Probable Maximum Precipitation (PMP) Response to Predicted Climate Change over North America

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ABSTRACT

RÉSUMÉ

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# Introduction

The Probable Maximum Precipitation (PMP) is defined by the World Meteorological Organization (WMO) as “the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year." (WMO, 2009). The main utilization of a PMP estimate is to calculate the Probable Maximum Flood (PMF), which provides information on the design specifications of infrastructure(s) (i.e. dams, reservoirs, flood diversion tunnels) in a particulate water catchment. With the growing body of scientific evidence supporting that in the future it is very likely that there will more intense and frequent extremes in precipitation over most of the mid-latitude land regions and over the wet tropics (e.g. IPCC 2012), and the fact that the typical design life of large water management infrastructure projects like dams are ~50-100 years, it is important to consider the impacts of climate change on PMP estimates. Providing engineers with this additional knowledge will help them make informed infrastructure design decisions that balance safety risks with economic concerns under a future changing climate.

Since historical trends in extreme observations are not a good predictors of future changes in a changing climate, climate models simulation of future Representative Concentration Pathways (RCP) scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC) for its fifth Assessment Report (AR5) are utilized (Moss et al., 2008). The goal of this study is to provide additional insight on future changes in meteorological factors that influence the PMP estimate and not too directly calculate PMP as this would require specific detailed inputs that depend on the particular drainage basin of interest that are generally not well resolved by a model. Even for present day PMP calculations, currently physical models are not usable due to their low-accuracy estimates of precipitation (WMO, 2009), and current research using numerical weather prediction (NWP) models to estimate PMP values is a topic of research (e.g. Cotton et al., 2003).

Given the importance of PMP for large infrastructure design there is surprising limited information on the impacts of climate change on PMP over North America at regional scales, especially over Canada (MEND, 2011). Kunkel et al., (2013) showed changes in water vapour concentrations to infer the potential effects of climate change on PMP globally by analyzing future and control GCM simulations from the Coupled-Model Intercomparison Project 5 (CMIP5) archive (Taylor et al., 2012). Their global scale study showed future increases in the maximum water vapour concentrations of ~10-20% and ~20-30% over the continental United States for the RCP4.5 and RCP8.5 scenarios, respectively. Since PMP calculations are typically performed at local or regional scales, it is desirable to provide further insights on the potential impacts of climate change on PMP by downscaling the global RCP scenarios. The COordinated Regional climate Downscaling EXperiment (CORDEX) project (http://www.cordex.org) is designed to dynamically downscale these global GCM CMIP5 RCP scenarios results to regional scales using Regional Climate Models (RCM) simulations. A focused PMP study using one of the CORDEX RCM model simulations over the southern region of Quebec, Canada show an overall significant increase of the PMPs throughout the current century compared to the recent past for this region (Rousseau et al., 2014). In the study presented here we utilize and ensemble of the four RCM model simulations currently available over the North American domain to study the impacts of climate predictions on future PMP over North America.

# Probable Maximum Precipitation (PMP)

The underlying approach of calculating PMP has not change significantly in the past ~30-40 years (Kunkel and Easterling, 2011). The basic principle in determining the maximum possible precipitation (“perfect storm”) is to simultaneously maximize all the factors that contribute to heavy precipitation for a given storm duration. To understand the definition of PMP it is helpful to note the basic processing steps leading to precipitation (NOAA, 1960). The basic precipitation process includes: (i) sufficient atmospheric moisture, (ii) lifting and cooling of the air, and (iii) condensation and growth of the hydrometers in precipitation. The common lifting methods include: (i) horizontal convergence of wind fields (i.e. low pressure systems), (ii) lifting along warm and cold fronts (along air masses), (iii) orographic lifting over barriers (i.e. mountains), and (iv) atmospheric instability created by radiative warming (surface) or cooling (aloft). Condensation into cloud droplets will occur once an air parcel is lifted and cooled to its saturation point (assuming there are enough condensation nuclei present). Precipitation out of a cloud will occur once the cloud droplets have grown into sufficiently sized hydrometers. The rate of precipitation out of a cloud will depend on a number of factors include, upward vertical motion, rate of growth of the cloud droplets heavy enough to fall out of the cloud to the surface, and the availability of moisture to sufficiently replace the water vapour into the rainstorm system.

