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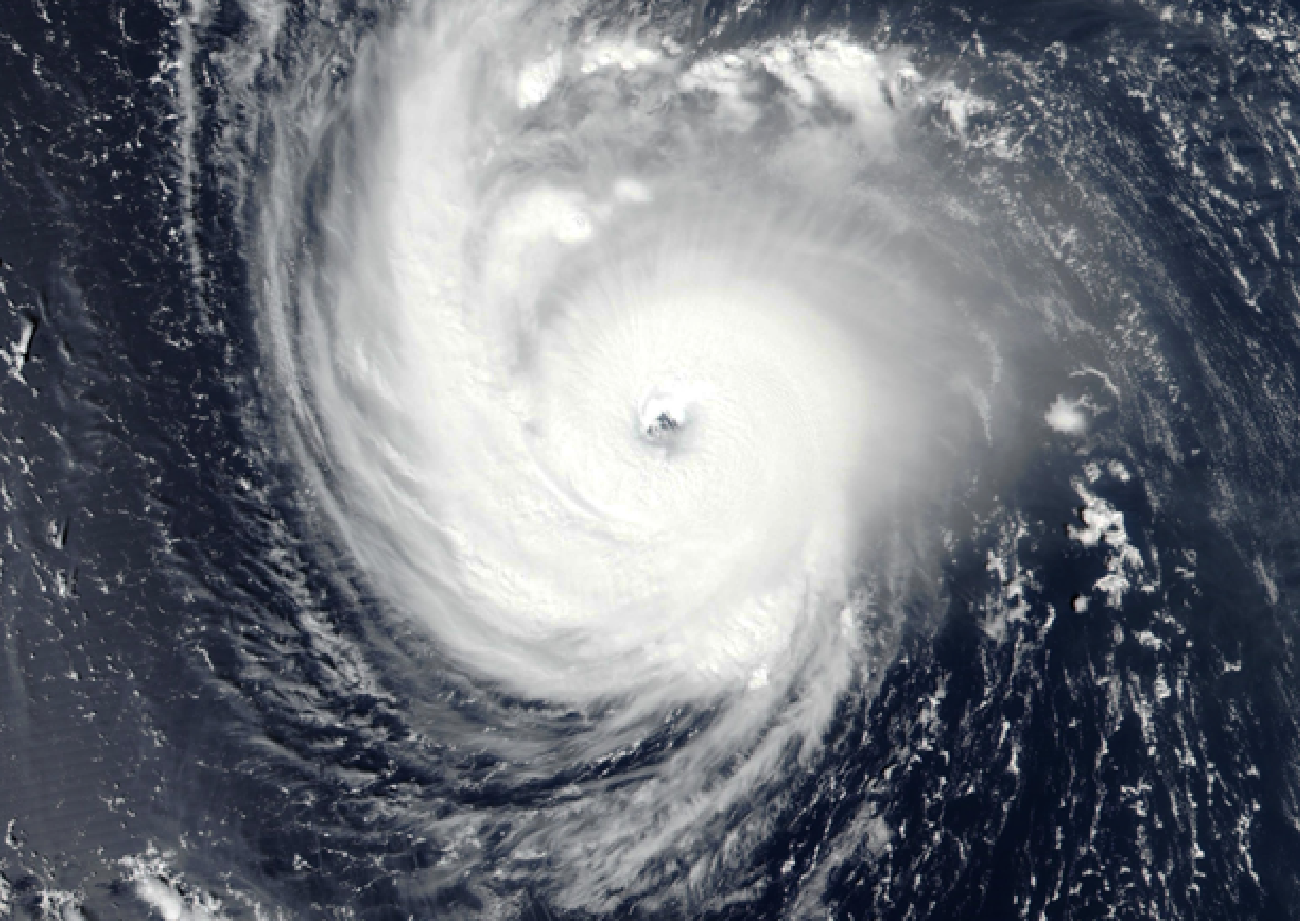
CLIMATE CHANGE AND PMP:
ARE THESE STORMS CHANGING?

EXTREME PRECIPITATION AND CLIMATE CHANGE:
OBSERVATIONS AND PROJECTIONS

21ST CENTURY DAM SAFETY RULES FOR EXTREME
PRECIPITATION IN A CHANGING CLIMATE



Hurricane Florence in September 2018.

Climate Change and PMP: Are These Storms Changing?

Bill Kappel | Doug Hultstrand | Kristi Steinhilber | Jake Rodel

Introduction

Recent extreme rainfall events, such as Hurricane Harvey in 2017 and Hurricane Florence in 2018, have raised the question of whether storms important for Probable Maximum Precipitation (PMP) development are changing or becoming more frequent because of climate change (Kappel and Hultstrand, 2018; Kunkel and Champion, 2019). Applied Weather Associates (AWA) was able to evaluate this question utilizing a detailed, data-driven approach. AWA investigated hundreds of storms analyzed for PMP development and used in PMP studies completed since the early 2000s. Most of these storms have been analyzed using our Storm Precipitation Analysis System (SPAS). In addition, every storm considered has been through an extensive independent review process to ensure the rainfall accumulation depths are acceptable and each storm has been accepted for use in PMP calculations.

The storm screening process followed a stepwise approach to identify any storm that has controlled PMP depths at one or more area sizes and durations in previous PMP studies. From this analysis, AWA established a database of all PMP-controlling storms. It is important to note that this was not a modeling approach; we simply let the data talk to us to find out which storms are controlling PMP depths and identifying when they occurred. From this PMP database, numerous investigations were made possible, including evaluating the date of storm occurrence, the locations of the storms, and the storm types. The PMP database was the foundation of this analysis and allowed for a observational, data-driven investigation of whether storms that control PMP are becoming more frequent and whether changes are occurring by region and/or by storm type.

Climate Change Background

In recent years the claim that "this year is the hottest year on record" (NASA, 2019) is frequently made. However, there is tremendous uncertainty in using surface temperature observations to quantify the Earth's temperature on a global scale (D'Aleo, 2020). Issues that increase uncertainty include a severe lack of coverage of observational sites, manipulation of raw observed data, inconsistency in observations, and improper siting, among others. Regardless, climate is changing, but this is nothing new. Climate has always changed and always will change, whether humans are involved or not. Instead this paper answers the question of whether significant changes are showing up in the database of storms used to calculate PMP and if those changes match the reported trends in observational data and climate model projections.

