Colorado – New Mexico
Regional Extreme Precipitation Study

Summary Report
Volume VI
Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety

November 30, 2018

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Summary Report

Volume VI

Considering Climate Change in the Estimation of Extreme Precipitation for Dam Safety

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COLORADO
Division of Water Resources
Department of Natural Resources

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Interstate Stream Commission

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1. Executive Summary

The potential effects of anthropogenic (human-caused) climate change are not generally reflected in the estimates of probable maximum precipitation (PMP) and other metrics of extreme precipitation that are being currently applied to the design and regulation of dams and other infrastructure in the U.S. The procedures used to produce these estimates effectively assume climatic stationarity. There is a solid chain of evidence, however, that the climate at global to local scales has become non-stationary due to anthropogenic influences, with the main change being a pronounced warming trend. There is also increasing evidence that this anthropogenic climate change is affecting, and will increasingly affect in the future, key aspects of storm environments and characteristics, potentially impacting PMP. Additional warming of the global land surface, sea surface, and lower atmosphere is a near-certainty, with Colorado and New Mexico expected to warm by another 3-9°F by 2070, well within the design lifetime of much of the built infrastructure to which PMP is applied.

Following a well-established physical relationship (the Clausius-Clapeyron equation) that is employed in current PMP-estimation procedures, the warming of the atmosphere will lead to greater values of precipitable water (PW) on a global basis, and generally at regional scales as well. Other key factors affecting extreme precipitation—storm dynamics, storm intensity, storm duration, and precipitation efficiency and phase—will also be influenced by climate change, but the current science is less certain about the future changes in these factors, particularly at the regional scale. The several recent studies which have attempted to explicitly incorporate climate change in PMP estimates, using the output of global climate models (GCMs), have all indicated that PMP will increase in the 21st century, largely as a consequence of the PW increase. Similar studies which have produced precipitation-frequency analyses (PFA) incorporating climate change have also projected that precipitation magnitudes will increase in the future for the rare but fathomable events at the far end of the frequency-magnitude curve where PMP resides ($<10^{-4}$ AEP).

As the scientific understanding of extreme precipitation under climate change has rapidly progressed in recent years, Federal dam owning/operating and regulatory agencies and professional engineering associations have been reconsidering practices for PMP/PFA estimation and application in risk assessment. Agencies such as U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation have mandated the consideration of climate change in infrastructure planning and management, conducted project-scale pilot studies, and made other steps towards implementation. This reassessment is ongoing, and no methodologies for estimating PMP or PFA under climate change have as yet been elevated to an official or preferred status.

We recommend that the implementation of PMP and other metrics of risk from extreme precipitation in infrastructure design and regulation by the states of Colorado and New Mexico account for the climate-change effect in which there is the most confidence, and is likely to be the most consequential overall: the fundamental, thermodynamically-driven increase in precipitable water. We suggest three different "families" of approaches for incorporating this effect, either qualitatively or quantitatively, depending on the type of decision framework that is currently being used or is desired.

2. Introduction

Under the prevailing engineering practice in the U.S., the effects of human-caused (*anthropogenic*) climate change are not considered when developing probable maximum precipitation (PMP) estimates, consistent with current guidance on PMP estimation from the World Meteorological Organization (WMO 2009). Accordingly, the PMP approaches used in nearly all recent state and site-specific PMP studies assume climatic *stationarity*, i.e., that the underlying factors governing PMP risk will not change appreciably over time, and so the observed historical record of precipitation events can be used to robustly characterize future risk. These approaches do not explicitly consider the possible ongoing and future effects of anthropogenic climate change on PMP values and the frequency of extreme precipitation events. (These approaches and the resulting PMP values may partially incorporate anthropogenic changes in climate that have *already* occurred, in that they include recent storms and dewpoint-temperature observations that may have been influenced by climate change.)

There is increasing evidence, however, that the risk from extreme precipitation events, including PMP-class events, is being elevated by anthropogenic climate change. Physical theory suggests that a warmer atmosphere will bring systematic changes in storm environments and extreme precipitation amounts. Observations indicate that some of those changes are already occurring, and global climate models consistently project even larger changes in storm environments and extreme precipitation amounts in the future. Observed exceedances of the PMP in Sydney, Australia, Houston, Texas, and other locations (Abbs 1999, Stratz and Hossain 2014, Emanuel 2017) have also raised concerns about current practices in PMP estimation given the changing climate. The extraordinary magnitude of Houston-area rainfall during Hurricane Harvey has been partially attributed to recent anthropogenic climate change by four separate studies, each with different data, methods, and models (Emanuel 2017, Risser and Wehner 2017, van Oldenborgh et al 2017, Wang et al. 2018). The longstanding assumption that PMP is a "conservative measure...designed to provide a high degree of safety" (NRC 1994) may be less valid in a changing climate.

Thus, it is important to ask whether the standard of practice for PMP estimation, including future updates to the CO-NM REPS study, should evolve to explicitly address climate-change effects. Even if one believes that the effects of climate change as of today can be accommodated within existing stationarity-assuming approaches for PMP estimation (and for precipitation frequency analysis; PFA), the effects of climate change are expected to become larger relative to natural variability and other factors over the next several decades, well within the design lifetimes for the water-control structures for which PMPs are developed. In fact, in the past decade there has been increasing discussion in the engineering community about incorporating climate change in infrastructure design, and initial steps towards corresponding changes in practice, mainly among key Federal agencies such as the Nuclear Regulatory Commission (NRC), USACE, and Reclamation.

The main purpose of this volume is to provide the background and guidance necessary for informed discussion about climate change and potential impacts to extreme precipitation and PMP among regulators, dam owners, and other stakeholders in Colorado and New Mexico. To that end, we assess the current state of the science, and of engineering practice, regarding the consideration of climate change in extreme precipitation analyses for dam safety. The primary sources of information were peer-reviewed scientific literature and agency reports and assessments, augmented by personal communications with experts in the research and practitioner communities, including members of the CO-NM REPS Project Review Board.

We first provide an overview of anthropogenic climate change, and summarize the observed and projected future changes in temperature and precipitation globally, and for Colorado and New Mexico. We summarize the studies of how several key mechanisms of extreme precipitation may be altered, given these fundamental changes in the climate system. We describe the current state-of-practice, and recent shifts, in PMP/PFA estimation and related risk assessment among Federal agencies and other entities. We then summarize and evaluate different approaches to PMP/PFA estimation that have been proposed by the research community to explicitly incorporate future climate change. We conclude with recommendations regarding PMP/PFA estimation practices and their application, but rather than attempting to single out a particular approach, we instead consider families of approaches in the context of different decision-making frameworks for dam safety. Ultimately, the question of whether PMP estimation practices *should* change, and if so, *how*, cannot be addressed by the science alone; societal values and perceptions—such as what level of risk is acceptable—will need to shape the answer as well.

In the summer of 2017, we administered a web-based survey to the CO-NM REPS study team, Project Review Board, and other study stakeholders, to gage their personal assessments of the state of the science and practice, and identify the evidence, such as specific papers and reports, that they used to support those assessments, and elicit specific questions that they would like to see answered in this document. The survey results were used to confirm and refine the overall direction of this document, the thoroughness of our literature search, and the scope of the scientific assessment. A summary of the survey results can be found in Appendix A.

3. Overview of Anthropogenic Climate Change

The global climate has changed throughout the Earth's history, due to multiple factors that vary over different timescales: the radiative output of the Sun, Earth's orbital parameters, volcanic activity, continental drift, and geologic uplift and erosion. What is different now is that there are unusually rapid changes in climate conditions for which human activity is extremely likely to be the primary driver, mainly through increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IPCC 2013). These gases alter the Earth's energy balance by slowing the loss out to space of the infrared energy re-radiated by the Earth's surface, effectively trapping more heat in the lower atmosphere and at the surface. CO_2 has increased by almost 50% from 280 parts per million (ppm) in the preindustrial era (before 1750) to 407 ppm in early 2018, a level that has not been reached in at least 800,000 years (Lukas et al. 2014, NOAA 2018).

The heat-trapping property of these greenhouse gases was first identified over 150 years ago by English scientist John Tyndall (Tyndall 1861). A few decades later, Swedish chemist Svante Arrhenius predicted that human-caused global warming would occur in the future as concentrations of greenhouse gases increased due to the burning of fossil fuels (Arrhenius 1896). The current scientific understanding about the recent and ongoing changes in global climate is based on multiple and consistent lines of evidence, supported by thousands of research studies and datasets: the basic radiation physics invoked by Arrhenius in his early prediction; paleoclimate records from ice cores, ocean sediments, and other proxies; observational records from the land surface, oceans, and satellites; and simulations from global climate models (GCMs). This understanding, in brief, is that it is extremely likely that the dominant cause of recent global warming is human activities; and it is almost certain that this global warming will continue, and likely accelerate, depending on how fast the concentrations of greenhouse gases in the atmosphere continue to increase (IPCC 2013, USGCRP 2017).

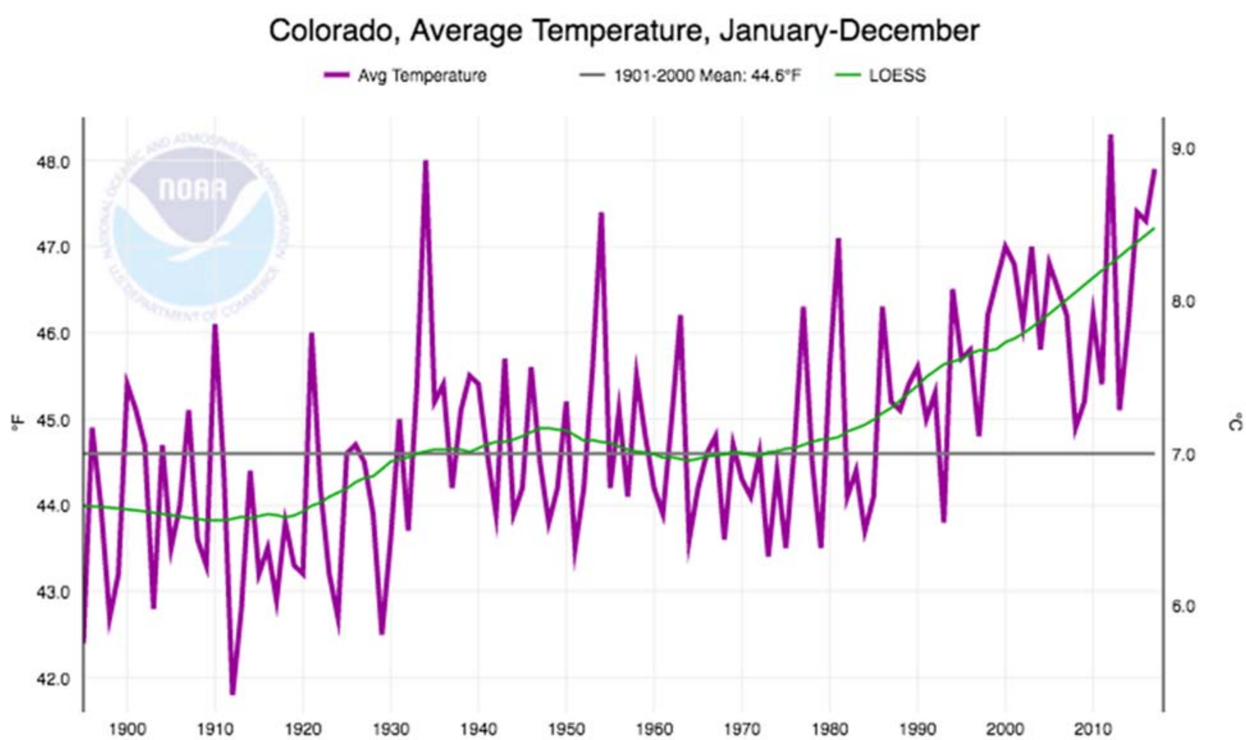
4. Observed Climate Trends: Global and Regional

4.1 Annual temperature and other indicators of warming - global

It is an observational fact that the Earth's climate system has warmed in the past century; global average annual temperature has increased by 1.8°F since 1900 and 1.0°F since 1980 (USGCRP 2017). Over 90% of the additional energy accumulated in the climate system since 1980 has gone into warming the oceans, and the global sea level rise of about 0.7 feet since 1900 reflects the thermal expansion of water from this warming and increasing melt from mountain and polar glaciers, the Greenland ice sheet, and the Antarctic ice sheets. Other global and hemispheric trends in the past several decades that are physically consistent with the observed warming include a reduction in northern hemisphere spring snow cover, the loss of 75% of the volume of summer Arctic sea ice since 1980, and, particularly relevant to the CO-NM REPS study, increasing water vapor in the atmosphere (IPCC 2013, USGCRP 2017).

4.2 Annual temperature - regional

In Colorado and New Mexico, the recent observed changes in the climate are consistent with the global changes, in particular a pronounced warming trend. The average annual temperatures in both states have increased by about 3˚F since 1900, with most of that warming, about 2.5˚F, having occurred since 1980 (Figure 1; NOAA NCEI 2018). In Colorado, 2012 was the warmest year on record (since 1895), and four of the six warmest years on record have occurred after 2011. In New Mexico, 2017 was the warmest year on record, and the three warmest years have occurred after 2011.



