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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|  | . | (1) |

We can rearranging the right-hand side of Equation (1) gathering the storm variables together as , which can be thought of, and defined here, as a simple storm precipitation efficiency, *PES(xS)*, that does not include water removal from the system (e.g. Sellars, 1965),

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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*.

# RCM Description

Climate model simulations are not utilized to directly calculate a specific PMP as the detailed input requirements change 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), and the combined effects of these future meteorological factors towards estimates in future PMP responses to climate change scenarios.

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). This method is also representative of the traditional local and transposition PMP approach (Equations (2) and (3)) of obtaining an indirect estimated of the storm’s vertical velocity (Equation (11)). Following this PMP approach we attempt to first identifying a “perfect” or highly-efficient storm 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.

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) (reference) downscaled from the Canadian Earth System Model (CanESM2) (reference) 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 (1971-2000) 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 1971-2000 and 2011-2040 as an example. First, the difference in means between future 30-year period (2011-2040) and historical 30-year period (1971-2000) 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 meteorlogical factors that influence PMP based on the RCP scenarios the historical RCM simulations are presented in Figure 1. The main purpose of this figure is to just show the general spatial pattern in the annual maximum extreme values of the reference simulations used in the response calculations. These intra-model ensemble median values from the four RCM for the historical period (1971-2000) 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. 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.

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| **Historical (1971-2000)** |
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Figure . Median of the RCM simulations of preciptable water (PW), precipitation efficiency (PE), and probable maximum precipitation (PMP) for the historical (1971-2000) 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 preciptable 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.

**Bullet Points for Figure 2 RCP4.5:**

* *2011-2040*
  + *PW*
    - *As expected statistically significant increases everywhere across North America as indicated by the black dots (stipple)*
      * *Consistent with C-C equation with increasing temperatures*
        + *this can be used with the ratio plot*
    - *During this first 30-year period there is ~10% increase in PW response over western part of USA and over most of Canada except for the southern part of Ontario and large regions in Northern Canada.*
    - *The rest North America shows <10% increase in PW.*
  + *PE*
    - *The precipitation efficiency of the daily “perfect” storms response various across North America during this period.*
    - *The PE has decreased across most of the central US and Mexico with the response being significant for many values < ~-4 to 6 % changes. Other large regions of significant decrease in the PE response are: up the northern coast of B.C. and into the Western part of Yukon Territory Canada and Alaska, USA; the eastern part of the Northwest Territories up into Nunavut and the Arctic; and Ontario. Most of central Canada also shows a weaker decreasing PE response (0 to -4%) that is not statistically significant for this period.*
    - *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 central Canada and USA, and east coast of Hudson Bay down to the St. Lawrence region of Quebec. However, only a very limited area with values above 4% are statistically significant for this period.*
    - *Note: one needs to keep in mind that PE is just the ratio of PR/PW. Thus, in general both have an increasing response to the predicted changing climate over most of North America, it is just the negative PE response typically indicates that for the perfect storms the PW is increasing at a faster rate that the PR. (See supplemental plots).*
  + *PMP* 
    - *The PMP response is increasing over most of North America in the range of 0 to +10%. During this period the increasing response is significant over only parts of the continent, typically when the response is increasing by at least +10%. This statistically significant response regions include over ~1/2 of Canada, and most of the eastern seaboard of the US and Canada, excluding Florida and parts of US NorthEastern States.*
    - *There are also some smaller pockets of decreasing PMP response of ~-10% or weaker 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 period none of the decreasing PMP responses are statistically significant.*

