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PCIC SCIENCE BRIEF: THE EVOLUTION OF SNOWMELT AND DROUGHT

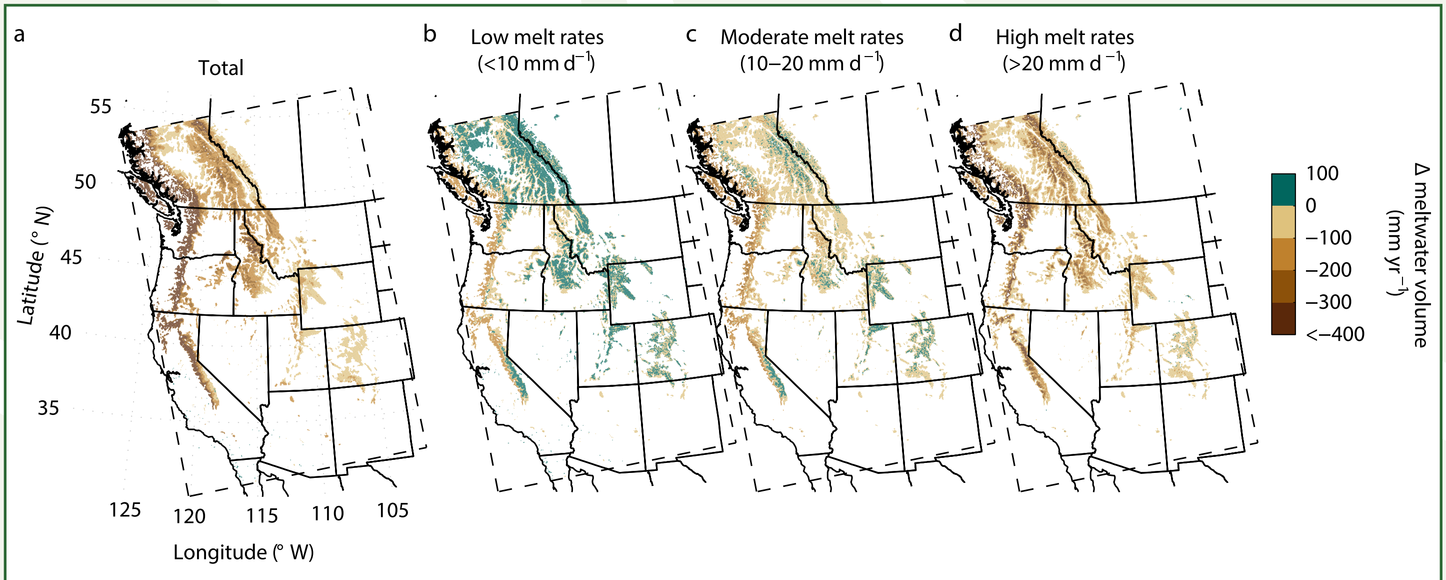

Figure 1: Maps of projected mean annual change in meltwater volume in western North America, from Musselman et al. (2017).

This figure shows projected changes in meltwater volume in regional climate model simulations, comparing the future period from the pseudo-global-warming experiment[2], meant to capture the average conditions at the end of the century (2071-2100), to the 2000-2010 control period. Panel a shows the projected change in total meltwater volume, and panels b-d show projected changes in low (less than10 mm per day), moderate (10-20 mm per day) and high (greater than 20 mm per day) snowmelt rates. Note that regions with snowpacks with less than 150 millimetres in mean annual maximum snowwater equivalent are excluded from these maps.

Two articles recently published in the peer reviewed literature examine how the rate of snowmelt may change as the Earth's climate changes, and how droughts can evolve and move over time.

Publishing in *Nature Climate Change*, Musselman et al. (2017) examine the effect that global warming may have on snowmelt. They find that the portion of snow melt occurring at moderate and high melt rates in Western North America is projected to decrease, while the portion occurring at low melt rates is projected to increase. Total meltwater volume is projected to decrease.

In recent research published in *Geophysical Research Letters*, Herrera-Estrada et al. (2017) explore how droughts evolve in space and time across six continents. They find that clusters of droughts can travel hundreds to thousands of kilometers across each continent. In addition, the authors find that longer-lasting droughts tend to travel farther, as well as be more severe.

The Earth's hydrologic cycle[1] determines the distribution and movement of water throughout the Earth system. Because of its importance for water resources and ecosystems as well as its significance for events with costly impacts, such as flooding and drought, having a strong understanding of how the hydrologic cycle functions today and may change in the future is important for future planning.