The procedures used in estimating PMP are not standardized and in practice vary depending on such specific factors such as the size and location of the basin, available moisture, orographic effects, storm morphology of the region, and the availability of input source data (WMO, 2009). The two overall approaches to estimating PMP are a direct approach based on the specific watershed area (i.e. local method (local storm maximization), transposition method (storm transposition), combination method (temporal and spatial storm maximization), inferential method (theoretical model)), and (ii) an indirect approach based on storm area (i.e. generalized and statistical methods). The WMO (2009) report provides a good summary of these current practices for estimating PMP. Regardless of the methodology used to compute PMP, the main factors to consider when estimating the extreme PMP are vertical motion and moisture availability. When topographic effects are important (i.e. mountainous regions) then the maximum wind must also be taken into consideration. Often in practice it is assumed that it is impractical either theoretically or empirically to directly estimate the maximum possible value for the storm convergence and vertical motion factors. Therefore, in practice representative extreme rainfall observations from historical high-efficiency rainstorms (also referred to as “perfect” or “design” storms) are used to provide a measure of the persistent maximum possible wind convergence (upward motion) (e.g. Chen and Bradley, 2006). The main steps for a PMP estimation following the direct (watershed area) approach are to identify a highly-efficient storm representative of the design watershed (i.e. local, transposition, etc.) that is assumed to be dynamically maximized, and then maximize the potential moisture available to the highly-efficient storm from the watershed region (typically based on climatological maximum values). The local method PMP calculation involves taking at the storm at location, *xs*, the storms observed precipitation, *Ps*, accumulated over a duration, *tdur*, with precipitable water, PWs, and maximizes the potential available moisture (Showalter and Solot, 1942) using the climatological maximum precipitable water observations, *PWmax*, at that same location. This traditional *local method* PMP concept can be further expressed following common definitions and descriptions (i.e. WMO, 1986; Chen and Bradley, 2006; Kunkel et al., 2013) as,

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We can rearranging the right-hand side of Equation (1) gathering the storm variables together as , which can be defined climatologically as a simple storm precipitation efficiency, *PES(xS)*, which is the ratio of the mean daily precipitation to the average precipitable water of a given location (e.g. Sellers, 1965; Market et al., 2003) that does not include water removal from the system,

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|  | . | (2) |

As shown in Equation (11) of Appendix A, using this PMP approach one gets an estimated of the storm’s average vertical velocity by scaling the precipitation efficiency by the vertical height of the storm and its duration, which shows the underlying assumption in the PMP calculation that the average vertical motion is assumed to be the same for the storm and the estimated *PMPlocal* (the equilibrium assumption).

It is also common practice to compute the PMP using the *transposition method* by taking the computed local PMP from a representative highly-efficient or perfect rainstorm located at *xs* (Equation (1)) and transposition it to the location of interest, *x*, (i.e. watershed region) (Chen and Bradley, 2006), which provides the system with the maximum available atmospheric moisture conditions (“moisture maximization”) for the specific location and season. In order to account for differences in location, the transposition PMP is calculated by adjusting the local PMP values at the storm location *xs* by the ratio of the *PWmax* values between the storm location and the site of interest *x*. The transposition adjustment is:

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|  | , | (3) |

where *PMPtrans(x)* is the transposed *PMPlocal* from the storm site (xs) to specific watershed of interest at site *x*.

# Regional Climate Model (RCM)

Climate model simulations are not utilized to directly calculate a site-specific PMP as the detailed input requirements vary depending on the particular drainage basin of interest and are generally not well resolved in a climate model. Currently even physical models are not usable due to their low-accuracy estimates of precipitation (WMO, 2009), and current research using numerical weather prediction (NWP) models to estimate PMP values is still a topic of research (e.g. Cotton et al., 2003). Rather, future RCP regional climate model simulations are analyzed to provide insight on future changes in meteorological factors that influence PMP, mainly the available precipitable water and how efficient the storms are at converting the precipitable water to precipitation (e.g. storms vertical motion). Predicting future changes in the extremes of vertical motion based on RCM simulations is challenging. There no vertical velocity (or omega) information in the RCM CORDEX standard products that represents the extreme vertical velocities as seen in a storm (i.e 700 hPa vertical velocities). Plus, even if it was provided as a standard output model variable for CORDEX, the vertical velocity cannot be well verified in a RCM at the model grid scale due to the lack of comparison values. Therefore, to gain insight into the future response in the extreme storm vertical motion dynamics from the daily model simulation values we compute a ratio of the precipitation to the precipitable water, which are two quantities well verified in the model that can be used as a simple indicator of storm precipitation efficiently (that does not include water removal from the system).

In terms of future PMP responses to climate change scenarios we also analyze the combined effects of these two future meteorological factors. This is achieved by following a method that is representative of the traditional local and transposition PMP approach using an indirect estimated of the storm’s vertical velocity (Equation (11)). Following this PMP approach we identifying a “perfect” or highly-efficient storm estimate for each model grid using daily precipitable water and precipitation values over the various 30-year periods. This perfect storm PE values can be derived locally only using the storm values within each model grid box, or they can be selected from a search region around each model grid box to be more representative of a transposition calculation. Since the duration (tdur ) is fixed by the model temporal sampling of 1 day, these precipitation efficiency values can be use with typical constant storm top height (H) values (i.e. 9.2 km) to derived average estimated vertical velocity values (refer to Appendix A for more details). We don’t expect the *PE* to represent the true absolute magnitude of a perfect storm over a certain location (i.e. varying durations, vertical extent, etc.), but given the model constraints it provides a useful metric to help indicate the response of the vertical motions given the various climate change scenarios.