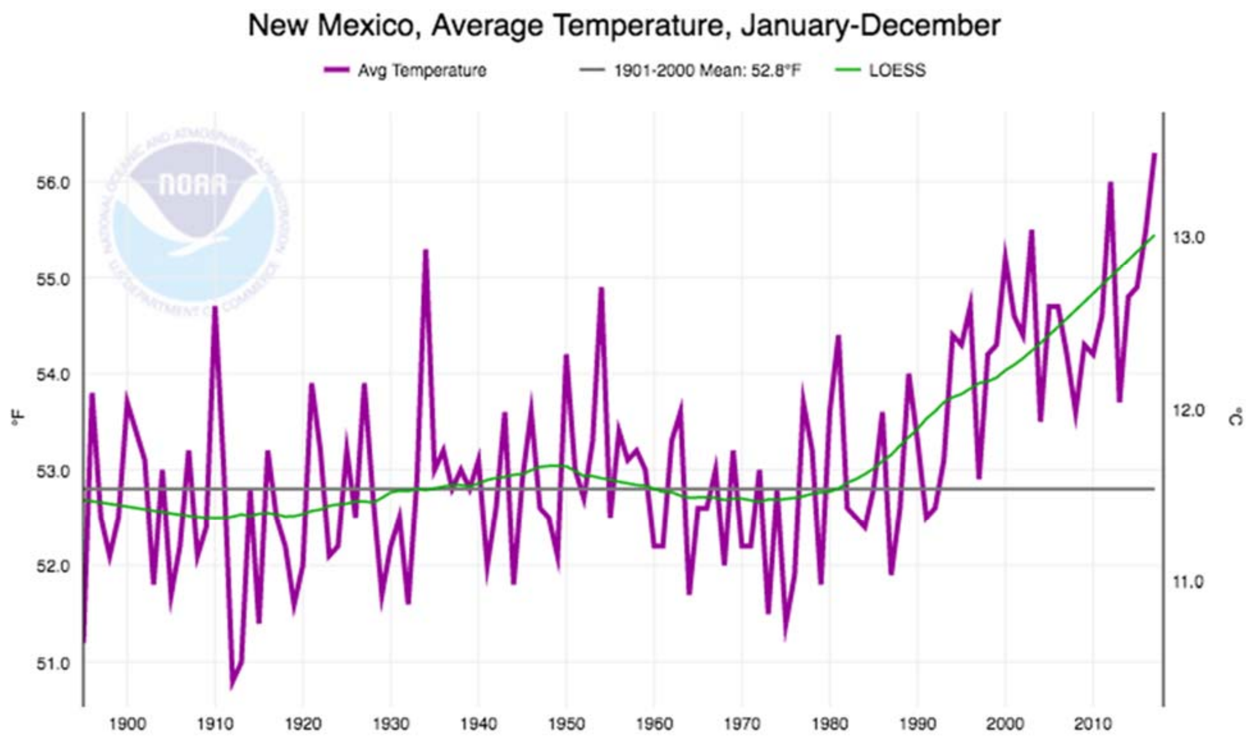
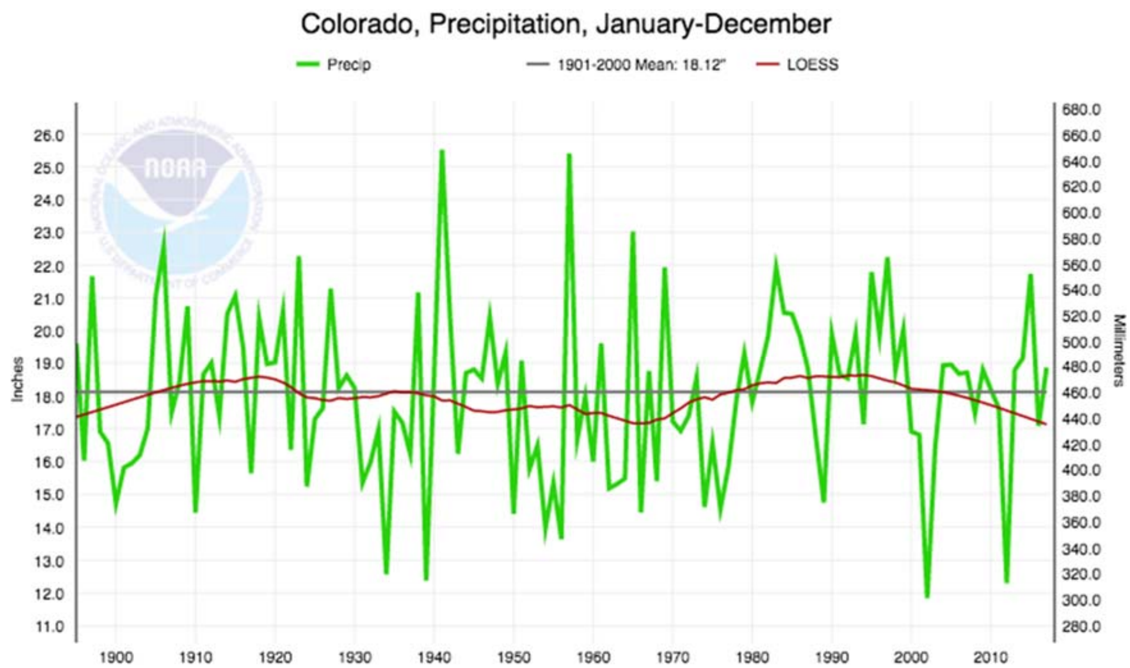


Figure 1: Annual (January-December) average temperatures, statewide, for Colorado (upper graph) and New Mexico (lower graph), from 1895-2017. The green line is a LOESS smooth that emphasizes multi-decadal variability and trends. Both states have warmed by about2.5°F since 1980. (Source: NOAA NCEI; https://www.ncdc.noaa.gov/cag/time-series/us/)

4.3 Annual and seasonal precipitation - regional

Precipitation is much more variable from year to year than temperature; in Colorado and New Mexico, roughly twice as much precipitation occurs in the wettest 10% of years than in the driest 10%. For trends to emerge from the background noise of this high variability, they need to be large. There have been no significant trends in statewide annual precipitation since 1900 or 1980 in Colorado or New Mexico, nor any trends in seasonal precipitation (NOAA NCEI 2018).



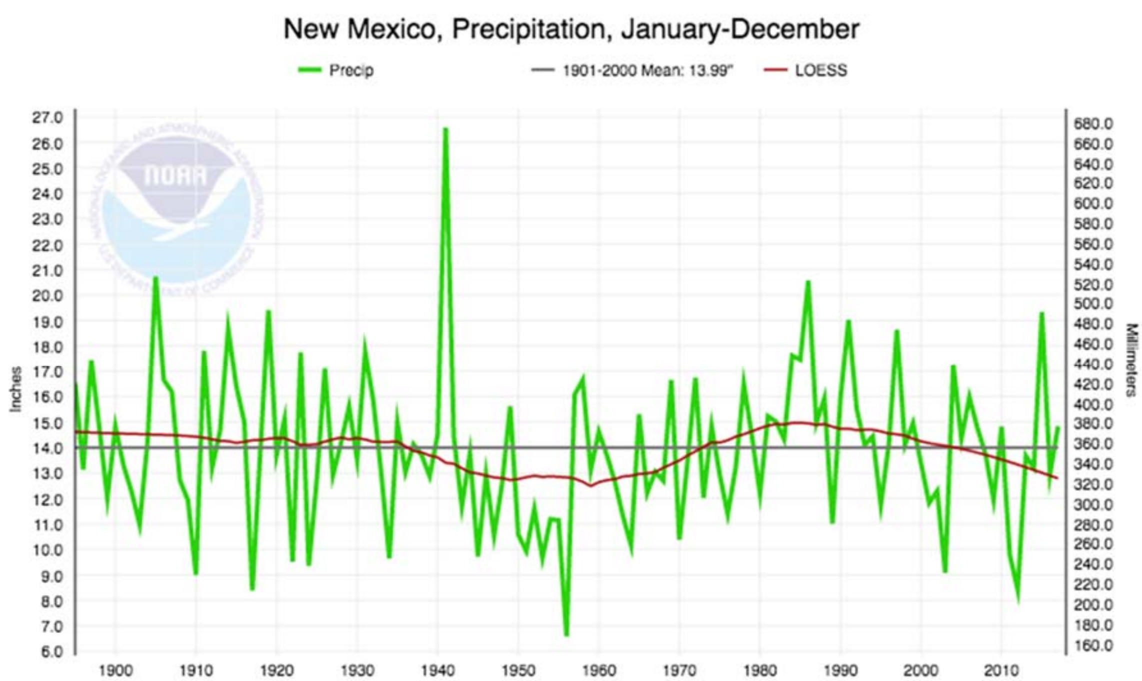


Figure 2: Annual (January-December) precipitation, statewide, for Colorado (upper graph) and New Mexico (lower graph), from 1895-2017. The red line is a LOESS smooth that emphasizes multi-decadal variability and trends. In both states, there are no significant recent trends in annual or seasonal (not shown) precipitation. (Source: NOAA NCEI; https://www.ncdc.noaa.gov/cag/time-series/us/)

4.4 Comments on extreme precipitation

First, note that as one considers increasingly rare precipitation events, the population of historical occurrences gets increasingly smaller, and the uncertainty in estimating the slope of the observed trend increases. Only a relatively large trend will be statistically detectable. The physical risk factors for extreme precipitation could change without that change being clearly expressed as a trend in the event of interest.

Also, note that when considering the likelihood of extreme precipitation events in the context of PFA, frequency and magnitude do not change independently of each other. An increase in the frequency of an event above a certain magnitude threshold (e.g., >3”) implies an increase in the magnitude for the corresponding frequency threshold (e.g., the 5-year event or 0.2 AEP), and vice versa. In other words, if we use a threshold to define “extreme” precipitation events, then if we find these events are becoming more frequent, then the average event is also becoming larger.

4.5 Extreme precipitation – global

Increases in the frequency and magnitude of extreme precipitation events (<0.2 annual exceedance probability; AEP) have been observed in recent decades on a globally-averaged basis, in most regions worldwide, and in the central and eastern U.S (Bonnin et al. 2011, IPCC 2013, Kunkel et al. 2013b, Lehmann et al. 2015, USGCRP 2017). For example, an analysis of record-highest 1-day precipitation events (~0.01 AEP to ~0.03 AEP) found that the number of record events from 1981-2010 was higher than the baseline expectation for most regions (Lehmann et al 2015).

4.6 Extreme precipitation - regional

In contrast to the observed global trends, there is less evidence for increasing extreme precipitation in the western U.S., including Colorado and New Mexico. Several analyses have found that extreme precipitation events (0.2 AEP to 0.01 AEP) do not appear to have increased in frequency over the past 30-50 years in the western U.S. (Bonnin et al 2011, Hoerling et al. 2013, Lukas et al. 2014, Lehmann et al. 2015, USGCRP 2017). The most recent of these analyses found that for the six-state Southwest U.S. region (CA, NV, UT, AZ, CO, NM), there has been a slight declining trend (-2%) in the number of 2-day events larger than the 5-year (0.2 AEP) amount over the period 1958-2016, compared to increases ranging from +11% to +92% for the six other regions in the coterminous U.S. (NCA 2017). However, an analysis of changes in the 20-year (0.05 AEP) precipitation event found that such events had increased in magnitude, on average, from 1948-2010 at the vast majority of stations across the U.S., including in Colorado and New Mexico, and the increases seen in those two states were generally not as large as in the Midwest and Eastern U.S. (Kunkel et al. 2013b). An update of that analysis found that the increases in the 20-year event across the Southwest U.S., including Colorado and New Mexico, were larger in the winter and spring than the summer and fall (USGCRP 2017).

Hoerling et al. (2016) offer a potential explanation for why the observed trends in extreme precipitation events in the western U.S., including Colorado and New Mexico, are inconsistent with the increases observed elsewhere in the U.S. and much of the world. They compared observed regional variation in U.S. trends from 1979-2013 in heavy daily precipitation events (>95th and >99th percentile) to a large ensemble of climate model simulations run under different conditions, and conclude that internal (natural) variability in sea-surface temperatures (SSTs) over that period was the main driver of the differences in regional trends in heavy precipitation. For the Southwest U.S., the prevalence of La Niña-like patterns of SSTs and associated northward displacements of storm tracks led to fewer events in the second half of that period. It is plausible that this explanation also holds for the rarer (>0.02 AEP) and more extreme precipitation events. More generally, the modeling and analyses by Hoerling et al. (2016) suggest that factors associated with natural climate variability may temporarily mask—or accentuate—anthropogenic influences on extreme precipitation. Thus, one cannot assume that a recent local or regional trend in extreme precipitation will continue at the same slope or sign.

Also, in the context of PMP, it is important to note that analyses of station (point) precipitation, such as in the papers cited above, speak primarily to precipitation intensity/depth, and not necessarily to the size of the footprint and overall precipitation volume of a storm event—which both enter into considerations and calculations of PMP.

5. About Global Climate Models

Global climate models (GCMs) are computer-based, mathematical representations of the Earth's climate system. GCMs partition the Earth into thousands of gridboxes or cells and use equations based on both observations and fundamental physical laws to represent the movement of energy, air, water, and other constituents between the gridboxes. They are the principal tools used by climate scientists to diagnose past and recent climate changes, and to generate physically plausible scenarios of the future climate, globally and regionally. GCMs share many features with global numerical weather prediction (NWP) models used for weather forecasts, but GCMs are run over much longer time frames (10-100 years or more), and represent additional processes that change slowly, such as ocean circulation and biogeochemical cycles (IPCC 2013, Lukas et al. 2014).

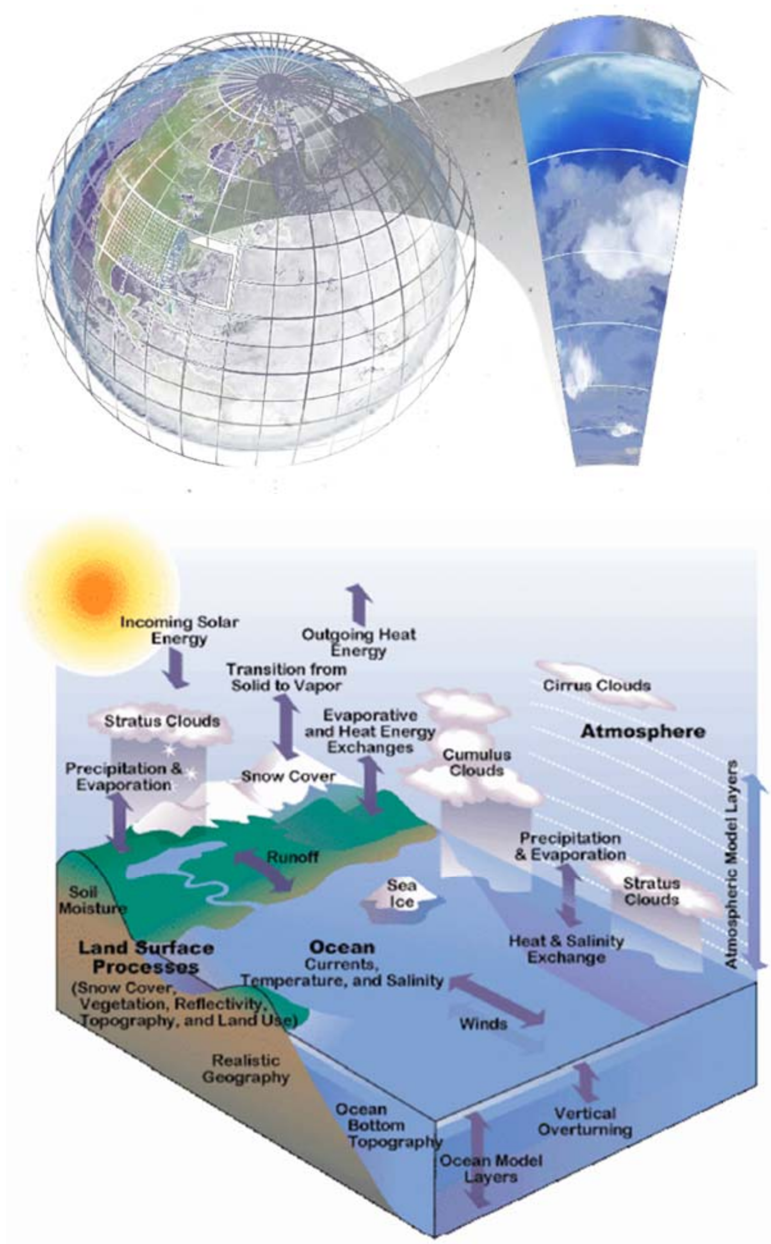


Figure 3: Global climate models (GCMs) are computer-based representations of the Earth's climate system. GCMs divide the planet into a 3-dimensional grid, apply fundamental equations of physics, fluid motion, and chemistry, represent many other processes using parameterizations derived from observations, and then calculate winds, heat transfer, moisture transfer, and other interactions between each gridcell, ultimately outputting dozens of key climate and hydrology variables over time and space. (Source: Upper - Adapted from Nicolle Rager Fuller, National Science Foundation; Lower - University Corporation for Atmospheric Research)

GCMs produce realistic simulations of the key physical phenomena, broad-scale patterns, and statistical characteristics of the historical and current global climate.

