PCIC SCIENCE BRIEF: PROJECTED CHANGES TO SHORT-DURATION EXTREME RAINFALL

Publishing in the *Reviews of Geophysics*, Westra et al. (2014) summarize the current state of research in the analysis of future changes to the intensity, frequency and duration of extreme rainfall. Their literature review highlights the complicated relationship between short duration extreme rainfall and atmospheric temperature. In some locations, such extreme precipitation does not simply scale with the ability of the atmosphere to hold moisture (i.e. at the Clausius-Clapyron rate of 6 to 7% per °C). Instead, at these locations the general pattern is that such a relationship is found to hold up to about 12 °C, but between 12 and 24 °C extreme precipitation appears to increase more strongly with warming. This is partly due to an increase in convective rainfall. However, above about 24 °C, the pattern at these locations is one in which the response of precipitation to increasing temperature appears to be weaker, eventually reversing. This may be due to decreased moisture availability at these temperatures, though Westra et al. note that "the mechanism that causes these moisture deficits remains to be investigated." The authors also find that anticipated changes in sub-daily precipitation associated with a warming climate will "significantly affect the magnitude and frequency of urban and rural flash floods."

Compared to daily rainfall, Westra et al. find that sub-daily and sub-hourly rainfall are more sensitive to local surface temperatures. They also report that while sub-daily precipitation observations are too scarce to determine regional trends, geographic location will likely affect rates of change in daily precipitation extremes. In terms of making projections of future changes in these events, the authors find that, owing to the resolution of current global climate models, they are limited in their ability to simulate such precipitation events. In particular, the models are generally not run at sufficient resolution to accurately resolve the necessary convective processes, though some very high-resolution "convection permitting" regional climate models operate at a sufficient resolution to potentially be useful in projecting such extremes[1]. One implication of these findings is that we cannot currently make credible projections of sub-daily rainfall events.

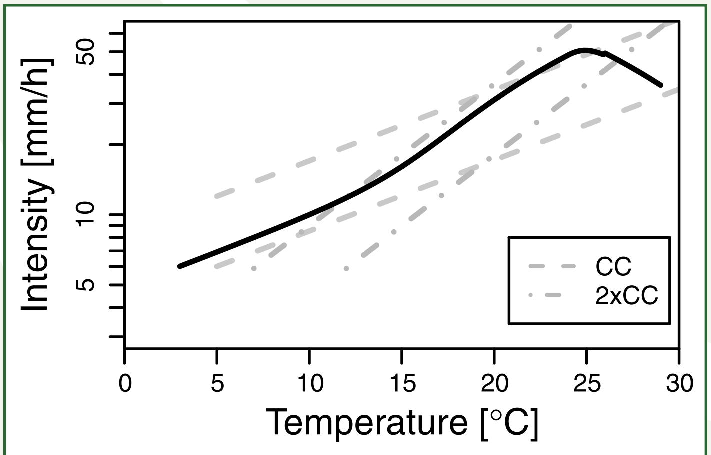

Figure 1: Conceptual diagram of the observed relationship between temperature and extreme rainfall from Westra et al. (2014).
The sub-daily rainfall intensity versus temperature for Clausius-Clapeyron scaling for three temperature ranges, as described by Westra et al.: Clausius-Clapeyron scaling below about 12 °C, double Clausius Clapeyron scaling between approximately 12 °C and 24 °C and negative scaling above about 24 °C. It should be noted that, while this general pattern emerges in a number of locations, it is not uniform and present everywhere, and it can vary by region and season.

INTRODUCTION

There is widespread interest in information about projected changes to extreme rainfall events. This is, in part, because there is growing evidence that climate change may

1. Such models operate at kilometer-scale resolutions. Because they are very expensive to operate, their use is currently still experimental and is restricted to very small regions. See, for example, Argüeso et al., 2013 and Kendon et al., 2014.

be affecting such events. It is also, in part, because of the association of extreme precipitation with flooding, which is costly in terms of human life and infrastructure damage. Globally, for each year over the 2004-2013 period, floods were one of the three deadliest natural disasters in terms of reported deaths and, for four years out of this period, they were the most deadly[2]. The cost of damages due to flooding around the world was estimated to have been 70 billion dollars in 2011. Research published in *Nature Climate Change* by Hallegatte et al. (2013) suggests that without increased protection, the economic impact of floods may reach up to one trillion dollars per year by 2050. Floods are the most common natural disaster in Canada and, in 2013, the Alberta floods were the most costly natural disaster in Canadian history.