The focus of this paper is not on accuracy or validity of climate change and increasing temperatures, but instead on whether observational data representing the most extreme rainfall events used for PMP show any significant changes and, if so, how that affects the dam safety community and design of dams.
Not surprisingly, climate change projections of precipitation have shown a wide range of outcomes regarding future precipitation (e.g. Kunkel et al., 2013; Easterling et al., 2016; Clavet-Gaumont et al., 2017; Kunkel et al., 2020; Hultstrand et al., 2020). Some model projections have shown an increase, others no change, and others a decrease. This varies by storm duration (i.e. hourly, daily, monthly, yearly), by storm location, by storm type, and by intensity or recurrence interval being investigated. The variance of projections and the wide variety of evaluation procedures adds to the uncertainty related to extreme precipitation and climate change projections.

To address the uncertainty inherent in climate change projections, AWA utilized the observed data from extreme rainfall events used to develop PMP depths. AWA investigated observed trends of the storms which control PMP depths and related those to various projections of what might happen in a changing climate, as it relates to PMP. To do this, we investigated temperature trends for the United States and assumed those are valid. These temperature data sets show a significant upward trend of temperature and concurrent atmospheric moisture content over the past century (Kunkel et al., 2020). If this is accurate, are those rising temperatures and higher levels of moisture being reflected in extreme rainfall events which control PMP? Are we seeing an increase in PMP-type storms in the observational record? If not, why?

Most model projections show that the climate has warmed since the end of the "Little Ice Age" cold period from the 1400s through the late-1800s. A basic physical property of the atmosphere known as the Clausius-Clapeyron relationship demonstrates that a given volume of air can hold about 7% more moisture per one degree Celsius increase in temperature (Lawrence, 2005). Therefore, if the temperature trends are accurate and the atmosphere is warming, and all other variables related to the production of precipitation are changing accordingly, we should see a concurrent increase in precipitation. This would also include the most extreme precipitation events used for PMP development. These assumptions could break down, however, if there are factors as important as an increase in temperature and moisture and/or if our understanding of the meteorology which produces extreme rainfall is not properly modeled.

Trends of temperature and precipitation across the United States can be investigated by plotting the average annual temperature versus average annual precipitation. The information plotted in Figures 1 and 2 are from the National Centers for Environmental Information climate interface, where temperature and precipitation are plotted as a yearly average from 1895 through 2020. These plots show a steeper increasing trend for temperature than precipitation during the period and do not follow the expected Clausius-Clapeyron relationship.

The difference between observed precipitation and the Clausius-Clapeyron expected relationship is likely the result of several factors, ranging from improper adjustments of the temperature observations (D'Aleo, 2020) to the fact that there are many other improperly quantified processes likely as, or more, important for precipitation production than simply increasing temperatures and moisture.

Continuous U.S. Average Temperature

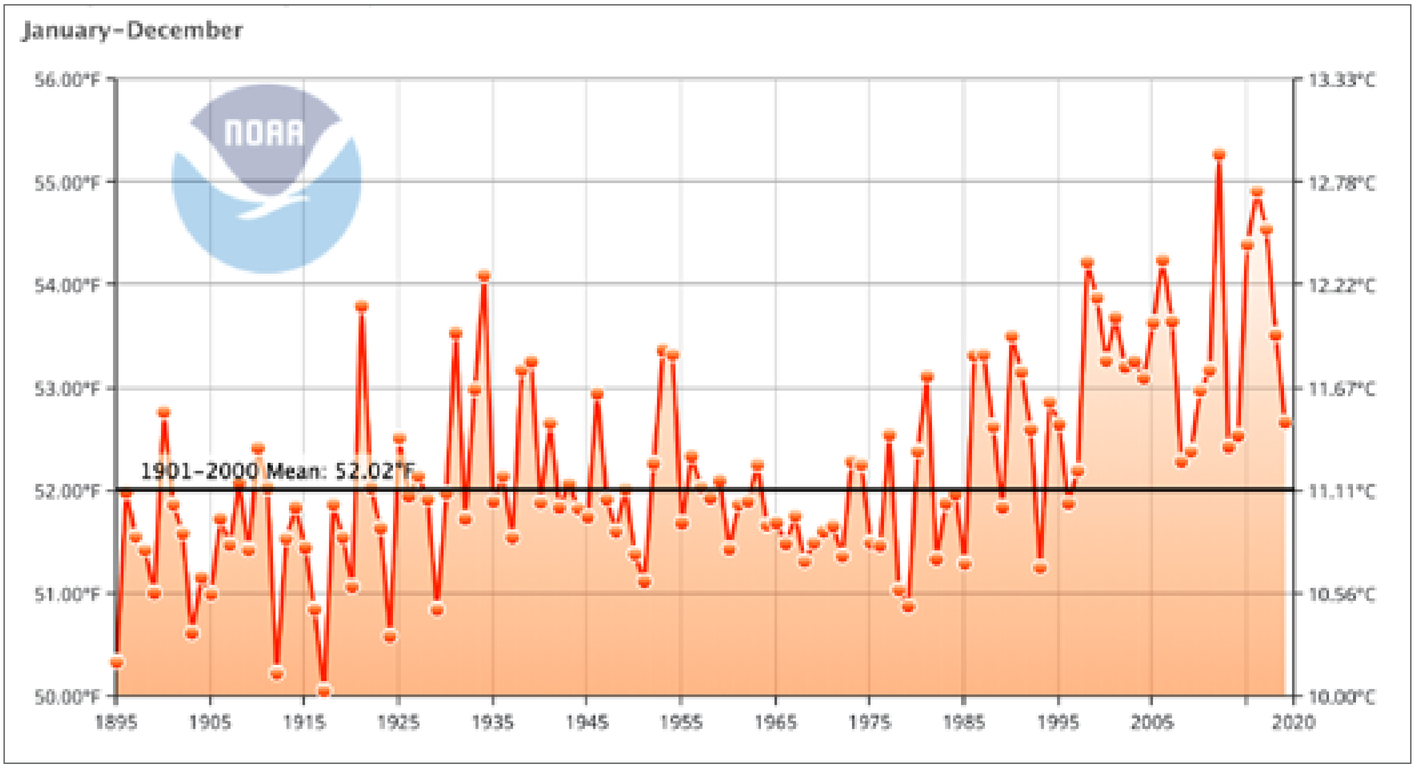


Figure 1. Yearly mean temperature over the contiguous United States from 1895 through 2020

