PACIFIC CLIMATE IMPACTS CONSORTIUM

PCIC SCIENCE BRIEF: TRENDS IN CANADIAN SNOW COVER OVER RECENT DECADES

As the climate warms, the Earth's cryosphere, comprised of snow, ice and frozen soil, including permafrost, has been shrinking. Changes in snow cover, depth and the timing of snow melt can have impacts on ecosystems and human communities. Data on snow cover and depth is used to identify historical trends and provides a baseline with which to compare projected future changes.

Recent research published in *Atmosphere-Ocean* examines trends in snow cover as measured at observing stations by ruler and sonic sensors, looking at how snow cover has changed over the 1955-2017 period and comparing the two methods of measurement. Here we discuss what these results tell us about snow cover in Canada's changing climate.

Introduction

The Earth's warming climate is affecting the planet's cryosphere, that portion of the Earth system that contains frozen water. Ice sheets and glaciers have been losing mass, Arctic sea ice minimums have grown ever smaller and the area covered by snow in the Northern Hemisphere in the spring has been shrinking since the middle of the 20th Century[1].

Changes in snow cover, snow depth and the timing of snow melt can have multiple effects on human systems and ecosystems, altering things such as river flows, regional temperatures and the length of growing seasons. Because of this, it is important for regions that receive annual snowfall to measure and record snowfall amounts.

Snow is difficult to accurately measure in situ (on site or in place) because it is subject to drifting, melting and compacting. Multiple methods of measuring snow depth are in use[2], each with its own set of strengths and shortcomings. In Canada, snow depth has historically been measured with rulers, with a slowly increasing number of stations[3] using sonic sensors that send out ultrasonic pulses and then measure the elapsed time until the echo reaches the sensor in order to determine snow depth.

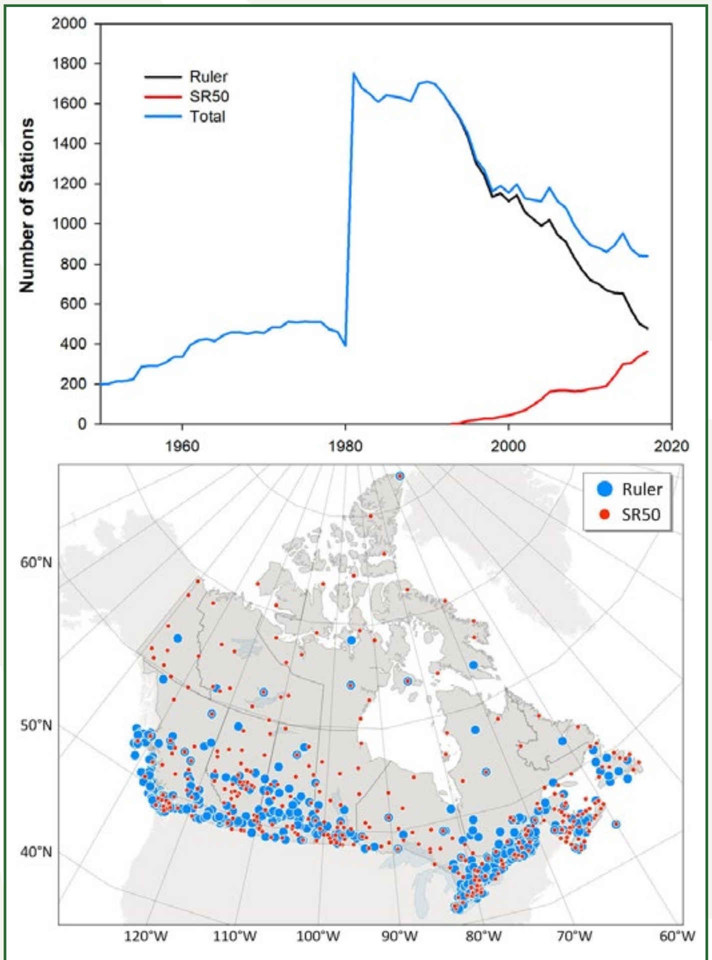

Figure 1: Canada's Snow Observing Network (from Brown et al., 2021).
This figure shows Canada's snow observation network. The top panel shows the change over time in the number of stations reporting a non-zero snow depth in February, with the black line representing stations with ruler measurements, the red line representing stations with automated sonic sensor measurements and the blue line representing the total number of stations. The bottom panel shows the spatial distribution of stations with ruler measurements (blue) and sonic sensor measurements (red) as of the 2016-2017 snow season. (Here SR50 denotes stations using sonic sensors, for which the SR50 and SR50a sensors are both in use.) Note that station density is highest in southern Canada and becomes much more sparse north of about 55° latitude.