* *2041-2070*
  + *PW*
    - *As we project further in time to the PW response compared to historical values also increases with most of the N.A. continent having at least a +10% response with some pockets along the western edge reaching values of +20%.*
    - *Again all the increases are statistically significant.*
  + *PE*
    - *Most of the continent is now showing decreasing PE values, and there are more regions with a statistically significant response,*
    - *The majority of the statistically significant regions have negative PE below ~-4% that occur over almost all of Mexico, along most of the Western coastal regions of North America, North of 60N latitude, and parts of Manitoba, Ontario, and the Northern part of Quebec and Newfoundland and Labradar*
    - *There are isolated pockets of increased PE response in the North Central and Eastern part of North America, but the only small significant positive response of +4-6% occurs in South-Central Quebec.*
  + *PMP*
    - *The overall PMP response (PE \* PW) continues to increase over most of the NA during this period, with the exception being the Western half of Mexico, and a couple of small pockets in the Southwestern US.*
    - *Most of NA has PMP response values that are greater than 10% and are statistically significant, with the exceptions being Southwestern USA, around the Great Lakes region, along the West Coast and few small regions north of ~55N latitude.*
    - *The only statistically significant decreasing PMP response occurred in the small regions of central and western Mexico where the response reaches ~-20%. Note, that the Eastern part of Mexico has a small region of significantly positive PMP response.*
* *2071-2100*
  + *PW*
    - *The PW response continuous to increase with time with all regions continuing to have a statistically significant response. Now most of the Western part of NA, excluding Mexico, has a response greater than +20%.*
    - *There are also pockets of other regions in the arctic, Canadian MidWest, and Northeastern Canada that also reach PW responses > +20%.*
    - *The rest of the continent has a response between 10-20%.*
  + *PE*
    - *Now most of the continent has statistically significantly decreasing PE response with the statistically significant response moving into more easterly region, except for most of the eastern seaboard of USA and Canada excluding the tip of Florida, immediately along the coast of MA, NH, Maine and Nova Scotia, and southern Newfoundland.*
    - *The small pockets of positive PE response in Central Canada, Northern MidWest US, parts of the Eastern seaboard, and East of James Bay, have been further reduced with none of them now being statistically significant.*
    - *Note that PE response in central and Northern Quebec changes from the last period (storm track change????).*
  + *PMP*
    - *For this projected period there is a statistically significant positive response over most of Canada and the US, except for the South-Central US and the Great Lakes region (due to the significantly reduce PE response reducing the impact of the significantly increasing PW). The South-Eastern part of Mexico also shows a significant positive PMP response.*
    - *Again, the Western part of Mexico, a small region in the central US, and part of the Great Lakes region are the only regions that show decreasing PMP response during this period. However, only the Southern part of the Mexican Baja peninsula shows a significant decreasing PMP response*.

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

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

**Bullet Points for Figure 3 RCP8.5 Response:**

* *2011-2040*
  + *PW*
    - *Very similar to RCP 4.5 with all of NA having statistically significant positive changes, and a slightly larger percentage of the area with ~10% increase response. .*
  + *PE*
    - *Again similar to RCP 4.5 in that most of NA has decreasing PE with large areas of statistically significant changes are negative (~-6%)*
    - *Some localized regions pockets of positive change, but no positive change is deemed statistically significant during this period. The main areas of increasing PE response ranging between +2% and +4% are the now limited central Canada in Alberta and Saskatewan, Western Ontario, and east coast of Hudson Bay, Labrador and Newfoundland, and as small part of St. Lawrence region of Quebec, South of Chicago in the USA, and the coast of Gerogia and South Carlolina.*
  + *PMP* 
    - *Similar to RCP4.5 the PMP response is increasing over most of North America in the range of 0 to +10%. During this period the increasing response is significant over parts of the continent, generally when the response reaches about +10%. In RCP8.5 the PMP is increasing slightly less over the B.C, but more so over the Southern Canadian Praires and Northern Central Mid-West of the USA.*
    - *There are also some smaller pockets of decreasing PMP response of ~-10% or weaker that occur in the central and western USA region and the Great Lakes region (which is more similar to RCP4.5 in the 2071-2100 period response), there are also a few very small pocket up north of 60N. However, for this period none of the decreasing PMP responses are statistically significant.*