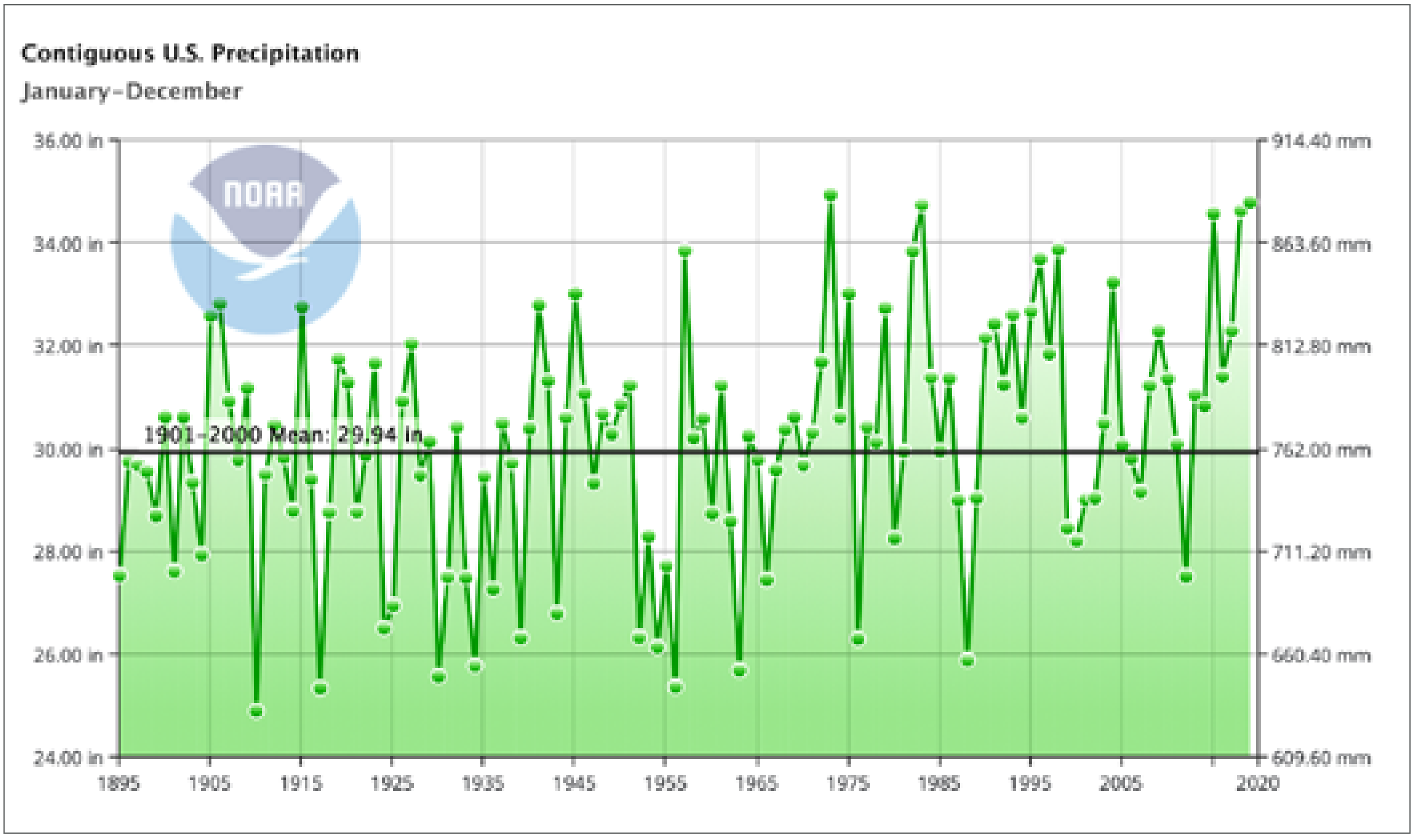


Figure 2. Yearly mean annual precipitation over the contiguous United States from 1895 through 2020

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It is important to note that climate change is not new, but instead is rather normal. In fact, a lack of climate change would be more unusual. As noted before, climate will change whether human activities are involved or not. The question in today's science is whether human activity is causing climate to change in ways that are different than the natural changes before significant human activity and, if so, will this cause PMP type storm events to become more severe and/or more frequent?

Climate models try to project the effects of human activity by solving atmospheric dynamics to replicate future climate conditions using various emissions scenarios of greenhouse gases as the variable (Wood, 2019). Unfortunately, many of the atmospheric processes the models try to solve are not known or quantified accurately. Therefore, climate models produce a series of outputs that are possible representations of future conditions. Of course, this means that the climate model projections are just as likely to be inaccurate (Dessler, 2020). These inaccuracies combined with the unknown effects of future emission scenarios result in climate model projections that produce a wide range of outcomes -- warmer, wetter, colder, drier, and everything in between -- all of which are possible, and all of which will happen at some point at some location, given enough time.

Utilizing these projections to make design and policy decisions is very difficult. In essence, one could estimate any answer they want. This doesn't mean the projections should not be evaluated and utilized as there is nothing wrong with applying "what if" scenarios to reduce risk and increase safety, but the unknown and uncertainty in the process must be properly communicated and applied.

One recent example of applying "what if" scenarios was addressed during the Colorado-New Mexico Regional Extreme Precipitation Study (2018) where Colorado Dam Safety evaluated potential effects of climate change projections on future rainfall. Colorado Dam Safety, in partnership with other study participants, evaluated numerous climate model projections and climate change in the region. These evaluations resulted in updated dam safety guidance which included an increase of 7% to the deterministically derived PMP depths (Colorado-New Mexico Region Extreme Precipitation Study, Volume VI, 2018).

Climate Change and Precipitation

The replication of precipitation in future climate scenarios is one of the least accurate aspects of climate model projections (e.g. Alexander et al., 2013; Toreti et al., 2013; and Kunkel et al., 2020). There are many important processes involved in the development of precipitation beyond the amount of moisture available within the atmosphere. These other processes have both positive and negative feedback combinations that can produce just about any combination of outcomes. For example, with a warming atmosphere the result may be more precipitation in some areas for some storms types and some durations and less precipitation in other scenarios (Hultstrand et al., 2020). A warmer atmosphere may also produce more overall precipitation, but less frequent extreme (PMP-type) precipitation depending on whether the instability produced by thermodynamic processes is decreased or increased (storm efficiency). Some recent analyses of observed precipitation and climate model projections of precipitation show that less extreme rainfall events are increasing, while the most extreme events are not (Kunkel, 2010; Schoof and Robeson, 2016; Hultstrand et al., 2020). Of course, these analyses have uncertainty as well (D'Aleo and Watts, 2010), but the general trends are still useful for a high-level analysis.