These perfect storm PE values can then be combined with the local climatological PW values to provide an estimate of the response in estimated PMP values to future predicted climate changes. As previously noted, and similar to the PE, the absolute magnitude of the model simulated PMP values themselves may not reach the theoretical maximum PMP values for a specific watershed, but the estimated PMP response from the simulations will provide valuable insight on the impacts due to a changing climate. Thus, following the PMP approach state in Equation (3) to calculate the response in time we compute the annual maximum (AM) values from the daily values for each period (not the single maximum values for the entire period) and then average them to provide 30-year future period future predicted values that are differenced from the historical 30-year period. This method results in the PMP annual maximum response values being computed as:

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where the annual maximum are then averaged in each 30-year period to generate the response. The and response is also computed the same, where the annual maximum values are computed from the daily values and then averaged over the 30-year period to compute the differences.

For this study only four of the CORDEX RCM model simulations were available over the North American (NAM) grid: the Canadian Regional Climate Model (CanRCM4) (Scinocca et al., 2015) downscaled from the Canadian Earth System Model (CanESM2) (Arora et al., 2011; von Salzen et al., 2013) and provided from the Canadian Centre for Climate Modelling and Analysis (CCCma); HIRHAM5 (Christensen et al., 2006) downscaled from the Irish Centre for High-End Computing - European Consortium - Earth system model (ICHEC-EC-Earth) (Hazeleger et al., 2012) and provided by the Danish Meteorological Institute (DMI); and two Rossby Centre regional Atmospheric (RCA4) (Samuelsson et al., 2011) model simulations downscaled from the CCCma-CanESM2 and the ICHEC-EC-Earth and provided by the Swedish Meteorological and Hydrological Institute (SMHI). The CORDEX project contains more details on the dynamically downscaled RCM models and data for CORDEX (http://www.cordex.org).

For this analysis we will investigate the response in the 1-day annual maximum RCM simulated values from the historical period (1961-1990) to three future predicted 30-year periods (2011-2040, 2041-2070, 2071-2100) at the horizontal spatial resolution of 0.44 degrees (~50x50 km2), which corresponding to the CORDEX downscaled RCM Tier 1 outputs. The resulting response signals of each parameter over each period are computed by taking the ensemble median of the currently available CORDEX RCM simulations over the North American domain.

In addition to calculating the magnitude of the response we also determined its significance. The significance test was performed by checking mean value differences of a future 30-year period with the 30-year historical period using a Monte-Carlo approach. To explain the procedure used we will take the periods of 1961-1990 and 2011-2040 as an example. First, the difference in means between future 30-year period (2011-2040) and historical 30-year period (1961-1990) is calculated, which is considered as test statistic, *T*. Then we select from this dataset two time periods to form a new time series with sample size of 60. Next, we randomly split the sample of 60 into two groups, each group contains 30 values. We calculated difference in means between two groups and repeated this process for 1000 times to obtain a set of 1000 differences. Since our test variables may increase or decrease, we select two-side test which is used to calculate the proportion of sampled permutations where the absolute difference was greater than or equal to the absolute value of *T*. If *T* is contained within the middle 95% of sampled permutations, we will not reject the null hypothesis. If not, we reject the null hypothesis at 5% significant level.

# RCM Historical

Before investigating the predicted responses in the meteorological factors that influence PMP based on the RCP scenarios, the historical RCM simulations are presented in Figure 1 to show the general spatial pattern in the annual maximum extreme values of the reference simulations in the response calculations. These inter-model ensemble median values from the four RCM for the historical period (1961-1990) are generally consistent with expected water vapor and precipitation fields observed during this period (\*\*\*references—observations and published model simulations\*\*\*). It should be noted that determining the climate model fidelity by assessing the quality of the model based on historical comparisons against observations does not necessarily provide a good gauge on how well the model responses to future climate predictions, and is not the focus of this paper. However, the model fidelity can help provide additional insight or guidance on potential intra-model differences in predictions/responses, and indicate that the simulations can at least represent the historical climate sufficiently to provide confidence in the underlying model physics.

The PW historical field in Figure 1 shows the larger PW values in the North America storm track region along the eastern part of North America, the western coastal regions, and parts of the most Southern Western US states. The reduced PW occurs mostly in the Western part of the USA and Canada, and up into the arctic.

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| **Historical (1961-1990)** |
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Figure . Median of the RCM simulations of the 30-year mean of the annual maximum precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for the historical (1961-1990) period at a single grid box resolution with a 5x5 model grid perfect storm search region for the PE and PMP.

# RCM Future Response

In this study we analyze the future response in estimated PMP by looking at the main meteorological drivers that will influence future PMP. The main focus will be on the change in the precipitable water and precipitation efficiency over North America under RCP 4.5 and RCP 8.5 scenarios, which represent radiative forcing of +4.5 Wm-2 and +8.5 Wm-2 from pre-industrial to 2100. The RCM’s predicted change in annual maximum response to the RCP 4.5 and RCP 8.5 scenarios are presented in Figure 2 and Figure 3, respectively.

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| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . Median response of RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for scenario RCP4.5 at the three future predicted 30-year periods of (2011-2040, 2041-2070, 2071-2100) for 1x1 RCM 0.44o grid-box regional resolution. The PE and PMP values plotted here use a 5x5 model grid-box search region for the perfect storm. The black dots are the stipple values indicating a significant response at the 5% significance level (95% confidence limit).

