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PCIC SCIENCE BRIEF: WAVES AND COASTAL SEA LEVEL AND THE HUMAN INFLUENCE ON CANADIAN TEMPERATURES

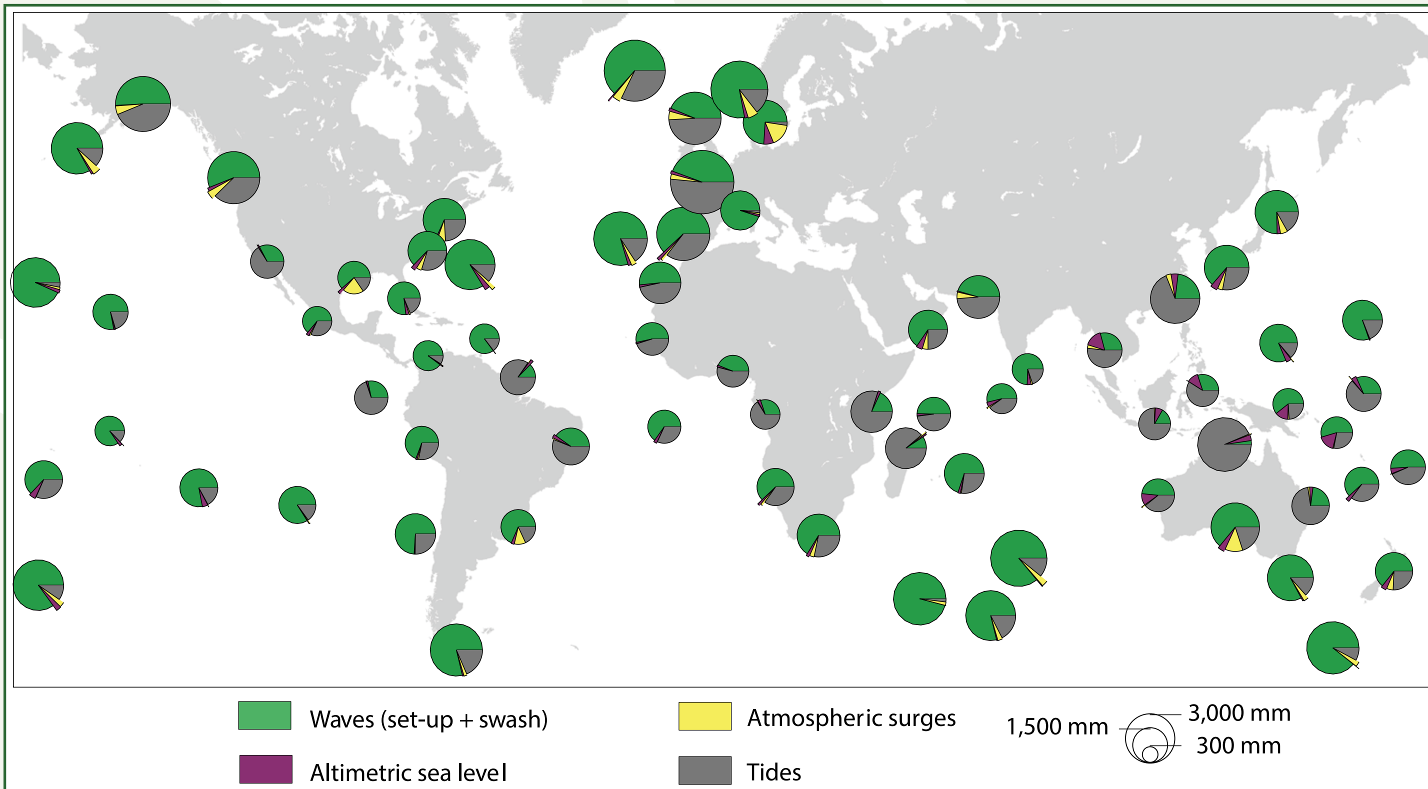

Figure 1: Contributions to sea level extreme events over 1993-2015, from Melet et al. (2018).
This figure shows the relative contributions of waves (green), atmospheric surges (yellow), sea level from satellite altimetry measurements (violet) and tides (grey) to extreme total water levels on the coast using pie charts. The amount of the pie chart shaded in a given colour shows the relative contribution of the corresponding process. Pie chart area indicates the average magnitude of extreme events at that location.