The current state-of-the-science computer models which try to replicate the Earth's climate are not able to accurately analyze precipitation processes in future climate scenarios. This is a result of many factors, including incomplete representation of the atmospheric process that produce clouds and rainfall, uncertainty about the state of the climate currently, and future climate projections. Therefore, rather than rely on inaccurate computer model projections, AWA utilized actual observed extreme precipitation data to evaluate any trends in characteristics of storms which control PMP through time.

Analysis Procedures

PMP studies completed by AWA over the last 20 years provide the data source needed for this evaluation (Figure 3). Each of those studies produced PMP depths which are controlled by one or more extreme rainfall events (PMP-type storms). From the storm databases utilized in each of these studies, AWA has created a database of more than 750 extreme rainfall events covering all North America from the early 1800s through 2020 (Figure 4). The database was evaluated to determine which of those storms are controlling of PMP depths by storm type, location, and the year of occurrence.

From these data, AWA plotted all storms which have controlled PMP depths at any area size and duration as part of one or more of our PMP studies. This produced 161 individual storm events being identified as controlling of PMP across North America (Figure 5). This storm list provides a robust data set from which to evaluate trends of PMP storms over time and by storm type as well as to evaluate whether storms controlling PMP are occurring more often. If so, does that match the climate change projections over the same timeframe?

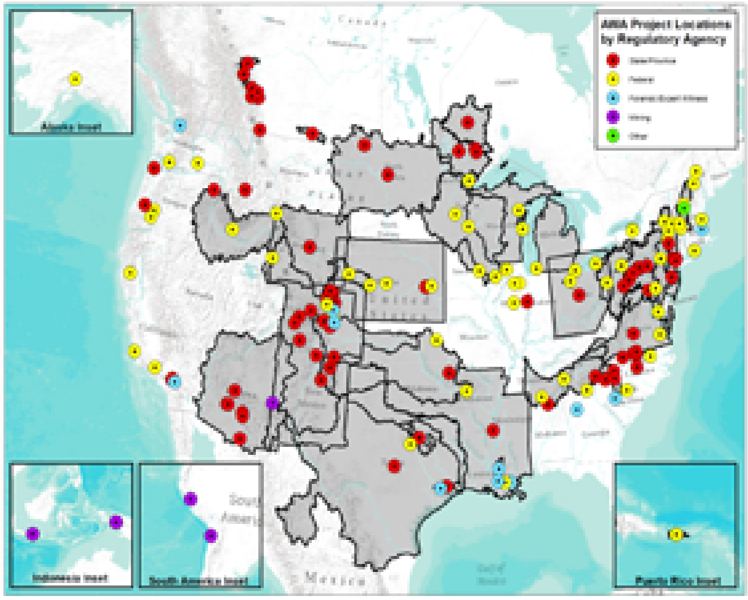

Figure 3. AWA project locations by regulatory agency

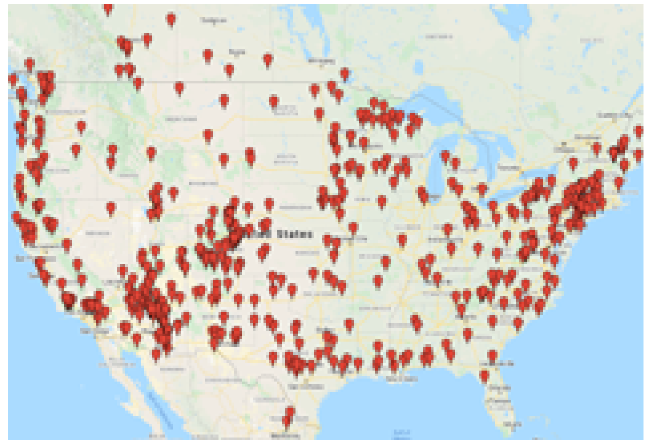

Figure 4. Locations of storms analyzed by AWA that have been used in PMP analyses in the United States