The first period from 2011-2040 in Figure 2 shows the general patterns of the future PW, PE, and PMP responses across North America. As expected, and consistent with the theoretical C-C equation that the atmosphere can hold more moisture content with warming temperatures (more details shown later in Section 7), the PW has a statistically significant (5% significance level) increase everywhere across North America as indicated by the black stipples (dots). During this first future 30-year period there is a +10% positive PW response over the western part of USA, and over most of Canada except for the southern Ontario and Quebec, and parts of Northern Canada. The rest of North America shows a < +10% increase in PW for this 2011-2040 period. As we move further out in the future to the 100-year (2071-2100) period assuming an RCP4.5 predicted scenario the pattern in the PW remains similar, with the magnitude in the PW response continuing to increasing by ~+10% to values of +20% over most of the western part of N.A., excluding Mexico, and the northern Canadian Prairies. There are also small pockets in the Arctic and around Newfoundland-Labrador that have PW response values of +20%. The rest of North America has a response between 10-20% by the 2071-2100 period.

The corresponding precipitation efficiency for RCP4.5 is also shown in Figure 2. The response in the climatological daily “perfect” storm precipitation efficiency various across North America. Starting in the first 2011-2040 period there is a negative the PE response across most of central USA and Mexico with the response becoming significant once the values reach ~-5%. The largest negative values of PE response occur of the west coast of Mexico as a result of the general subsidence (lack of vertical motion) in the tropics/sub-tropics over the Pacific Ocean. Other large regions of significant negative PE response are: (i) up the northern coast of British Columbia and into the western part of Yukon Territory and Alaska; (ii) the eastern part of the Northwest Territories up into Nunavut and the Arctic; and (iii) and in Ontario. Most of Canada shows a weaker negative PE response (0 to -3%) that is not statistically significant for this period. Note that one needs to keep in mind that a negative PE does not necessary mean that the predicted storm precipitation (PR) and PW are decreasing in the future. Rather, for the most part both PR and PW have an increasing response to the predicted changing climate over North America, it is just the negative PE response typically indicates that for the perfect storms the available PW is increasing at a faster rate that the PR. (See supplemental Figure 9 for the precipitation response). The main areas of increasing PE response ranging between +2% and +6% are the storm track up the eastern seaboard of the US and Canada, and some small pockets western Canada and the Midwest od USA, and east coast of Hudson Bay down to the St. Lawrence region of Quebec. However, only a very limited region with PE response values above +4% are statistically significant for this period. As we proceed further into the future to the 2071-2100 period the predicted PE values over most of the continent continue to decrease with most regions having values between 0% and -10%. The statistically significant negative response now covers more of North America; however it is still not statistically significant for most of the eastern seaboard of both the USA and Canada (excluding the tip of Florida, immediately along the coast of MA, NH, Maine and Nova Scotia, and southern Newfoundland). There are small pockets of positive PE response remaining in Central Alberta and the northern mid-west of USA, parts of the Eastern seaboard, and East of James Bay. However, all of the positive PE response regions have been reduced such that none of them by this final period are statistically significant.

As noted early the PMP response is calculated following the traditional transposition methodology way of combining the PW and perfect storm PE, however, instead of using single climatological maximum values the annual maximum values are computed and then averaged over the 30-year periods to determine of the response changes in time. The overall PMP response defined as the combination of the daily extreme local PW and the perfect, or design, storm PE is shown in Figure 2. Starting in the 2011-2040 period the PMP response is positive over most of North America at a rate of +5% to +15% with the response being statistically significant once it reaches ~+10%. This shows that even though the annual maximum daily extreme storm response is mostly decreasing over North America, the increase in the annual maximum PW response still dominates. The regions that show this statistically significant PMP response to the RCP4.5 scenario during this period includes over half of Canada, and most of the storm track along the eastern seaboard of the USA and Canada excluding Florida and parts of the northeastern US states. During the predicted 2011-2040 period there are also some smaller pockets of negative PMP response of ~-10% that occur in the USA just to the west of the Great Lakes region, southwestern part of North America, including most of West coast and Central Mexico. However, for this first period none of the decreasing PMP responses are statistically significant. As we progress into the future time periods the overall pattern in the PMP response remains relatively consistent with the positive response over most of North America intensifying by ~10% to values of +10% to +20%. By the time we reach the 2071-2100 period there is a statistically significant positive response over most of Canada and the USA, except for the South-Central USA and the Great Lakes region (due to the statistically significantly negative PE response reducing the impact of the significantly increasing positive PW over the region). Even small parts of southeastern Mexico shows a significant positive PMP response. Again, only the western part of Mexico, a small region in the central USA, and part of the Great Lakes region are the only regions that show negative PMP response during in this 100-year project period. However, the southern part of the Mexican Baja Peninsula the only region in N.A. with a significant negative PMP response, which is due to the overall subsidence in this region of the tropics/sub-tropics over the Pacific Ocean.

