Project/Network Title:

Short-duration extreme precipitation in future climate

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Summary (1/2 page)

Understanding of the physical processes affecting short-duration (less than 24 hours) extreme precipitation and their possible changes in the warming world is critical for many of GWF’s users. However, most global and regional climate models do not directly simulate the processes that produce extreme precipitation due to their coarse resolutions, which hinders the proper interpretation of the precipitation projections produced by these models. Such questions can be addressed by making extensive use of a convection-permitting modeling tool running in a pseudo-global warming mode, and comparing it with existing simulations by global and regional climate models. Here we propose to work specifically on the following four questions: i) Does temperature scaling work at convective-permitting resolutions for short-duration local precipitation extremes? ii) How will the characteristics of mesoscale convective systems (MCSs) such as the precipitation intensity, size, and life-span of storms change in the future? iii) What are the underlying physical processes that result in changes in MCSs and storm properties? iv) How do extreme precipitation features scale across resolution from GCMs to RCMs to convective permitting WRF? Our proposed work will lead to a better understanding of the physical soundness of future precipitation projections by climate models, thereby providing a scientific foundation for the proper use of model projections that many GWF’s users depend on.

Scientific Rationale (1 page)

This project will address a significant science gap for robust projection of extreme precipitation by examining physical processes affecting extreme precipitation. Changes in short-duration extreme precipitation in the past and in the future are critical for many sectors in GWF. The GWF has funded Pillar #3 project "Climate-related precipitation extremes" (Referred to EXTREME project) to produce, among others, future projections of extreme precipitation based on climate model simulations. Simulations by climate models, including both global and regional climate models (GCMs and RCMs) have been used to project changes in short-duration extreme precipitation. There is some confidence in model simulated changes in extreme precipitation, at least at larger scales, supported by the physical understanding of increases in moisture holding capacity of the atmosphere resulting from warming, and the fact that model simulated responses to external forcing can reproduce some types of observed changes at large scale. Nevertheless, it is unclear how to use the model projected future changes properly in adaptation planning at regional and local scales. This is because processes important to short-duration extreme precipitation such as convection are not explicitly resolved by the models. This represents a significant scientific gap that requires in-depth process study. Here, we will address this gap, at least in part, by focusing on processes that affect the intensity of daily and sub-daily extreme precipitation in cold regions like Canada, duration and size of storms, and how the processes may evolve in a changing climate, thereby providing scientific foundation for the proper interpretation and use of future projections such as those produced by EXTREME projects.

The saturation vapour pressure of water increases at a rate of about 7% per °C of warming according to the Clausius-Clapeyron (CC) equation. Atmospheric moisture has increased in observations and is also projected to increase in the future. The expected response of the heaviest rainfall events to warming has been thought to be dominantly controlled by the availability of atmospheric moisture (O'Gorman and Schneider, 2009), and the projection of future temperature is robust even at small scales, additionally, given the difficulties in interpreting model projections and very limited availability of convection-permitting model simulations. Our hypothesis is that temperature scaling breaks down at small space/time scales, but that it might nevertheless provide an adequate statistical means for projecting changes in the distribution of sub-daily precipitation extremes. That is, it works on average across a large ensemble of events despite not working in specific instances of extremes.

To test this hypothesis and to determine the degree that short-duration extreme precipitation may alter this relation at local and regional scales, we will make extensive use of existing WRF Pseudo-Global Warming (PGW) simulation that was forced with a large global temperature increase (RCP8.5) thereby providing best opportunity to identify such footprint, as well as specially designed WRF simulations to reveal changes in particular aspects of processes. As the km-resolution WRF modeling tool explicitly resolves moist convection, our analysis will shed new light on possible changes in the physical mechanisms involved in short-duration extreme precipitation in a warming climate. Our analyses are multi-facetted, involving the comparison of different aspects and processes under the current and future climates including seasonal evolutions of extreme precipitation in relation to seasonal mean temperatures, precipitation efficiency of storms, life-time and spatial size of storms and mesoscale convective systems (MCSs), pre-storm atmospheric stability, updraft in extreme storms, and convective available potential energy (CAPE), etc. By focusing on physical mechanisms, we will be able to answer questions related to not only how short-duration precipitation may change in the future, but also why it may change, thereby significantly enhancing our confidence in future projections.