In this Science Brief we consider two aspects of climate change that are of direct interest to Canadians—the warming of the Canadian climate and changes in high water events that affect our coasts. Two articles recently published in the peer reviewed literature discuss the contribution of waves to coastal sea level rise and the roles of human and natural influences in Canada's warming climate.

Publishing in *Nature Climate Change*, Melet et al. (2018) study the effect of atmospheric surges, tides and waves on total water level rise at the coast. Using a mixture of model output and observations from the 1993-2015 period, they find that the size of wave contributions from several processes varies regionally. These processes can strengthen, offset or, as is the case for locations on the west coast of North America, entirely dominate sea level rise due to thermal expansion and land ice melting.

In their article in *Climate Dynamics*, Wan, Zhang and Zwiers (2018) examine the roles that human and natural influences have played in Canada's warming climate from 1948 to 2012, both nationally and regionally. Comparing observations to climate model simulations, they find that about

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1.0°C of the 1.7°C warming that Canada experienced over that period can be attributed to anthropogenic influences, while natural external influences (the sun and volcanic eruptions) contributed only about 0.2°C. For the region comprised of British Columbia and Yukon, which has experienced a 1.6°C warming, they find that about 0.8°C is attributable to anthropogenic influences and about 0.2°C to natural influences. They also find that, in most cases, anthropogenic influences can be detected in changes to the annual hottest and coldest daytime and nighttime temperatures for Canada as a whole and at the regional level. Natural influences can generally only be detected in changes to the coldest winter nighttime and daytime temperatures, both nationally and regionally.

Projected changes to global climate will bring their own particular challenges to British Columbia (BC). Two large areas of concern have to do with changes in sea level and the overall warming of surface air temperatures.

Changes to sea levels can have many impacts, among them the risks posed by inundation, flooding, erosion and storm surge events. With more than two-thirds of BC's population living in coastal areas, this is a topic of interest to planners in the province. The warming of surface air temperatures can result in a cascade of effects. These range from those most obviously associated with temperature, such as changes in temperature extremes and changes in the timing and magnitude of the energy needed for heating and cooling, to increases in wildfire risk, reductions in glacier volumes and changes in pest distribution patterns. Such changes could have widespread implications for BC. Due to polar amplification[1], global warming is occurring more quickly in northern high-latitude regions. Over the 1948-2012 period the surface air temperatures of Canada and the BC-Yukon region have warmed at about twice the rate of the global mean. Understanding how and why these changes have happened in the past can help the research community to better understand how they may change in the future.

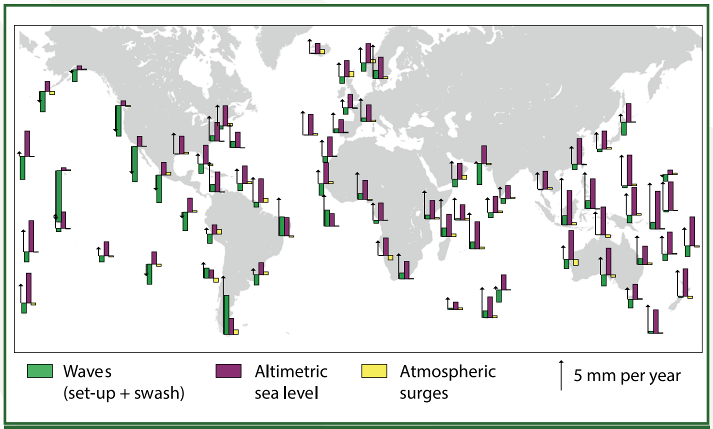

Figure 2: Contributions to total water-level trends over the 1993-2015 period, from Melet et al. (2018).
This figure shows the contribution of waves (green), atmospheric surges (yellow) and sea level from satellite altimetry measurements (violet) to total mean water-level trends over the 1993-2015 period. Colour bars indicate the contribution to the total trend for each process and black arrows indicate the total trend at each location.