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| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . Median response of RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for scenario RCP8.5, plotted convention the same as Figure 2.

The general overall patterns of the future predicted climate change response of the meteorological factors that influence PMP for RCP4.5 scenario (Figure 2) are similar to those from RCP8.5 as shown in Figure 3. The main difference in the responses from the two scenarios is that the RCP8.5 tends to have a more intense response, which is now surprising given that the predicted radiative forcing from pre-industrial to 2100 increased from +4.5 Wm-2 to +8.5 Wm-2 in going from RCP4.5 to RCP8.5. More specifically, the following are the results of comparing the 2071-2100 period responses between RCP4.5 and RCP8.5.

Similar to RCP4.5 the PW response for RCP8.5 is a statistically significant positive response that intensifying in time over all of North America. The future predicted 100-year (2071-2100) RCP8.5 PW response is generally double of that of that from the RCP4.5 scenario with most of North America showing a positive response of +30 to +50% from the historical period (1961-1990). The general overall pattern with the largest positive PW response typically being along the western part of Canada and the USA seen in RCP4.5 is the same for RCP8.5. In general the PE response to RCP8.5 scenario in Figure 3 has a more negative response that occurs earlier in time compared with RCP4.5 (i.e. RCP4.5 2071-2100 period is more similar to the earlier 2041-2070 period for RCP8.5). The most intense response occurs during the final future 100-year period for RCP8.5 were there is a decreasing PE response over entire North America, with most of the continent having statistically significantly negative PE response > -6%. The most intense negative PE of -20% occurs in Mexico and the southwestern USA (e.g. Arizona, New Mexico, Texas) where there is predicted increased subsidence. The only regions that don’t have a statistically significant decreasing PE are: a region in central Canadian Prairies, North Dakota, parts of the eastern seaboard and south of the Great Lakes in the USA, and south and eastern Quebec.

The overall PMP response for the RCP8.5 scenario in Figure 3 has approximately double compared to RCP4.5 for most of Canada and the northern USA states the it has increase by 10-20% to approximately +30% by the 2071-2100 period. During this period all of Canada and most of the USA show a statistically significant response (> +10%). The only positive PMP response regions that are not statistically significant are immediately around the northern Great Lakes of Superior, Huron, and Michigan, southern Midwest USA, and the far South-West USA mostly in Arizona, and the north and eastern part of Mexico. About half of Mexico and a small region in south-central Arizona are the only regions in North America that show a negative PMP response, with the only statistically significant negative PMP response being a small region on the south coast of Mexico and the southern part of the Mexican Baja Peninsula, where the negative PMP response reaches -30%.

# RCM Model Variability

In addition to evaluating the overall magnitude and significance of the future climate response signal computed from the RCM ensemble median results it is desirable to also determine an estimated of variability in this response. To gain insights into this variability we investigating both the inter- and intra-model variability by comparing the maximum spread in the future predicted response of the various PMP parameters.

## Inter-model Variability

The inter-model variability is estimated by looking at the variability of the ensemble of different RCM simulations as a function of the overall signal. Since there are a limited number of available downscaled CORDEX RCP runs, we estimate this variability by evaluating the maximum variability (± (maximum – minimum) / 2) in the response between all the available models.

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| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . The maximum inter-model spread of the ensemble of different RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for scenario RCP4.5, using the same plotted convention, storm search region of 5x5 grid-boxes, and resolution 0.44o as in Figure 2.

The spatial pattern in the maximum spread in the inter-model PW response for RCP4.5 in Figure 4 tends to follow closely that of the response signal itself shown in Figure 2 with larger value corresponding to regions with increased response signal. The inter-model spread tends to increase slightly in time (i.e. the models vary a little more the further out into the future). Overall the average inter-model PW spread is typically < ±6% for median response signal of 10-20% up to the predicted 2071-2100 future period. The most inter-model spread occurs on the west coast of the USA, Alaska and the Northern Arctic region, reaching in the 2071-2100 a maximum spread values of ±13% in these areas with a median PW response signal of 20-30%. Unlike the PW, the PE inter-model response spread tends not to change a lot in time. The maximum inter-model spread is in central and western Mexico including the southern Baja Peninsula, and up into the south-central US states of Texas, Oklahoma, Kanas with inter-model spread values from ±8 to ±12%. This is also the region containing among the highest PE response signal with values in the range of -12% to -18%. However, the majority of North America has maximum PE inter-model response spread of < 4%. The inter-model RCP4.5 spread in the PMP response is more similar to PW where it increases in time and thus with increasing PMP signal. The overall inter-model spread in the PMP response is generally < ±10%. The most inter-model PMP spread generally occurs in the arctic region reaching values of ±30%, which makes the PMP response signal in this region a little less certain as RCM models vary in there prediction. There are also regions of larger inter-model spread around the Great Lakes and Central US (Kanas, Oklahoma, Texas) corresponding to regions without a statistically significant PMP signal. There is also a small region of maximum model spread near the southern tip of the Mexica Baja Peninsula, which corresponds to large significant negative RCP4.5 PMP response signal of -10% to -20%.