Objectives and Methodology (both 3 years and 7 years plans) (8 page)

Introduction

Projection of future climate relies very heavily on simulations by global climate models forced with future emission scenarios. These models are based on physics that govern the earth's climate system. They are able to reproduce not only the observed climate, but also past changes in the climate. The past and future climates simulated by these models provide important science basis for national and international climate policy development such as the sequence assessment reports of the Intergovernmental Panel on Climate Change. Climate model simulations become less adequate at regional and local scales at which climate adaptation is typically performed. The credibility of model simulations and thus the robustness of model projected future climates can also differ significantly for different climate variables. In general, model simulations are very creditable for temperature related variables even at relatively small regional scales. As for extreme precipitation that is very relevant to GWF, there is some confidence in model simulated changes, at least at larger scales. This comes about because model simulated responses to external forcing can reproduce observed changes in annual maximum 1-day and 5-day precipitation over land where observational data are available. This is also supported by the physical understanding of increases in moisture holding capacity of the atmosphere resulting from warming, and the expectation that more moisture shall lead to more extreme precipitation. While model simulated extreme precipitation has found many applications, there are significant issues in properly interpreting model projected changes in extreme precipitation especially for short-duration (daily and sub-daily) extreme precipitation at regional and local scales as we will explain below. Short-duration extreme precipitation is especially important for many GWF users.

A typical GCM runs at a spatial resolution of 100-200 kilometers, while typical RCM runs at a spatial resolution of 25-50 km. Some RCMs are capable of running at a spatial resolution just slightly coarser than 10 km. A model running at a spatial resolution of 10 km may represent large-scale features such as frontal and storm systems well, but does not explicitly simulate convective processes that are associated with short-duration extreme precipitation because the convective elements are of much smaller spatial scale, only up to a few kilometers. A practical solution for climate models is to rely on a mass-flux cloud-plume convection parameterization scheme to compute the estimated average effects of convection over model grid squares (e.g., Tiedtke, 1989). Convection parameterization schemes act to modify the vertical profile of model variables on the grid to take account of the redistribution of the heat, moisture, and momentum associated with the convective cells that cannot be resolved, with an assumption that convection is in equilibrium with the larger-scale forcing. The use of a convective parameterization scheme is essential in these coarser-resolution models to maintain the stability of the model. However, they are not designed to produce locally realistic rainfall amounts. Additionally, a GCM and a typical RCM use the hydrostatic approximation simplify the vertical equation of motion. The approximation assumes that the absolute vertical acceleration in the atmosphere is negligible, which is valid for synoptic-scale motions. This assumption becomes problematic for processes with length scales less than 10 km (Dutton, 2002) such as convection. For these and other reasons, GCMs are not considered to be reliable for simulating sub-daily precipitation (Stephens et al. 2010). There is thus an issue regarding proper interpretation of model simulated changes in extreme precipitation.

In contrast, convection-permitting models (CPMs) use non-hydrostatic governing equations and cloud microphysical processes that explicitly trigger deep convection, producing much more realistic precipitation at small scale (Dudhia 1993). At grid lengths of less than approximately 4 km, a "convection-permitting" model is able to represent the convection on the grid sufficiently well with convective structures, such as peninsular convergence lines, convective clusters and bands, squall lines, and mesoscale convective systems, are all represented with a high degree of realism. The models are able to successfully discriminate between smaller scattered showers and more organized structures, and between less intense and more intense convection (Westra et al. 2014). Limited available CPM simulation has already shown features that had not been known before. For example, Prein et al. (2017a) showed that warming may result in not only larger magnitude of extreme precipitation at a location, but also larger sized and slower moving storms which would produce substantially more severe floods. A kilometer spatial resolution model has to integrate at very fine time step to maintain numeric stability. This means that CPMs are very expensive to run and it is not feasible to produce hundreds and thousands years of simulations, as what are available from GCM simulations, to enable quantification of future changes and their associated uncertainty.

The expected response of precipitation to external forcing is small when compared with its natural variability. Given the lack of processes to directly simulate small scale extreme precipitation by GCMs and RCMs as well as limited availability of CPMs simulations, it is very difficult to robustly estimate past and future changes in short-duration extreme precipitation based on existing observational data and model simulations (Zhang et al. 2017). On the other hand, models are able to simulate temperature robustly even at small scales. There is a well understood connection between saturation vapour pressure and temperature through the so-called Clausius-Clapeyron relation and the expected response of the heaviest rainfall events to warming has been thought to be dominantly controlled by the availability of atmospheric moisture.

Our hypothesis is that temperature scaling breaks down at small space/time scales, but it might provide an adequate statistical means for projecting changes in the distribution of sub-daily precipitation extremes. That is, it works on average across a large ensemble of events despite not working in specific instances of extremes. To test this hypothesis and to determine the degree the response of extreme precipitation may alter this relation at local and regional scales, we will need to gain in-depth understanding of physical mechanisms involved in short-duration extreme precipitation and how they may change in the warming world. For this purpose, we have designed 4 interrelated programmatic work packages, with a focus on process-level understanding and the help of WRF modeling tools. The project will involve the following approaches: physically based diagnostics, specialized WRF experiments, and analysis of the circumstances under which temperature scaling can be used to understand changes in short-duration extreme precipitation. For the latter, the hypothesis would be that it fails for individual sub-daily, local, precipitation extremes (for physical reasons that is going to diagnose in this project), but that it may nevertheless be an adequate way to described changes in the population (distribution) of extreme events due to long-term warming.