* *2041-2070*
  + *PW*
    - *Unlike the RCP4.5 for this period the PW response is increasing by +20% over most of Canada, Central and Western USA, and Central Mexico.*
    - *Again all the increases are statistically significant.*
  + *PE*
    - *The overall pattern in the PE has not changed much from RCP4.5, however, the RCP 8.5 for this period is more similar to the RCP4.5 for the future period of 2071-2100 (response is a little earlier in RCP8.5).*
    - *The only pockets of positive PE that remain are in the St. Lawrence region, South of the Great Lakes starting from Chicago.*
  + *PMP*
    - *The overall PMP response (PE \* PW) continues to increase over most of the NA during this period, with the exception being the Western half of Mexico, and a couple of small pockets in the Southwestern US.*
    - *Most of NA has PMP response values that are greater than 10% and are statistically significant, with the exceptions being Southwestern USA, around the Northern Great Lakes of Superior, Huron, and Michigan, along the West Coast and few small regions north of ~55N latitude.*
    - *The only statistically significant decreasing PMP response occurred in the small regions of central and western Mexico where the response reaches ~-20%. Note, that the Eastern part of Mexico has a small region of significantly positive PMP response.*
* *2071-2100*
  + *PW*
    - *The PW response continuous to increase with time with all regions continuing to have a statistically significant response. However, compared the RCP8.5 the PW response is essentially double that of the RCP4.5 scenario, reaching large regions with a 40% increase in response from the historical period. The overall pattern remain similar with largest response typically being along the Western part of the US and Canada.*
  + *PE*
    - *For RCP8.5 there is a decreasing PE response over entire NA, with most of the continent having statistically significantly decreasing PE response > 6%. The only regions that don’t have a statistically significant decreasing PE are: a region in Central Canada, North Dakota, parts of the Eastern seaboard in the USA, and South and Eastern Quebec.*
  + *PMP*
    - *The RCP8.5 PMP response has a similar overall pattern RCP4.5, however, the magnitude in the positive response has increased by ~+10 to 20% and reaching values of up to 30 and 40 % in Canada and Alaska. Again almost all of Canada and most of the USA show a statistically significant response. The only positive PMP response regions that are statistically significant are the Northern Great Lakes of Superior, Huron, and Michigan, Southern-MidWest USA, and the far South-West USA mostly in Arizona, and the Central and Eastern part of Mexico.*
    - *About half of Mexico and a small region is south-central Arizona are the only regions in NA that show a decreasing PMP response, with the statistically significant decreasing PMP response being the Southern part of the Mexican Baja peninsula and a small region in South Coast of Mexico.*

OLD

* general lack of vertical motion or subsidence in the tropics/sub-tropics over the Pacific and Atlantic oceans as expect
* with increasing precipitation efficiency (vertical velocity) in the mid-latitudes following the West-to-East storm track, and then lower values in the arctic regions. In terms of the future response in precipitation efficiency the overall patterns across North America are similar between RCP 4.5 and RCP 8.5.

# 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 preciptable 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.

* PW
  + The maximum spread in the inter-model response tends to increase with the magnitude of the response signal (similar pattern)
    - Thus the inter-model variability increases as the prediction time increases (i.e. the models vary more the further out in 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 ±12% on a median response signal of 20-30%.
* PE
  + Unlike the PW, the PE inter-model spread values tend not to change a lot in time.
  + The maximum inter-model spread is in central and western Mexico including the southern Baja Pennisula, and up into the south-central US states of Texas, Oklahoma, Kanas 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%
  + The majority of North America has an inter-model spread in the PE response that is less than 4%.
* PMP
  + More like PW, the inter-model spread increases in time and thus with increasing magnitude of 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%. There is also a region of larger 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 Penninsula, which corresponds to large significant -10-20% PMP response signal.

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

Figure . The maximum inter-model spread of the ensemble of different RCM simulations of preciptable 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.

