PCIC SCIENCE BRIEF: CONTRASTING THE RESPONSES OF MEAN AND EXTREME SNOWFALL TO CLIMATE CHANGE

Recent research by P.A. O'Gorman (2014), in the journal *Nature*, uses an ensemble of global climate model (GCM) simulations to examine the projected changes in both mean snowfall and daily snowfall extremes in a high greenhouse-gas emissions scenario. He finds that, while both mean snowfall and extreme snowfall decrease as the climate warms due to the influence of greenhouse gasses, the reduction in daily snowfall extremes is smaller than the reduction in mean snowfall. O'Gorman suggests, based on a simple physical model, that this may be due to snowfall extremes occuring near an optimal temperature that is insensitive to climate change.

Changes to mean snowfall and snowfall extremes can bring with them multiple impacts, altering river flow for snow-melt dominated rivers, affecting the rate at which sea ice melts, changing the amount of insulating snow that is beneficial for some plants and wildlife, and affecting transportation, the electrical grid and business. Because of these impacts and the fact that anthropogenic climate change affects both the mean state of the Earth's climate and some climate extremes events—such as temperature and precipitation extremes—the potential effect of climate change on snowfall is of interest.

Two physical quantities are useful for guiding our intuition about how snowfall may be affected by climate change. The first is saturation specific humidity; this is the amount of water vapour that a given amount of air can "hold"[1] at a given temperature and pressure (past this point, water starts to condense faster than it evaporates). Saturation specific humidity is much more sensitive to changes in temperature than to changes in pressure. In general, in the troposphere, warmer air can hold more moisture than cooler air and so, as the climate warms, there is more moisture available for precipitation. The second quantity is snowfall fraction; this is the fraction of precipitation that falls as snow. Loosely, as temperature increases, the fraction of precipitation that falls as snow decreases[2].

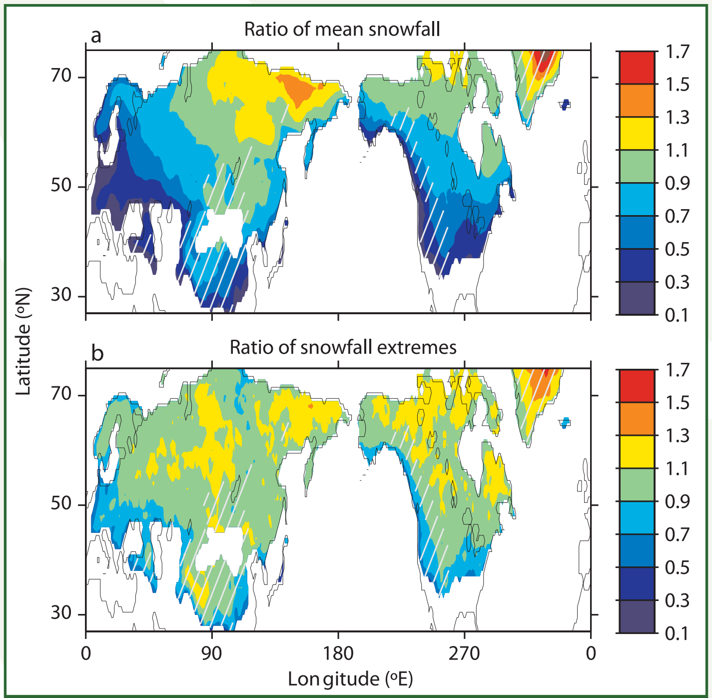

Figure 1: Ratio of simulated snowfall for projected 2081-2100 climate compared to simulated 1981-2000 control climate from O'Gorman (2014).
The ratio of the simulated mean snowfall (a) and daily snowfall extremes (b) in the warm climate to the simulated control climate. All values are calculated using the median from the ensemble of climate models and extremes are calculated from their 20-year return values. White hatching indicates regions that contain elevations of 1000 metres or higher. Projections for the 2081-2100 period assume greenhouse gas emissions follow RCP 8.5[4].

To examine how mean snowfall and snowfall extremes may change as the climate changes, O'Gorman uses simulated Northern Hemisphere precipitation from an ensemble of 20 climate projections from 20 Global Climate Models (GCMs) participating in the fifth phase of the Coupled Model Intercomparison Project[3] (CMIP5). The projections that he uses assume high greenhouse gas emissions[4] that would lead to atmospheric carbon dioxide concentrations of approximately four times the preindustrial level by the

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1. To speak of air "holding" water vapour is to speak loosely. The partial pressure of water vapour in equilibrium with a solid or liquid body of water is described by the Clausius-Clapeyron equation and is independent of the presence of air or other gases.
2. As O'Gorman notes, this is only true as a first-order approximation: the type of precipitation that falls at the Earth's surface is dependent not only on surface temperature, but also upon the local temperature structure of the lower troposphere.

year 2100. He compares projected changes for the 2081-2100 period with a 1981-2000 control period.

Before examining the future projections, the author compares simulated mean and extreme snowfall from climate models to observations and finds them to be in good agreement. In the future projections, he finds that as the climate warms, both mean snowfall and daily snowfall extremes decrease, but that the latter decrease to a much lesser degree (Figure 1). In addition, he finds that mean snowfall starts to decrease at a lower temperature than daily snowfall extremes. Because of this, the author suggests that it may be difficult to detect changes in daily snowfall extremes at the regional level.