Objectives and work packages

The main objective of this project is to gain an in-depth understanding of physical mechanisms involved in short-duration extreme precipitation and how they may change in the warming world, thereby providing an important scientific foundation for interpreting projected future changes in extreme precipitation. We will aim to better understand the roles of thermodynamics and dynamics in storm system changes. While studies on relative roles of thermodynamics vs dynamics in tropical extreme precipitation are emerging, there are very few studies on similar topics for mid- and highlatitude extreme precipitation by convective storms. Our approach will be to make extensive use of the convection-permitting WRF modeling tool to investigate how physical mechanisms, including pre-storm atmospheric stability, convective lifting strength, convective inhibition, precipitation efficiency, size and life span of storms, may change in the future; and to compare simulations by WRF, classical RCMs and GCMs to understand how features of extreme precipitation scale across resolutions among models. Our 7-year objective is to advance our knowledge of in the characteristics of storms including intensity in extreme precipitation, size and life-span of extreme storms intensity over Canada under future climate conditions. Our three-year objectives will focus on the following questions organized as 4 interrelated work packages (WPs) including

- WP1. Precipitation and temperature relationships,
- WP2. Changes in mesoscale convective systems (MCSs) and characteristics of storms,
- WP3. Physical processes underlying the changes in MCSs,
- WP4. Physical realism of GCM and RCM simulated extreme precipitation.

Details of these WPs are outlined below.

WP1. Precipitation and temperature relationships

This work package focuses on the following questions. What are the relationships between precipitation scaling that is defined intra-annually (so called binning scaling) and that which is defined inter-annually (trend scaling)? What are the future changes in binning and trend scaling? Does their relationship change in the future? Binning scaling reflects influence of seasonal cycle of storm systems. Comparison between binning scaling in the observations and in model simulations can provide a useful diagnose of performance of modeling tools. Changes in binning scaling reflect changes in storm systems and their seasonality or in dominate storm types (convective vs non-convective). Trend scaling in contrasts predominately reflects the influence of long-term warming on the intensity of extreme precipitation. A significant change in binning scaling is an indication that trend scaling may not follow CC relationship.

The temperature-precipitation scaling will be examined based on observations and simulations by different sets of models including CMIP5, CanRCM large ensemble, and the continental WRF pseudo warming simulations, with an aim to elucidate temperature scaling effects related to different temporal and spatial scales. Scaling based on the CCRN version WRF simulations for Western Canada will also be computed. Some of this work will come from the EXTREME project, with important addition. The additional work focuses on binning scaling and its use in model diagnosis especially for WRF simulations and potential for identifying regions where seasonal evolution of storm systems may change in the warming world. The effect of temporal and spatial scales will be investigated using the 4-KM WRF (Liu et al., 2017). The high space-time resolution of the WRF output will be aggregated to the space-time resolution comparable from RCM outputs to understand the effect of spatial interpolation on extreme precipitation intensity. These will also be compared with relevant statistics derived from RCM simulations to identify added values (or lack of) of WRF simulations. As 4-km resolution is nearly at the boarder where convection-permitting start to function, WRF experiments at resolutions of 1-km or 250-m will be conducted for a small region using a one-way nesting approach NDOWN to examine the realism of 4-km resolution simulation in producing short-duration extreme precipitation. Precipitation scaling especially the binning scaling from the higher resolution WRF simulations will be analyzed and compared with those obtained from simulations by other types of models. This may provide some insight of hourly and sub-hourly extreme precipitation.

WP2. Changes in MCSs and characteristics of storms.
This work package focuses on the following questions. How will mesoscale convective systems (MCSs) change in the future? How do those changes affect changes in impact-causing storm? How do the properties of storms including maximum precipitation rate, precipitation efficiency, life-time and spatial size may change? Are earlier findings that a storm gets larger and lasts longer in a warming world robust and applicable across Canada?