Waves and Coastal Sea Level Rise

Publishing in *Nature Climate Change*, Melet et al. (2018) examine the contribution of waves to coastal-sea level rise and extreme events. Globally, satellite and tide gauge observations show that sea level has been rising over the period for which records have been kept. Climate model projections suggest that this will continue under all anthropogenic greenhouse gas emissions scenarios. On the global scale, the two main contributors to sea level rise are the thermal expansion of sea water and melt runoff from land-based ice, including the ice sheets on Greenland and Antarctica. Local changes in sea level are influenced by a number of additional factors, including changes in waves, ocean circulation, local ocean temperature, changes in the Earth's gravitational field due to polar ice loss, the movement of land due to tectonic processes, including the readjustment that occurs after ice sheets are removed.

It may not be immediately obvious how waves can contribute to sea level rise. After all, as waves pass by a given location in the open ocean, the effect of wave crests (the high points of the displaced water) on sea level height is

1. Polar amplification refers to the tendency for polar regions to experience greater climate changes than regions at lower latitudes and is especially pronounced in the Arctic. Several processes lead to amplified warming at higher latitudes, including the following: melting ice and snow at higher latitudes exposes darker ocean and land surfaces underneath, which in turn increase warming as these surfaces absorb more energy from solar radiation. As sea ice melts, heat from the oceans is more easily exchanged with the atmosphere.
2. As a waves travels into shallower water, it interacts with the sloping ocean bottom near the shore and starts to deform. In the shallower water, the bottom of the wave experiences friction from the underlying sea bed. The wave slows down, but the bottom in particular begins to move more slowly than the top of the wave. This causes the leading surface of the wave to steepen. The height of the wave increases. Eventually, the top of the wave is moving fast enough that it begins to spill down the leading face. The energy of the wave is transformed into turbulent kinetic energy as it spills over itself and rushes up the surf zone. The shape of the breaking wave depends on the size of the wave and the slope of the underwater terrain that it is travelling over.

offset, on average, by the depth of wave troughs (the low points of the displaced water). What is key here is that Melet et al. examine the role that waves play on the coast. In the near shore areas in which waves break[2], the water is too shallow to sustain waves and they deform, slowing, rising and then spilling over themselves, traveling up the shore and momentarily increasing the water level.

Melet and colleagues use tides from a tidal model, global mean sea level from satellite observations, atmospheric surges[3] from an ocean model and wave data from reanalysis[4] products in order to estimate the contribution of waves to both extreme events and sea level rise—by which they mean, total mean water-level changes[5]—on the world's coasts, at the time scales of years and decades. The authors attempt to replicate mean water levels and extreme events over the 1993-2015 period at 158 locations for which tide gauge data exists.

The authors first compare their simulations, without wave components, with tide gauge records. They find that their estimated sea levels match tide gauge records, suggesting that their methods have captured the essential processes other than of waves. When the wave contributions calculated by the authors are included, their estimates reproduce extreme events that are recorded in the tide gauge data and some extreme events that are recorded elsewhere but do not show up in the tide gauge data. They suggest that this may be because tide gauges miss some extreme events because they may be located in areas that are protected from large waves.

Satisfied that their simulations represent enough of the essential processes to be of use, Melet et al. move on to examining the contribution of waves to extreme events and total mean water-level changes at the coast. Turning to extreme events first, they find that waves and tides are the two most important factors for sea level extremes at most of the locations that they test, with atmospheric surges and the overall sea level rise from other causes playing a lesser role (Figure 1).