Their simulations of future climate do differ among the several dozen different GCMs developed by research groups worldwide, which mainly reflects unresolved scientific uncertainty regarding some key climate processes, and the different ways that the respective modeling teams represent those processes in their models. For planning purposes, it is important to look across the range of model output for the possible direction and magnitude of future change, and not just focus on the average of the models. Consistency among the models in a particular outcome can be taken as a rough measure of scientific confidence in that outcome (IPCC 2013, Lukas et al. 2014).

While the horizontal resolution (gridbox size) of the GCMs has progressively improved over the several model generations since the 1990s, the gridboxes, now typically 30-80 miles on a side, are still too large to reflect the complex terrain of mountainous areas such as Colorado and New Mexico, or to directly represent processes like cloud formation or convective storms which occur at smaller, *sub-grid* scales (though clouds and storms are indirectly represented in GCMs through the use of model *parameterizations*). Thus, GCM output is often *downscaled* through statistical methods, or via regional climate models (RCMs), in an attempt to better capture more local changes to weather and climate.

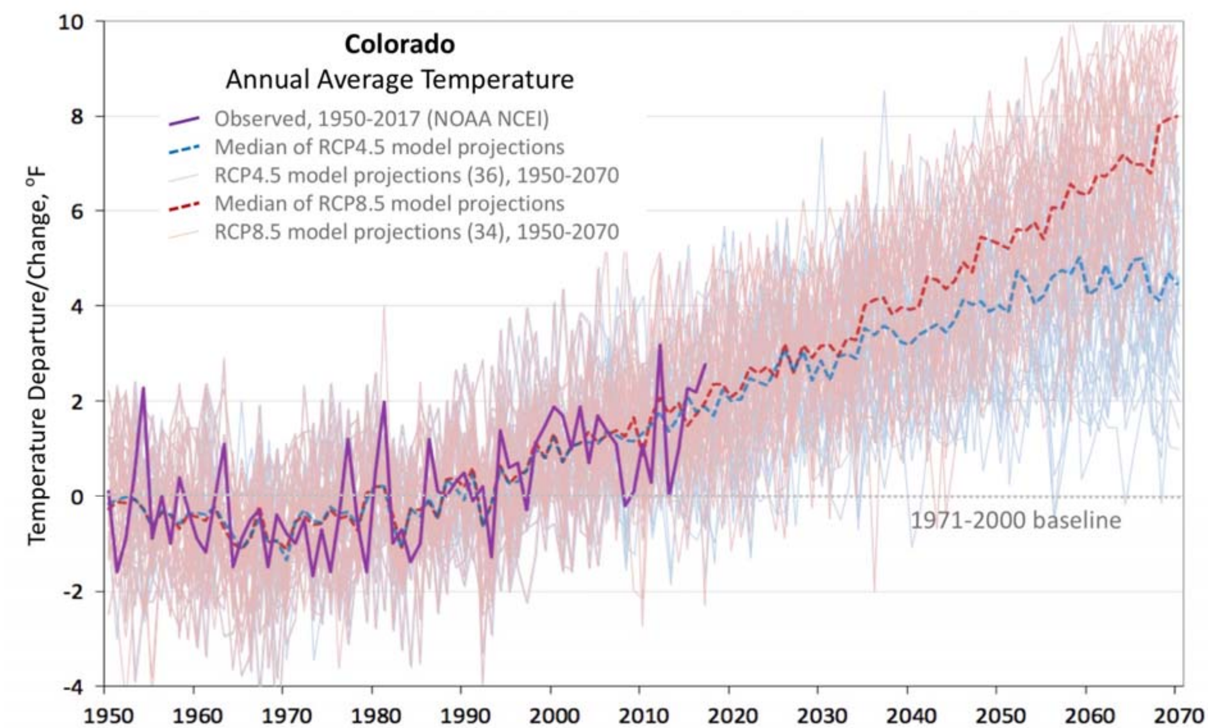
Simulations of future climate from GCMs are known as *projections*, as opposed to predictions or forecasts, because the projections are conditional on an assumed future trajectory for greenhouse gases and other human influences on climate. To represent the uncertainty in the future emissions of greenhouse gases, four trajectories called *representative concentration pathways* (RCPs) have been developed; these are numerically labeled according to their impact on the Earth's surface energy balance by 2100, in units of W/m^2: RCP2.6 (low emissions), RCP4.5 (medium-low), RCP6.0 (medium), and RCP8.5 (high emissions). Most published analyses of climate change focus on RCP 4.5 and/or RCP8.5; RCP2.6 is considered by many experts to be implausibly optimistic in its assumed reduction of emissions.

Several dozen GCMs have been developed by over 20 modeling centers in 10 countries. Under the auspices of the Coupled Model Intercomparison Project (CMIP), the available models are run under standardized protocols, including emissions scenarios as described above, to produce future climate projections to support the periodic Intergovernmental Panel on Climate Change (IPCC) reports. The last phase of CMIP and the most recent set of projections was CMIP5 (released in 2011-2012), which followed CMIP3 (2006); the next set of projections, CMIP6, will be released in the 2018-2020 timeframe. (There was no CMIP4.) A list of the modeling centers and the GCMs for which CMIP5 projections are available can be found at: https://esrl.noaa.gov/psd/ipcc/cmip5/help.html.

6. GCM Projections of Future Regional Climate

6.1 Average temperature

All of the GCM projections run for CMIP3 and CMIP5 indicate that Colorado and New Mexico will continue to warm in all seasons through the mid-21st century, under RCP4.5, RCP6.0, and RCP8.5, by +2˚F to +6.5˚F for the period 2035-2064 (~2050) compared to a 1971-2000 baseline (Figure 4; Lukas et al. 2014, USGCRP 2017). The range for the projected warming through mid-century is primarily due to the differences among the GCMs, and secondarily due to the emissions scenario. Even under a lower-end warming outcome (+3˚F), average temperatures in Colorado and New Mexico would be at or beyond the upper end of the envelope of historical climate variability, i.e., "normal" years around 2050 would be similar to the very warmest years of the last century. The overall warming for Colorado over the next several decades is projected to be slightly higher than for New Mexico, by 0.1˚F to 0.3˚F, reflecting that Colorado is closer to the Great Basin "bullseye" that is expected to see the greatest warming over the conterminous US.



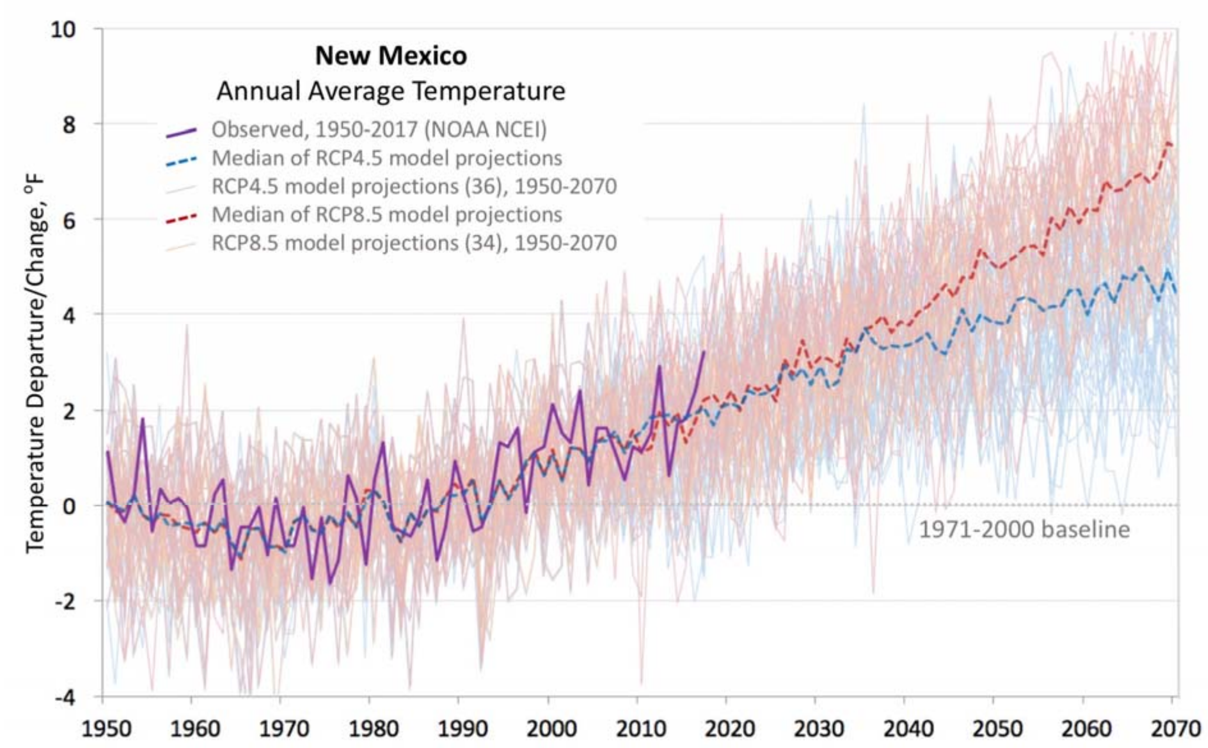


Figure 4. Annual (January-December) average temperature, statewide, for Colorado (top) and New Mexico (bottom), comparing observed temperatures (1950-2017; purple) with historical simulations and future projections from CMIP5 global climate models under the medium-low emissions scenario RCP4.5 (blue) and high emissions scenario RCP8.5 (red). (Source: Updated from Lukas et al. 2014, Figure 5-2)

After about 2040, the magnitude of the projected warming is increasingly driven by the emissions scenario, as seen in Figure 4, with the rate of warming slowing under RCP2.6 and RCP4.5, but continuing at the same or greater rates in RCP6.0 and RCP8.5. Accordingly, for a later-century period (2055-2084; ~2070), the projected warming ranges from 2.5˚F to 6.5˚F under RCP4.5, but from 5.5˚F to 9.5˚F under RCP8.5, compared to a 1971-2000 baseline.

The warming is projected to be slightly greater in summer (June-August) and fall (September-November), the seasons during which the vast majority of PMP-class events occur, than in winter and spring. This is true for all RCPs, for all future time periods. For example, for the 2035-2064 period (~2050) under RCP4.5, the median annual projected warming for Colorado across 37 models is 4.0˚F, while the breakdown by season is fall, 4.3˚F; summer, 4.2˚F: spring, 3.8˚F; and winter, 3.5˚F.

For all time periods and emissions scenarios, the projected warming for Colorado and New Mexico is roughly 50% greater than the projected globally-averaged warming, reflecting several factors that favor more warming in our region: mid-latitudes are expected to warm more than the tropics; continents are expected to warm more than oceans; and continental interiors are expected to warm more than coastal regions. These differences in the rates of warming have already been observed over the last 30 years (IPCC 2013, USGCRP 2017).

The moisture source regions for precipitation that falls on Colorado and New Mexico, primarily the eastern Pacific Ocean and the Gulf of Mexico, are also projected to warm substantially, but not as much as in Colorado and New Mexico themselves, as indicated above. Sea-surface temperatures (SSTs) in those two source regions are expected to warm at a rate similar to the globally-averaged warming, for a given emissions scenario and future time period, and thus the warming in Colorado and New Mexico will likewise be about 50% greater than the moisture-source SST warming (USGCRP 2017).

6.2 Annual precipitation

GCM projections of future annual average precipitation for Colorado and New Mexico show less agreement about the direction of change, compared to projections of future temperature. In general, the models agree that the prevailing westerly storm tracks across western North America will shift northward, and that individual storms will become more moist, consistent with the Clausius-Clapeyron relation (see Section 6). The models do not agree on future changes in ENSO (El Niño/La Niña) events, which can impart a strong influence on precipitation in our region.

As a group, the GCM projections of average annual precipitation for Colorado in the mid-21st century (2035-2064) are evenly split between increases up to +5-10%, decreases up to -5-10%, or no change, compared to a 1971-2000 baseline. Examining projections of seasonal precipitation, there is a pronounced tendency towards future increases in winter precipitation, and decreases in summer precipitation. For New Mexico, the northward shift in storm tracks is more important than other factors, and so the GCM projections of average annual precipitation are tilted towards drier outcomes in all seasons (up to -10%), especially for southern New Mexico, and especially in summer (Lukas et al. 2014, USGCRP 2017). Because of the high interannual and decadal variability in precipitation described earlier, it will be difficult to discern if future observed changes in precipitation are systematic trends due to anthropogenic climate change, or temporary excursions from the long-term average due to decadal-scale natural variability.

6.3 Extreme precipitation

GCMs produce projections of future precipitation at daily and more frequent time-steps, and there have been many studies that have examined GCM output to infer likely future global and regional changes in daily precipitation. However, as described earlier, the grid-boxes of GCMs are too large to directly represent some key mechanisms of extreme precipitation, particularly convection, and also the fine-scale topography that drives orographic lift in mountainous areas. Thus, it is more appropriate to use the projections of hourly or daily precipitation from the GCMs to inform us about broad shifts in the nature of precipitation events in Colorado and New

Mexico (and elsewhere) rather than to provide robust estimates of the specific changes in future risk of extreme precipitation.