Prein et al. (2017b) analyzed MCSs and storm systems in the continental 4-km WRF simulation that includes a portion of Canada. They showed an increase of flood potential to an unexpected level in the pseudo warming projection in southern Canada. The increase in flood potential is due to larger number of MCSs, slower motion of MCSs, higher maximum rain rate, and larger storm sizes that result in disproportional increase in the storm total amount of precipitation. Such finding, if stands, will have significant implications for many of GWF users. Because of the significance of the potential impacts, the robustness of these findings must to be examined. We will conduct similar analysis based on the CCRN version WRF simulations for Western Canada and the new transit WRF simulation that is planned which extend further in Canada than the continental WRF simulation. Results from these analyses will be compared with those of Prein et al. (2017b) to determine robustness of their findings to the changes in domain, domain sizes, and configuration of boundary forcing. A similar analysis will be conducted based on the CAM5.1 model runs at the 0.25° resolution. We realize that the 0.25° CAM5.1 run does not produce true mesoscale convective systems. Nevertheless, it would still be useful to compare MCSs with those simulated by the convection-permitting model to identify what might have been missed in the CAM5.1 simulation and aspects that CAM5.1 can simulate reliably and any collaborative evidence for slower moving and large sized storms in the warming world.

The Method for Object-Based Diagnostic Evaluation (MODE) with the included Time Domain (MODE-TD) analysis has been used to identify MCSs in convective-permitting WRF simulations to study MCS properties such as track, movement, size and life-span. The method can trace each storm system and provide information such as area coverage, center, axis angle, and intensity. The PI's group has already gained considerable experience in using this NCAR developed tool for the verification of the continental scale 4-KM WRF model simulated composite radar reflectivity and compared them with the Weather Surveillance Radar-1988 Dopplers (WSR-88Ds) national mosaic. The tool will be used to analyze additional features of a MCS such as its initiation, development, and dissipation. Since WRF model simulates composite radar reflectivity, the proportion change of convective versus non-convection precipitation during the event lifecycle can also be quantified (Li et al. 2017). Using this technique, we will be able to gain some insight on the statistics of the propagating speed, shape and duration of storms as well as intensity, precipitation type (convective vs stratiform), and total rain amount may change in response to warming, and how such changes relate to the changes in short-duration extreme precipitation.

WP3. Physical processes underlying the changes in MCSs.
This work package focuses on the following questions using two different approaches. What are the underlying physical processes for changes in MCSs and storm properties? What are the relationships between large-scale circulation and mesoscale dynamics in the context of future storms? How do aspects of mesoscale dynamics such as pre-storm atmospheric stability, convective inhibition (CIN),

convective lifting strength, precipitable water and convective available potential energy (CAPE) change in the future?

An idealized WRF simulation will be designed to model the full three-dimensional (3-D) dynamics of clouds (Robinson et al. 2008) to isolate aspects that may respond to warming more strongly. The experiment will be repeated using different model setup representing a selection of many cases of convective events. Warming effects on pre-storm convective available potential energy (CAPE) and CIN, column integrated water vapor and condensation rate will be examined. Additionally, warming effects on background stability, atmospheric humidity and strength of the mean uplifting will be analyzed. The role of CAPE in precipitation intensity, relationship between mean and extreme CAPE, the relationship between condensation rate and the precipitation efficiency will all be evaluated.

Mesoscale convective processes are very complex with different structures of organization (Houze, 2004). Their response to warming would be more complex than can be revealed in idealized WRF simulation and may depend on the convective environment, the type of convection, as well as storm movement. The impact of warming on changes of the convective regimes will be further assessed using the output of CCRN and continental scale 4-KM WRF simulations. Changes in mesoscale dynamics will be diagnosed using indicators such as updraft velocity, pre-storm CAPE, etc. for the CCRN and continental scale WRF simulations as well as CAM5.1 simulation. The influence of microphysics and precipitation processes on precipitation efficiency and hourly rainfall rate will be evaluated for CCRN and continental scale WRF simulations for both historical and PGW simulations and the difference will be compared. The influence of microphysics processes on precipitation efficiency and precipitation rate in WRF will also be compared with CAM5.1 for both historical and future climate. Large-scale and small-scale interactions and their impact on MCSs and characteristics of impact-causing storms will be evaluated using WRF output. The relative contribution of processes of different space-time scales will be examined using tools such as wave dispersion analyses (Kiladis et al. 2009; Carbone and Li 2015) for different areas for both WRF historical and PGW simulations.

WP4. Physical realism of GCM and RCM simulated extreme precipitation.

This work package focuses the following questions. How physically realistic is extreme precipitation simulated by GCMs and RCMs, compared to convection-permitting models? How do extreme precipitation features scale across resolution among models and vary across ensemble members in the case of GCMs and RCMs?

A particular difficulty in evaluating model simulated precipitation is the lack of proper observations. The output from model simulations will be validated using station observations and precipitation products. Observations, which are sparse over much of Canada, will be used to constrain model-based estimates of the precipitation intensity extremes. The combined use of observations and various products as well as different models will allow estimates of the intensity of extremes with the least uncertainty possible.