Turning to the role of waves in observed total water-level changes, the authors find that, on timescales of years to decades, waves are a significant factor in many locations around the globe, especially at higher latitudes. When their influence on the total coastal water-level trend over the 1993-2015 period is measured, it is clear that they have been the dominant factor on the west coast of the Americas (Figure 2) over recent decades. It is worth noting that the authors do not take into account isostatic adjustment[6], which can play an important role at the regional scale over long time periods.

Melet and colleagues note that changes to local winds, in particular mid-latitude westerlies and trade winds, are likely responsible for the wave contribution to water level changes, especially in the tropical Pacific and Atlantic, and near Japan and Europe. They suggest that strengthening Pacific trade winds and winds over the Southern Ocean are in line with climate model projections. Changes to these winds may cause certain regions to be more exposed to water level changes due to altered wave activity while other regions are less exposed. This is an especially important point, because projections of future extreme water levels are often made using the assumption that the wave climate is stationary. The authors note that wave contributions to changes in total water levels at the coast may continue to be significant, so long as the contribution from other processes is only of a few millimetres per year in magnitude.

The Human Influence on Canadian Temperatures

In their recent article in *Climate Dynamics*, Wan, Zhang and Zwiers explore the relative contributions of human and natural influences on both average and extreme temperatures across Canada. The influence of anthropogenic greenhouse gas emissions has already been detected on a number of climate variables and indices at global and continental scales, and in some regions. At sub-continental and regional scales, some of these climate variables include, average temperatures, precipitation, temperature extremes, streamflow regimes, snowcover and Arctic sea

3. Atmospheric surges, or storm surges, are large displacements of surface water that occur due to the winds that accompany storms.
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, run in hindcast mode. In this paper, Melet and colleagues use the European Centre for Medium Range Weather Forecasts' Re-Analysis Interim (ERA-Interim). For more information on ERA-Interim, see Dee et al. (2011).
5. Total mean water-level changes here means the average of the water level from all contributions over the timescales of years and decades. This is not the same as the still water elevation (sea level height without wave contributions) or extreme high water (which are some subset of the highest sea level heights and occur over a much shorter period of time).
6. Isostatic adjustment refers to the response of the solid, outer part of the Earth to being placed under a load (such as by water, sediment or ice accumulation) or having a load removed from it (such as by erosion or ice loss). This is an important factor for many regions on the coast of British Columbia, as the reaction of the crust to the removal of ice at the end of the last ice age continues to this day. For example, Tofino has seen a reduction of more than ten centimetres in sea level since 1910, due to vertical land movement.
7. Here external influences refers to the influence of volcanic and anthropogenic aerosols, as well as land-use changes, changes in solar output and anthropogenic greenhouse gas emissions. These are taken to be external in contrast to the processes, such as patterns of climate variability (see below), that occur within the climate system itself.