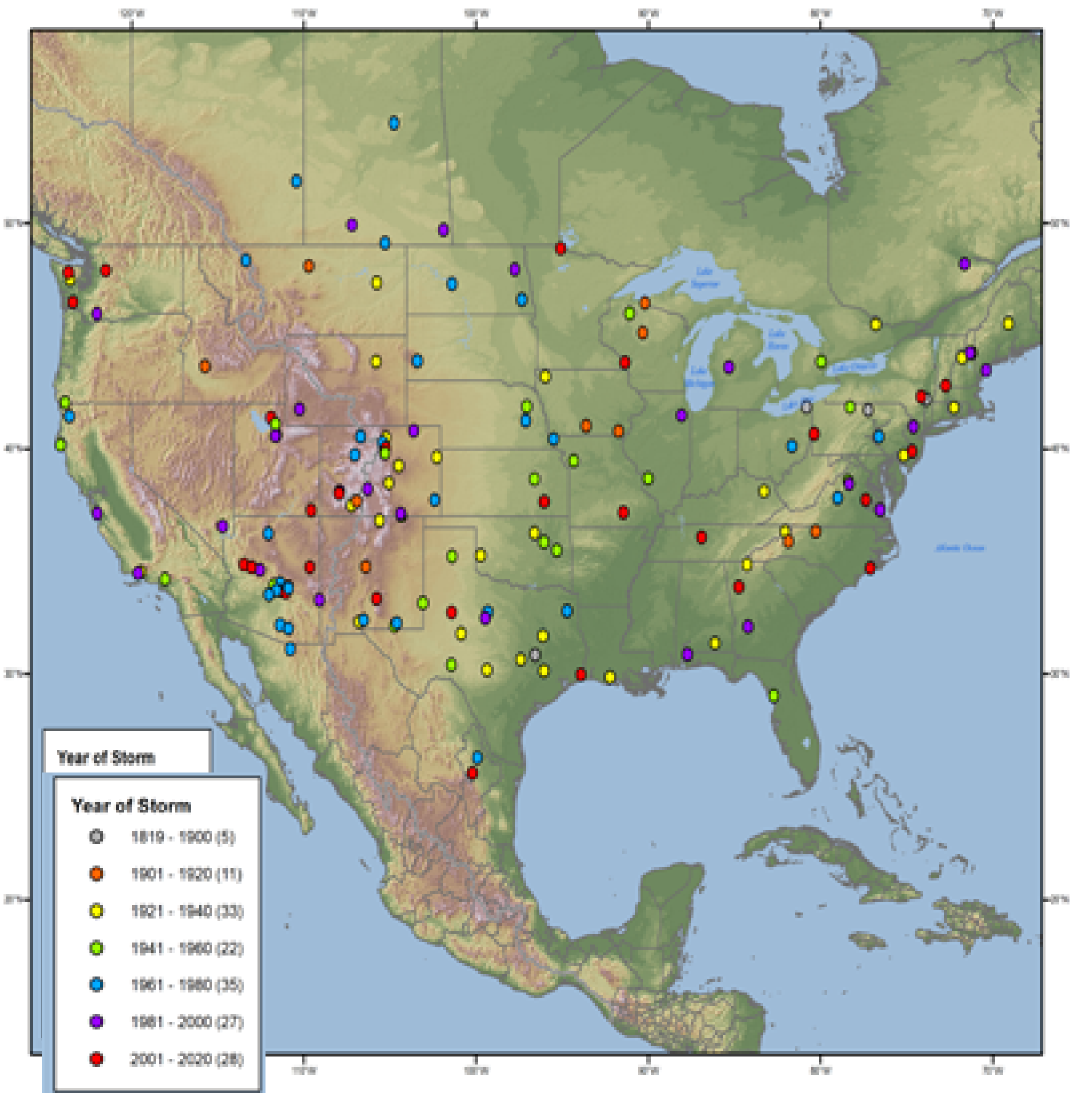

Figure 5. Locations of storms controlling PMP depths

Note. Color notes decade of occurrence, legend notes number of storms per timeframe.

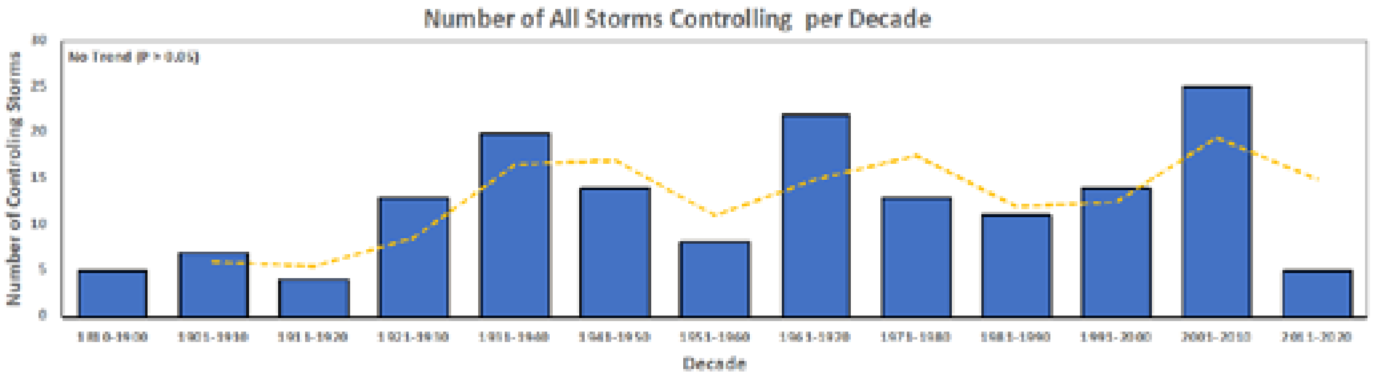

Figure 6. Number of PMP type controlling storms per decade for "All Storm" types

Note. Orange dash lines are the moving average trend.

Methods Used to Evaluate the PMP Storm Database

Initially, all the PMP controlling storms were grouped, normalized, and plotted by decade of occurrence. A moving average trend was applied to the grouped dataset, and the analysis was used to quantify whether a trend of PMP controlling storms through time across North America existed.

Figure 6 shows the results of this trend analysis for "All Storm" types. This shows the most active decades for PMP controlling storms were the 1930s, 1960s, and the first decade of the 2000s. This "All Storm" type trend analysis resulted in no significant trend ($p > 0.05$) through time, with a larger number of controlling storms occurring during the first half of the period (86 storms prior to 1965) versus the second half of the period (79 storms after 1965).

This initial "All Storm" type analysis included all storms at all locations, and, therefore, may not show trends for different storm types (i.e. local, general, or tropical). AWA then separated the data by three storm types (Local, General, and Tropical) and performed the same trend analysis. This is important because each of these storm types are produced by different meteorological conditions and, therefore, would reflect different precipitation producing processes. Local storms are short duration, high intensity rainfall events resulting from thunderstorms and isolated from larger scale storm systems (e.g. see HMR 55A Section 12.1.1; Hansen et al., 1988). The General storm type produces long duration, large area size storms, with lesser intensity rainfall accumulation compared to Local and Tropical storm types. These are often associated with slow-moving frontal systems or Atmospheric River events (Zhu and Newell, 1998; Ralph et al., 2004; Neiman et al., 2011). Tropical storm-type PMP events are rainfall directly related to a tropical storm (depression, tropical storm, and/or hurricane). These can be landfalling events or moisture moving onshore from a nearby storm. Tropical events only occur during the tropical storm season (June through October) and produce rainfall with intensity similar to Local storms but often covering larger areas with longer durations.

The following figures (Figures 7-12) show the analysis for each storm type (Local, General, Tropical) as well as the location of each storm. Similar to the overall data set, no significant increasing or decreasing trends through time are evident.

Trend analysis of the data by decade showed the most active decade for local storms was the 1930s and the first decades of the 2000s, while for the general and tropical storms the most active decades were the 1960s and the first decades of the 2000s. This is likely reflective of natural climate variability, as several well-known climate indices effecting temperatures and precipitation across North America on a 30 to 60-year cycle (Mantua et al. 1997; Enfield, 2001; Small and Islam, 2008; Giovannettone, in progress).

Trend analysis of the data by decade showed the most active decade for local storms was the 1930s and the first decades of the 2000s, while for the general and tropical storms the most active decades were the 1960s and the first decades of the 2000s.