In British Columbia, floods are a hazard to many communities each year. While some flood events take the form of meltwater-driven spring flows along rivers such as the Fraser, flash flood events driven by extreme precipitation have also been destructive and represent a challenge for those involved in integrated flood management. Kamloops was struck by flash floods as recently as July of this year and some towns suffer flash flood damage almost yearly. Cache Creek, for instance, has been struck by flooding for the last three years. Many of the extreme rainfall events that overwhelm stormwater systems are short-lived, lasting less than an hour.

Given the need for projected changes to extreme rainfall for the development of tools and guidelines, impact assessment models and infrastructure planning, there is a burgeoning area of research into the potential effects of climate change on such events. Westra et al. survey this literature in order to determine what is known about the underlying physical processes, how well these are represented in current models and the quality of current observational data sets. They summarize some current avenues of research that are likely to better our understanding of sub-daily precipitation extremes.

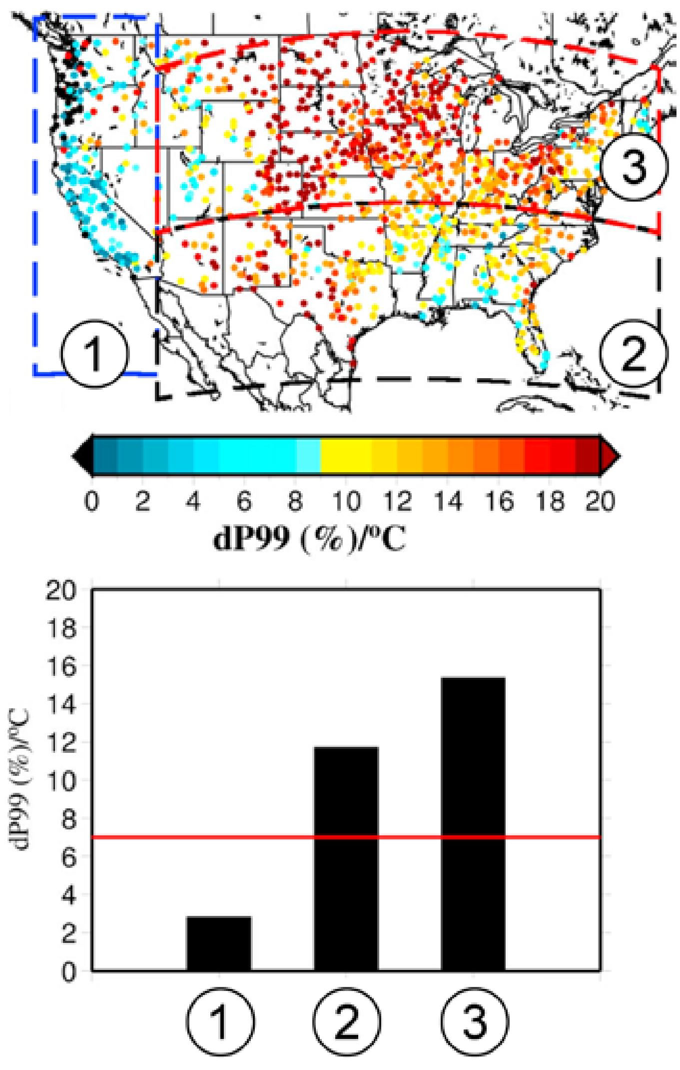

Figure 3: Percent changes in the 99th percentile of hourly extreme precipitation (dP99), modified from Mishra et al. (2012).

The colours of the dots on the map above indicate the regression slopes between hourly extreme precipitation and daily mean temperature at surface stations in the United States over the 1950-2009 period. The values of these regression slopes indicate the percent change in the 99th percentile of hourly extreme precipitation per °C of warming.