1. The hydrologic cycle, or water cycle, describes the distribution and movement of water throughout the Earth system. This includes its storage in places such as oceans, surface snow and ice, rivers and lakes, its movement through the atmosphere, oceans, and across and through the Earth's surface, and changes of phase, such as melting, condensing and evaporating.

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One aspect of the hydrologic system that may change in response to climate change is snowpack, the melting of which has important effects on streamflow in many areas. Changes to the volume, timing and rate of snowmelt can have downstream impacts on ecosystems, water availability and flood risk. As regional temperatures rise, snowmelt rates may react in ways that seem to be contradictory. On the one hand, the rate of snowmelt may increase as the air temperature rises and more precipitation in the form of rain falls on the snow. On the other hand, the loss of snowpack volume means that the snow may not persist long into the spring or summer, when there would be sufficient energy to cause rapid snowmelt. Instead, it may melt slowly, earlier in the season, when there is less energy available in the environment to melt the snow.

Publishing in *Nature Climate Change*, Musselman et al. study how the rate of snowmelt may change as western North America continues to warm as a result of anthropogenic climate change. The authors use a mix of observational data from nearly a thousand snowpack monitoring stations and high-resolution regional climate simulations[2] in order to see how snowmelt was related to snow-cover depletion in the past, check if the features of the station observations are also present in the simulations, and examine how snowmelt may change in the projected future climate.

Beginning with an analysis of the observational data, Musselman and colleagues find that snow-cover depletion is related to snowmelt rates, with those areas that have shallower snowpack also exhibiting slower rates of snow loss than areas with deeper snowpack. This is in line with their hypothesis that the shallow snowpacks melt slowly, earlier in the season when there is less energy available. The authors also find that the regional climate model simulations over the 2000-2010 historical period closely match the observations of snow loss rates across four different snowpack depths, suggesting that the regional climate models are able to capture the relevant features of snowmelt dynamics. This provides some confidence in the model's ability to simulate future snow accumulation and loss.

The future projections of snow loss show two main features: (1) an overall reduction in meltwater volume (Figure 1, Panel a) and (2) a shift from high meltwater rates to low meltwater rates (Figure 1, Panels b, c and d). Both of these are due to an overall reduction in snowpack thickness. The shift to slower snowmelt rates is of particular interest, as it adds nuance to the notion of increased water cycle intensity under climate change.

Musselman and colleagues note that their findings may have several important implications. The shift to an earlier streamflow peak and reduced streamflow may reduce both the amount of water available to basins and the amount of carbon that forests can draw down. It may affect fish survival rates and increase the risk of wildfire. The authors speculate that, while the reduction in spring snowmelt may reduce the risk from snowmelt-driven floods, the increase in winter melt rates, combined with an increase in the amount of precipitation falling as rain, could increase the risk of winter floods.

It is important to note that these findings reflect broad patterns of change that may be subject to further regional considerations. For example, snowpack at higher elevations and in colder regions may be less sensitive to warming than low-lying and warmer areas, and the effect of small-scale effects that are too fine for the regional climate model's four-kilometre resolution to capture, such as mountainous terrain casting shade on specific areas, may affect spatial variability in important ways.

Another aspect of the hydrologic cycle that can have serious impacts on ecosystems and society is drought. The impact of these events can include things such as agricultural losses, reduced water quality and availability for human communities, increased wildfire risk and loss of habitats for animals. Unfortunately, the onset of droughts is hard to predict because they often arise from atmospheric variability and as a result of climate teleconnection[3] patterns. However, the evolution of a drought in space and

2. Musselman and colleagues used the Weather Research and Forecast numerical weather prediction model, run at a four-kilometre resolution, as their regional climate model. For the control run, reanalysis data from the 2000-2010 period with a 75 kilometre resolution was used to drive the much higher-resolution regional climate model. In order to obtain the projected future climate, the authors created what is termed a "pseudo-global-warming" experiment. In this experiment, they added the monthly average output from a set of global climate models running under the Intergovernmental Panel on Climate Change's business as usual emissions scenario (RCP 8.5) over the 2071-2100 period to the reanalysis data used to run the model to obtain ten years worth of model output for comparison to the control run. For details on the method used, see Musselman et al. (2017) and the references therein.
   For more information on the WRF model, see Skamarock et al. (2008).
   For more information on the emissions scenario used, see: van Vuuren et al. (2011).
   The reanalysis data used was ERA-Interim. For more on this product, see Dee et al. (2011).
   For more on reanalysis data in general, see Footnote 4.
3. A teleconnection is a link between meteorological conditions occurring in different regions of the world that are separated from each other by large distances.
4. A reanalysis is a representation of the historical climate that is created from historical observations that are "assimilated" into a model, often a global weather forecast model, that is run in a hindcast mode.