* PW
  + Very much the same pattern as RCP4.5, but with larger maximum spread in the inter-model response with the increasing magnitude of the RCP85 response signal compared with RCP4.5
    - Thus the inter-model variability increases as the prediction time increases (i.e. the models vary more the further out in the future).
    - The average inter-model PW spread is typically < 10% for median response signal of 30-40%.
    - 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%.
* PE
  + The overall pattern is similar to RCP4.5.
  + Again, unlike the PW, the PE inter-model spread values tend not to change a lot with time.
  + Also, the maximum inter-model spread is in central and western Mexico including the southern Baja Pennisula, 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%
  + The majority of Canada, Northern and Western States have an inter-model spread in the PE response that is <6%.
* PMP
  + More like PW, the inter-model spread increases in time and thus with increasing magnitude of PMP signal. The general overall pattern of the inter-model spread is similar between RCP4.5 and RCP8.5, with the magnitudes generally being larger for the RCP8.5 and corresponding to the larger PMP response signal.
  + In the earlier 2011-2040 period most of inter-model PMP spread is < ±10% with most of the larger spread occurring in pockets round the Arctic region North of 60N with a spread of values of ±15-30%.
  + As time progresses into the next 100-year period the general pattern of the inter-model variability remains similar generally following the increase magnitude of the PMP signal with the smaller values <±10% remaining mostly on the North-West Coastal region, Southern Canada Prairies into Western Ontario, parts of Northern Manitoba and Quebec, most of the Canadian Atlantic Provinces, the US Mid-West from Canada down to North-Western Mexico.
  + Most of the rest of North America have inter-model variability ~ < ±20% for median PMP responses of ~ 20% to 30%. There are also regions of larger spread in the Arctic and around the Great Lakes, South-Central US, and southern California and Nevada. There is also a small region of maximum model spread near the southern tip of the Mexica Baja Penninsula, which corresponds to large significant -10-20% PMP response signal.

## Intra-model Variability

In addition to evaluating the inter 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 for one 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.

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

Figure . The maximum intra-model spread of the ensemble of CanRCM4 RCM simulations of preciptable 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 very much as the simulations proceed out into the future.

* PW
  + The intra-model spread in the PW response is generally < ±4%, with a region in the SouthWest USA (California, Nevada, Arizona, Utah), and a small region in the Arctic that has the intra-model spread reaching ±6-8 %
* PE
  + 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 showing slightly larger intra-model variability between ±4 and ±12 %
* PMP
  + The intra-model spread in the PMP response is generally < ±10%. (do we want to put in median values here and in other places to be a little more quantitative????)

# 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 would expect a relative percent change in the saturation vapour pressure of ~25% (or 5% per K).

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

Figure . Plot of the median response of RCM simulations of preciptable 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 (degree Kelvin) 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 from the RCP4.5 and RCP8.5 scenarios.

* PW
  + The overall PW response to change in temperature pattern remains the same throughout the 100-yr simulation, however, the ratio increases slightly in time.
  + For NA the change in the PW response to change in degree Kelvin of temperature are generally in the range of +5 to +9% per K, which is consistent with the C-C equation.
  + North of ~60 N, small region in the centre of the USA, and the Western part of Mexico, typically show a smaller rate of change with values between 3 and 5% per K.
* PE
  + Again the general overall pattern of the response in PE with change in temperature 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 PE 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.
* PMP
  + The pattern in the PMP response to changes in temperature follows the pattern in the PMP response. 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% response to change in degree K. In the last period 2071-2100, there are regions of negative change around the upper Great Lakes region around Lake Superior, Lake Michigan, and Lake Huron, the Western Part of Mexico, and south-central US around Kanas and Oklahoma.

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

Figure . Plot of the median response of RCM simulations of preciptable 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 follows closely the same pattern discussed for RCP4.5.

* PW
  + Slightly stronger response of PW with changes in temperature with more regions having 7% or greater change with 1 degree change in temperature. This is especially true in the Arctic where the response increased by ~ 2%/K.
* PE
  + Very similar in pattern and magnitude to RCP4.5
* PMP
  + Very similar to the pattern and magnitude to RCP4.5, with the notable difference that from the 2041-2070 period and further, there are no negative response with change in temperature around the Upper Great Lakes and the central US. The only region of negative response after 100-years in the USA is the most southern tip of Arizona.

# Conclusions

# 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,

|  |  |  |
| --- | --- | --- |
|  | , | (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 climatologies of atmospheric precipitable water PW from specific humidity soundings are 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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# 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.

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