1. For more on the impacts of anthropogenic climate change on the Earth's cryosphere, see Chapter 9 in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (Fox-Kemper et al., 2021).

Given the importance of snow to Canadian ecosystems and human communities, and the ongoing shift from ruler measurements to sonic sensors, it is worth asking: (1) if there are any trends in Canadian snow cover and depth and, (2) if the shift in measurement methods introduces any biases into estimates of these quantities.

Addressing these questions in a recent paper in *Atmosphere-Ocean*, Brown and coauthors (2021) evaluate in situ snow measurements from Environment and Climate Change Canada (ECCC) over the 1955-2017 period, estimating trends in snow cover and comparing manual ruler measurements to those taken by automated sensors.

The Canadian Snow Network

Canada's snow-depth observation network has gone through a number of changes since the first measurement recorded in ECCC's archives was made at Chaplin, Saskatchewan, in 1883. Initially, measurements were only made once at the end of each month at a small number of locations using rulers. In 1941 stations began making daily measurements and in 1980 the network expanded to include the volunteer station network, causing the number of stations to more than quadruple (Figure 1). Starting in the 1990s, however, the number of stations with manual measurements began to decline sharply (by 45% between 1995 and 2017), while automated sonic sensors came into use in the late 1990s. Losses in high-latitude regions have been disproportionately larger than in southern regions. The observational network is largely clustered in southern Canada, with stations becoming much more sparse north of about 55° in latitude (Figure 1, lower panel).

Comparing Ruler and Sonic Sensor Measurements

For the comparison between ruler-based and sonic sensor observations, the authors select data from 2000-2017 from a subset of 92 stations that had no more than 20 missing daily snow depth values over a season. Where possible, they paired stations that used ruler-based measurements with stations that used sonic sensors, making sure that they were no more than one kilometre apart and that they differed by no more than 100 metres in elevation. The sites were well distributed across the country and in terms of elevation.

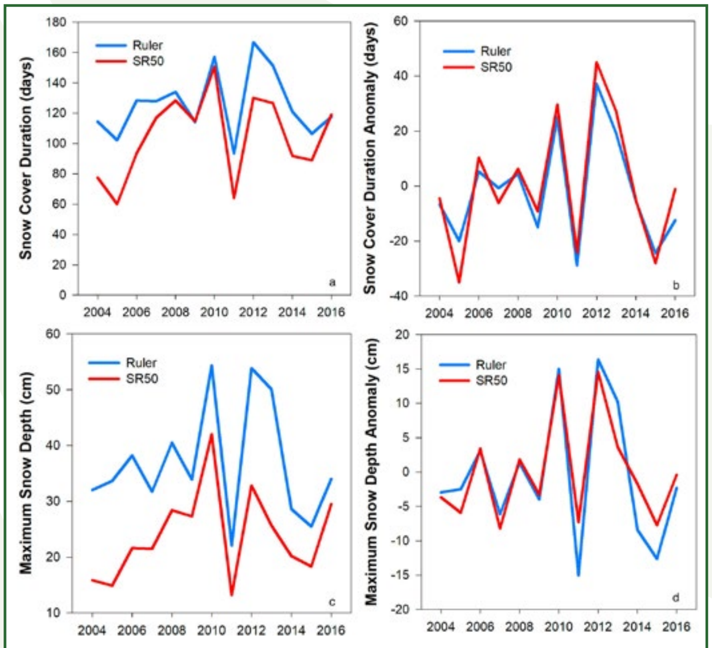

Figure 2: Prairie Snow Depth and Cover (from Brown et al., 2021).
This figure shows the snow cover duration and anomaly (top panels) and the maximum snow cover depth and anomaly (bottom panels) for 2004 to 2016 from ruler measurements (blue) and SR50 sonic sensors (red) over stations in the Canadian Prairies (a region covering 49°–54°N, 95°–115°W). Note that while the measurements of snow cover duration and maximum depth vary between the ruler and sonic sensors, the anomalies show much closer agreement.

Brown et al. found that there was no statistically significant difference between the ruler measurements and the sonic sensor measurements in terms of the number of days with recorded snow cover each year. There was, however, a statistically significant difference between the two forms of measurement when it came to snow depth. On average, the sonic sensors recorded about five centimetres (cm) less snow than the ruler measurements, with the discrepancy increasing for greater snow depths. This suggests that snow depth indicators and variables may be more affected by the change in measurement method than snow cover duration indicators.