However, model simulations typically represent averages over a grid square while observations are usually taken at a point location (e.g. precipitation measure by a rain gauge). The availability of convection-permitting model simulations makes it possible to examine if extreme precipitation features scales across spatial resolutions and if similar scaling exists among models and the robustness of the scaling across ensemble members in the case of GCMs and RCMs when a large ensemble is available. For example, it is possible to aggregate convection-permitting model simulations into coarse resolutions that are comparable with those of GCMs and RCMs. We can then compare extreme precipitation statistics across spatial resolutions. Similarly, extreme precipitation simulated by RCMs can also be aggregated into spatial resolutions comparable to those of GCMs. Extreme precipitation features across resolutions can also be compared. Uncertainty in such relationships can be explored through the use of large ensemble simulations. Such comparison may provide some indication of physical realism of GCM and RCM simulated extreme precipitation as well as the way to adjust precipitation outputs from the RCMs based on precipitation outputs of convection-permitting models such as WRF.

A particular attention will also be paid to precipitation in regions of complex terrain such as the Canadian Rockies. Orography has a highly localized effect and rainfall response to local conditions (Rasmussen et al. 2011) can potentially confound the general conclusions drawn for a continental scale. Current RCMs have limitation in the horizontal resolution, which especially affects their performance in the Canadian Rockies without enough resolution and accuracy. In collaboration with other GWF groups such as the project led by Theriault which aims to focus on complex terrain precipitation processes, we will be able to examine whether the high-resolution WRF model is able to adequately represent the heterogeneity and small scale processes that control extreme precipitation in complex terrain and the model's ability in capturing short-duration extreme events over mountainous regions (Gutmann et al. 2016; Shi and Durran, 2014). Although this work will focus on the Canadian Rockies, the methodology to be developed will be applicable across Canada, and will be of interests in other regions where orographic enhancement is important.

7-year Plan

Whether short-duration precipitation extremes will change with the change of weather pattern under future climate condition?

Once GWF version WRF run (which cover the whole US and Canada south of 70°N) is completed, we will expand the year 1-3 analyses to simulations with a much larger domain and with longer time series to the end of the 21st century. More comprehensive analyses will be conducted using GWF version 4-KM WRF simulations. We will evaluate how realistic extreme precipitation is simulated by the GWF version WRF simulation. The difference between the GWF version 4-KM WRF future simulation and the CCRN version PGW simulation is that although the climatological means are still shifted to match those in warmer-world GCM simulation as the PGW approach, but the day-to-day weather is driven by perturbations at the lateral boundaries whose frequencies and intensities represent the future climate instead of the current climate (Dai et al. 2017). By comparing these two different versions, we are able to examine the changes in the frequency and intensity of precipitation extremes driven by changes in the frequency of mid-latitude storms which represents the change of the future weather pattern, for different parts of Canada.

Whether a specific devastating event will become more severe under future climate condition?

We will explore the event-based approaches. For selected historical devastating events, dynamical downscaling will be conducted from coarser-resolution models to storm scale under current or future climate condition (Trenberth et al., 2015). This approach will provide insight into how changes in large-scale convective environment may affect small-scale storms potentially at sub-daily time scales, without providing a definitive answer as to whether extreme rainfall will increase or not in general.

This method will only examine changes in the intensities of specific events and ignore changes in frequency or changes to the large-scale atmospheric circulation associated with those events (Mahoney et al., 2013). This can be used to investigate changes in extreme precipitation by local storm dynamics under changes in the larger-scale convective environment for predicting future change in severe storms.

Project deliverables and Timelines (1 pages)

2017 (November) – 2018 (October)

- Relevant observational data (PDF#2) and model outputs (PDF#1/PDF#2) are collected and in proper form for the analyses. WRF data are extracted (PhD#1).
- Develop/acquire/test statistical and physical diagnostic tools. Compute and compare binning and trend scaling rates from observations and simulations (**WP1**, PDF#2). Initiate diagnosing changes in mesoscale dynamics based on indicators/variables on CAM5.1 and WRF simulations (**WP3**, PDF#1).
- Design idealized WRF sensitivity tests (**WP3**, PhD#1/PDF#1) and produce test runs considering influence of environment temperature, stability, pre-storm CAPE on condensation rate.