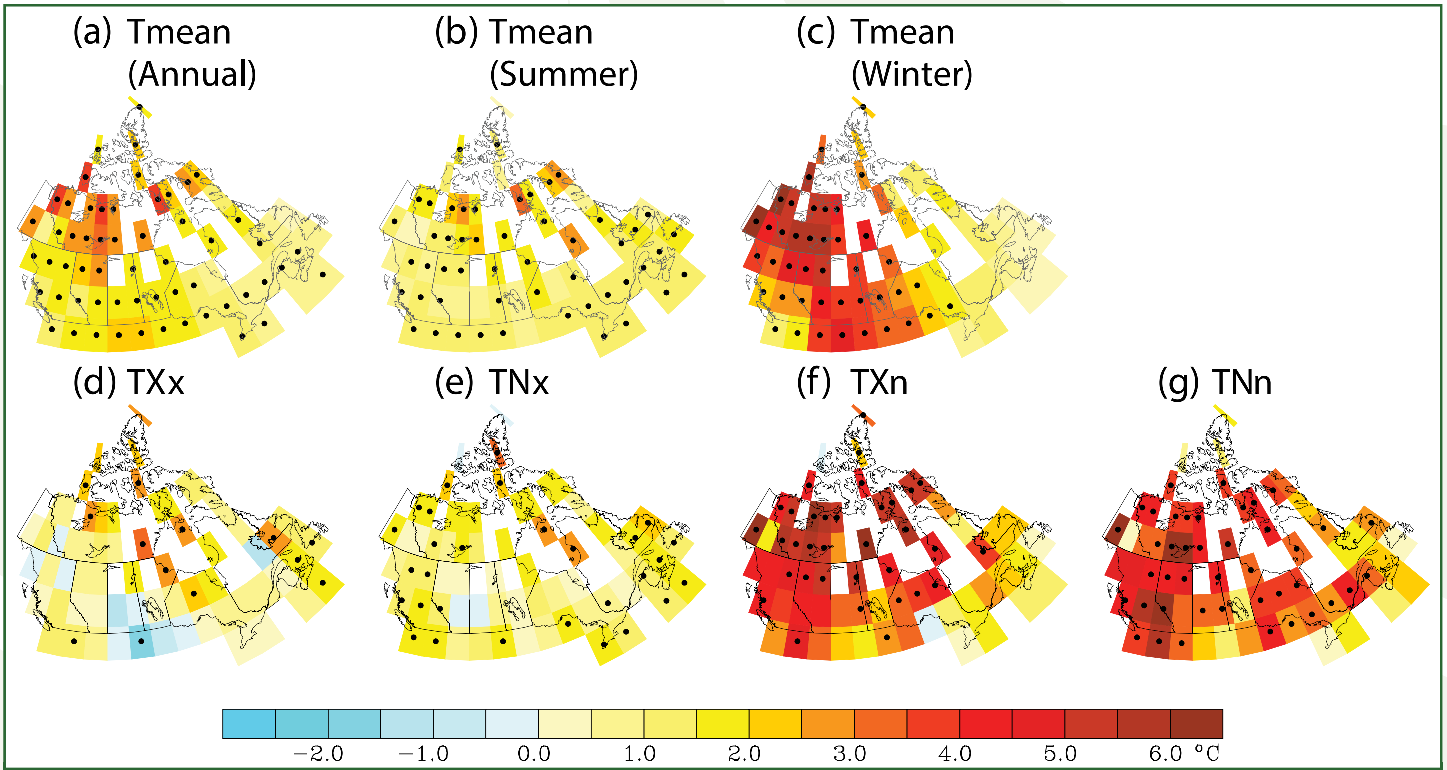

Figure 3: Observed trends for the 1948-2012 period, from Wan, Zhang and Zwiers. (2018).
This figure shows the observed trends in (a) annual mean, (b) summer mean and (c) winter mean temperature, as well as four extreme temperature indices: the temperatures of the hottest summer day (TXx), hottest summer night (TNx), coldest winter day (TXn) and coldest winter night (TNn) annually. All trends are in °C over the whole 65 year period. Black dots indicate areas in which trends are statistically significant while white areas indicate regions with insufficient data for analysis.

ice. These trends are projected to continue. A better understanding of the human influence on the climate system will allow for more skilful and confident use of climate projections in adaptation, and improvements to be made to the climate models used to make the projections.

In order to discern the relative contributions of both human and natural external influences[7] on average and extreme temperatures, the authors use observations of temperatures over Canada for the 1948–2012 period and compare these to global climate model output. They also consider the influence of two large-scale patterns of internal climate variability, the Pacific Decadal Oscillation[8] (PDO) and the North Atlantic Oscillation[9] (NAO).