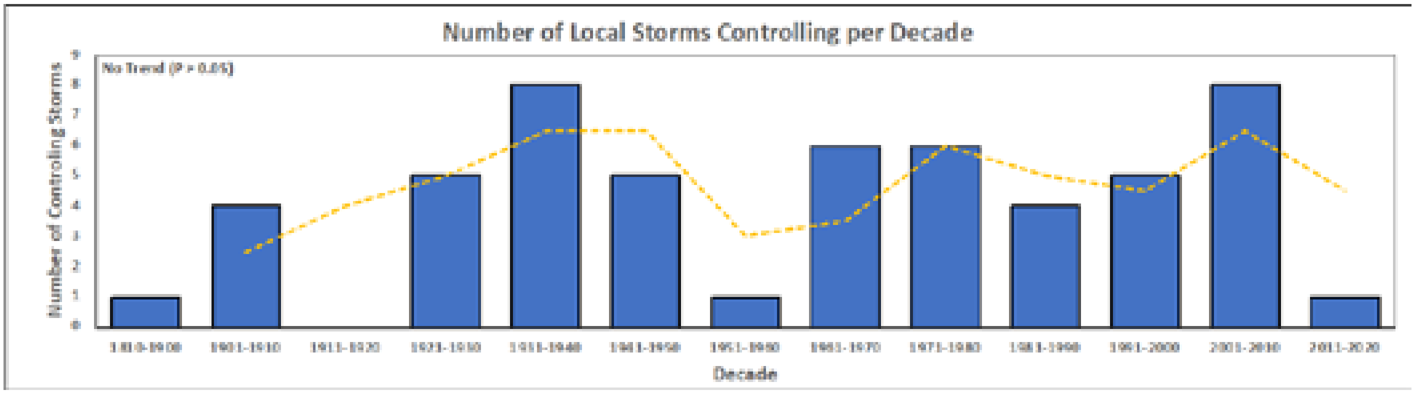

Figure 7. Number of controlling local storms per decade

Note. The orange dash line is the moving average trend.

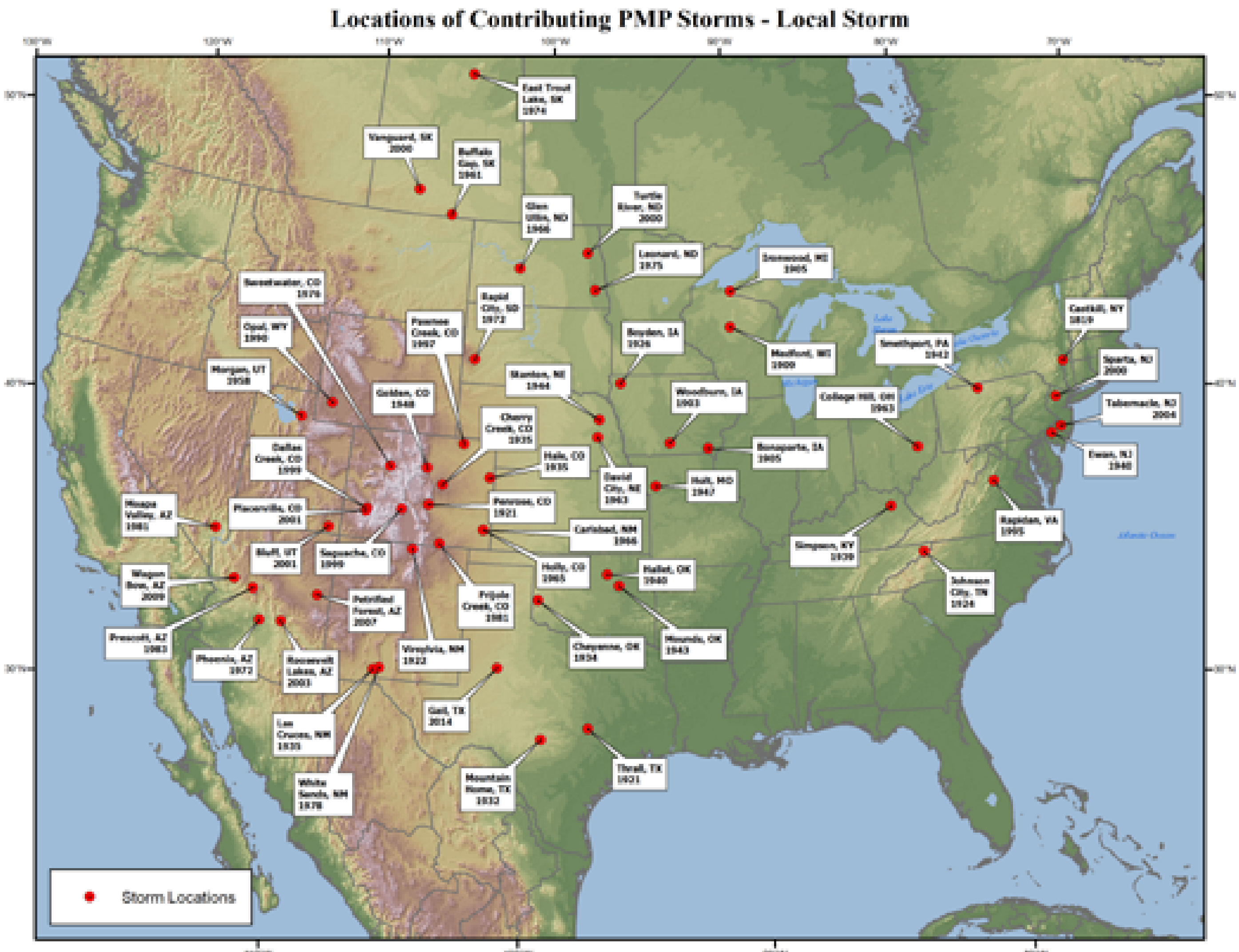

Figure 8. Locations of local storms controlling PMP depths

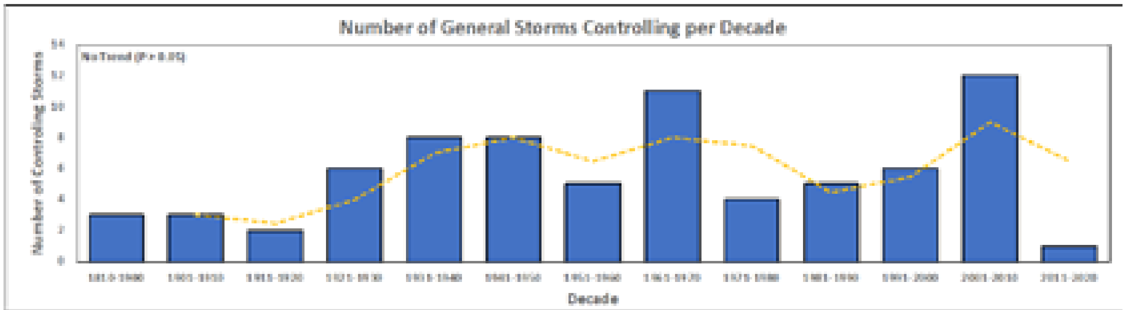

Figure 9. Number of controlling general storms per decade

Note. The orange dash line is the moving average trend.