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| **(2071-2100) (2041-2070) (2011-2040)** |  |

Figure . The maximum inter-model spread of the ensemble of different RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for scenario RCP8.5, using the same plotted convention, storm search region of 5x5 grid-boxes, and resolution 0.44o as in Figure 2.

The spatial pattern in the maximum inter-model spread in the PW, PE, and PMP responses for RCP8.5 in Figure 5 is very much the same as for the RCP4.5 scenario in Figure 4. The main difference is the magnitude of the inter-model spread for RCP8.5 tends to be larger corresponding to the larger RCP8.5 response signal. The average inter-model PW spread is typically < ±8% for median response signal of 30-40% for the predicted period of 2071-2100. Similar to RCP4.5, the most inter-model spread occurs on the west coast of the USA, Alaska and the northern arctic region, reaching in the 2071-2100 a maximum spread values of ±16% on a median response signal of 40%. Again the spatial pattern in inter-model spread in PE for RCP8.5 is very similar to RCP4.5, with the majority of Canada and the northern and western states of USA have a maximum inter-model PE response spread < ±6%. The maximum PE inter-model spread is in central and western Mexico, including the southern Baja Peninsula, and up into the south-central and south-Eastern US states with inter-model spread with values from ~±8 to 12%. This is also the region containing among the highest PE response signal with values in the range of 12% to 18%. For the RCP8.5 inter-model PMP response spread is < ±10% with most of the larger spread occurring in pockets round the Arctic region with a spread of values of ±15-30%. As time progresses into the next 100-year period the maximum inter-model PMP variability for RCP8.5 increases with magnitude of the PMP signal with smaller values <±10% remaining mostly on the northwest coastal region of North America, southern Canada Prairies into western Ontario, parts of northern Manitoba and Quebec, most of the Canadian Atlantic Provinces, and the Midwest USA from Canada down to northwestern Mexico. Most of the rest of North America have inter-model variability ~ < ±15% for median PMP responses of ~ 20% to 30%. There are also regions of larger spread in the Arctic and around the Great Lakes, southcentral USA, and southern California and Nevada. There is also a small region of maximum model spread of ~±16% near the southern tip of the Mexica Baja Peninsula, which corresponds to large significant <-20% PMP response signal.

## Intra-model Variability

In addition to evaluating the inter-model variability between different RCM models for the same initial boundary conditions, it is also valuable to gain insight on the RCM intra-model variability (or spread) from an ensemble of simulations from different initial conditions from the same RCM. For this analysis we look at an ensemble of simulations comprising of 5 members (different initial conditions) of CanRCM4 RCM CORDEX over the North America domain at a spatial resolution of 0.44 degrees for the RCP4.5 future scenario (RCP8.5 simulations have not been performed) forced with 6 hourly SSTs and sea-ice from the CanESM2 GCM.

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| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . The maximum intra-model spread of the ensemble of CanRCM4 RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for scenario RCP8.5, using the same plotted convention, storm search region of 5x5 grid-boxes, and resolution 0.44o as in Figure 2.

As one might expect the intra-model variability generated from an ensemble of simulations from different initial conditions for a single RCM is much less than the inter-model variable from a suit of models. Also, the intra-model spread does not vary much as the simulations proceed out in time into the future. The intra-model spread in the PW response is generally < ±4%, with a region in the southwestern USA (California, Nevada, Arizona, Utah), and a small region in the Arctic that has the intra-model spread reaching ±6% to ±8%. The intra-model spread in PE is also generally < ±4% in Canada and USA. Mexico and parts of some the most southern USA States, and some isolated regions in and around Saskatchewan, Manitoba, and Nunavut show slightly larger intra-model variability around ±6%. The maximum intra-model spread in the PMP response is generally ≤ ±10%, which does not change much moving out into the future.

# Ratio Response With Respect to Temperature

Another general way to gain insights on the future predicted simulations of the meteorological parameters that influence PMP is to compare these model predicted responses against the predicted temperature changes. For example, the Clausius-Clapeyron (C-C) relationship states that as the temperature increases the air can hold more water vapour (saturated water vapour pressure increases). For example, with a change in temperature from 25 to 300 C one might expect a relative percent change in the saturation vapour pressure of ~25% (or 5% per K). Figure 7 shows the percent changes in the meteorological parameters of PW, PR, and PMP response as a function of changes in temperature (per degree Kelvin) for the RCP4.5 scenario.

|  |  |
| --- | --- |
| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . Plot of the median response of RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) as a function of the change in temperature Kelvin for scenario RCP4.5, plotted convention the same as Figure 2.