The authors did not diagnose one specific cause for the observed difference between the measuring methods when recording snow depth, but, ruler-based measure-

2. The primary snow measurement methods in use are: snow stakes and rulers, by which snow depth can be read by eye; ultrasonic and laser snow sensors that use reflected sound waves and light to measure snow height; passive gamma sensors that detect the reduction in gamma rays from the decay of isotopes (mostly potassium and thallium) on Earth's surface when snow is present; and snow scales that weigh the snow on top of them. For more information on these see the World Meteorological Organization's Solid Precipitation Intercomparison Experiment (Nitu et al., 2018). Satellite radar measurements are also being used to measure snow depth.
3. At the same time, the number of stations in Canada's snow observation system has declined sharply, with a reduction in stations of just under 50% between 1995-2017. These losses have been relatively larger in high-latitude regions, with about 80% of the network north of 55° north no longer operating.

ments and sonic sensors have different sets of potential error sources that could have contributed. The former have an element of subjective selection of measurement points where the ruler is placed, whereas the latter can be affected by vegetation growing in the instrument's field of view, the point nature of the measurement, the snow crystal type that they are observing, the presence of heavy snowfall, blowing and drifting snow, snow density and the rattling of the sensor in the wind.

Given this systematic difference in estimated snow depth by the two methods, the authors asked the question: could this affect the estimation of trends? To answer this question, they examined a subset of station data from Alberta that were recorded over the 2004-2017 period. Brown and coauthors noticed that while the absolute values of snow cover duration and snow depth clearly differ between the two methods (Figure 2, left panels), the difference is much less when corresponding anomalies from a reference period are used (Figure 2, right panels).

Trends in Canadian Snow Depth and Cover

With the issue of changing measurement methods addressed, the authors turned their attention to the observed trends in snow depth and cover. They focused on seven variables: the annual maximum snow depth and the corresponding date at which it occurs, the first and last days of the year with snow on the ground, and the number of days each year with snow cover (annual, spring and fall). Brown et al. also considered two periods. The first, 1955-2017, is the period since the network expanded to include regions outside of southern Canada. The second, 1981-2017, is the period over which the network included volunteer climate stations. The authors created a gridded data set in order to perform this analysis, first filling in missing data, then calculating anomalies, then interpolating[4] the data to a 190.5 kilometre grid.