The bar plot shows the median values for the stations in the three sections of the map, as indicated. The red line corresponds to the Clausius-Clapeyron rate (an increase of 7% per °C of warming).

CURRENT SUB-DAILY OBSERVATIONS & THEORY

Some understanding of current observations of short duration extreme rainfall events, and the physical processes believed to underlie them, is necessary to consider the current challenges in modelling them. To begin, Westra and colleagues discuss the relationship between short duration, sub-daily rainfall and the temperature of the atmosphere. The Clausius-Clapeyron relation describes how the ability of the atmosphere to "hold water" varies with temperature. It shows that the amount of water vapour that the atmosphere can hold increases rapidly (almost exponentially) with temperature. Working from the Clausius-Clapeyron relation, the amount of water vapour in a parcel

2. For more information on disasters over this period, see the International Federation of Red Cross and Red Crescent Societies' 2014 World Disasters Report (in cited literature).

of air that is available to feed precipitation should increase by about 7% for every °C of warming, in the global average. Of course, changes to precipitation on a variety of scales are more complex, ultimately depending on things such as the ability of the atmosphere to radiate away the heat released when moisture condenses before falling as rain[3]. However, observations show that the median intensity of daily maximum rainfall, on an annual average, is increasing by between 5.9% to 7.7% per °C, close to the rate expected from the Clausius-Clapeyron relation. Though the rate of increase varies with latitude and altitude.

At time scales that are shorter than a day, observations from some locations in the Netherlands, Belgium, Germany, Switzerland, Australia, North America, Japan and Hong Kong suggest that the scaling of extreme precipitation with temperature predicted from the Clausius-Clapeyron relation breaks down. At these locations and over these shorter intervals, the Westra et al. analysis suggests that precipitation extremes tend to scale at the Clausius-Clapeyron rate for surface temperatures up to about 12 °C, but at faster than this rate between about 12 °C and 24 °C. There is a dependence on the time scale here, as sub-daily precipitation in this temperature range follows a power law relationship. Above about 24 °C, the intensity of rainfall seems to drop sharply, increasing at below the Clausius-Clapeyron rate (Figure 1).

It should be noted that these departures from the Clausius-Clapeyron rate are general tendencies only and the actual rate can vary both seasonally and by location. For example, there are areas, such as the west coast of the United States (Figure 2) that exhibit scaling that is less than the Clausius-Clapeyron rate[4]. There are also regions, such as the southern United States, in which the rate is greater in winter than in summer[5]. In Canada, as in the United States, the west coast exhibits a rate of extreme precipitation scaling with temperature that is slightly less than the Clausius-Clapeyron rate, whereas regions in the interior of the continent exhibit scaling that is greater than the Clausius-Clapeyron rate[6].

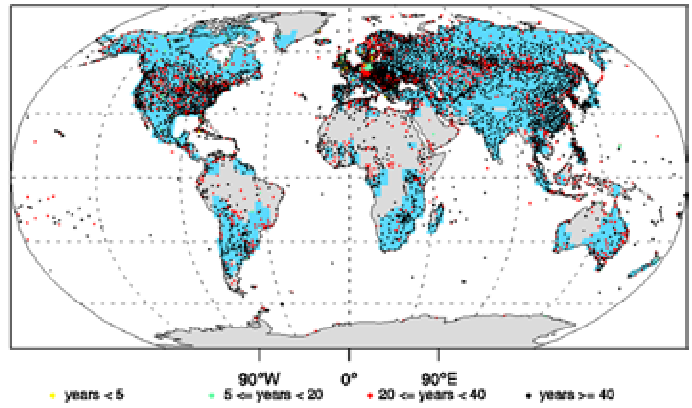

Figure 3: Locations of freely available subdaily precipitation from the HadISD data set, from Westra et al. (2014). The dots represent places for which there are subdaily precipitation records available. The length of the record at each location is given by the colour of the dot. The blue shading indicates regions for which daily intensity measurements are available from the HadEX2 data set, for the 1951-2010 period.