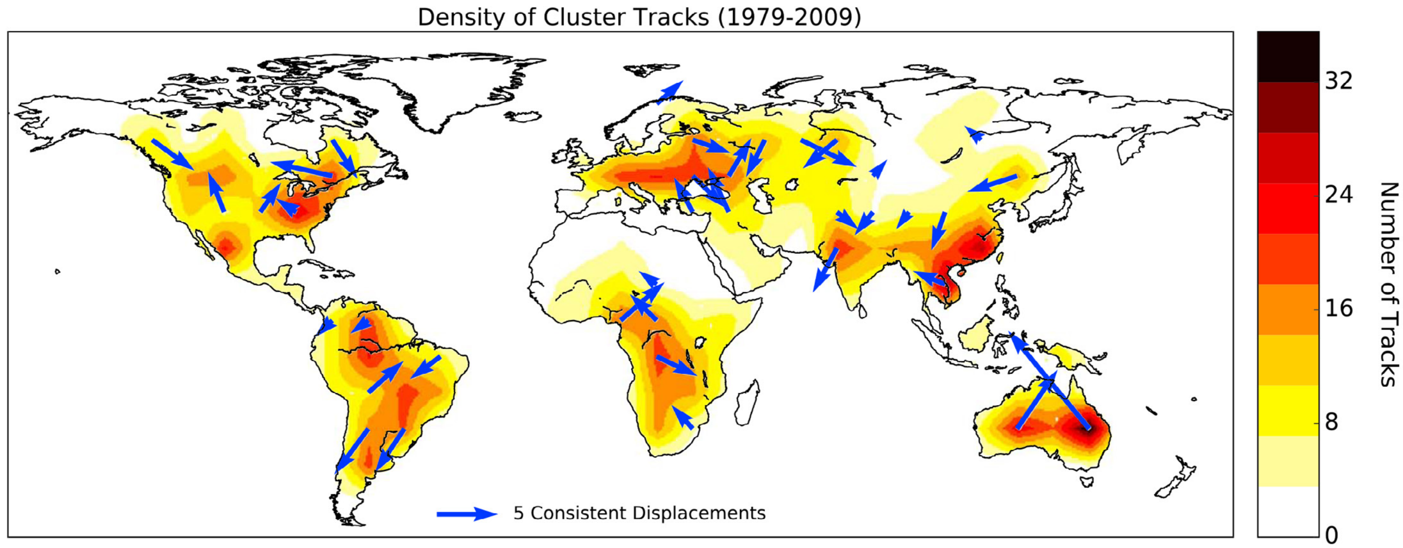

Figure 2: Map of the density and direction of global drought cluster tracks, from Herrera-Estrada et al. (2017). This figure shows the density and movement of drought tracks over the 1979-2009 period in reanalysis data from the Climate Forecast System Reanalysis[6]. Blue arrows indicate the direction of drought migration, with longer arrows indicating that more droughts moved in that direction. Shading colour indicates the number of tracks, as indicated on the sidebar. Only droughts with areas larger than 200,000 square kilometres that were outside of Greenland and the Sahara Desert were considered.

time may be easier to predict. Understanding how they evolve may be of use for risk assessments and preparation for droughts before they hit. The authors point out that such an understanding may also allow for models that can be used for seasonal forecasting.

In a recent paper published in Geophysical Research Letters, Herra-Estrada and colleagues examine how droughts evolve in space and time, globally. In order to do this, the authors use global reanalysis data[4] including soil moisture content, wind speed, humidity, precipitation and the amount of heat carried in water vapour through the atmosphere. The authors defined droughts as periods when soil moisture is low enough that it falls in the bottom 15th percentile for that region. The authors then examined areas of drought that were larger at least 200,000 square kilometres across the world, excluding Greenland and the Sahara Desert, to see how they moved and changed over time, tracking them as they grew, shrank, meandered, merged and split.