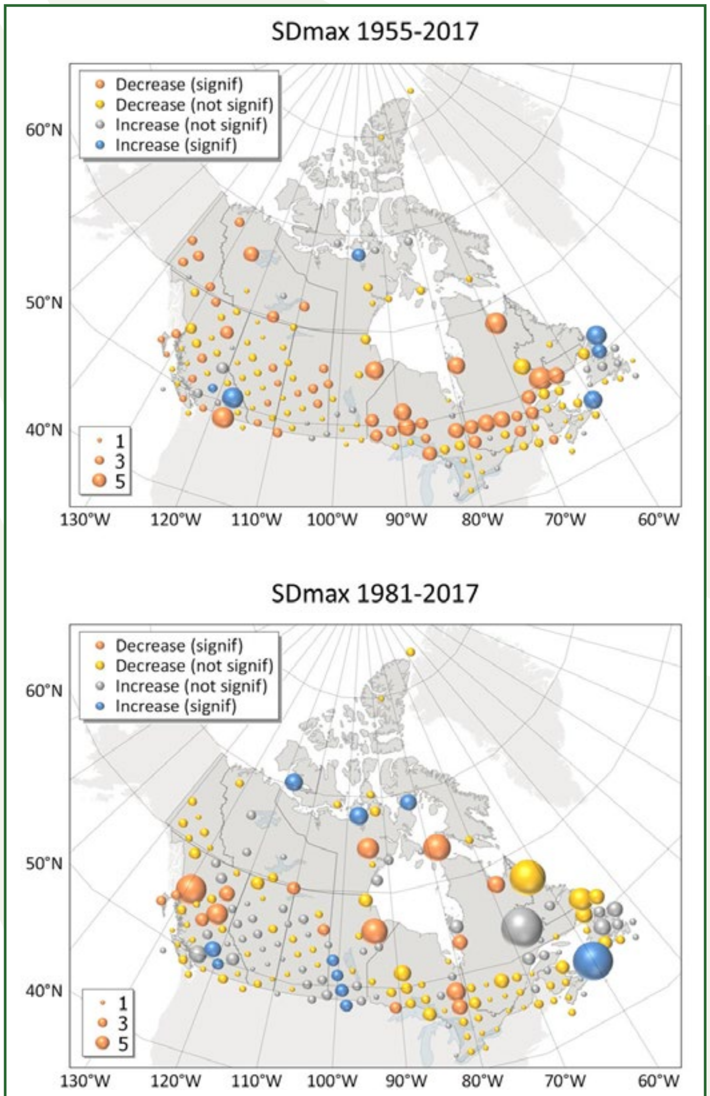

Figure 3: Maximum Snow Depth (from Brown et al., 2021). This figure shows gridded plots of maximum snow depth trends across Canada for the 1955-2017 (top panel) and 1981-2017 (bottom panel) periods, from rulers and sonic sensors. Orange and navy orbs denote grid points with statistically significant increases and decreases, respectively. Yellow and light blue orbs denote grid points with decreasing and increasing trends, respectively, but where the trends are not statistically significant. The size of the orbs indicates the size of the trend (in cm per decade) as per the legends in the bottom left of each panel.

The authors found that a long-term trend of decreasing snow depth is apparent in the observations over 1955-2017 (Figures 3 and 4). They attribute this to the combination of reduced winter precipitation over western and southern Canada and an increase in the amount of precipitation that is falling as rain. At points where there are significant trends (29.8% of locations), the snow depth has been declining by about 4.80 cm per decade. The Canada-wide decline is about 1.31 cm per decade. The trend is smaller over the 1981-2017 period, with a decline of about 0.58 cm per decade and significant trends are only present at 8.3% of the locations in the data set during that period, all of which show a decline. In total, about 63% of stations show a declining trend, significant or otherwise.

Brown et al. do not find evidence of long-term trends in the timing of the first and last days that have snow on the ground, or in the snow season length over the 1955-2017

4. Interpolation is the process of calculating unknown values, such as the snow depth at a given location for which data does not exist, from known values, such as snow depth data from nearby stations, using statistical methods and observed relationships between these quantities.

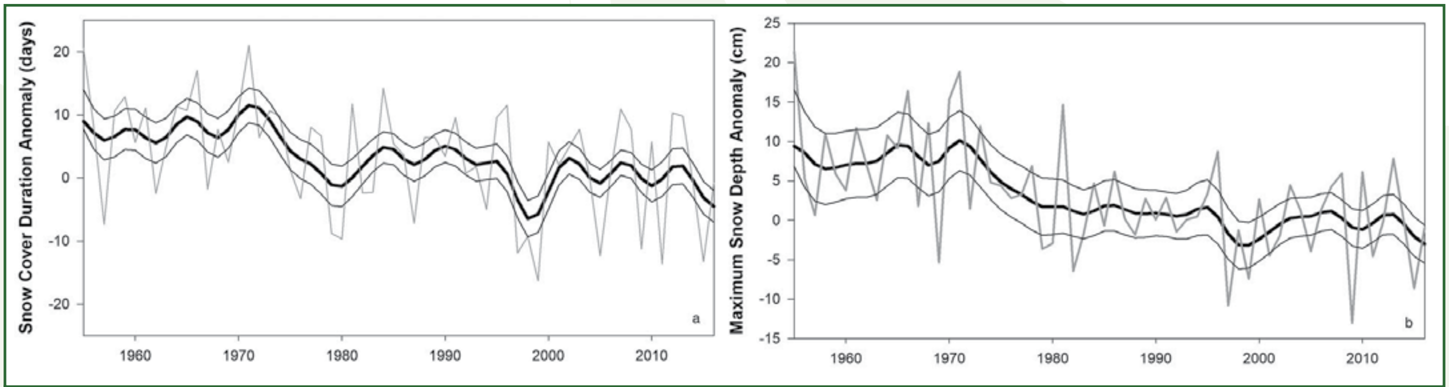

Figure 4: Snow Cover Duration and Depth Anomalies (from Brown et al., 2021).
This figure shows the regionally-averaged anomalies for snow cover duration (left panel) and maximum snow-cover depth (right panel) for the 1955-2017 period relative to a 2003-2016 reference period, for all of Canada. Note in particular the strong decline in both variables over the 1970s.

period. Nevertheless, a reduction in snow season length of about two days per decade was apparent over the more recent period of 1981-2017, due to the snow season starting later.