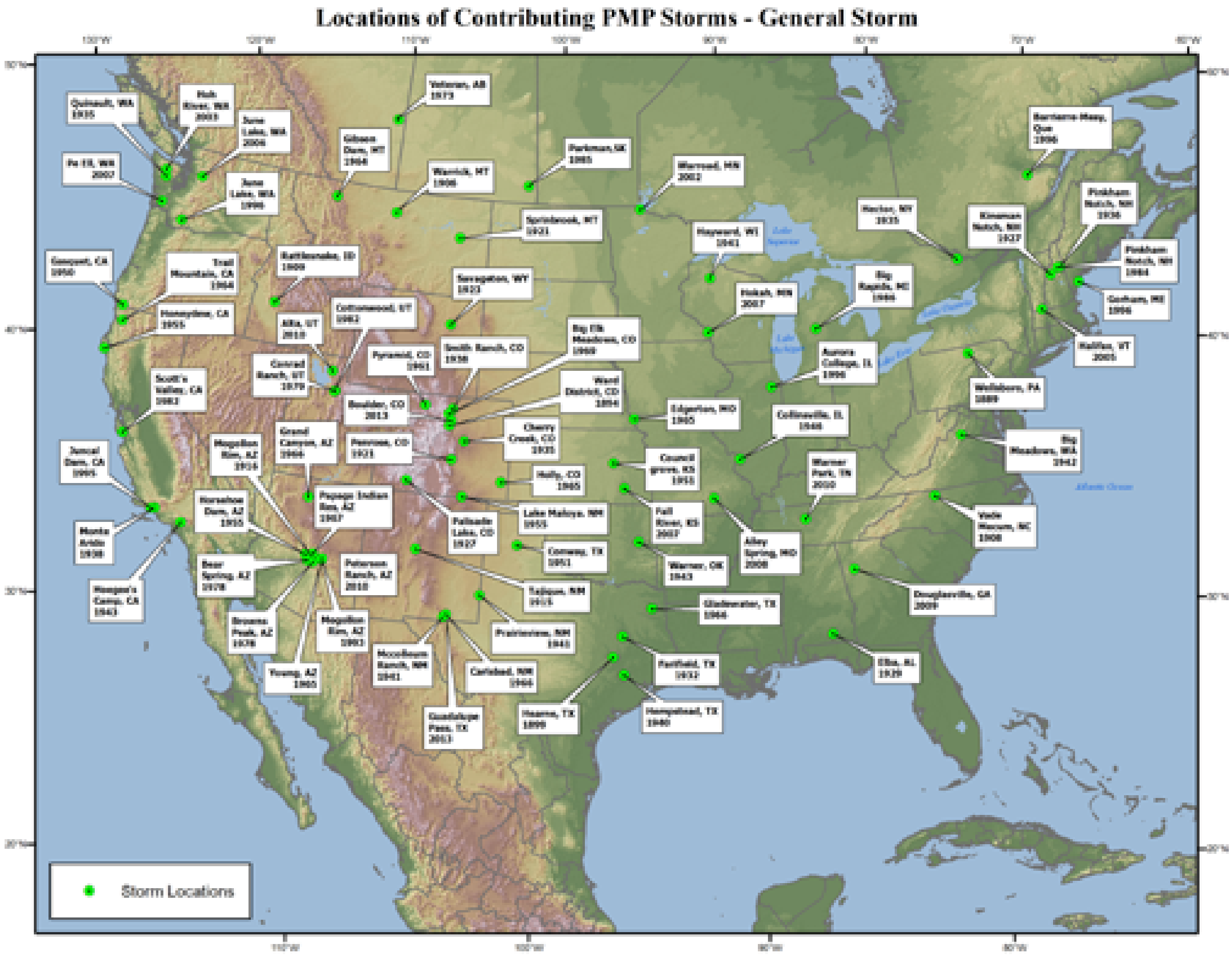

Figure 10. Locations of general storms controlling PMP depths

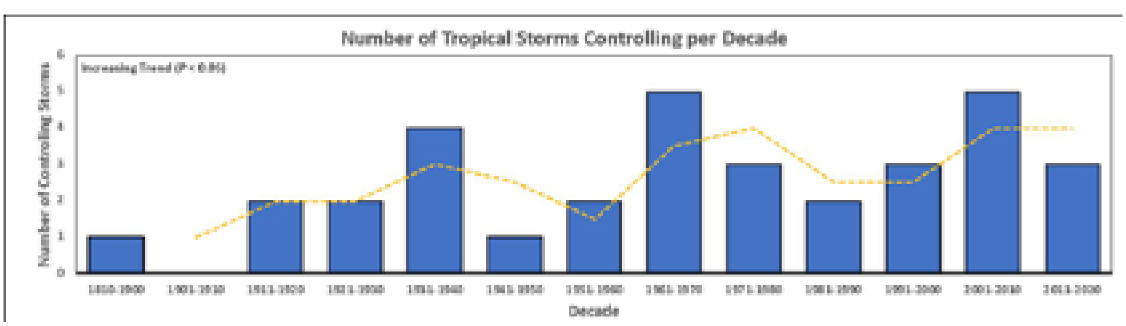

Figure 11. Number of controlling tropical storms per decade

Note. The orange dash line is the moving average trend.