The degree to which downscaling can address the limitations of the direct GCM output with respect to extreme precipitation depends on the downscaling method. For example, the BCSD5 (Bias-Corrected, Spatially Disaggregated CMIP5) archive is a set of statistically downscaled GCM projections produced by consortium including US Bureau of Reclamation, USACE, and Lawrence Livermore National Laboratory, and has been used extensively to inform water resources planning (Reclamation 2013). These downscaled data, however, are optimized for monthly to annual timescales, and so the statistics of model-simulated *daily* precipitation do not match the observations very well in the western U.S. Other statistically downscaled datasets such as MACA (Multivariate Adaptive Constructive Analogs), ARRM (Asynchronous Regional Regression Model), and LOCA (Locally Constructed Analogs) are more appropriate for the analysis of projected precipitation extremes, as they are downscaled at a daily time-step, with the specific intent of capturing changes in extreme daily events.

Another method for producing more credible simulations of future extreme precipitation events is to drive very-high-resolution regional weather models (such as the HRRR model used in Task 3) with inputs that have been perturbed according to those changes, as a kind of super-downscaling. This is further detailed in Section 8.2.

With these caveats in mind, the GCMs as a group do consistently indicate that extreme precipitation events (>99th percentile) will become more frequent/intense in the future in Colorado and New Mexico, whether the output is downscaled or not, and regardless of downscaling methodology (Kharin et al. 2013, Janssen et al. 2014, Janssen et al. 2016). Janssen et al. (2014), analyzing non-downscaled GCM data, found that for the Southwest US (including Colorado and New Mexico), what is currently the 1-in-5-year (0.2 AEP) 2-day event will become, by the 2070s, the 1-in-3-year event (0.33 AEP) under RCP4.5 and the 1-in-2.5-year (0.4 AEP) event under RCP8.5. Expressed a different way, the current 1-in-5-year event would occur 67% and 100% more often, respectively. These modeled changes in extreme precipitation are driven largely by the projected widespread increases in precipitable water (PW), as described in the next section.

7. Mechanisms by which Climate Change may Impact Extreme Precipitation Events/PMP

7.1 Introduction

The magnitude of a precipitation event is broadly dependent on several physical factors including the amount of atmospheric moisture (precipitable water; PW), the transport of moisture into the storm (convergence), and net upward motion in the storm (NRC 1994).

Deterministic approaches to estimating PMP, such as in Task 1 of the CO-NM REPS study, attempt to optimize these factors simultaneously for an area of interest, so that the PMP reflects the product of the local upper limits on all factors. The first factor, PW, is optimized directly through the use of a moisture maximization ratio, where a design storm's total precipitation is scaled up by a factor of PW_{max}/PW_{obs}, where PW_{max} is the largest value of precipitable water meteorologically possible in that region and at that time of year and PW_{obs} is the precipitable water that was actually observed in association with a design storm. In the absence of a sound physical basis for up-scaling the other factors (convergence and upward motion), they are indirectly optimized through the transposition of design storms from a broader region to the area of interest (NRC 1994, WMO 2009).

Probabilistic approaches to estimating heavy and extreme rainfall potential (i.e., PFA), such as in Task 2 of the CO-NM REPS study, implicitly assume the presence of favorable environmental conditions and storm drivers in estimating the likelihood (potential frequency) of a storm of a given intensity occurring (and thus by association, the driving set of environmental "ingredients"). To obtain a larger sample size with which to compute precipitation frequency distributions, space and time are often interchanged for one another and thus decisions regarding whether and how to include data (e.g., for storms from other regions or seasons) in storm-frequency analyses are analogous to those used during the storm transposition performed in the deterministic PMP approach. Thus, significant changes in certain critical processes and mechanisms have implications for the estimation of both PMP and PFA.

The body of knowledge concerning the impact of climate change on the factors that drive extreme precipitation is growing rapidly. Recognizing that this field continues to evolve and expand quickly, the following sections summarize the current state of scientific progress toward understanding the mechanisms by which climate change may affect extreme precipitation as presently described by the peer-reviewed scientific literature. Section organization and mechanisms included were informed by both relevance to extreme precipitation as well as interest levels of CO-NM REPS participants as indicated by survey results. The factors addressed include: (1) Moisture, (2) Environmental storm characteristics, (3) Event duration, (4) Storm tracks, and (5) Precipitation type. The discussions are framed to be relatively geographically general, with processes and mechanisms most critical to Colorado and New Mexico further detailed in subsequent sections.

7.2 Moisture

Moisture, unlike other extreme precipitation factors, has a clear physical linkage to temperature. The Clausius-Clapeyron relation, established from the First and Second Laws of Thermodynamics, dictates that the saturation vapor pressure (~moisture-holding capacity) of the atmosphere increases exponentially with temperature, at a rate of about 6.5% per °C (3.5% per °F). The total moisture of an atmospheric column is often measured by PW, and the effect of the Clausius-Clapeyron relation is clearly seen in the seasonal climatology of PW in temperate climates such as in Colorado and

New Mexico, where the mean, minimum, and maximum PW values observed from atmospheric soundings in the summer are several-fold higher than in winter season. While the PW value at any given time is strongly influenced by the synoptic weather pattern and its effectiveness at bringing moisture from near and distant sources, temperature fundamentally constrains the range of values that PW may take, especially the extreme values.

Globally-averaged PW as observed from satellites, atmospheric soundings, and ground-based GPS receivers has increased in recent decades at a rate consistent with Clausius-Clapeyron relation (i.e., ~6.5%/°C), given the warming in globally-averaged surface and tropospheric temperatures (Hartmann et al 2013; AR5 WG1 Ch. 2). Future projections of increased globally-averaged PW from global climate models (GCMs) are remarkably consistent and demonstrate high confidence across different climate models, forcings (i.e., the processes causing the climate changes), and emissions scenarios (e.g., Kunkel et al. 2013a; O' Gorman 2015). At the Colorado-New Mexico regional scale, large increases in extreme values (most relevant to PMP) of PW (+13% to +20%) by mid-century are seen in the average GCM projection under both low- and high-emission scenarios (Figure 5).

Given the observed upward trends in greenhouse gas concentrations, the long residence time of greenhouse gases like CO2 in the atmosphere, and the thermal inertia imparted by the oceans, further warming of global surface and tropospheric temperatures is a near certainty over the next several decades. It is thus extremely likely that global and regional average and extreme PW will also increase, though there is less certainty in the *magnitude* of the warming and PW increases, particularly on local scales (e.g., Kunkel et al. 2013a). PW has been increasing and is expected to increase further (Figures 5 and 6). Regardless of storm type, a given future storm event is likely to be supplied with increased moisture compared with today. The same logic that underpins the current practice of moisture maximization suggests that it would be reasonable to increase moisture maximization ratios to accommodate these future changes in PW.

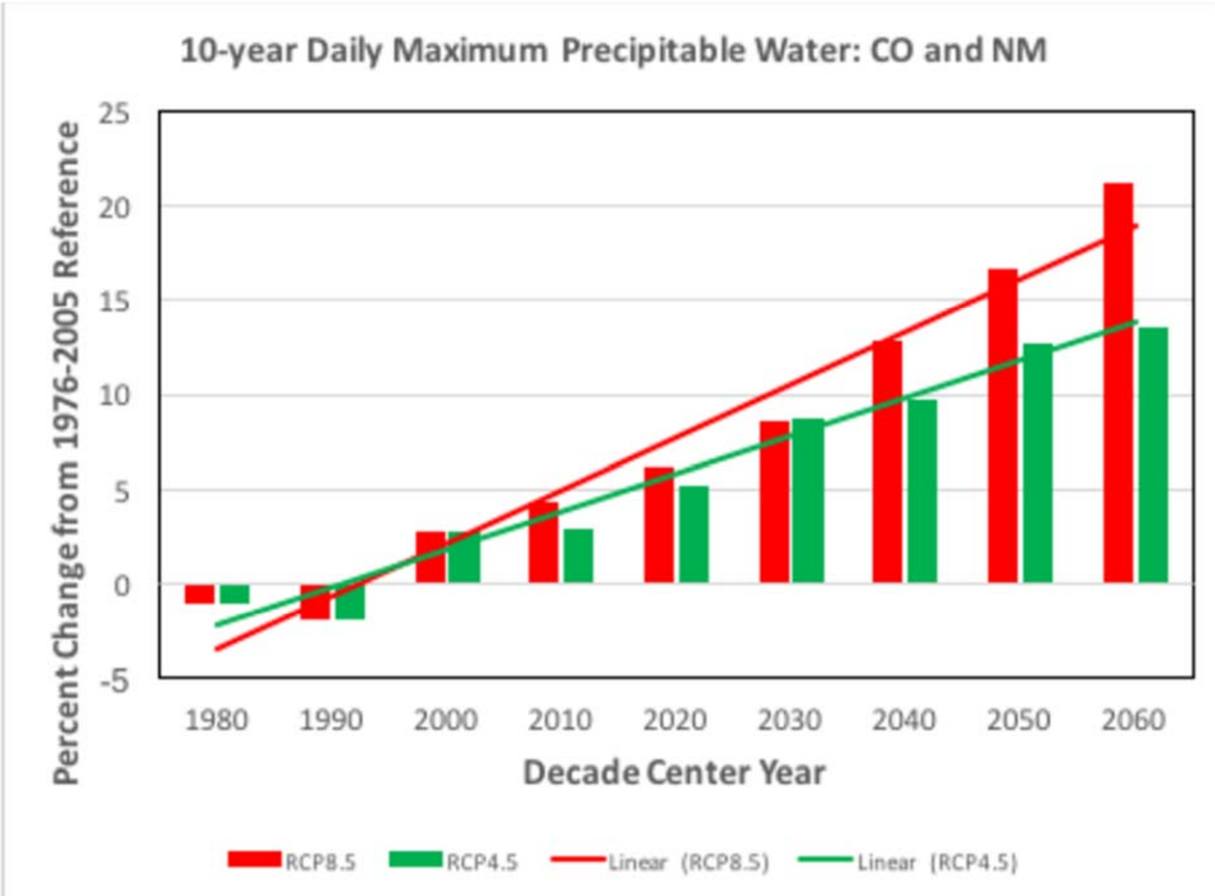


Figure 5: The maximum daily PW over decadal periods averaged for Colorado and New Mexico from 14 climate model simulations in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive for the RCP4.5 scenario (green bars) and RCP8.5 scenario (red bars) (K. Kunkel)

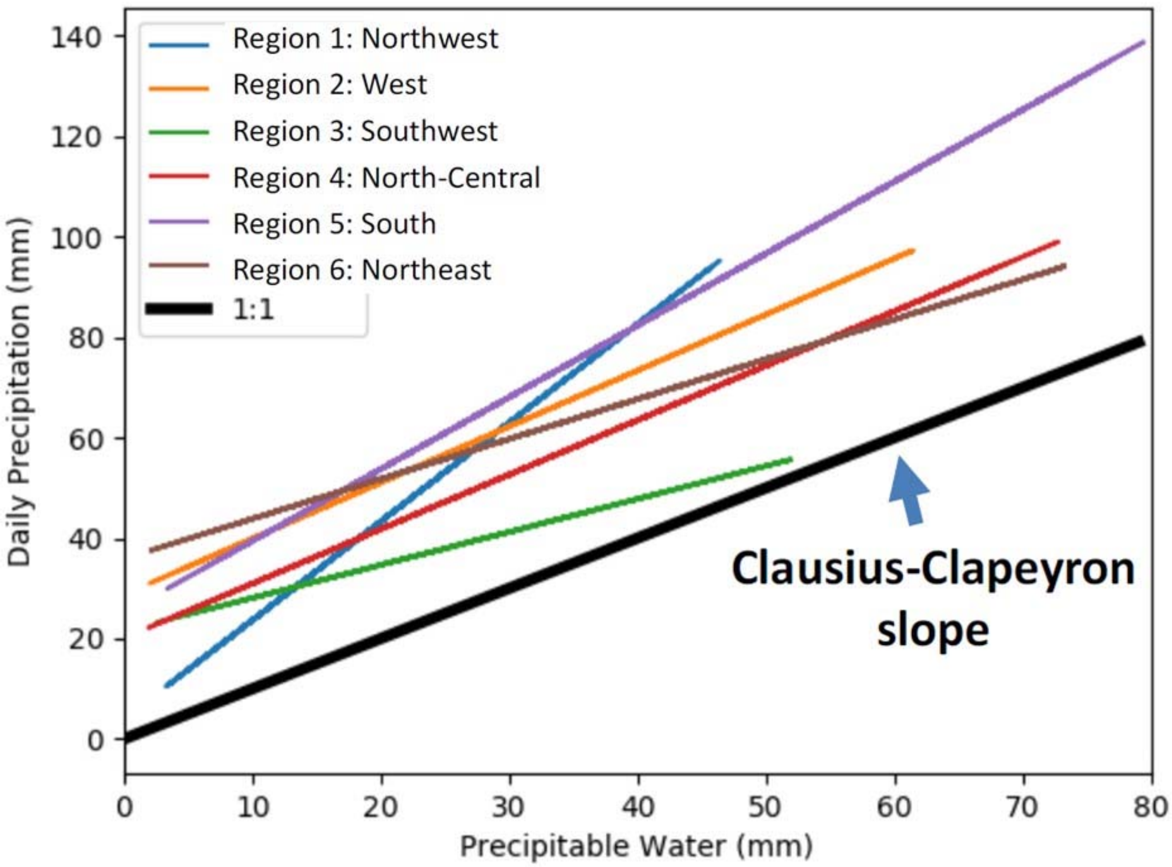


Figure 6. Regional relationships between precipitable water and daily precipitation using 1949 - 2016 annual maximum daily precipitation data from ~3000 precipitation stations and NCEP reanalysis estimates of precipitable water identified for each annual maximum event from nearest reanalysis grid point. While some studies show that local changes in PW do not scale evenly with changes in daily precipitation, this regional analysis of annual maximum daily precipitation shows that the relationship is often fairly close in the aggregate. (From Kunkel and Easterling 2017)

7.3 Storm characteristics: convective intensity and storm efficiency

7.3.1 Convective intensity

The intensity of precipitating storms is often framed in terms of convective available potential energy (CAPE), horizontal convergence, and updraft strength (vertical velocity). While increases in such measures generally contribute to stronger convective storms, the correlation between convective storm intensity and observed rainfall is often quite weak, contrary to what one might expect (e.g., Mahoney et al. 2013; Lepore et al. 2014).

In a warmer and more moist future climate, it is intuitive that CAPE might increase (e.g., Williams and Renno 1993; Ye et al. 1998; Van Klooster and Roebber 2009);

indeed, theory suggests that a warming atmosphere will increase both CAPE and mid- to upper-level updraft velocities (e.g., O'Gorman 2015 and references therein). However, given that the magnitude of warming and moistening may be greater at mid- or upper levels of the atmosphere relative to lower levels, it is possible that environmental stability can increase via lapse-rate stabilization and thereby reduce the intensity of convection (e.g., Marsh et al. 2009; Hill and Lackmann 2011; Loriaux et al. 2017). Analyses and model experiments performed across a wide range of space- and time- scales underscore the known problems associated with assuming a positive correlation between CAPE/vertical velocity and precipitation.