WHY SUB-DAILY OBSERVATIONS DO NOT MATCH THEORY

According to Westra and colleagues, this break from the anticipated Clausius-Clapeyron rate occurs for two reasons. For temperatures between about 12 °C and 24 °C observations indicate that there are at least two separate mechanisms causing precipitation. One mechanism is the large-scale meeting of boundaries between masses of warm and cooler air. When these meet, the warmer, less dense air is forced over the cooler air mass. As this warmer air rises, it cools and water vapour condenses, causing precipitation. This is called stratiform precipitation. The other mechanism, responsible for more extreme precipitation and sometimes operating on the much smaller scale of a few kilometres or less, is the rising of air masses that occurs when one area of the Earth's surface is warmer than its surroundings. This air rises and cools, again causing water vapour to condense, resulting in precipitation. This is known as convective precipitation. This can be strengthened by a feedback that arises within clouds. The general idea of this process is that warm, moist air enters the cloud from near its base and rises. As it rises, it cools and condenses, releasing heat. This warms the air inside the cloud, which causes

3. See Allen and Ingram (2002).
4. This has to do with the types of precipitation that are dominant in these regions. The explanation given by Westra et al. for the break with the Clausius-Clapeyron scaling rate has to do with small-scale convection. So, in the interior of the continent, where rainfall is more likely to be short, intense and often tied to smaller scale convection, we might expect a scaling rate that is greater than the Clausius-Clapeyron rate. Whereas, along the west coast of North America, where rainfall tends to be more uniform and storms tend to be longer and tied to larger-scale processes, we might expect a scaling rate that is close to or smaller than the Clausius-Clapeyron rate. See Mishra et al., 2012 for more information.
5. See Mishra et al. (2012).
6. See Panthou et al. (2014).

it to rise further increasing the updraft which draws more warm, moist air into the cloud. This feedback operates on the scale of a few kilometres. The size scale is important here because future climate projections almost always come from climate models that have resolutions that are much coarser, on the order of ten kilometres to a grid cell or larger, and must rely on sub-grid scale parameterization rather than explicitly represent such convective cloud feedback processes. These parameterizations are simplified representations of the processes that occur within the individual grid cells of the climate models. They allow the models to account for at least some of the influence of small-scale processes in the distribution of things such as heat, moisture and momentum within the overall environment that the climate model simulates.

Another mechanism that Westra et al. note may cause a break from the anticipated Clausius-Clapeyron rate above about 24 °C in these regions is the changing availability of atmospheric moisture[7]. For reasons that are still under investigation, moisture availability increases rapidly up to about 24 °C and then increases more slowly thereafter.

THE STATE OF SUB-DAILY PRECIPITATION OBSERVATIONS

Turning from a discussion of the basic physical processes, Westra et al. move to existing observations of precipitation extremes. Daily observations suggest that since the middle of the 20th century, precipitation extremes have increased. However, for sub-daily precipitation data, records are much more scarce than daily data and, in many cases, of lower quality (Figure 2). Station data at the hourly or sub-hourly scale are more sparse still. In Canada, for instance, there are very few stations with sub-hourly precipitation data sets and most of these have records that are only a few years long.

The accurate measurement of sub-daily precipitation is also difficult. The device most often used for sub-daily measurements is the tipping bucket rain gauge. This gauge has a funnel that directs water into the device, which contains a small bucket with two chambers. Once a chamber is positioned under the funnel it fills up with rain water and then tips over, quickly draining the chamber and positioning the second chamber under the funnel. This second chamber then fills and tips over, and so on, with the two chambers making a see-saw motion. Using a magnet and a switch, the number of times that the bucket fills and tips is recorded, from which the amount of rain that has fallen can be calculated. However, Westra et al. note that these gauges generally cannot achieve the level of accuracy established by the World Meteorological Association for precipitation intensity measurements. There are two primary types of errors that the gauges encounter. The first are catching errors, such as drops splashing out of the funnel that feeds the apparatus, wind-induced errors and evaporation. The second are mechanical errors, such as calibration errors and water lost inside the device during the tipping motion of the bucket. For high intensity precipitation events, catching errors are less important than mechanical errors, contributing uncertainties of between 0% to 10% and 10% to 15% respectively. Errors are also greater for a five-minute time scale than for an hourly time scale. In addition to these issues, quality control methods and accuracy vary between records. Westra and colleagues conclude that, "[t]he lack of long, homogenous, high-quality extreme rainfall data at sub-daily time scales represents a significant barrier for further progress in assessing whether sub-daily extremes are intensifying under climate change."