2018 (November) – 2019 (October)

- Evaluate the influence of environment temperature, stability, pre-storm CAPE on short-duration extreme precipitation as simulated by WRF sensitivity experiments (**WP3**,PhD#1).
- Evaluate influence of microphysics and physical processes on precipitation efficiency and rain rate in CCRN version WRF for both historical and PGW runs and compare the difference (**WP3**, PDF#1).
- Evaluate influence of microphysics processes on precipitation efficiency and precipitation rate in CAM5.1 simulation for both historical and future climate and compare the difference (**WP3**, PDF#2).
- Identify MCSs in the CCRN version WRF simulation and examine MCS properties using MODE-TD. Evaluate changes in the size and life-span of impact causing storms for Canada (**WP2**, PDF#1).
- Identify MCSs in the CAM5.1 simulations and their future change. Examine what have been missed and aspects simulated reliably through comparing with those simulated by WRF (**WP4,** PDF#2).
- Evaluate large-scale and small-scale interactions and their impact on MCSs and characteristics of impact-causing storms (**WP3**, PDF#1/PhD#1).
- In collaboration with the EXTREME project, compare projection of extreme precipitation obtained from the EXTREME project with those inferred based on physical understanding, assess scientific soundness of the projections by GCMs and RCMs (**WP4**, PDF#2).
- Document findings and present results at conferences and in journal paper publications.

2019 (November) – 2020 (October)

- Identify MCSs in the GWF version WRF simulation and determine influence of global warming on MCS properties of impact causing storms in other regions of Canada (**WP2**, PDF#2).
- Evaluate influence of microphysics and precipitation processes on precipitation efficiency and rain rate in the GWF version WRF simulation and determine effect of global warming (**WP3**, PDF#1).
- Conduct WRF tests for orographic precipitation over Canadian Rockies. (**WP4**, PhD#1/PDF#1).
- Ensure all data/model/analysis have been documented and/or validated and available for sharing within and outside the GWF community. Document all findings and present results at conferences and in publications. Ensure all findings communicated to relevant GWF projects and core activities.

2020-2024

- Conduct more comprehensive analyses and comparisons between GWF version WRF simulations vs CCRN version WRF simulations.
- Conduct WRF experiments for several selected historical devastating events at small sub-domain with < 4-km resolution under current or future climate condition.
- Expand on linkages with practical applications such as engineering design and flood prevention.

Roles of Collaborators and User/Stakeholder Organizations (1 page)

Our international collaborators are essential for realizing our project. Their contributions are briefly summarized as follows:

World Climate Research Program (WCRP) Grand Challenge (GC) on Weather and Climate Extremes
The project will benefit and form an integral part of the WCRP GC through the coordination of Xuebin Zhang, a co-chair of the GC and a non-eligible collaborator of this project. On the other hand, the work will directly contribute to two of the four themes of the GC, namely simulate (Are models able to reliably simulate extremes and their changes, and how can this be evaluated and improved?) and understand (What are the relative role of large-scale, regional and local scale processes, as well as their interactions, for the formation of extremes?). Relevant knowledge learnt from other parts of world through the GC coordinated research will be used to advance this project in a timely manner.

Andreas Prein, National Center for Atmospheric Research (NCAR), United States, prein@ucar.edu
Andreas Prein is a project scientist at NCAR working in the Mesoscale & Microscale Meteorology Laboratory (MMM). He was the co-coordinator of the Convention Resolving Climate Modeling Working Group of the CCLM community and an active member of the EURO-CORDEX initiative. This project will benefit from his extensive working experience on extreme precipitation with convection-permitting climate models. From this project, he will gain more understanding through the collaboration on the examination of scaling problem and the application of MODE-TD analysis for tracing MCSs in Canada.

Ethan Gutmann, NCAR, United States, gutmann@ucar.edu
Ethan Gutmann is a project scientist at NCAR working with the Research Applications Lab (RAL). This project will benefit from his expertise on atmospheric modeling of precipitation in the mountains and the Intermediate Complexity Atmospheric Research model (ICAR). For this project, it will be mutual benefit to compare the future precipitation over the Rockies simulated by convective-permitting WRF with ICAR simulated future scenarios.

Frank Robinson, Yale University, United States, frank.robinson@yale.edu

Dr Robinson is an Assistant Director of Faculty Teaching Initiatives and Lecturer at Department of Geology and Geophysics and Department of Astronomy at Yale University. He is an applied mathematician. This project will benefit from his expertise on numerical modeling of the Earth's atmosphere and laboratory convection experiments. From this project, he will be involved in and gain more experience on the design of idealized WRF sensitivity tests for moist convection.

Jason Evans, University of New South Wales, Australia, jason.evans@unsw.edu.au
Jason Evans is an associate Professor at the Climate Change Research Centre and an associate investigator at the ARC Centre of Excellence for Climate System Science at the University of New South Wales. He has plenty of experience with regional climate models, land surface and hydrology models. He is the lead modeler on the NSW/ACT Regional Climate Modeling project (NARCliM). That project produced an ensemble of regional climate projections over south-east Australia for use in impacts and adaptation research. For this project, he will not only contribute to but also benefit from the examination of high- resolution regional climate model output for Canada the cold region.