For example, on a global modeling scale, Gastineau and Soden (2009) evaluated a multi-model ensemble of coupled models and found that heavier rainfall occurred in response to global warming despite a reduction in upward vertical motion. (Note that while horizontal convergence is often used as a proxy/indicator of vertical velocity, it is prone to the same limitations of correlation with precipitation.) At regional and smaller scales, the connections become even more tenuous; Mahoney et al. (2013) showed that over Colorado, different regional climate model experiments indicated differing signs and levels of correlation between CAPE, vertical velocity, and precipitation. Thus, using environmental proxies such as horizontal convergence/upward vertical velocity or CAPE to extrapolate likely changes in extreme precipitation is not advised. Thus, given the known non-linearities of extreme precipitation dynamics and the increasing tractability of explicit model simulation of extreme precipitation events themselves, ingredients-based approaches are likely to be of limited value in assessing meaningful shifts in regional precipitation trends.

7.3.2 Efficiency

Unlike moisture, instability, and uplift, which are essential ingredients for rainfall, precipitation efficiency is rather an extrinsic property of precipitation environments or precipitating systems. Precipitation efficiency is considered to be an important physical parameter describing generally the degree to which atmospheric motion converts moisture into precipitation, yet it remains a complex and elusive term to actually define and estimate. However, given the role of the general concept of precipitation efficiency in current PMP estimation practices, it seems relevant to consider this metric through the lens of a warming climate.

Idealized studies using cloud-resolving models suggest that changes in precipitation efficiency could impact shorter-duration convective precipitation extremes in particular, but the relationship between precipitation efficiency and temperature is complex. While large-scale studies show that precipitation extremes follow Clausius-Clapeyron scaling (C-C) at roughly 6–7%/°C (~3.5%/°F) for temperatures above ~21°C (~70°F), studies that focus on smaller space and time scales show considerable deviation from C-C scaling (e.g., Westra et al 2014; Prein et al. 2017). Furthermore, for temperatures below ~21°C (~70°F), precipitation efficiency varies widely in a manner that is not fully understood but depends on temperature and accumulation period. Changes in precipitation efficiency might be expected to occur for variability within a climate as well as for longer term climate change, but results from simulations indicate high levels of sensitivity to the way in which precipitation is modeled, and the potential relevance to observed precipitation extremes is unknown.

Kunkel et al. (2013a) frames storm efficiency as an indicator of the potential for factors other than moisture availability—namely forcing for ascent and horizontal convergence—to affect PMP estimates. Of particular interest is the role of climate warming on frontal features, with an emphasis on how changes in such features might affect storm dynamics and precipitation efficiencies. CMIP5 model projections of such changes are much smaller in magnitude than those indicated for thermodynamics. Kunkel et al. (2013a), along with others cited therein, further points out that changes in the attendant vertical motion will be controlled by still larger-scale controlling dynamics, which, as discussed further below, tend to have less certain regional projections. Thus, while there may be little compelling reason to expect large changes in vertical velocities or storm efficiencies in general, there may be regional dynamical signals suggestive of enhanced intensity and/or frequency of a given event type (e.g., atmospheric rivers; Dettinger 2011).

As PMP practice assumes maximum storm efficiency already, and because precipitation efficiency is more a theoretical concept than actual atmospheric variable or characteristic, we refer to O'Gorman (2015) and references therein for further detail of the theoretical framework.

7.4 Event duration

While an absolute limit to moisture over a given location may exist, there is likely no corresponding absolute limit in storm duration. Hurricane Harvey (2017) is one example of a PMP-exceeding event that was less exceptional for the amount of moisture at any one time (PW) than for the incredible duration of heavy rainfall over the Houston region. Following Doswell et al. (1996), precipitation amount is determined by rate times duration. The factors discussed above mainly pertain to precipitation rate. The duration of precipitation extremes is yet another complex consideration, with both theory and research results indicating that future changes in storm duration vary considerably by region, storm type, and spatial scale.

On global climate scales, results have shown a relatively simple, logarithmic upward shift in intensity-duration-frequency curves as the climate warms, for accumulation periods ranging from 6 hours to 10 days (e.g., Kao and Ganguly 2011). However, given weaknesses in GCM representation of convection, and the likely importance of convective processes in determining subdaily extremes, higher-resolution model studies are recommended, particularly for shorter-term (sub-daily) accumulation periods (e.g., Ban et al. 2014; Kendon et al. 2014).

As PMP is defined using specific event durations, it is necessary to consider mechanisms that may differentially affect event durations on both short (hourly) and longer (multi-day) timescales. On longer (multi-day) timescales, trends in the duration of stagnant or slowly-evolving large-scale weather patterns must be considered. To first-order, a polar amplification of warming as has been observed and further projected would indicate weaker mid-level winds and wind shear via a reduced thermal wind gradient, but how this manifests to control dynamics within precipitation events themselves is uncertain. Stationary, “blocking” patterns have been cited for contributing to PMP-controlling storms such as in the 2013 Colorado Front Range flood by increasing the period over which the environment for heavy rainfall is supported. However, different research approaches produce conflicting results regarding whether, where, and by how much such large-scale, stationary patterns might increase in the future, and what the ultimate influence of such changes would be on extreme precipitation events (e.g., Hoerling et al. 2014; Trenberth et al. 2015; Pall et al. 2017).

For shorter time- (and thus usually smaller space-) scales on which convective processes often dominate, as well as in regions of complex topography, weaker mid-level steering currents may conceivably increase the durations of sub-daily extreme precipitation events by decreasing the forward speed of the storm, and/or by increasing *training* (precipitation reformation over the same location; e.g., Trapp et al. 2007). Prein et al. (2017) examined changes in mesoscale convective system speed changes using high-resolution future climate simulations, and while in some regions systems that moved the slowest (<12 mph) in the present-day simulations reduced their speeds further by up to 20% in the future, such changes in storm speed were highly regionally variable. As changes in mesoscale precipitation system motions reflect complex interactions between steering level flow and changes in internal precipitation system processes (e.g., cold pool dynamics), hazarding even a guess at meaningful future trends would be difficult. However, given that general climate circulation theory as well as explicit storm-scale model studies indicate the potential for slow-moving precipitation systems to move even more slowly in the future, and that PMP seeks to maximize precipitation potential, a future with slower-moving storms and more stationary larger-scale weather and climate patterns might be considered in the PMP storm maximization process, even if in a qualitative manner.

The relationship between event duration and changes in overall storm precipitation is also an area of continued research. Though many scaling studies suggest that increases in precipitation rates outpace Clausius-Clapeyron scaling for shorter-duration events (e.g., Loriaux et al. 2013; Lenderink et al. 2017), others (e.g., Rastogi et al. 2016) have found the change in rainfall depth to be smaller in shorter duration and larger in longer duration storms.

Storm duration and its relationship to extreme precipitation in a changing climate is a relatively regional, phenomena-specific topic. Incorporating relevant changes in event duration into PMP estimation requires consideration and analysis of potential duration effects of the specific regional phenomena which most determine PMP.

7.5 Storm tracks

It is sometimes hypothesized that, on a global scale, a warming climate may result in an overall poleward shift of extratropical cyclone storm tracks by the end of this century, and that decreased low-level baroclinicity may decrease the frequency of mid-latitude storms (e.g., Bengtsson et al. 2006; 2009; Chang et al., 2012). However, regional changes, as well as actual linkage to extreme precipitation changes, may differ from this global trend (e.g., IPCC AR5 WG1 Chapter 12; Salathe 2006; Colle et al. 2013). Further, the IPCC AR5 WG1 report Section 14.6.2.1 concludes that the net effect of changes in baroclinicity is unclear.

Given that deterministic PMP estimation seeks a single "most stressing" design storm, and shifts in storm tracks are more likely to affect intensity-duration-frequency (IDF) curve analysis, the potential effect that storm track changes would have on PMP estimation process is likely negligible, apart from the possible consideration of widening potential storm transposition limits, given future projected changes in storm tracks for a given region. With respect to storm transposition limits changing to encompass projected storm track information, current understanding of dynamical shifts in storm tracks may be too limited to justify systematic changes given the level of regional and phenomena-specific detail one would need to consider, and the aforementioned uncertainties inherent therein (e.g., Deser et al. 2012; Shepherd 2014).

Shepherd (2016) summarizes the general state of the science for this type of dynamics-centric analysis, and details a framework in which the probability of an event occurring is diagnosed according to a specific dynamical situation conducive to that extreme. Despite the large dynamical uncertainties found in climate model projections, examining shifts in storm frequency may be a desirable step toward incorporating climate change information for probabilistic precipitation frequency analysis.

7.6 Precipitation type

Frozen precipitation (snow, hail, graupel) extremes may respond differently to climate warming than liquid precipitation extremes (rainfall). On a global scale, snowfall extremes have been found to behave differently from rainfall extremes (O'Gorman 2015). Specifically, high-elevation snowfall extremes, and the potential for snow to become rain as the surrounding large-scale environment warms, is an even more nuanced and region-specific consideration that lacks clear answers to date. Changes in the frequency and types of hail and other frozen precipitation species are also of interest given the existing rationale to reduce PMP estimates above certain elevation thresholds based on their assumed occurrence as frozen (hail or graupel) and thus less of an influence on instantaneous runoff response.

Observational studies have shown highly variable trends in snowfall extremes, demonstrating great variability by region, metric used, and time period examined. Physically, snowfall extremes are expected to be affected by climate warming through both increases in saturation vapor pressures and changes in the frequency of occurrence of temperatures below the rain-snow transition temperature, but reliable, long-term observations from which to draw representative conclusions are severely limited (O'Gorman 2015). Studies considering the effects of observed warming on hail have largely relied upon the linkage of proxy atmospheric indicators and (usually sparse) hail observations, and are thus fundamentally inhibited by a) the inadequate historical record of past hailstorms, b) the coarseness of the datasets employed (usually global data and climate model simulations), and c) the often tenuous connection between large-scale environmental parameters and small-scale weather extremes. Thus, the conclusions that can be drawn from these types of studies are limited (e.g., Mahoney et al. 2012; Brimlow et al. 2017).

Given the challenges of observing snowfall and precipitation in remote, high-elevation locations, modeling studies (particularly regional modeling studies) likely offer the most useful guidance on this topic. For example, Salathé et al. (2014) used a regional dynamical downscaling approach to demonstrate projected increases in future flood risk in many Pacific Northwest river basins due to both more extreme and earlier (in the season) storms, and warming temperatures that shift precipitation from snow to rain. Rasmussen et al. (2014) found very similar findings for the Colorado Headwaters region in the western U.S. A significant body of research also demonstrates that increases in synoptic system intensity and low- and mid-level temperatures are likely to produce more winter precipitation in the form of rain as opposed to snow, and that such a trend would increase flood risk particularly at higher elevations in complex terrain (e.g., Leung and Qian 2009; Rasmussen et al. 2014, Guan et al. 2016).

Model studies of extreme precipitation events under future climate conditions also suggest a conversion of some small hail/graupel precipitation to liquid precipitation (Mahoney et al. 2012, 2017; Brimlow et al. 2017). These studies also find that warming temperatures in the vicinity of elevated terrain are particularly notable both in their relative magnitude to lower elevations as well as in their potential to alter impacts and flood risk based on precipitation type. This resultant precipitation-type transition from frozen to liquid in higher-elevation locations suggests the potential for increased flood risk via instantaneous runoff generation as opposed to more gradual snowmelt processes; implications for PMP estimation in elevated terrain are discussed in the Recommendations section.

7.7 Summary of physical mechanisms

Future changes in moisture, dynamics, storm intensity, duration, and precipitation efficiency and type will all play a role in changing precipitation extremes. Confidence in future projections of each of these critical aspects, based on the current state of the science, varies considerably. While there is strong confidence in the sign of change in thermodynamic quantities (increasing large-scale temperature and moisture), there is decidedly less confidence in changes in circulation-based/dynamical effects, and particularly the manifestation of all such changes for extremes at local scales. As precipitation is controlled by both thermodynamics and dynamics, and extreme precipitation is itself a highly localized phenomenon, the large uncertainties surrounding dynamical effects threaten to impede progress to incorporate climate change information in a fully deterministic framework. Yet given the high confidence that changes of some type are likely to occur, and the relatively high confidence in the thermodynamic change mechanisms specifically, there may be merit in moving from a confidence-based, essentially deterministic approach to a more explicitly probabilistic, risk-based approach that can accommodate a larger spectrum of change potential (Shepherd 2014). Ramifications of such a shift are discussed in the Recommendations section.

8. The Current State and Direction of PMP/PFA Practice with Respect to Climate Change

With very few exceptions, PMP and PFA estimates as currently used in Federal, state, and local infrastructure decision-making in the U.S. have not been explicitly informed by information about climate change. The past decade, however, has seen climate change emerge as a key topic in discussions within and among regulatory agencies regarding future directions for PMP/PFA practice. Some Federal agencies have conducted pilot studies of approaches that incorporate climate change into infrastructure planning and management and taken other steps towards implementation. To date, these efforts have not yet led to the systematic use of climate-change-informed approaches within an agency, or to concrete and accepted guidance for the broader engineering community on how to incorporate climate change in PMP or Probable Maximum Flood (PMF) estimates, or in PFA or similar flood frequency analyses (FFA).

8.1 Operational estimates of PMP as used by multiple stakeholders

The most recent series of Hydro-Meteorological Reports (HMRs) reports and their respective state and regional PMP estimates, released by NOAA NWS from 1963 to 1999, predate the emergence of climate change as a consideration in the design of civil infrastructure. The subsequent development of state-level and site-specific PMP estimates has been conducted largely by consultancies, including Applied Weather Associates (AWA), the lead for Task 1. Most of the recent PMP reports by AWA have included brief sections acknowledging climate change as a potential factor influencing future PMP amounts, while concluding that “the current practice of PMP determination should not be modified in an attempt to address potential changes associated with climate change” (AWA 2015).

8.2 Operational PF estimates as used by multiple stakeholders

The current NOAA Atlas 14 point precipitation frequency estimates available for Colorado, New Mexico, and most of the U.S., like their predecessor analyses by the NOAA NWS Hydrometeorological Design Studies Center (HDSC), assume stationarity and do not explicitly account for any trends or changes in precipitation frequency, including the potential effects of climate change. As a recent quarterly report from HDSC acknowledges, the Atlas 14 estimates “may not be suitable for frequency analysis in the presence of non-stationary climate conditions” (NOAA NWS 2017).