Radar measurements show some promise for the analysis of extreme rainfall, especially for providing information about the spatial structure of these events. A review paper by Berne and Krajewski (2012) explains that radar data sets can be of a high spatial resolution, on the order of a kilometre or so, and of a very high temporal resolution, between five minutes to an hour. This makes them suitable for analysing weather events at the scale necessary for the study of flash floods. However, they tend to have much shorter records, generally about a decade or so, and suffer from shortcomings related to the scattering and propagation of the radio waves used. First, the waves can be altered or blocked entirely by the ground and local terrain. Second, the radar can be altered by atmospheric conditions, leading to errors in rainfall measurements. Third, non-rainfall precipitation, such as snowflakes in the atmosphere, can also cause such errors. (A related problem is determining, from the detection of a given type of precipitation in the air, exactly what sort of precipitation falls on the ground[8].) Fourth, the data sets originating from radar rainfall measurements are very large, which leads to challenges in storing, browsing and sharing the data. It is worth noting that each of these challenges are active areas of research and better methods to meet these challenges are being developed constantly.

PROJECTED CHANGES TO PRECIPITATION EXTREMES: CURRENT ABILITY AND LIMITATIONS

The next part of Westra et al.'s discussion focuses on projected changes to precipitation extremes from global climate models. They first explain that the current literature

7. See Panthou et al. (2014).
8. For more on this, see Matrosov et al. (2007) and Kirstetter et al. (2010).

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shows that frequency-based indices of extremes (e.g. the number of days with a given amount of precipitation) exhibit increases over the last century. They also note that climate models tend to be limited in their ability to simulate precipitation extremes, with errors in duration and intensity, especially in the tropics. Projections of future rainfall extremes from these models show increases in both frequency and probable maximum rainfall at the daily time scale.

For projections at the sub-daily time scale, the primary issue is that, for some locations, extreme rainfall that lasts only a few hours is mostly convective, resulting from physical processes on the scale of a few kilometres or smaller. Current global climate models have resolutions on the order of tens of kilometres or larger and so do not resolve the relevant cloud dynamics and convective processes directly. Instead, the models rely on parameterizations. Because current global climate models do not explicitly resolve these important underlying physical processes, we cannot expect that they will be able to fully represent extreme convective rainfall. This is an important consideration for some regions in the continental interior, but less important for other regions, such as on the West Coast of British Columbia, where larger-scale atmospheric phenomena such as atmospheric rivers drive extreme precipitation events.

Next, the authors explore results from higher resolution models that can resolve some of the processes necessary for simulating convective rainfall. These include both global climate models with embedded two-dimensional cloud-resolving models (sometimes called super-parameterization) and regional climate models of varying resolutions, from 1.5 to 25 kilometres. Westra et al. do not comment on embedded cloud-resolving models because, though they are a computationally cheaper option, relatively few examples of experiments using these models are available. Regarding higher resolution regional climate models, as model resolution increases the ability of the model to plausibly simulate rainfall extremes also increases. Models with a ten-kilometre resolution are able to represent the daily rainfall cycle quite well, though the daily cycle of convection in these models is incomplete and extremes at timescales shorter than a day still cannot be adequately simulated. Convection-permitting models with resolutions of less than four kilometres better represent the daily cycle of rainfall, its spatial characteristics and the intensity of the most extreme events. The experiments that have been performed thus far suggest that, the output from such models compares well to the precipitation observations that are available. Results from a study of simulated 20-year rainfall over the UK using a 1.5 kilometre model