Wan, Zhang and Zwiers use station observations from a network of 338 stations across Canada. From this data, they calculate daily mean temperature and obtain four extreme temperature indices for each year: the temperatures of the hottest summer day (TXx), hottest summer night (TNx), coldest winter day (TXn) and coldest winter night (TNn). They also use output from global climate

8. The Pacific Decadal Oscillation is a pattern of climate variability defined by sea surface temperatures in the North Pacific Ocean. The signature of its positive phase is a mix of warm sea surface temperatures in the eastern North Pacific and cool sea surface temperatures both in the middle of the basin and in the eastern North Pacific. In the negative phase the opposite pattern of sea surface temperatures is observed. It has a period between phases that ranges from years to decades. The PDO is linked to sea surface temperatures elsewhere and seems to be largely a response to three other elements of the climate system. These are: a persistent region of low pressure in the atmosphere above the North Pacific known as the Aleutian Low, the memory of the North Pacific Ocean itself and a major ocean current called the Kuroshio that flows northward along the western edge of the Pacific Ocean.
9. The North Atlantic Oscillation is a pattern of climate variability defined by the surface air-pressure difference between a semi-permanent high pressure area called the Azores High that is found just south of the Azores (an archipelago of nine islands about 1000 miles west of the coast of Portugal), and a semi-permanent low pressure area that resides over the ocean between and to the south of Greenland and Iceland, called the Icelandic Low. Phases of the NAO seem to be driven in part by the state of the tropical Pacific Ocean, North Atlantic sea surface temperatures, sea ice extent in the Kara Sea (part of the Arctic Ocean) and the state of jet streams (narrow streams of fast-flowing wind) in the upper atmosphere.