When it comes to the number of days with snow on the ground, Brown and colleagues found that about a third of the study region showed long-term decreasing trends over 1955-2017 of about 3.90 days per decade, and a median reduction across Canada of about 1.54 days per decade. This decreasing trend affected snow cover days in the spring more than those in the fall, with about a third of locations showing significant decreases in the spring and only about 14% of locations showing decreases in the fall. Snow-free days increased at 28% of the stations examined over this period, with no stations showing a decrease in snow-free days. Owing to the relatively stronger influence of interannual variability over the shorter time scale, the authors found trends in snow cover days to be less apparent over the 1981-2017 period, with only about 7.7% of locations showing a significant decrease over this time frame.

Brown et al. note that a large portion of the declines in snow cover duration and maximum snow depth occur over the 1970s. The authors explain that this occurs at the same time as a period of rapid spring warming, a change in atmospheric circulation over the North Pacific Ocean and a change in the North Atlantic Oscillation[5] that has been tied, in particular, to declines in winter storm activity and snow depth in eastern Canada.

Summary: Declining Snow Cover Across Canada, a Mixed Trend in BC

As the climate warms, the Earth's cryosphere will continue its retreat, and Brown et al.'s research adds to the body of work that shows that similar reductions are occurring across Canada when considered as a whole. The authors' results paint a picture of a country experiencing fewer days with snow cover and with reduced maximum snow depth. Future climate projections[6] indicate that these trends will continue throughout the century, although the rate and magnitude of the change depends upon the corresponding rate of global anthropogenic greenhouse gas emissions. The authors showed that, when analyzing trends in snow cover, one way of handling the shift from ruler-based measurements to sonic sensor measurements is by looking at the anomalies, for which the two methods are in good agreement. Brown and colleagues did not attempt to quantify the effect of the ongoing loss of stations reporting snow cover on the quality of data in the data set, or the impact of the reduction in the number of climate stations comprising the volunteer climate station network, but did express that the reduction is concerning and

5. The North Atlantic Oscillation is a climate pattern characterized by periodic variations in the pressure of the atmosphere at sea level in the Atlantic Ocean. Its positive phase is characterized by a strong low pressure region just south of Iceland, called the Icelandic Low and a high pressure region near the Azores, called the Azores high. Its negative phase is characterized by a weaker Icelandic Low and Azores High. It has effects on weather both regionally and globally. In its positive phase, it brings warm, wet winters to northern Eurasia and cooler, drier winters to northeastern North America and the Mediterranean. In its negative phase, it brings the opposite, with cooler, drier winters in northern Eurasia, and warmer, wetter winters to the Mediterranean and northeastern North America. In the summer, its effects are generally weaker, but it can still affect the weather of northern North America, Greenland, northern Eurasia, the Mediterranean and parts of Africa. In Canada, the NAO's effects are generally felt in central and northeastern regions.
6. For more information on changes to snow cover in Canada, see Chapter 5 in Canada's Changing Climate Report (Derksen et al., 2019).

urge the conservation of stations with long-term manual measurements.

At the regional scale, the picture becomes less clear. In British Columbia (BC), a general trend of decreasing snow depth and days with snow cover is apparent throughout much of the province, but this is not uniform. In general, it is difficult to infer snow changes across BC from the ECCC network because of the province's complex topography with mountains and sharp changes in elevation across the province. While ECCC stations are generally situated in valley bottoms, where snowfall tends to be lower. An analysis that determines snow cover and depth changes across BC would have to account for the effect of elevation on snow measurements, and this was not done by Brown et al. Accounting for station elevation is less important east of the Rocky Mountains.

It is worth noting that, given the sparsity of the stations outside of southern Canada, their positions in generally lower elevations and along coasts in northern Canada, and the variability of snow cover at the local scale, these in situ measurements are limited in what they can tell us about changes in Canadian snow cover. However, taken together with satellite measurements and land surface models, this work supports ongoing efforts to quantify changes to Canada's climate and to provide a baseline to which future changes can be compared.

References:

Brown, R.D. et al., 2021: Canadian In Situ Snow Cover Trends for 1955–2017 Including an Assessment of the Impact of Automation. *Atmosphere-Ocean*, **59**, 2, 77–92, doi:10.1080/07055900.2021.1911781.

Derksen, C. et al., 2019: Changes in snow, ice, and permafrost across Canada; Chapter 5 in *Canada's Changing Climate Report*, (ed.) E. Bush and D.S. Lemmen; Government of Canada, Ottawa, Ontario, 66 pp.

Fox-Kemper, B., et al., 2021, Ocean, Cryosphere and Sea Level Change. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press, 271 pp.

Nitu, R. et al., 2018: *WMO Solid Precipitation Intercomparison Experiment (SPICE), Instruments and Observing Methods. Report No. 131*. World Meteorological Organization, 1445 pp.