In 2015, the Federal Highway Administration asked the HDSC to assess the effect of the stationarity assumption on the Atlas 14 estimates. HDSC selected frequency analysis methods suitable for distribution fitting under non-stationary conditions, and performed preliminary analyses, effectively weighting more recent precipitation data. While this pilot project generated “more questions than answers,” HDSC is currently continuing this work, with the goal of developing a modeling framework that will allow non-stationary climate effects to be integrated into the NOAA Atlas 14 process, for production of updated estimates at a national scale. The effort will both identify the most suitable non-stationary precipitation frequency analysis methods, and test the feasibility of incorporating climate projections into precipitation frequency analysis. A report on the former is expected in late 2018 (NOAA NWS 2017, NOAA NWS 2018).

8.3 Operational FFA as used by multiple stakeholders

The Bulletin 17 series provides recommended guidance for determinations of flood-flow frequencies by Federal agencies and others. In spring 2018, the U.S. Geological Survey (USGS), with Reclamation, USACE, and the Advisory Committee on Water Information (ACWI), released the first update since 1981, called Bulletin 17C, *Guidelines for Determining Flood Flow Frequency* (England et al. 2018). The brief (one half-page) section on climate variability and change notes that “time invariance [e.g., stationarity of climate and hydrology] was assumed in the development of this guide,” but then suggests that “where there is sufficient scientific evidence to facilitate quantification of the impact of climate variability or change in flood risk, this knowledge should be incorporated in flood frequency analysis by employing time-varying parameters or other appropriate techniques.”

8.4 Policy guidance and pilot studies by Federal agencies and others

8.4.1 US Army Corps of Engineers (USACE)

In 2014, USACE released an Engineering and Construction Bulletin (ECB 2014-10) containing initial guidance for incorporating climate change information in hydrologic analyses, in accordance with USACE’s broader climate change adaptation policy. That policy requires consideration of climate change in all current and future studies to reduce vulnerabilities and enhance the resilience of water-resource infrastructure. The ECB was reissued and updated in 2016 as ECB 2016-25. This ECB requires that *qualitative* analysis of potential climate change threats and impacts to projects and operations be conducted for all hydrologic studies for inland watersheds. This qualitative analysis is “not expected to alter the numerical results” of other aspects of the hydrologic analyses, but it can inform the decision process related to project planning, engineering, operation, and maintenance.

The ECB states that future versions of this guidance will include requirements for *quantitative* assessment of climate-change impacts, including for PMF, but at present, “there is no compelling evidence that would support climate-related changes in PMFs.

[...] Only after a substantial body of research has been amassed to facilitate a quantitative understanding of the relationship between climate change and the magnitudes of extreme storms, can USACE begin to develop the tools necessary to facilitate a quantitative assessment of how to incorporate climate change impacts into applied hydrologic analyses supporting PMF magnitudes and/or the uncertainties associated with them" (USACE 2016). In other words, USACE is recognizing the potential for climate change to affect PMP and PMF, but it will not revisit PMP/PMF estimates until there is a stronger scientific basis for performing PMP/PMF analyses under climate change.

8.4.2 Bureau of Reclamation

In 2011, the Reclamation Dam Safety Office issued new Dam Safety Public Protection Guidelines (Reclamation 2011). While these guidelines did not directly address climate change, they recommended a shift from the prevailing deterministic framework for hazard analysis to a probabilistic risk-informed framework that is more amenable to the inclusion of time-varying risk factors such as climate change.

In 2014, Reclamation released a Climate Change Adaptation Strategy. This strategy identified four key goals to improve Reclamation's ability to adapt to climate change. Goal 3, "To improve infrastructure reliability," included several action items, including the development of climate change pilot studies by the Reclamation Dam Safety office. The first quantitative pilot study, "Climate Change in Hydrologic Hazard Analyses: Friant Dam Pilot Study" (Bahls and Holman 2014, Novembre et al. 2015), used downscaled CMIP5 (BSCD5) climate projections of monthly temperature and precipitation to adjust historical observations (1950-1999) to represent five different scenarios of potential future climate conditions (2020-2069) in the hydrologic model used to generate peak flows for simulated storm events. The hydrologic conditions that were future-climate-adjusted included antecedent precipitation, snowpack, and soil moisture; air temperatures for snowmelt; initial reservoir level; precipitation magnitude-frequency; but *not* storm duration or spatial characteristics. The study found that precipitation and thus reservoir inflows at PMP-class probabilities (10^{-4} to 10^{-5} AEP) increased in two of the five climate scenarios by 20-30%, but decreased in the other three scenarios by 10-20%.

The Friant Dam pilot study was a first step to develop a methodology for incorporating future climate projections into hydrologic hazard analyses, and it was expected that the methodology would require modifications before application to additional dam projects. Significantly, the study used monthly ratios to adjust the precipitation magnitude-frequency curves, which may not be physically realistic. The study authors proposed additional steps to refine the methodology for future studies, including the use of different downscaled data to generate daily ratios. A smaller pilot study for Green Mountain Dam (Sankovich et al. 2012) and a related subsequent study for Taylor Park Dam in Colorado test a different methodology based on high-resolution weather model simulations with climate change projections imposed (see Section 8.2); the Taylor Park study is slated to be completed in late 2018.

Reclamation has also conducted *qualitative* assessments for climate-change effects on several dozen high-hazard dams, and is taking the lead on a revision of the Interior's Departmental Manual on Dam Safety and Dam Security Programs. The revision will add a new section committing Interior agencies to develop and periodically review their policy and guidance to address climate change adaptation as the science advances and the impacts become more quantifiable.

8.4.3 Nuclear Regulatory Commission (NRC)

In response to the 2011 tsunami-induced severe accident at Fukushima Daiichi nuclear generating plant in Japan, NRC established a Probabilistic Flood Hazard Assessment (PFHA) research plan, in support of developing quantitative, risk-informed probabilistic framework for assessing flood hazards and promulgating design standards, in contrast to the longstanding deterministic procedures used by NRC. One focus area of the PFHA plan is assessing the potential impacts of climate change and other dynamic, non-stationary processes on site characteristics, flood hazard assessment, and flood protection. Research in this focus area has been carried out by Pacific Northwest National Laboratory (PNNL). NRC has also convened several multi-agency workshops on PFHA to share information on probabilistic flood-hazard assessments for extreme events among Federal regulators and other stakeholders. Since the first workshop in 2013, climate change has become increasingly prominent as an item of concern and discussion in relation to hazard assessment practice.

8.4.4 Department of Defense (DoD)

In 2014, the DoD issued a Climate Change Adaptation Roadmap (CCAR), which, among other mandates, directed the department to modify its infrastructure design, construction, and maintenance to adapt to the effects of climate change, calling out the need to "accommodate more frequent and intense precipitation events." The Strategic Environmental Research and Development Program (SERDP) is DoD's environmental science and technology program, executed in partnership with DOE and EPA. In 2015, SERDP initiated funding of five research projects, led by university-based investigators, to pilot different but complementary approaches for informing precipitation intensity-duration-frequency IDF curves (i.e., PFA) with climate-change information. All of the studies are using output from global and/or regional climate models, in combination with historical data, in varying conceptual, statistical, and modeling frameworks. Some studies are using event precipitation directly from the models, while others are using an ingredients-based approach as described in a previous section. In Section 9, Recommendations 2 and 3 are based in part on results from one of these SERDP-funded projects (Kunkel and Easterling, 2017).

8.4.5 American Society of Civil Engineers

In 2011, the American Society of Civil Engineers (ASCE) formed the Committee on Adaptation to a Changing Climate (CACC) to evaluate the technical requirements and civil engineering challenges for adapting to a changing climate, and in 2015 the CACC produced a white paper, "Adapting Infrastructure and Civil Engineering Practice to a Changing Climate." In a brief discussion of PMP/PMF and flood frequency analyses, the white paper notes that "new methods for estimating the PMF may be needed to account for climate change." In May 2017, the CACC held a workshop at ASCE headquarters in Reston, VA on engineering methods for precipitation under a changing climate; afterwards, the workshop participants began work on a technical report intended to describe such methods.

9. Review of Approaches for Incorporating Climate Change into PMP and PFA

Recent research studies have used a suite of approaches to quantify the potential effects of future climate change on PMP and PFA. These studies have served to (a) pilot methodological approaches that may be appropriate for broader applied use, (b) provide specific results (e.g., % change in PMP by a given date) which can inform discussion of PMP under climate change, and (c) identify sensitivities and uncertainties that are relevant to that approach or multiple approaches. The use of climate models is a key commonality among the studies, but the model output has been produced at different scales and used in different ways. Models are necessary for gaining understanding of conditions and changes that have not yet been observed.

9.1 Global and regional climate modeling studies

Studies using model output from GCMs and RCMs generally use an “ingredients-based” approach to conclude that PMP is likely to increase under a warming environment (e.g., Kunkel et al., 2013a; Beauchamp et al., 2013; Rousseau et al., 2014; Stratz and Hossain, 2014). While GCMs and RCMs are critical tools for obtaining climate-scale future projections, they are not suitable for the explicit representation of extreme precipitation due mostly to the limitations of convective and microphysical parameterization required at larger grid lengths. Thus, studies that examine actual precipitation output from GCM and even RCM projections often employ statistical or dynamical downscaling procedures to make the information more relevant to the local scale.

Ingredients-based methods, and those that focus on changes in moisture in particular, benefit from the relatively high confidence in GCM and RCM projections of thermodynamic properties (temperature and moisture). An often-cited example of this approach for PMP specifically is that of Kunkel et al (2013a), in which climate model simulations and conceptual models of relevant meteorological systems are used to project 20-30% increases in maximum water vapor concentrations over CONUS by 2071-2100. In this study, changes in other ingredients such as maximum horizontal and vertical winds were too small to offset the impact of increased moisture, and thus it was concluded that PMP values will increase due to higher water vapor content and consequent higher moisture transport into storms.

Other studies using GCM output to address changes in the moisture maximization ratio PW_{max}/PW_{obs} similarly find that PMP increases, in some regions by very large amounts, due to robust increases in future precipitable water (e.g., Beauchamp et al 2013, Rousseau et al 2015, Afrooz et al 2015, Klein et al 2016, Lee et al 2016, Rouhani and

Leconte 2016). However, as stated previously, the dynamics of extreme precipitation events are often highly non-linear and resulting precipitation does not always scale directly with changes in ingredients.

While GCMs are not suitable for extreme precipitation analysis due to their coarse resolution, simulated precipitation from these models is sometimes analyzed for other applications. For instance, the unique aspect of the extended duration (5+ days) of the 2013 Colorado Front Range flood event was examined using GCM simulations contrasting the likelihood of multi-day September heavy rain events between present-day (climate change) and pre-industrial (no climate change) cases (e.g., Hoerling et al. 2014; Quan et al. 2018). In the models and scenarios examined for this event, the likelihood of a particular 5-day pattern of precipitation was shown to decrease for the northeast Colorado region. While limitations of the GCMs examined may necessitate additional work on this topic, the general method addresses how atmospheric dynamics may affect extreme precipitation frequency, an effect that is often missing in studies that consider only thermodynamic effects. Therefore, such approaches can address how the frequency of a given event type might change in the future climate, but cannot address possible changes in maximum intensity (which is more relevant to PMP) due to the inadequate resolution of GCMs.

In light of these challenges with the “raw” global climate model data, many studies utilize various downscaling techniques to produce precipitation projections at space- and time-scales relevant to PMP estimation. There are several studies that have used dynamical downscaling of historical atmospheric reanalysis data to produce PMP-type estimates (e.g., Ishida et al. 2015; Chen and Hossain 2016; Chen et al. 2017b; Mahoney et al. 2018); the same approaches can be used for downscaling of climate model data to produce higher-resolution extreme precipitation estimates (Beauchamp et al., 2013; Lee et al., 2017; Ohara et al., 2011; Rastogi et al., 2017; Rouhani & Leconte, 2016; Rousseau et al., 2014; Tan, 2010; Chen et al. 2017). Though these studies demonstrate potential value for historical PMP estimates, all also stress the sensitivity of the results to the selection of climate models due to the variable (and often unknown) model skill (i.e., the ability of the model to adequately simulate the phenomena of interest).

Regional climate model output has also been used for PMP estimation; RCMs provide more spatially resolved precipitation features, though run generally at ~20-km to 50-km (~12-mi to 30-mi) grid spacings, they still struggle to adequately represent processes and mechanisms critical to extreme precipitation generation (e.g., Beauchamp et al., 2013; Rastogi et al., 2017; Rousseau et al., 2014). Clavet-Gaumont et al. (2017) uses an ensemble of 14 RCM simulations and traditional PMP and PMF estimation methods to examine possible changes in PMP and PMF in Canadian springtime extreme precipitation events. They conclude that while RCMs “can generate a large number of physically plausible events leading to PMFs as well as include the effect of climate change...very large ensembles would be required to reduce the sampling uncertainty of extremes such as the PMP and make the results useful to decision-makers and regulators.”

Chen et al. (2017) presents a "hybrid approach" that combines the moisture maximization steps of the traditional, HMR-indicated engineering PMP estimation procedure and CMIP5 GCMs to generate model-based estimates of PMP for current and future climate conditions over the Pacific Northwest. An ensemble of five statistically downscaled CMIP5 models are used to try to reproduce roughly historical PMP estimates as found in HMR57; future projections indicate an increase in PMP 50% ± 30% by 2099 under the RCP8.5 scenario. The study concludes that most of the increase is caused by warming via enhanced moisture availability through increased sea surface temperature, with minor contributions from future changes in storm efficiency. This approach leverages the availability of long climate model data records in both the past and future, but still suffers from the coarse resolution at which the CMIP5 models are originally run. An additional caveat to an otherwise promising idea is that since extreme precipitation in the Pacific Northwest is largely the result of landfalling atmospheric rivers (ARs), which are themselves better represented by relatively coarse models, approaches that work well for this particular region may be considerably less skillful in regions with more diverse and small-scale precipitation generation mechanisms.

9.2 Higher-resolution, explicit model simulation of extreme storms

Computational power and numerical weather forecasting models have sufficiently improved over the past decade or so to enable storm-scale PMP evaluation by simulating "PMP storms" explicitly. Convection-permitting climate models are necessary to simulate heavy precipitation, especially at sub-daily scales, as sufficiently high resolution (generally ≤2.5 mi) permits explicit simulation of deep convection (e.g., Prein et al. 2015). Use of high-resolution models for examining "PMP storms" began in the late 1990s; studies such as Abbs (1999), Cotton et al. (2003), Tan (2010), Ohara et al. (2011), Woldemichael et al. (2012, 2014), Ishida et al. (2015a, b), and Chen and Hossain (2016) demonstrated the utility of high-resolution dynamical modeling for PMP-relevant extreme precipitation events via successfully downscaling historical storms from various reanalysis datasets, introducing moisture maximization and boundary-shifting methods to extend the results of storm simulations to actual PMP estimation, and experimenting with various model physics and data inputs to assess specific effects of land use and land cover.