In order to explain why mean snowfall and daily snowfall extremes respond differently to warming, O'Gorman develops a simple physical model. After verifying that his model captures the important aspects of the response of daily snowfall extremes, he uses this model to analyze their response and finds that there is an optimal temperature for snowfall extremes that occurs because of the competing effects of saturation specific humidity, which increases, providing moisture for precipitation as the atmosphere warms, and snowfall fraction, which decreases as temperatures warm and more precipitation falls as rain. Crucially, both climate model simulations and O'Gorman's simple model suggest that, as climate warms, the mean snowfall is reduced to a greater extent than are snowfall extremes (Figure 2). Using his simple model, O'Gorman suggests that this is due to the balance between the effects of changing saturation specific humidity and snowfall fraction, which causes extremes events to occur most often in a relatively narrow range, near an optimum temperature (-2 °C). In future climates, this optimum temperature will still be reached during some extreme events even for locations with relatively warm present-day climatological temperatures. So, for present-day cold regions, the amount of snowfall in extreme events will increase because the optimum temperature is readily reached and more moisture is available in the atmosphere for snow. As one looks at warmer present-day climate regions, the optimum temperature occurs a bit less frequently but the amount of moisture available for snow is still high. This results in little change to the amount of snowfall in extreme events. Eventually, at high enough temperatures, too few events that are cold enough occur and extreme events decrease (crossing below the dotted line in Figure 2). This is in contrast to mean snowfall where a shift in mean temperature simply reduces the likelihood of snow anywhere the daily temperature variability is within reach of the melting point in the future climate. So, as the climate warms, the reduction in snowfall extremes is smaller than the reduction in mean snowfall.

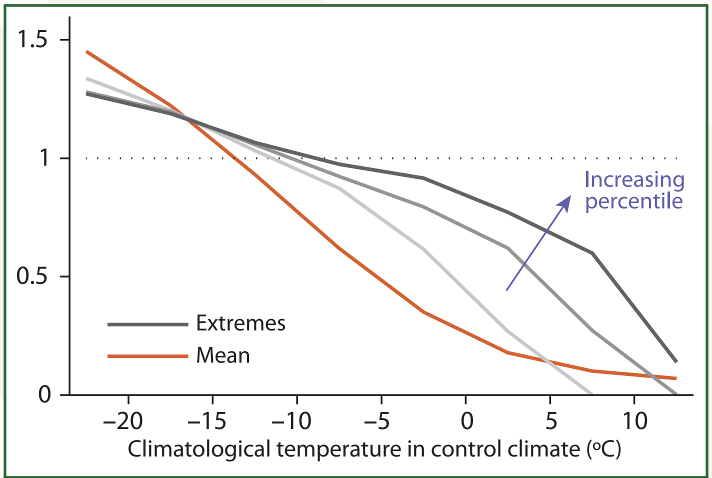

Figure 2: Snowfall ratios, from O'Gorman (2014). Ratios of mean (red) and 99th (light gray), 99.9th (medium gray) and 99.99th (dark gray) percentiles of snowfall for the warm climate compared to the control climate, as a function of the climatological monthly surface air temperature in the control climate. All ratios use multi-model median values.

The agreement between O'Gorman's model and climate model simulations is better the greater the daily snowfall extreme that is considered, but worse for mountainous regions with elevations greater than 1,000 metres, though the difference between changes in mean snowfall and daily extreme snowfall hold regardless of elevation considered. He postulates that this may be due to "variations in the thermodynamic response of orographic precipitation [i.e. precipitation that occurs as air rises and cools while passing over regions of high elevation] to climate change." It may also be due in part to variations in moisture supply.

For British Columbia, the impact of these results would vary with the region considered. Figure 1 shows that the greatest decrease in projected mean snowfall is in southwest BC, while the northeast shows smaller changes. However, for snowfall extremes, the difference across the province is less pronounced, with small decreases in daily

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3. For more on the fifth phase of the Coupled Model Intercomparison Project, see here: http://cmip-pcmdi.llnl.gov/cmip5/.
4. The Intergovernmental Panel on Climate Change uses four trajectories of atmospheric greenhouse gas concentration, known as Representative Concentration Pathways (RCP) for its Fifth Assessment Report. The four trajectories are denoted by the change to radiative forcings that would result from each concentration by the year 2100. O'Gorman uses RCP 8.5 which results in an increase of 8.5 Watts per square meter by year 2100 as compared to the preindustrial period (taken to be the year 1750). For more information on the RCPs, see: 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.
5. See Figure 11: Mekis, É and L.A. Vincent, 2011: An Overview of the Second Generation Adjusted Daily Precipitation Dataset for Trend Analysis in Canada. *Atmosphere-Ocean*, **49**, 2, 163-177, doi:10.1080/07055900.2011.583910.

snowfall extremes in the southwest and small increases in the northeast. Reduced snowpack could affect snow and rain-and-snow fed watersheds, potentially altering seasonal discharge volumes. Reduced snow could also affect ecosystems containing flora and fauna that depend on snow for insulation. British Columbia has already seen a reduction in annual, winter and spring snowfall, though trends for autumn are more ambiguous and while southern Canada has seen mostly decreases, northern Canada has seen increases[5]. The minimal change to snowfall extremes may be of interest to those doing long-term planning for public safety, energy and transportation.

O'Gorman, P.A., 2014: Contrasting responses of mean and extreme snowfall to climate change. *Nature*, **512**, 416–418, doi:10.1038/nature13625.