ECCC is not only listed as a user because of the direct involvement of several of its scientists, especially Xuebin Zhang, who will be directly involved in examining intense precipitation with YL, FZ and HQPs concentrating on sub-daily extremes. Future projections of precipitation extremes are at the core of many ECCC activities and ECCC will play a critical role, both as a user and a collaboration.

Data management Plan (1 page)

Our project will adhere to the GWF data policy and data management plan. All data collected in this project will be archived in the GWF central data repository in a timely manner.

Data Collection. Data collection and data processing will be conducted with the support from Core Data Management team and other investigators. Station observations including high-resolution (hourly) precipitation and temperature data from ECCC will be acquired and bias corrected (Scaff et al. 2015; Pan et al. 2016), especially the underestimation of the rain rate due to gauge under-catch. Diverse sets of Canadian observational products include ANUSPLIN, CaPA, NARR, GPM will be acquired. We will rely on not only conventional observations, soundings, radar, reanalysis and satellite products, but also existing and proposed field campaigns data, i.e. the one to be led by Julie Theriault, to provide events measurement at very high spatial and temporal resolutions. The detailed monitoring from the Saskatchewan River Basin will be utilized, which is a benefit of the Regional Hydroclimate Project (RHP) of the GEWEX WCRP and Changing Cold Region Network (CCRN). The existing infrastructures include meteorological stations, instrumented towers, soil moisture sensors, SODAR and wind RASS.

Model output that will be used include GCM and RCM from various resolutions, i.e., NACCAP, CORDEX, CMIP5, CRCM, CanRCM datasets. Detailed analysis will be made for CCRN and GWF version 4-KM WRF simulation, CAM5.1-0.25degree simulations conducted at LBNL, and large ensemble simulations with CanRCM for high temporal resolution surface variables including temperature and precipitation, pressure and wind, and upper air variables including humidity, wind, vertical velocity.

Model Data Validation. The output from model simulations will be validated using station observations, precipitation products. Observations, which are sparse over much of Canada, will be used to constrain model-based estimates of the precipitation intensity extremes. The combined use of observations and various products as well as different models will allow estimates of the intensity of extremes with the least uncertainty possible.

Data Sharing. Output from the core WRF simulations will be analyzed intensively in this project. This includes the existing historic simulation for 2000-15 and pseudo-global warming (PGW) simulation under RCP8.5 emission scenario for the end of 21st century. These have been completed for western Canada as part of CCRN project (CCRN version WRF simulation) and the continental US (CONUS) simulations by NCAR for whole Canada south of 56°N. The other set of simulations is GWF version WRF runs that cover the whole US and Canada south of 70°N, collaborating with NCAR, driven by the RCP8.5 scenario. This set of simulations is planned to be completed within next three years. The 4-KM data that produced and used in this project, including the original model data and data analysis results, will be made available to the entire GWF community through working together with the Core Data Management Team. This will also contribute to the core activities. Besides that, we will work together with the Core Computer Science Core Team on creating the visualization of our research outcomes and the access of the relevant modeling products, and to develop the most efficient ways to deliver our results derived from the enormous model and observational datasets to other users.

Data Storage. Since this project will involve a huge volume of data both from observations and model simulations, we will work together with the Core Data Management Team to ensure our data storage needs are met and our use of storage is efficient, and our data are accessible by others. So far we have nearly 1000 TB storage space which is available for at least next three years at Compute Canada Graham System NDC-Waterloo, with 650 TB of project storage and 300 TB of nearline storage. This huge amount data storage space is secured through another independent competition Compute Canada's Research Platforms and Portals 2017. We plan to store most of our data on Compute Canada, a few of them will be stored locally at GIWS data server. Large volume data transfers with >1 TB each time between different GWF groups can be through Globus data transfer.

HQP Training (0.5 page)

This Project will train 1 PhD student and 2 post-doctoral fellows (PDFs). The HQPs will receive high-quality, multi-disciplinary training that integrates meteorology, hydro-climatology, big data statistical analysis and numerical modeling in a challenging yet supportive team-based environment. Supervisors will help the HQPs to develop essential skills at all stages of research: initial planning, methods development and selection, numerical experiments and modeling, statistical data analysis, communication of results. Considering the increasing demand for HQPs from related fields in Canada, HQPs will also be trained for project organization and leadership skills.

The HQPs also will be interacting with other HQPs hired through other GWF funded projects and core activities as a group. This will enable everyone to acquire knowledge and skills beyond the scope of his/her own work. Group meetings will be regularly organized on weekly or bi-weekly basis, both in person and through remote attendance. The meeting will be led by one HQP discussing his/her project. HQPs will learn and improve their research capability through discussing and critiquing each others' work. Senior HQPs (i.e. PDF) are required to directly interact with junior HQPs (i.e. PhD) and contribute to their growth as scientists. Matching students at different stages increases the productivity of both. This mini-mentoring experience will also benefit the HQPs in their future job applications.