The high-resolution "PMP-storm" modeling framework has been recently adopted to assess the potential effects of climate change on PMP as well. Ishida et al. (2016) use a dynamical model approach to demonstrate how PMP changes with temperature over the American River watershed in California. They performed experiments showing monotonic increases in PMP according to idealized, uniform temperature increases, as well as significant PMP increases in response to using climate model-projected temperatures for adjustments to their initial and lateral boundary conditions. Their results indicate increases in PMP of 14.6% in the middle of the 21st century and 27.3% in the end of the 21st century. Rastogi et al. (2017) use a physics-based numerical weather simulation model to estimate PMP across various durations and areas over the Alabama-Coosa-Tallapoosa (ACT) River Basin in the southeastern United States. Six sets of Weather Research and Forecasting (WRF) model experiments driven by both reanalysis and global climate model projections, with a total of 120 storms, were conducted in manner that blends aspects of the traditional PMP moisture maximization procedures with high-resolution model simulation. Depth-area-duration relationships were derived for each set of WRF simulations and compared with the conventional PMP estimates. The results show that PMP driven by projected future climate forcings is higher than 1981–2010 baseline values by around 20% in the 2021–2050 near-future period and 44% in the 2071–2100 far-future period.

A follow-up study to Rastogi et al. (2017) extended the PMP study to encompass additional factors affecting PMF. Gangrade et al. (2018) used the WRF model in conjunction with the distributed hydrologic model (DHSVM) over the ACT River Basin to examine the how PMP variability, climate change, land use land cover change, antecedent soil moisture conditions, and reservoir storage may individually or jointly affect the magnitude of PMF. Moisture-maximized PMP storms under historic and projected future climate conditions were used to drive DHSVM in current and projected future LULC conditions; results showed that for this basin, PMP and PMF are projected to increase significantly, and the largest sources of sensitivity were found to be the precipitation forcing and climate change, followed by antecedent soil moisture, reservoir storage, and then LULC change.

High-resolution, convection-allowing models may represent the current best, state-of-the-science tool for explicit simulation of extreme precipitation, but due to their high computational expense, they are less often used to address climate change, which generally requires consideration of much longer time periods. However, cutting-edge adaptations to (and hybrid combinations with) this approach are becoming more commonplace in the study of extreme precipitation and climate change in general (e.g., Mahoney et al. 2013; Lackmann 2015; Emanuel 2017; Pall et al. 2017; Dominguez et al. 2018).

Table 1: Summary of North American studies of changes in PMP due to climate change

Study	**Region of study**	**Projected change in PMP due to climate change**
Kunkel et al. (2013a)	US	Changes in maximum water vapor concentrations, which are a principal input to PMP estimation techniques, will change by an 20%–30% by 2071–2100
Beauchamp et al. (2013)	Canada (Summer-Fall PMPs)	+0.5–6% over 2071–2100 period

Stratz and Hossain (2014)	South Holston Dam in Tennessee, Folsom Dam in California, and Owyhee Dam in Oregon	Significant increase over current PMP values when future changes in dew points extrapolated from observational trends or numerical models are taken into account
Ishida et al. (2016)	Northern California	+14.6% by middle of 21st century +27.3% by end of 21st century
Rastogi et al. (2017)	Alabama-Coosa-Tallapoosa River basin (southeastern US)	+20% in 2021–2050 near-future +44% in 2071–2100 far-future periods
Chen et al. (2017)	Pacific Northwest	+50% ± 30% by 2099 under RCP8.5 scenario
Clavet-Gaumont et al. (2017)	Canada	Projected increases in spring PMP except for the most northern basin.

9.3 Precipitation frequency analysis (PFA)-type approaches

Statistical nonstationary analyses of extreme precipitation also suggest that the upper bound of extreme precipitation (PMP and other precipitation thresholds with very low annual probabilities) is likely to change in the future (Cheng & AghaKouchak 2014; Cheng et al. 2014; Gao et al. 2016; Wi et al. 2016).

There are numerous statistical distribution types and methods to estimate key precipitation frequency estimation parameters available and several are used in the literature. Khaliq et al. (2006) provided an excellent review of methods to conduct frequency analysis for dependent and non-stationary variables in general. Non-stationarity is also a common topic in flood frequency analysis (FFA), which is analogous to PFA, only assessing streamflow observations instead of precipitation observations. Delgado et al. (2014) describe a typical chain to assess FFA and flood hazard projections under climate change: "emission scenario → global climate model → downscaling, possibly including bias correction → hydrological model → flood frequency analysis". Delgado et al. (2014) also propose a simplification of this model chain in which other climate model output fields (e.g., wind) are used in place of precipitation, stating that the implementation of existing precipitation-based model chains require major effort, and their complexity is high.

Many FFA studies examining the impact of climate change (e.g., Vogel et al 2011, Gilroy and McCuen 2012, Lopez and Frances 2013, Westra et al 2014, Prosdocimi et al 2014, Delgado et al 2014, Cheng and AghaKouchak 2014, Roman et al 2015), especially those dealing with urbanization and climate change, recommend adoption of nonstationary procedures in FFA due to notable differences with stationary procedures. Examples of recently-suggested approaches include that of Xiong et al. (2015)'s consideration of the effect of non-stationarity in the annual daily flow series on the non-stationarity in the annual maximum flood series, concluding that such a method has potential for widespread application in the face of current general acceptance of the weakness of the stationarity assumption of flood events. As intensity-duration-frequency (IDF) curves are widely used in design and current applications, Cheng and AghaKouchak (2014) propose a generalized framework for incorporating the effect of nonstationarity into updated IDF curves; their analysis suggests that the assumption of a stationary climate may underestimate extreme precipitation by as much as 60%. Alternative methods such as the stochastic storm transposition method also offer possible ways to include the effects of non-stationarity in a frequency-based framework.

Finally, the aforementioned ongoing work to update NOAA Atlas 14 will likely be an important resource for up-to-date understanding how non-stationarity may be best included in PFA for practical applications such as dam safety. The reader is advised to consult the HDSC website for updates on this work.

9.4 Dynamical modeling approaches with extreme precipitation- and flood-frequency components

Due to computational challenges of simulating storms at high resolution over long enough periods to represent relevant AEPs, using high-resolution dynamical simulations of storms within an FFA-type framework is difficult. One recent innovative attempt to do this for the PMP-exceeding 2017 Hurricane Harvey (AWA 2017) is described in Emanuel (2017). This study estimated current and future annual probabilities of areally-averaged hurricane rain of Hurricane Harvey's magnitude by downscaling large numbers of tropical cyclones from three climate reanalyses and six climate models. While the details of the downscaling process are important and relatively specialized to tropical cyclones, the study estimated that the annual probability of 500 mm (20 in.) of area-integrated rainfall was about 1% in the period 1981–2000 and will increase to 18% over the period 2081–2100. Another "hybrid" approach is found in Pall et al. (2017), in which dynamical modeling is combined with an observational-based event attribution approach to estimate that anthropogenic drivers increased the magnitude of heavy northeast Colorado rainfall for the September 2013 floods by 30%, and the occurrence probability of having a week at least as wet as that one which was observed was increased by anthropogenic drivers by at least a factor of 1.3. A similar study of Hurricane Harvey by Wang et al. (2018) combines event-specific, higher-resolution downscaled mesoscale model simulations with GCM analysis of "Harvey-like systems" to address questions of both precipitation intensity and frequency, respectively.

9.5 Summary

Despite the high uncertainties in directly modeling rainfall depth, numerical climate and weather models can provide a theoretically sound framework for a process-based understanding of climate change effects on extreme rainfall and PMP. Analogous to tradeoffs in space and time over the observational record, it is likewise challenging (due to computational constraints) to perform high-resolution, realistic simulations of extreme precipitation over a long enough period of time to address questions on PMP (or even low AEP)-types of events. Thus using various models and model methods in a complementary manner will offer the most complete type of model-based assessment (e.g., Shepherd 2016).

However, it is important to note that conducting such computationally-expensive work (or modeling studies at all) may not be feasible for many agencies and stakeholders. Also, many regional modeling studies to date still apply a fairly large degree of subjectivity in the process, e.g., method selection; model selection; visual assessment of model skill; tuning model parameters to best represent various storm characteristics in specific regions. Numerical modeling offers much potential, and is arguably a necessary vehicle to understand and potentially incorporate specific aspects of climate change into extreme precipitation estimation-based decision-making, but it is does not eliminate (or necessarily even reduce) uncertainty, and no approach to date has emerged as even a potential "one-size-fits-all" [regions, applications, etc.] solution.

10. Conclusions and Recommendations

There is a solid chain of evidence that temperatures globally, and in Colorado and New Mexico, are warming due to human causes, and that this warming will continue in the coming decades. Physical law tells us that increasing atmospheric temperature will, in general, increase the water vapor available to storms, though this general trend is subject to local effects and variability. While anthropogenic climate change may have other, less certain, effects on storm characteristics, observations and model simulations suggest that the basic thermodynamic effect—the increase in precipitable water (PW) with warming temperatures—is likely to take precedence over the other effects, at least at regional to global scales. At local scales, other effects may become more prominent than the PW increase.

By the same logic that underlies the step of moisture maximization in deterministic PMP-estimation procedures as in Task 1, if we expect widespread future increases in PW, then PMP values should also increase, roughly scaled with the magnitude of warming. Multiple modeling studies have produced results consistent with this expectation, showing increases of 15 to 50% in PMP later in the 21st century (Table 1).

Accordingly, our recommendation is that the implementation of PMP or other metrics of risk from extreme precipitation in infrastructure design and regulation by the states of Colorado and New Mexico account for this fundamental, thermodynamically-driven PW change, either qualitatively or quantitatively.

It has been argued that future climate change is “too uncertain” to be incorporated into infrastructure design and regulation. It is true that many aspects of future climate change are uncertain, and even the most certain change with respect to PMP/PFA—warming and the consequent increase in PW—has an uncertain magnitude for any given future period. But we *do* know that the weight of a large body of robust, peer-reviewed scientific evidence leans strongly towards an increasing risk from extreme precipitation events in future decades, and we do have quantitative guidance as to the *range* of potential future changes. Engineering practice dictates that uncertain risks should be addressed by building conservatism into analyses and their implementation (e.g., through safety factors),

It has also been suggested (e.g., by study stakeholders surveyed by the authors; Appendix A) that explicit consideration of climate change may be unnecessary, since future climate-change effects will be implicitly incorporated into PMP through changes in dewpoint climatology and new additions to the storm library. Similarly, future climate-change influenced storms will be incorporated into the frequency-magnitude curves in PFA. In other words, PMP and PFA estimates will “self-adjust” over time. This has some truth, but the climate is changing rapidly, while PMP-class storms are rare events. A self-adjustment process will inevitably lag the true physical changes in risk, potentially by several decades or more. We would argue that it is much better to build the *anticipated* changes in risk into design standards for infrastructure whose lifetimes will encompass significant shifts in the storm environment.

Different methods have been proposed or suggested in the scientific literature to incorporate likely future climate change in PMP and PFA estimation. These are summarized in Section 8. Several of these methods consider and apply the thermodynamic PW effect in isolation, while others involve modeling of multiple “ingredients,” encompassing a suite of effects of climate change on storms, including the thermodynamic PW effect. In general, the methods that isolate the thermodynamic PW effect are more straightforward to communicate and interpret, and involve fewer modeling assumptions and uncertainties.

The question of which method is appropriate, let alone the “best,” needs to be addressed in the context of the decision-making and regulatory framework in which that method is to be used. Currently, the prevailing practice in state dam safety offices is to develop deterministic (i.e., single-number) estimates of PMP and apply them in a fixed, standards-based framework. The single-number PMP is applied as-is for each storm type (Local or General), or scaled in a prescribed manner according to the hazard rating and elevation of the dam structure, leading to discrete decisions with clear justifications.

There has been a recent and significant shift among key Federal agencies towards probabilistic, risk-informed decision-making frameworks for infrastructure design, in which uncertain information is ingested as a probability distribution rather than a single number, and the uncertainty is maintained and considered throughout the analysis. These probabilistic frameworks highlight the uncertainties (e.g., Micovic et al. 2015) that tend to be obscured in a deterministic framework. In this respect and others, probabilistic frameworks are better suited for incorporating information about future climate change, which inherently has large uncertainty bounds. However, probabilistic frameworks have their own disadvantages. They place larger demands for time, resources, and technical capacity on regulators and other decision-makers, as they require a greater number of subjective, site-specific judgments that must then be justified to stakeholders (Morss et al. 2005).

Accordingly, we make recommendations for different “families” of approaches for incorporating climate change, depending on the type of decision framework that is currently operating or desired. State dam safety offices may well adopt probabilistic decision frameworks in the future, but doing so is not a prerequisite for incorporating climate change into decision-making.

1. **Qualitative consideration of climate-change risk within current standards-based PMP framework**

This approach would be applied within the current regulatory framework, and it also assumes use of the current approaches for estimating PMP. Climate-change analyses would be considered insofar as they indicate the future trends in overall risk (i.e., increasing) and in risk factors (like phase of precipitation), and then the guidance would be used only qualitatively. When there are choices in the design and application of rules, between more- and less-conservative options, the more conservative option would be chosen. For example, in the current study, if the three Tasks produce or imply different PMP values (which we would expect), the highest set of values would be adopted, or the preferred values would be weighted towards that highest set. Or in the application of inflow design requirements (e.g. Table 5.2 in the 2007 Colorado Dam Safety Rules and Regulations), the current rule for each dam size/hazard classification would be applied instead to the next-lower size/classification. Similarly, where the 0.01 AEP (100-year) event is used instead of PMP as the basis for the standard for lower-risk dams, the next-less-frequent event, in this case the 0.002 AEP (500-year) event, would be used.

This recommendation is in line with the current guidance at USACE, ECB-2016 (see Section 7.4.1), which mandates qualitative assessments of climate change risk that do not enter into formal, quantitative engineering analyses (i.e., Tasks 1-3), but instead “can inform the decision process related to future project conditions, formulation and evaluation of the performance of alternative plans, and other decisions related to project planning, engineering, operation, and maintenance” (USACE 2016). Contrary to the conclusions in ECB-2016, we believe that there *is* compelling evidence of climate-related changes to PMP; this volume effectively provides qualitative assessment of general changes (i.e., increases) in risk for the study region.