The overall patterns in the responses as a function of change in temperature (per K) generally remain consistent as the simulations proceed into the future. Also, the overall patterns in the ratio of the responses to changes in temperature follow closely the patterns in the responses themselves, as one might expect with a predicted warming climate in the RCP4.5 and RCP8.5 scenarios (see Supplementary Figure 10 for the temperature response). The spatial pattern in the PW response to a change in temperature for RCP4.5 shown in Figure 7 remains relatively the same throughout the 100-yr simulation and generally range in the +5% to +9% per K, which is consistent with the Clausius-Clapeyron equation. In the cooler arctic region there is typically a smaller rate of change with values between 3% and 5% per K, even down to 1% to 3% per K in far northern Pole region. Again for precipitation, PR, the general overall spatial pattern of the response in PR with change in temperature in Figure 7 for RCP4.5 is relatively consistent with the response changing slightly in time depending on the region. After the 2011-2040 period all of Canada and most of the USA show an increase in PR response with increasing temperature. Mexico and parts of the southern most states show a negative response with temperature, however, the negative response is becoming weaker as the simulations further proceed into the future. The spatial pattern in the PMP response to changes in temperature follows very much the same spatial pattern as the PMP response itself. Thus, over most of North America there is a positive increase in the PMP response to changes in temperature mostly in the range of 1% - 7% per K. There are regions of negative change around the upper Great Lakes (Lake Superior, Lake Michigan, and Lake Huron) the Western Part of Mexico, and south-central USA around Kanas and Oklahoma during the 2071-2100 period.

|  |  |
| --- | --- |
| **(2071-2100) (2041-2070) (2011-2041)** |  |

Figure . Plot of the median response of RCM simulations of precipitable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) as a function of the change in temperature Kelvin for scenario RCP8.5, plotted convention the same as Figure 2.

The response of the meteorological parameters that influence PMP as a function of temperature for scenario RCP8.5 is presented in Figure 8 follows closely that of RCP4.5. There is a slightly stronger PW response with changes in temperature with more regions having 7% per K. This is especially true in the Arctic where the PW response with temperature increased by ~ 2% per K to 5%- 7% in the Arctic and 3 - 5% per K in the most northern polar regions. The spatial pattern and magnitude of the change in PR with change in temperature are very similar to RCP4.5. The RCP8.5 PMP response with change in temperature also has a similar spatial pattern and magnitude as seen in RCP4.5, with the notable difference that from the 2041-2070 period onward there are no negative PMP responses with change in temperature around the upper Great Lakes and the central USA. The only region with a negative PMP response with changing temperature after 100-years in the USA is the most southern tip of Arizona.

# Conclusions

In this study we presented valuable insights on the response of meteorological factors that influence future PMP calculations given a changing climate prescribed by IPCC adopted RCP4.5 and RCP8.5 scenarios using RCM model simulations over North America. In general the spatial pattern of the responses between RCP4.5 and RCP8.5 are very similar with the responses intensifying for the RCP8.5 scenario, which is expected given that the radiative forcing from pre-industrial to 2100 is +4.0 Wm-2 greater for RCP8.5. The daily precipitable water and perfect storm precipitation efficiency are the two driving factors that influence PMP and for the most part have an opposite overall response with PW response generally being stronger resulting in a positive future PMP response over most of North America. The PW response for most of North America goes from a +5% to +10% in the first period of 2011-2040 to values of ~+20% by the 100-year 2071-2100 period under the RCP4.5 scenario, with the PW response being statistically significant for all of North America. For RCP8.5 scenario the statistically significant positive PW response has intensified compared with RCP4.5, where the future predicted 100-year (2071-2100) RCP8.5 PW response is generally double of that of that from the RCP4.5 scenario with most of North America showing a positive response of +30 to +50% from the historical period (1961-1990). The largest positive PW response under both scenarios is typically along the western part of Canada and the USA. Also, shown is that the PW response as a function of change in temperature is in line with the Clausius-Clapeyron relation with most of North America showing changes of +5-9% per K, with the northern Arctic regions showing a reduce ratio by ~2% per K. The perfect or design storm precipitation efficiency for most of North America shows a weak or negative response that continues to become more negative in time, stating that the positive PW response is typically increasing a faster rate than the precipitation for the annual maximum daily high efficiency storms. As we reach the final period (2071-2100) of RCP4.5 most of North America has a negative PE response between 0% and -10% with the statistically significant negative (~<-6%) now covering more than half of North America, but excluding much of the eastern seaboard, upper Midwest USA, Canadian Prairies, Northern Quebec and Newfoundland-Labrador, and small pockets in the Arctic. Under the most intensive RCP8.5 scenario during the final future 100-year period a statistically significant negative PE response covers most of the continent with the most intense negative PE of -20% occurs in Mexico and the southwestern USA (e.g. Arizona, New Mexico, and Texas) where there is predicted increased subsidence.

Most of North America shows an overall PMP positive response ranging from +10% to +20% for the future 100-year period under a RCP4.5 scenario, with the PMP response being statistically significant over most of Canada and the USA. The only regions showing a negative PMP response during this period being the western part of Mexico, a small region in the central USA, and part of the Great Lakes region. Only the southern part of the Mexican Baja Peninsula shows aa significant negative PMP response, which is due to the overall subsidence in this region of the tropics/sub-tropics over the Pacific Ocean. The overall PMP response for RCP8.5 scenario approximately doubles the RCP4.5 response by the time the 2071-2100 period is reached, where most of Canada and northern USA states have a statistically significant PMP response of +30%. Under these conditions, only about half of Mexico and a small region in south-central Arizona show a negative PMP response, with the only statistically significant negative PMP response being a small region on the south coast of Mexico and the southern part of the Mexican Baja Peninsula where the negative PMP response reaches -30%.