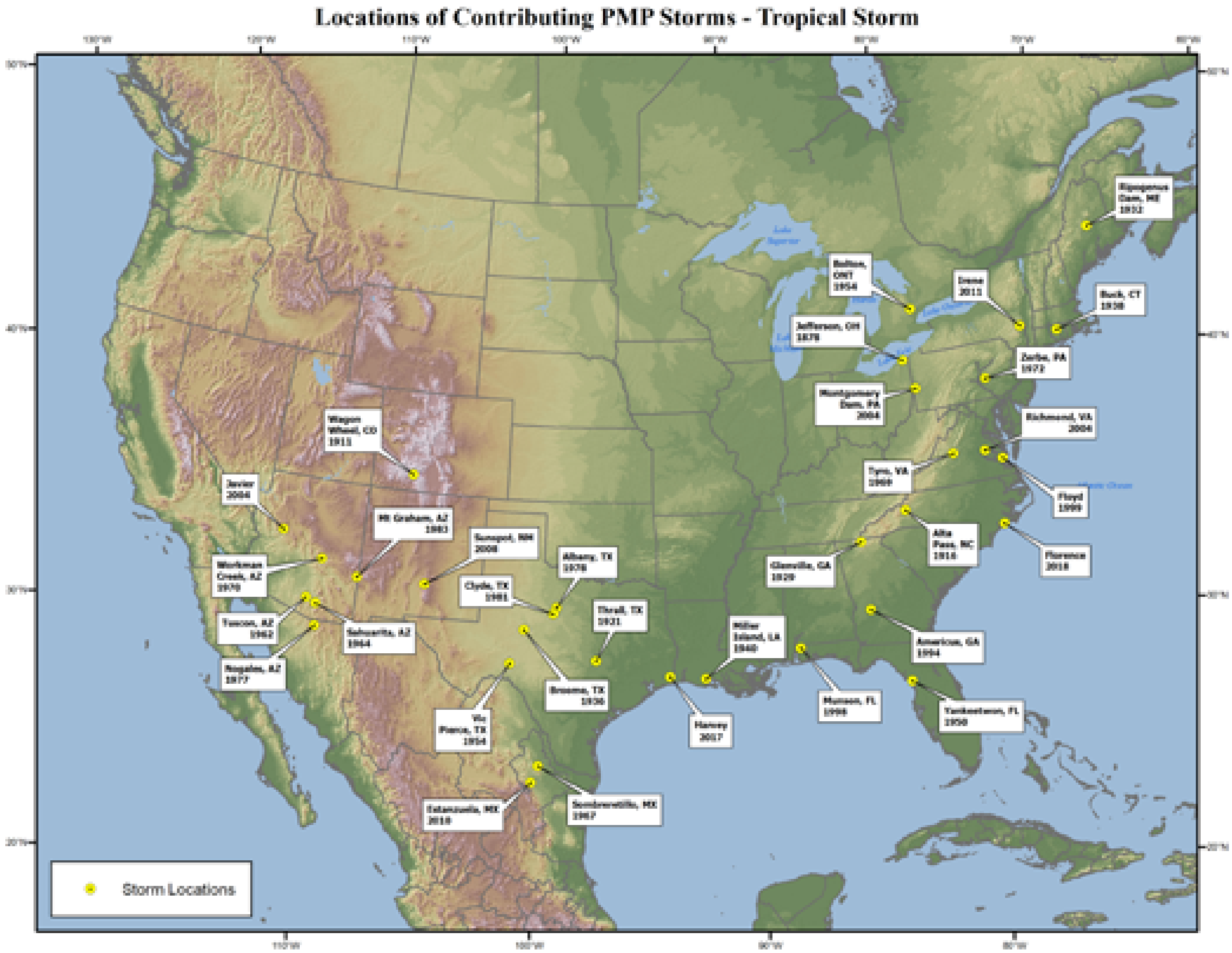

Figure 12. Locations of tropical storms controlling PMP depths

Conclusion

The analysis of the PMP controlling storms throughout North America demonstrated no significant trend through time for All, General, and Local storm type over the period from the early 1800s through 2019, though it did identify more storms controlling PMP depths prior to 1965 than after. The Tropical storm types did result in a positive trend over the period from the early 1800s through 2019; however, if the trend analysis was started after 1910, when better observational data are available, no significant trend would exist. This is important because it is likely that many tropical rainfall events that occurred prior to the 1910s were not captured adequately in the observational record. In addition, tropical storm events also contained the smallest sample size of the storm types, given their unique location of occurrence and seasonality.

The lack of overall significant trends is somewhat surprising given reported warming of the atmosphere over the same timeframe and the associated ability of the atmosphere to hold more moisture. This demonstrates that, at least for the most extreme rainfall events controlling PMP depths, other processes that may not be well understood or modeled may be as important or more important in extreme rainfall production. In addition, it is likely that changes in observation quality, quantity, and accuracy effect the number of storms captured and their associated rainfall accumulation analysis.

The result of this analysis provides confidence that the current suite of PMP estimates which utilize storm data from the entire period of record are valid today and adequately represent the intent of the PMP process. Studies completed by AWA include all changes in climate that have occurred since the 1800s and are likely occurring today. Therefore, they also represent the expected range of changes that will continue to occur going forward through the timeframe covered by current climate model projections.

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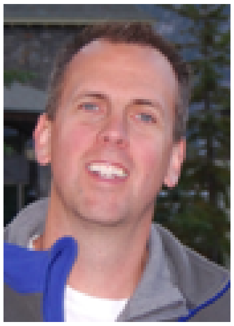

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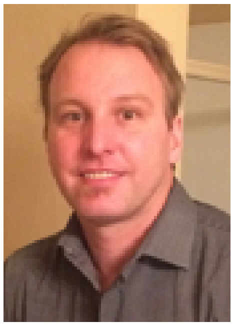

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Doug Hultstrand is a senior hydrometeorologist at Applied Weather Associates with 17 years of experience in meteorology, hydrology, and hydrometeorology. He has been involved in all aspects of probable maximum precipitation (PMP) development, an expert in extreme storm analyses, regional precipitation frequency analyses, annual exceedance probability (AEP) of PMP analyses, deriving rainfall areal reduction (ARF) factors, and is a co-developer of the Storm Precipitation Analysis System (SPAS) and associated storm databases.

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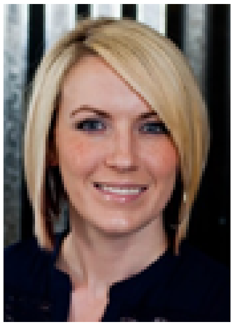

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What does ASDSO do to support me, my program and/or my company?

ASDSO works side-by-side with its members to build a unified community of dam and levee safety experts, recognized as leaders in their field, through the creation of industry standards and best practices; advocacy of legislative policy matters that impact the dam and levee safety community; development of training programs to help members build upon their knowledge of core foundational topic areas, latest technology and practical trends; education of the general public on issues of concern for dam and levee safety professionals; and support for future growth in the profession.

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