2. **Quantitative incorporation of climate-change risk within current standards-based PMP framework**

This approach also works within the current deterministic regulatory framework, as well as current approaches for estimating PMP. Here, the relatively robust scientific understanding of increased moisture (PW) with increased global temperatures is used to adjust deterministic PMP values, such as those generated by Task 1. Thus, using PMP estimates generated by traditional methods, one would use the "delta method" (i.e., the changes from a past to future period) to incorporate the effects of projected changes in moisture, e.g.,

$$PMP_{future} = PMP_{present} * \left(\frac{max\ moisture\ (future)}{max\ moisture\ (present)}\right)$$

Using the above framework, the moisture quantity used to calculate the future/past ratio could be projections of whichever moisture quantity was used in the original storm maximization process, which is often maximum persisting surface dewpoint. Another possibility would be to use a related quantity more robustly projected by climate models, such as sea surface temperature or, more directly, precipitable water in the upstream moisture source region for PMP-type storms. As climate model projections of individual storms become more reliable, even more directly-relevant quantities such as precipitation itself might be utilized.

Future and present periods would be chosen according to the design lifetime of facilities included in a given study (e.g. 50 years is a common estimate of dam design life, though the structure itself generally does not go away after that period, and so a given structure may simply need to be reanalyzed at that time), and, following other peer-reviewed delta-method studies, the future vs. past periods chosen would likely represent an average taken over periods on the order of 10-30 years in length.

Two examples are provided:

1. Changes in sea surface temperatures as proxy for changes in inflow moisture: Texas State Climatologist Dr. John Nielsen-Gammon has proposed using projected changes in mean sea surface temperature (SST) between a present and a future period as a proxy for changes in storm inflow moisture that would directly affect PMP values. In presentation examples and unpublished state report drafts, he has linked these projected changes in surface-based moisture to changes in PMP via a relationship derived in various PMP sensitivities, which is that "for the range of dew point values used in most PMP studies, the maximization factor for a particular storm will change about 5% for every 1°F difference" in surface dew point values (Kappel et al. 2016). Therefore, for a Texas example using projected changes of upstream sea surface temperatures of 5.4°F by the year 2075, such changes would correspond to a 27% projected increase in PMP values. In other words, according to this example, PMP values would need to be amplified by 27% in order to design for projected future high-

end climate changes. (Nielsen-Gammon 2017) (Note that SST is often used in place of surface dew point temperature for regions such as Texas in which the upstream moisture fetch is over water; other more inland regions would likely use representative surface dew point projections.)

2. Application of a gridded precipitable water adjustment factor (Kunkel and Easterling 2017): A current project led by climate expert Dr. Ken Kunkel (and supported by the Strategic Environmental Research and Development Program (SERDP); mentioned in section 7.4.4) proposes a similar type of moisture adjustment to various metrics of extreme precipitation, only using model-projected changes in full-column moisture, or precipitable water (Figure 7). Since this diagnostic is available or easily computed from many climate project datasets, it offers a relatively easily, accessible option for quantifying the max moisture(future)/max moisture(past) ratio.

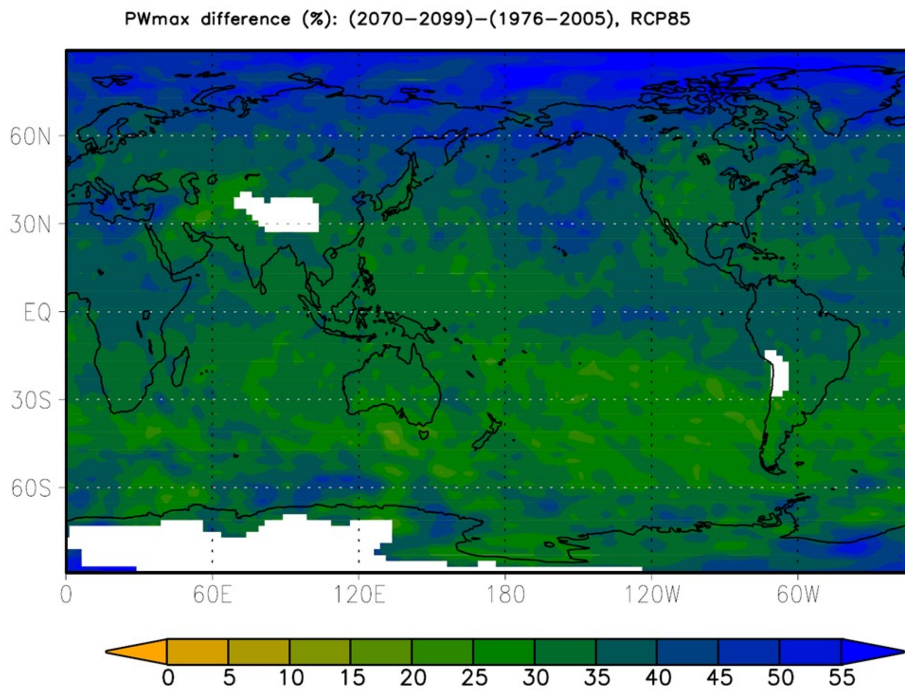


Figure 7: Difference of maximum PW values (% change, shaded) between global climate model projections of future (2070 - 2099) and past (1976 - 2005) PW values under high emissions scenario. The map shows the mean of 13 CMIP5 models: CanESM2, CMCC-CM, FGOALS-g2, GFDL-ESM2G, inmcm4, MIROC-ESM, MRI-CGCM3, CCSM4, CNRM-CM5, GFDL-CM3, GFDL-ESM2M, MIROC5, and MPI-ESM-MR. For each model at each gridpoint, the highest single daily PW was identified for both the future and the historical 30-yr periods; thus, this represents something similar to the maximized moisture in PMP calculations. The gridpoint maxima were averaged for the 13 models for each period: 1976-2005 and 2070-2099, and then the difference was taken and expressed as a percentage of the 1976-2005 value. (Source: K. Kunkel, North Carolina Institute for Climate Studies, North Carolina State University)

3. Quantitative incorporation of climate-change risk within new probabilistic risk-informed framework

A probabilistic, PFA-style approach such as in Task 2 in the present CO-NM REPS project requires a different style of incorporating climate change risk. To this end, the ongoing work at the NOAA Hydrometeorological Design Studies Center (HDSC) to develop a modeling framework that permits non-stationary climate effects into NOAA Atlas 14 may be the most up-to-date, expert-reviewed effort for end-users to follow and potentially emulate once the project concludes in late 2018. Updates are posted on the HDSC Quarterly Progress Report website. Those seeking to undertake additional exploratory work in this regard may also follow the lead of Cheng and AghaKouchak (2014) or Kunkel and Easterling (2017) which focus on changes in future IDF relationships.

An example of incorporating climate change information within a PFA framework is also demonstrated by Reclamation's Friant Dam pilot study (see Section 7.4.2). This study used downscaled CMIP5 (BSCD5) climate projections of monthly temperature and precipitation to adjust historical observations (1950-1999) to represent five different scenarios of potential future climate conditions (2020-2069) in generating peak flows for simulated storm events. As this was an exploratory early study, we point out that improvements and updates can be made to this approach, including using finer-scale data (rather than using monthly ratios) to adjust precipitation magnitude-frequency curves and using the most regionally-appropriate , state-of-the-art downscaled data available as input. The Friant Dam pilot study also demonstrates the possibility and potential benefit to incorporating the impacts of climate change within hydrologic simulation methods that translate PMP to the probable maximum flood (PMF). Many of these issues at the interface of precipitation and hydrologic impacts were exposed and discussed during and following California's Oroville Dam crisis in February 2017. Allowing hydrologic variables (e.g., antecedent precipitation, snowpack, soil moisture, air temperatures for snowmelt; initial reservoir level) to vary along with precipitation magnitudes and frequencies offers additional -- and perhaps more complete -- ways to deal with the suite of potential climate change impacts on flood risk.

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Appendix A - Summary of results of stakeholder survey

A web-based survey sent out in summer 2017 to ~80 CO-NM REPS participants: researchers, sponsors, project review board members, and stakeholders. There were 28 respondents (~35% response rate), with multiple respondents from each of the four groups. Respondents had the option of remaining anonymous, so the response rate of each group is unknown, nor is it known if the 28 respondents were representative of the larger group in terms of their views.

The main objectives of the study were to learn the study participants' assessments of the science and PMP practice with respect to climate change, and adjust the contents of the white paper and identify additional questions and references.

To address the first objective, two key questions were asked. First,
Which statement comes closest to your personal assessment of practices for PMP estimation in the context of climate change?

a) Current approaches to PMP estimation such as those being deployed in CO-NM REPS can adequately accommodate changes in future risk from climate change without explicit adjustments, and so can continue to be used into the foreseeable future
b) Current approaches cannot accommodate changes in future risk from climate change; explicit adjustments to those approaches, or different (e.g., non-stationary) approaches, will need to be used in the foreseeable future

61% of respondents (17 of 28) answered (b), "Current PMP approaches **cannot** accommodate future changes in risk from climate change", while 39% of respondents (11 of 28) answered (a), that current PMP approaches can accommodate future changes in risk from climate change.

The second question was asked only of those who answered (b) to the first one,
Having indicated that current PMP estimation approaches cannot accommodate changes in future risk from climate change, which is closest to your personal assessment?

a) We currently lack the scientific and technical basis to explicitly include climate change in PMP estimation
b) We have sufficient scientific and technical basis to explicitly include climate change in PMP estimation, but for other reasons it is not justified to implement at this time
c) We have sufficient scientific and technical basis to explicitly include climate change in PMP estimation, and doing so is justified at this time

47% of respondents answered (a), 29% answered (b), and 24% answered (c).
So to summarize, most respondents felt that climate change should be considered in PMP studies at some point, if not now, and a handful of those respondents felt that climate change
should be included in PMP studies now.

To address the second objective, respondents were then asked several more questions:
What papers or reports, direct consultations with experts, or experiences would you cite as having most influenced your assessment?

From those who answered the first question (b), the responses included:
- My own [published, peer-reviewed] research on the topic
- USACE-IWR research, NOAA-CPC models
- Paleohydrology papers
- Kunkel paper, IPCC reports, CO Climate Change Paper, use of climate model downscaling data
- Reports written by USBR on PMP and rainfall extremes (1990-2015), NOAA ESRL reports/research, many journal articles since 2005, such as Kunkel and others [2013], current activities led by US NRC
- Kunkel, et al. (2013a), Probable maximum precipitation and climate change, Geophys. Res. Lett., 40, 1402–1408, doi:10.1002/grl.50334
- Rastogi, et al. (2017), Effects of climate change on probable maximum precipitation: A sensitivity study over the Alabama-Coosa-Tallapoosa River Basin, Journal of Geophys. Res. Atmos., 122
- 20+ years of experience performing probabilistic hydrologic hazard studies

For those who answered the first question (a), the responses included:
- NOAA Atlas 14, Volume 8, Appendix A.2
- NOAA Atlas 14, Climate Change Discussions.
- Operational experience and background.
- Discussion with meteorologists, climatologists, extremeness of REPS already will take non-stationarity into account.
- Direct consultations with experts.
- Observations of the CO-NM REPS process show that the storm library can be updated as more observations are made.
- HMRs and knowing that the CO-NM REPS approach is based on the actual storms (with theoretical maximization) and that the tool can be updated as more storm data becomes available in future and that the future storms will inherently be influenced by climate change.
- The main climate change driver for PMP changes in the CO-NM region may simply be persisting higher water vapor opportunities. This may not be adequately addressed in the current processes, but has seemingly always been

more than compensated for by the impact of cumulative conservative approaches.

The following question was asked only of those who answered (b) to the first question:

What approach or set of approaches do you feel is best-suited for PMP estimation that accommodates climate-change risk?

- Incorporation of forecasts of moisture changes (i.e., dew point climatology) as well as the identification of potential ranges (or margins of error).
- Basic Clausius-Clapeyron considerations can provided a robust 1st-order estimate of future changes. Targeted high-resolution climate model simulations might be able to address questions about whether increased latent heat release will have positive or negative feedback effects.
- Recent publications use WRF modeling to simulate 120 storms to explore the effects of climate change on PMP.
- WRF downscaling with subset of CMIP5 future projections and varying time windows for particular watersheds; combine with conceptual Clausius-Clapeyron calcs on increases in max dewpoint future projections.
- PMP estimation approaches…for accommodating climate change should be probabilistic in nature.
- We do not support a single number analysis (i.e., PMP). The best approach is probabilistic and incorporates uncertainty.

Do you have specific questions about approaches to PMP estimation with respect to climate change that you would like to see answered in the project white paper?

- Potential changes to dew point climatology? - which impacts both maximization and transposition factors
- Storm efficiency modifications--are future storms in the future more or less capable of maximizing precipitation from available moisture?
- Is there an upper limit to storm maximization (storm efficiency, etc.) and how has that changed historically and what does the trend look like (if any)? Can the effect of climate change be teased out?
- Direct effect [of climate change] on rainfall intensity?
- How is atmospheric moisture anticipated to change in the future?
- Why PMP may or may not change as a function of Clausius-Clapeyron relationship?
- How might changes in storm tracks affect the transposition limits?
- What are the bounds and mean of changes in the key variables in PMP? Can NWP approaches be used to better assess the role of convection?
- Is there potential for the frequency of liquid precipitation events to increase at the expense of non-liquid events, especially in late fall/early spring? What is the potential impact to all-season PMP and seasonal PMP estimates [...] since current PMP estimates consider only historical liquid precipitation events?

- Does moving to a probabilistic approach (with uncertainty bounds) adequately account for climate change?

Do you have any other comments, suggestions, or concerns about the white paper and its contents?

- Documenting the current scientific understanding of the impact of climate on extreme events is critical for the field of dam safety and other infrastructure and public safety planning and design fields.
- White paper is a critical contribution and is definitely needed for the CO-NM study. Current and near-term operational PMP studies ignore it and this is misguided. Research suggests there is no physical upper limit to PMP in presence of warming.
- It would be helpful if "Recommendations for future practice" could include research needs to improve upon the "uncertainties and assumptions inherent in different PMP approaches" toward better consideration of climate change impacts.
- These questions are focused on the impact of climate change on PMP [amounts]. Task 2 could benefit from similar information regarding frequency [i.e., effects of climate change on frequency analysis].
- Please be sure to explicitly note that any conclusions or recommendations regarding climate change have as much if not more uncertainty than the PMP development process. Climate is changing, climate has always been changing, climate will continue to change whether humans are involved or not. PMP development should address the changes when possible, but not make ad hoc adjustments unless scientifically justified. [...]