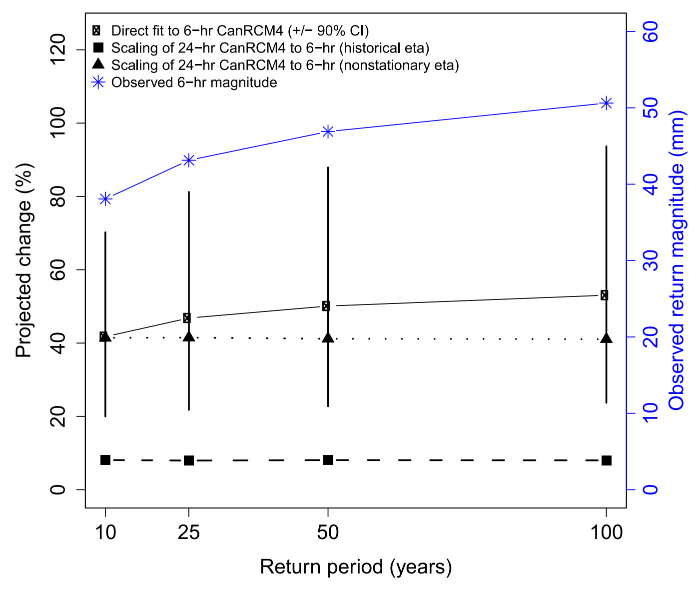

Figure 4: The Projected Change in 6-Hour Precipitation Return Values at Victoria International Airport. (Figure courtesy of Dr. Alex Cannon, Environment Canada.)
This figure shows the projected percent change in precipitation amounts for the 6-hour duration for return periods from 10 years to 100 years for the Victoria International Airport computed in three different ways. Changes are for the 2041-2070 period relative to the 1971-2000 baseline period. The return period is the average length of time over which we can expect a certain threshold to be surpassed. In this case, the threshold has to do with the magnitude of rainfall over a six hour duration, e.g. we would expect a rainfall event such that the most intense six hours of precipitation during the event occurs about once every hundred years for the 100 year return period, and so on for the other periods. The solid black indicates the estimated value of the changes to extreme precipitation for a given return period, using simulated six-hourly precipitation explicitly. The vertical lines about the solid line represent 90% confidence intervals. The dashed line along the bottom indicates the value that would be obtained if future six-hourly precipitation is estimated from future daily values and the historical statistical relationship (eta) between six-hourly and daily precipitation intensities. The dotted line indicates the values that are obtained if future six-hourly precipitation is estimated from future daily values and the statistical relationship (eta) between six-hourly and daily precipitation intensities in the future period. If no information about sub-daily precipitation in future is available, then only the dashed line can be calculated. The solid black line represents the most accurate estimate. The solid blue line indicates the observed return magnitude in millimeters for six-hour rainfall events at the Victoria airport (e.g. events with a total magnitude of about 47 mm have occurred about once every 50 years, on average).

show substantial improvements over coarser resolution models in terms of the daily cycle of precipitation, the spatial characteristics of the rainfall and better representation of extremes at the hourly timescale. While these high-resolution models show promise for providing projections of future changes to precipitation extremes, they still rely on the ability of global climate models to simulate large-scale atmospheric circulation. While models capture many large scale features of the Earth's atmospheric circulation quite well, this is an active area of research with a variety of challenges remaining[9]. It should also be noted that the relative scarcity of sub-daily and sub-hourly precipitation data with which to compare model output may present a challenge for testing the ability of regional climate models to replicate such extremes events.

DIFFERENCES IN TERMINOLOGY BETWEEN CLIMATE SCIENTISTS AND ENGINEERS

What constitutes extreme precipitation varies between the climate science community and the engineering community. In the climate science community, extreme precipitation may refer to annual maxima, events past a certain threshold in millimetres or events that fall on a given percentile of a cumulative distribution function, often taken from daily rainfall data. For engineers, much rarer and more extreme events must be considered, owing to the long lifetimes of infrastructure. For instance, an event with a 1% Annual Exceedance Probability (AEP) is so extreme that it only has a 1% chance of being exceeded in magnitude every year. So, on average, one such event would be expected per century. However, a piece of infrastructure that is designed to stand for 50 years has about a 50% chance of experiencing such an event in its lifetime. There is need to design for events that are much rarer than a 1% AEP event. There are similar needs for estimates of probable maximum precipitation and probable maximum flooding.