Herrera-Estrada et al. find that travelling droughts can move hundreds of kilometres and, much as with tropical storm tracks, there are hotspots and tracks that droughts travel along over the Earth's continents (Figure 2). On the west coast of Canada, these tracks were aligned roughly north to south. While most droughts stayed near their origins, roughly 10% travelled at least 1400-3100 kilometres over the time span of months to years. Longer droughts tended to be more severe and travel farther.

One mechanism that the authors find to have contributed to drought propagation is the lack of moisture travelling downwind from an area undergoing drought. If an area is under drought conditions, less water will be released from this area through evaporation and plant transpiration. This results in less water vapour travelling downwind and hence, drier conditions there, contributing to drought conditions in the downwind area. The importance of this effect seemed to vary by area, contributing most frequently to areas in North and South America. The authors identify several other potential underlying mechanisms for further study regarding the role that they play in drought evolution, including precipitation recycling[5], climate teleconnection[3] patterns related to sea surface temperatures elsewhere and the positioning of certain types of weather systems.

Many ecosystems and communities within BC rely, at least in part, upon meltwater to supply them with water, and are affected by floods. So, changes to the volume and timing meltwater is of strong interest to planners. The results

5. Precipitation recycling refers to the tendency of some portion of precipitation that falls in a given region to evaporate and fall within that region again.
6. The Climate Forecast System Reanalysis is a global, high-resolution reanalysis product. For more information on this product, see Dee et al. (2014).

of Musselman et al. do suggest a potential overall shift to lower melt rates and reduced meltwater volume in their study region, which includes the southern half of BC, by the end of the century. Their results are in line with the current trend of reduced snow depth across the southern interior and central interior regions of the province, though this trend has not been the same throughout BC, as the coast and northern BC have experienced no significant change from the 1950s until the present. Moreover, there are a variety of other factors involved, including regional effects that occur over scales too small to be resolved by the model, potential changes in precipitation amounts and timing, and a warming spring that will bring with it increased energy to melt snow. So, much work remains to be done before we can move from these results to specific regional impacts, or general statements about how specific events such as floods may be altered across the province.

The past few years have seen strong drought conditions in BC, especially over the southwestern part of the province, including Vancouver Island. Because of the impacts that drought can bring with it, understanding how droughts evolve in time and space is important for stakeholders in our province. In unpacking the implications of Herrera-Estrada et al.'s findings, we should first note that the results are from one reanalysis product and variables such as precipitation and soil moisture are strongly model dependent and so tend to vary from one reanalysis product to the next. The authors do state that the reanalysis data set6 they chose generally does a better job of reproducing observed drought than other reanalysis data sets, but comparison with other reanalysis data sets could provide more confidence in these results. We should also note that the definition of drought that they use is abnormally low soil moisture. These sorts of low soil-moisture conditions are important, as they can affect forest health, stressing trees and making them less resistent to pests, and increasing fire risk. However, in terms of impacts to communities, drought occurs when a community's water needs exceed availability during dry conditions. In BC, most community water used comes from surface water, such as lakes, and so they may or may not be directly affected by reduced soil moisture. Most of the droughts we experience in the province are due to abnormally low streamflow (termed, "hydrologic drought") which deplete these surface water reservoirs. BC also lies within a region that has a relatively small number of drought tracks according to the results of Herrera-Estrada et al's study. Once the mechanisms underpinning drought movement are better understood, it would also be of interest to see if the clusters of drought tracks shift under projected future climate change, especially if these tracks shift such that drought frequency or severity change in BC.

Dee D.P., et al., 2011: The ERAInterim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, **137**, 656, 553–597, doi:10.1002/qj.828.

Dee D.P. et al, 2014: Toward a consistent reanalysis of the climate system. *Bulletin of the American Meteorological Society*, **95**, 1235–1248, doi:10.1175/BAMS-D-13-00043.1.

Herrera-Estrada, J.E. et al., 2017: Spatiotemporal dynamics of global drought. *Geophysical Research Letters*, **44**, 5, 2254–2263, doi:10.1002/2016GL071768.

Musselman, K.N. et al., 2017: Slower snowmelt in a warmer world. *Nature Climate Change*, **7**, 214–219, doi:10.1038/nclimate3225.

Skamarock, W. C., et al., 2008: *A Description of the Advanced Research WRF Version 3*. NCAR Technical Note NCAR/TN-475+STR, 113 pp. doi:10.5065/D68S4MVH.

van Vuuren et al., 2011: The Representative Concentration Pathways: An Overview. *Climatic Change*, **109**, 1-2, 5-31, doi:10.1007/s10584-011-0148-z.

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