

If atmospheric greenhouse gas concentrations continue to increase, atmospheric water vapor concentrations are virtually certain to increase in the future as sea surface temperatures rise because of the fundamental relationship between saturation water vapor pressure and temperature. Since moisture maximization is a central component in the estimation of PMP, historical PMP estimates likely underestimate the true future extreme rainfall potential. There are several sources of uncertainty about the magnitude of future PMP increases, including the amount of greenhouse gas emissions and how much warming will occur for a given level of greenhouse gas concentrations. However, the direction of change is virtually certain because overall global warming is virtually certain.

The specification of a future PMP increase for design depends on the timeframe and assumptions about the future. Extrapolation of the historical SST trend (Fig. 4) would lead to an increase of about 7% by 2050 and 9% by 2065 (compared to late 20th Century) and represents a conservative assumption about future warming. A more risk-averse approach would consider the potential for accelerated warming of the oceans due to continued reliance on fossil fuels as a primary energy source.

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