The actual relationship between extreme rainfall and flooding also depends on a number of issues, including the duration and spatial extent of the rainfall, and the size and shape of the surface onto which the rain is falling, as well as the type of ground onto which it is falling (e.g. wet or dry, snow covered, populated by vegetation, whether it is soil or concrete, etc.). For coastal regions, tides and storm surges coincident with extreme precipitation must also be considered. In addition to these factors, the size of the area collecting water is important. Smaller catchment areas are more vulnerable to flash flooding from short duration, extreme precipitation, whereas larger catchments are more vulnerable to sustained periods of rainfall. Catchments with main channel lengths up to 100 kilometres in length can be sensitive to precipitation changes over time scales shorter than a day, which highlights the need for sub-daily precipitation projections.

CURRENT DIRECTIONS IN RESEARCH

With this information in hand, Westra et al. discuss some current directions of research into sub-daily extreme precipitation events. First, there is a need to gather data at sub-daily and sub-hourly timescales, subject it to quality control and to form this into a global data product. The authors stress the importance of improving both rain gauge and remote sensing observations. Given that there are significant amounts of radar data available, and in light of the difficulties faced in converting such data into rainfall rates, blending radar data with rain gauge measurements is a way to increase the quantity of data available. This is useful not just for climatological records, but also to have data to enable the evaluation of high-resolution climate models. In addition, work is being done using techniques that draw inferences from the spatial patterns and frequency of rain to determine characteristics about its timing, though this is made difficult due to changes in the measuring instruments as well as record lengths and missing data values.

Second, the development of very high-resolution regional climate models is ongoing and, as computers become more powerful, it is likely that these models will be used for climate simulations over an increasingly large number of regions. While lower resolution models can be (and have been) very useful for answering a large number of precipitation-related questions, Westra and colleagues see very high-resolution models as being the dominant source of information for projections of future extreme precipitation events. The authors call for a concerted research effort and framework to ensure that models are correctly simulating the relevant processes, as measured by a set of physical metrics. They also call for work to be done to bridge the gap between atmospheric science and flood hydrology, in which atmospheric scientists provide the information needed by hydrologists and engineers to better facilitate planning and design.

One of the outcomes of the research that Westra et al. cover is that we may not be able to apply the statistical relationships between daily and sub-daily rainfall from the historical period to determine how sub-hourly rainfall will change in the future. This result is supported by preliminary investigations performed at PCIC using output from high-resolution regional climate models. This work, which uses high-resolution rainfall output ranging from five min-

9. For more information on the ability of the current generation of climate models to simulate features of atmospheric circulation and what challenges remain, see: Flato et al. (2013).

utes to 24 hours in duration, finds evidence that statistical scaling relationships may change in the future (Figure 3).

CONCLUSIONS

What can we take from this? Projections of sub-daily rainfall in the changing climate cannot yet be made with the confidence necessary for decision making. Observational data is still sparse, both in British Columbia and globally, and making projections by taking the relative changes projected for daily events and applying those values to sub-daily events may be unreliable. *We cannot expect that the same statistical relationships that currently hold between daily and sub-daily precipitation will continue to hold in the future.* Climate model resolution is one limiting factor, but a lack of observational data limits both our knowledge of past extremes and our ability to compare high-resolution regional climate model output with conditions in the real world. We agree with Westra et al.'s conclusion that increasing the number of stations recording sub-daily precipitation should be a priority for increasing our understanding of short-term extreme rainfall events. Radar precipitation measurements also show some promise to increase both the number of records available and their spatial resolution.

Overall, making projections of sub-daily precipitation is going to be more difficult than simply increasing the resolution of statistical or dynamical downscaling. *Because of this, it will be some time before it will be possible to deliver credible projections of sub-daily rainfall events.* Though there are some tools available that aim to provide projections of intensity, duration and frequencies for future rainfall events, it is not clear that current approaches are able to provide accurate information regarding future rainfall extremes or that uncertainties are well understood. Consequently, there is an urgent need to better understand the limitations and uncertainties of projections of changes to precipitation extremes, so that BC communities that have to move forward with infrastructure design can better understand the aspects of projections in which they can have greatest confidence. In parallel, there is also an urgent need to advance our understanding of precipitation extremes and their expected changes at all time scales. Planners and engineers may need to rely on projections of daily extremes and professional judgement in the absence of credible subdaily rainfall projections.

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