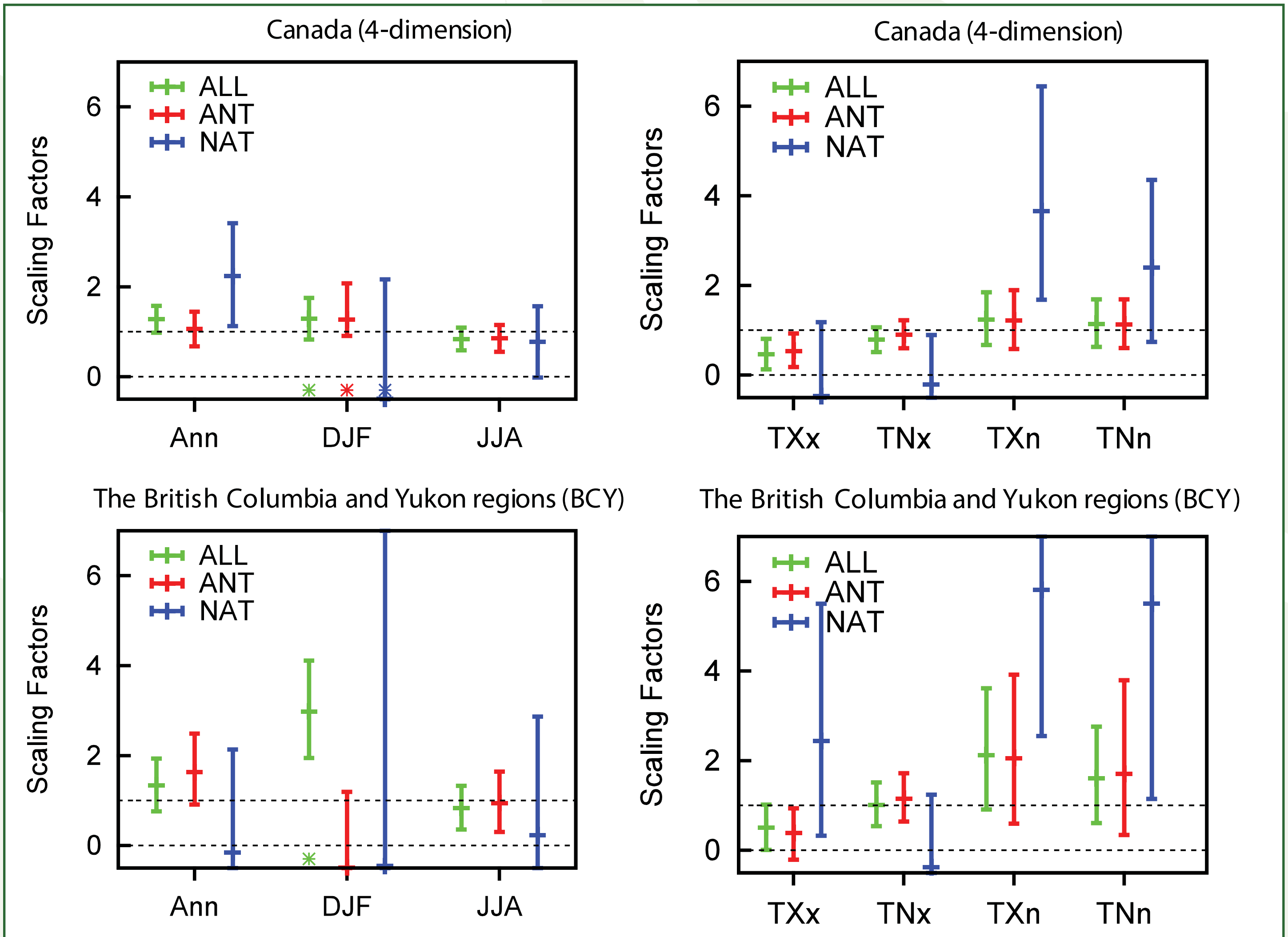

Figure 4: Estimates of scaling factors from detection analyses, from Wan, Zhang and Zwiers. (2018).
This figure shows the best estimates of scaling factors[10] and their 90% confidence intervals[11] for all forcings considered together (ALL in green) from a single-signal detection analysis[12], and anthropogenic forcings (ANT in red) and natural forcings (NAT in blue) considered separately, from two-signal optimal detection analysis[13] for seasonal mean temperatures and four temperature extremes indices. Left panels show the results for annual, winter (December, January February, DJF) and summer (June, July and August, JJA) mean temperatures. Right panels show the results for the temperature extremes indices: the temperatures of the hottest summer day (TXx), hottest summer night (TNx), coldest winter day (TXn) and coldest winter night (TNn). Results for Canada are shown on the top panels and results for BC and Yukon are on the bottom panels. Zero and one are marked with dashed lines. A signal (ANT, NAT or ALL) is detected and attribution is inferred if its scaling factor is positive and its 90% confidence interval includes one and excludes zero. An asterisk indicates that there is evidence that the climate models used in the study may have underestimated the climate's internal variability[14], meaning that the uncertainty of the corresponding scaling factor might also be underestimated. The label of "four dimensions" for Canada indicates that the four sub-regions regions were used for an analysis in which model output from the sub-regions was compared against both the temporal and spatial patterns of change found in observations.

10. Scaling factors are used in regression analysis, which is a set of statistical techniques that are used to assess the relationship between one variable of interest (called the dependent variable) and some other factors, or variable(s) of interest (the independent variable[s]), in order to determine how the dependent variable responds to changes in the dependent variable. Scaling factors, or regression coefficients, describe how much the dependent variable changes as an independent variable changes (assuming that the other independent variables are held constant). Here, the scaling factors can be thought of as showing how much each signal contributes to the observed response.
11. Confidence intervals indicate the uncertainty associated with a given statistic. There is a given level of confidence that the confidence interval includes the true value and the estimate of this confidence can be given as a percent. A 90% confidence interval indicates that there is only a one-in-ten chance that the confidence interval does not include the true value of the quantity.

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models that were run using only natural external forcings (volcanic aerosols and changes in solar output), only anthropogenic forcings (greenhouse gas emissions, aerosols and land use changes) and both anthropogenic and natural forcings combined. A number of other runs including simulations of the preindustrial control period were also used to estimate the naturally unforced internal variability of the climate system. They then analyzed annual, winter (December to February) and summer (June to August) average temperatures. The authors broke Canada down into four regions for their analysis, Eastern Canada, the Prairies, Northern Canada and a region comprised of BC and Yukon. They then applied a set of modern detection and attribution techniques[15] to the data from each region.