In this study we also looked at the variability in the resulting future response signal by examining the maximum inter- and intra-model spread in the RCM North American simulations. The intra-model spread in the PMP response from an ensemble of runs from the same RCM with different initial conditions is generally between ±5% and ±10%. Typically the maximum inter-model spread between RCM models over most of North America is between ±5% and ±15%.

This analysis concludes that for most of the Canada and USA there will be statistically significant positive response to the combination of meteorological factors that drive PMP if the future climate change follows scenarios that are similar to those predicted from RCP4.5 to RCP8.5. Even though direct future PMP magnitude values themselves cannot be well resolved in a regional climate model, the presented climate change response of these meteorological factors that drive the PMP can be used by stakeholders (i.e engineers) to make informed decisions on future long range projects designed to operate in a future climate (i.e. dams).

Additional future refinements and additions to this analysis in terms of going from PMP values to PMF values for future prediction of extreme floods will be to take into consideration the seasonal impacts of surface runoff conditions, such as snow-melt and frozen surface conditions, on estimating the PMP/PMF response in higher latitude across North America, especially in the spring.

# Appendix A:

Common equations used for the traditional PMP local method (i.e. WMO, 1986; Chen and Bradley, 2006; Kunkel et al., 2013) are gathered up and provided here for easy of reference in explaining the basic concepts of the PMP method used in this study. As shown in the PMP discussion in Section 2 the traditional local PMP method is estimated as,

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| --- | --- | --- |
|  | , | (4) |

The PW is the total column of water vapour and can be expressed as,

|  |  |  |
| --- | --- | --- |
|  | , | **(5)** |

where *g* is the gravitational acceleration and *qv* is the specific humidity at pressure level *p*. In practice the integral is often simplified in the PMP estimate to the summation over *n* number of pressure layers, *l*,

|  |  |  |
| --- | --- | --- |
|  | , | **(6)** |

Where is the pressure depth of the layer [hPa] from level *i* to (*i+1)*, is the layer specific humidity [g/kg], and ρwater is the density of water (1 g/cm3). Note that generally the desired long-term climatology of atmospheric precipitable water PW from specific humidity soundings is not available at the site of interest in order to make the PMP moisture adjustments. Thus, it is common practice to compute the PW from surface dew point temperatures and assume a pseudoadiabatic temperature lapse rate.

Rearranging Equation (4) (Kunkel et al., 2013) shows the underlying assumption of the PMP approach in that the total number of tropospheric column water replacement cycles, *N*, of the design storm and the estimated maximum PMP is the same for the duration of the storm,

|  |  |  |
| --- | --- | --- |
|  | . | (7) |

The number of cycles *N* expressed in terms of time scales for a storm raining for *tdur* with the water column being is replaced every trepl expressed as

|  |  |  |
| --- | --- | --- |
|  | , | (8) |

which is essentially the moisture “pumping” of the system. For example, a storm that lasts for 1-hr with a replacement time of 15 min will have 4 cycles. One can also estimate the average vertical velocity, (), of the parcel of air rising in a storm of vertical extent (*H*) in time (trepl) as:

|  |  |  |
| --- | --- | --- |
|  | , | (9) |

Combining above equations (7), (8), and (9):

|  |  |  |
| --- | --- | --- |
|  | , | (10) |

which can be rearranged so that the average vertical motion in the storm can be estimated as:

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

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We would like to thank Mike Lazare from Environment Canada for his help with the RCM CORDEX output data discussions. We would like to thank World Climate Research Programme (WCRP) for supporting the CORDEX project and the RCM downscaling groups at the Canadian Centre for Climate Modelling and Analysis, the Danish Meteorological Institute, and the Swedish Meteorological and Hydrological Institute for providing the regional model simulations used in this study.

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# Supplemental Figures

|  |  |  |
| --- | --- | --- |
|  | **RCP4.5** | **RCP8.5** |
| **2011-2040** |  |  |
| **2041-2070** |
| **2071-2100** |

Figure . Median response of RCM simulations of precipitation (P) for scenario RCP4.5 and RCP8.5 at the three future predicted 30-year periods of (2011-2040, 2041-2070, 2071-2100) for 1x1 RCM grid-box regional resolution of 0.44 degrees.

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| --- | --- | --- |
|  | **RCP4.5** | **RCP8.5** |
| **2011-2040** |  |  |
| **2041-2070** |
| **2071-2100** |

Figure . Median response of RCM simulations of temperature (T) for scenario RCP4.5 and RCP8.5 at the three future predicted 30-year periods of (2011-2040, 2041-2070, 2071-2100) for 1x1 RCM grid-box regional resolution of 0.44 degrees.

EXTRA JUST FOR EASY FIGURE COMPARISONS, WILL REMOVE LATER AS PLOTS ARE ALREADY PROVIDED.