HQPs will be co-supervised by university professors as well as research scientists at Environment and Climate Change Canada (ECCC). This model has been proven to be a successful strategy to train students in multidisciplinary fields. They will gain collaborative knowledge from scientists at government agencies including ECCC, and research institutes such as PCIC, National Center for Atmospheric Research (NCAR), through formal/informal collaboration. HQPs will benefit from visiting NCAR and ECCC. They will have an exceptional opportunity to be involved in the GWF research community and have the opportunities to present themselves at national and international stages.

Knowledge Dissemination Plan (1 page)

Our expected research outcomes include:

1) long-term, various type of precipitation data collected and archived, advanced analyses of variables for the short-duration precipitation extremes over Canada;

2) test and application of the coupled modeling system in a cold region with significant climate change;

3) train students and scholars at both UofS and PCIC to have high-resolution regional climate modeling and big data analysis skills;

4) communicate scientific results via conferences (AMS, AGU, CMOS, CGU), meetings and workshops; publish results via journal articles (AMS, AGU, EGU journals), and online information, develop a website hosted within the GWF main page and linked to other websites for greater visibility, share information on that website about schedules of activities, post reports regularly online for public access, communicate scientific results with general public through media releases, newsletter articles, social media such as twitter or facebook;

5) community partnerships, communicate with users, capable of interacting with scientists on multidiscipline study such as the water management decision making, share results with the GWF research community and policy makers;

6) increase attention to and collaboration around climate change adaptation and water related issues in Canada, collaborating with Canadian institutions;

7) international collaboration that responds to the needs of Canada.

Specifically, each HQP funded by this project is expected to be lead author of 1~3 publications and present at least twice in American Meteorology Society (AMS) and Canadian Meteorological and Oceanographic Society (CMOS) conferences. They are also required to present regularly at GWF regular meetings and workshops.

By the end of this project, the network among project collaborators, team members, faculties, scientists, community local partners, policy makers will be strengthened. Research findings and implications for policy will be shared with the collaborating teams, and the developed modeling tool and data will be released and provided to other research groups, and the public to provide expert advice.

This project offers us a great opportunity to upgrade this informal research links into a higher level of collaboration between several institutions. This proposed work opens up exciting opportunities for research collaboration, research exchange, faculty and student visits. Especially, the use of the convective-permitting high-resolution regional climate modeling will put us to the frontier of the international climate change research on precipitation extremes.

Linkage to GWF Core Support teams and Pillar 3 projects (1 page)

The project will require GWF core support in multiple aspects and it will also contribute to the core activities as outlined below:

Core Modeling Team:

Output from the core WRF simulations will be used here. This includes the use of two data sets: One is existing west Canada pseudo-global warming (PGW) simulation that was completed as a part of CCRN project (CCRN version WRF simulation). The simulations include a historic run for 2000-15 over Western Canada and a PGW run under RCP8.5 emission scenario for the end of 21st century. The other is GWF version WRF runs that cover the US and Canada south of 70N driven by the RCP8.5 scenario, in collaboration with NCAR. This set of simulations is planned to have completed within next three years. We will start analyzing the data once partial data are available from the simulations. Access to NCAR Group's climate simulation datasets, i.e, the NCAR CONUS 4-km WRF run will be facilitated through the Core Modeling Team. Data generated in this project will be made available to research community through the Core Modeling Team.

Core Data Management Team:

This project will involve a large volume of data both from observations and model simulations. We will use the data obtained by the core data management team if available. Data that we produced or obtained separately will be shared with GWF community through the Data Management Team. We will work with the Data Management Team to ensure our data storage needs are met and our use of storage is efficient, and our data are accessible by others.

Computer Science Core Team:

We will work with the Computer Science Core Team on creating the visualization of our research outcomes and the access of the relevant modeling products. We will work with the Computer Science Core Team to develop the most efficient ways to deliver our results derived from the enormous model and observational datasets to other users.

Pillar #3 EXTREME project

The project is designed to address a significant science gap in the Pillar #3 EXTREME project. The main goal of that project was to produce future projections based on existing science and tools. The in-depth process understanding that underlies scientific confidence of the future projection, while not within the scope of the user focused Pillar #3 program, will be the main focus of this project. Additionally, this project will also complement the EXTREME project by investigating future changes in storm size and duration because these storm characteristics have profound impact on flood risk. There is evidence that changes in the probability of extreme flood might be larger than those of intensity of extreme precipitation due to larger and more prolonged storms in the future. As the participants of this project are also among the main investigators and collaborators of the EXTREME project, scientific advances of this project will be integrated into the development of robust future projections and their user guidance in a very timely fashion.

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