Over the 1948-2012 period, Canada warmed by about 1.7°C and the BC and Yukon region warmed by about 1.6°C. Canada as a whole and the BC-Yukon region in particular experienced increases in heat-related temperature extremes (Figure 3). The authors find that the effects of all forcings and anthropogenic forcings in particular can be detected and their influence attributed over most regions and seasons (Figure 4) while the influence of natural external forcings generally cannot be detected. They also find that anthropogenic influences were responsible for about 1.0°C of the warming over Canada and about 0.8°C of the warming that the BC-Yukon region has experienced. Natural external forcings contributed about 0.2°C to both Canada and the BC-Yukon region. In general, the authors find that the warming from all external forcings, and from anthropogenic influences in particular, are especially large in northerly regions. Wan, Zhang and Zwiers highlight the fact that the warming signal is now large enough that it can be detected in what are relatively small regions (that is, small when considered in terms of global climate) with considerable climate variability.

Anthropogenic influence was detected on all of the temperature extremes indices, Canada-wide, and for most indices in each region, with the exception of the hottest summer day index in the BC-Yukon region and in the Prairies. Canada-wide and for most regions, the influence of natural external forcings could only be detected on the cold extremes, the coldest winter day and coldest winter night. In BC however, the influence of natural forcings was detectable on the hottest summer day. The influences of the PDO and NAO, which are natural modes of variability that can persist for long periods of time (years to decades), were pronounced in wintertime mean temperatures, had a small impact on winter temperature extremes and were negligible for summertime temperatures. Because these are oscillations that shift between positive and negative phases, their impacts are expected to be reduced as longer and longer periods are analyzed and negative phases offset positive phases.

Taken together, these findings improve our understanding of how the Earth's climate system has changed in the past few decades. The influence of changes in wave activity to sea level rise and sea level extreme events appears to be significant in some regions. The authors suggest that the wave climate could continue to change in the future, as global wind patterns continue to shift. This has potential implications for making projections of future sea level rise. Concerning surface temperatures, both natural external forcings and anthropogenic influences on the temperature can now be detected over relatively small sub-regions within Canada, seasonally and for several temperature extremes. This suggests that climate models are capable of simulating enough of the components of the Earth system to capture important elements of the Earth's climate at these scales and provides further confidence in projections of future temperatures.

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

Melet, A., B. Meyssignac, R. Almar and G. Le Cozannet, 2018: Under-estimated wave contribution to coastal sea-level rise. *Nature Climate Change*, **8**, 234–239, doi:10.1038/s41558-018-0088-y.

Ribes, A., S. Planton and L. Terray, 2013: Application of regularised optimal fingerprinting to attribution. Part I: method, properties and idealised analysis. *Climate Dynamics*, **41**, 11–12, 2817–2836, doi: 10.1007/s00382-013-1735-7.

Wan, H., X. Zhang and F. Zwiers, 2018: Human influence on Canadian temperatures. *Climate Dynamics*, doi:10.1007/s00382-018-4145-z.

12. In the single-signal analysis, observations are compared using regression analysis (regressed onto) the signal, or output, of the models driven by all forcings (ALL).
13. In the two-signal analysis, observations are simultaneously compared with (regressed onto) two signals: the output of the models driven by natural forcings only (NAT) and models driven by all forcings (ALL). From this, one can determine whether the influence of the natural forcings (NAT) can be separated from the influence of anthropogenic forcings (ANT), the signal of which is estimated by subtracting NAT from ALL.
14. Regression models have a deterministic component, made up of the regression coefficients and independent variables, and a component that represents the estimated errors. These errors should be random and they should exhibit variance (or scatter) similar in magnitude to the variance in the observations. If they aren't random, it suggests that another explanatory factor is being ignored. If they show less variability than the observations, this could lead to a false detection. The test that the authors performed was done to check for such issues.
15. While a description of the techniques used is outside of the scope of this Science Brief, they are, at heart, regression-based. (See Footnotes 10-13.) For more information, see the original paper and Ribes, Planton and Terray (2013).