PCIC SCIENCE BRIEF: STORM SURGES AND PROJECTED CHANGES TO ATMOSPHERIC RIVER EVENTS IN COASTAL BC

Two articles recently published in the peer reviewed literature examine two types of extreme weather events that affect coastal British Columbia, storm surge events and atmospheric river events.

The first paper, by Soontiens et al. (2016) in *Atmosphere-Ocean* examines the ability of a numerical ocean model to simulate storm surges in the Strait of Georgia and the relative contribution of several factors to storm surge amplitude in the region. The authors use the model to simulate six storm surge events from the 2006-2012 period at four locations and find that the model does well at reproducing the magnitude of storm surges. They also find that the primary contribution to storm surges in the region are sea surface height anomalies from the Pacific, with local wind patterns causing small spatial differences in the sea surface height.

The second paper, by Hagos et al. (2016) in *Geophysical Research Letters* uses output from a global climate model to examine changes to atmospheric river events over western North America, assuming large, business-as-usual anthropogenic greenhouse gas emissions. The authors' projections show an increase of about 35% in days on which atmospheric rivers make landfall in the last 20 years of the 21st century when compared to the last 20 years of the 20th century. Their projections also show a resulting increase of about 28% in extreme precipitation days.

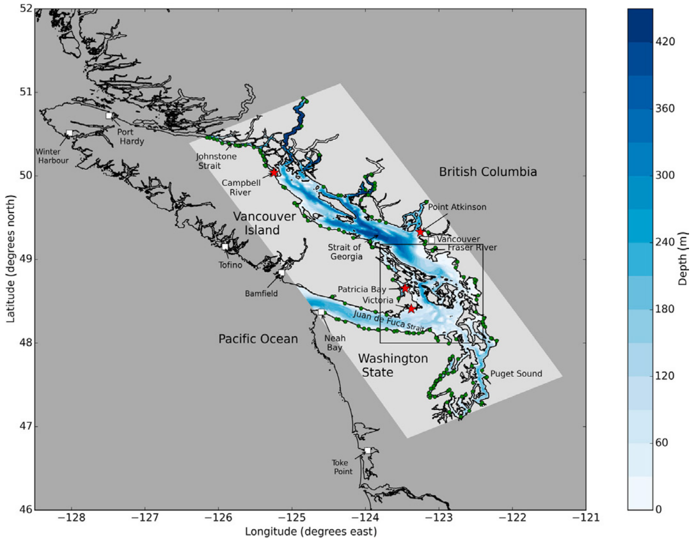

Figure 1: Study area, from Soontiens et al. (2016).
This figure shows the area studied by Soontiens et al. (light grey area). Rivers are represented by green circles and red stars indicate areas of particular interest for storm surge events.

British Columbia's coast is home to 11 ecoregions and over two-thirds of the province's population of about 4.7 million people. Our province's coast experiences several storm surge events each year, in which storms raise the height of the ocean's surface significantly, which can result in flooding. The region also bears the brunt of extreme rainfall events from atmospheric rivers, often called the "Pineapple Express," in which streams of warm, moist tropical air are forced to rise as they meet the mountains of the Coast Range, depositing large amounts of precipitation. While this can be beneficial for filling reservoirs and building snow pack, atmospheric rivers can also bring hazardous impacts, such as flooding and landslides.

As anthropogenic climate change continues, we expect a global increase in sea level height[1], possibly some changes in atmospheric circulation[2] and an overall increase in the amount of water vapour in the atmosphere[3]. These changes may affect the frequency and magnitude of extreme events such as storm surges and atmospheric river events. Because of the impacts that such changes could have on ecosystems and BC municipalities, improving our understanding of these events is of value to communities in coastal BC. The two papers covered by this Science Brief investigate these two types of phenomena.

In the first paper, by Soontiens et al. (2016), the authors drive a numerical ocean model with a mix of observational data and model output in order to test the ability of the numerical ocean model to simulate storm surge events in the Strait of Georgia and determine the largest contributors to the magnitude of such events. Five storm surge events were chosen, taken from the period of 2006-2012.

The Strait of Georgia is connected to the Juan de Fuca Strait in the south and the Johnstone strait in the northwest, each of which open to the Pacific Ocean. The Strait of Georgia is also connected to several smaller straits and inlets located between the mainland and Vancouver Island. Freshwater runoff from a number of watersheds flows into the Strait of Georgia, affecting the salinity, stratification and circulation in the Strait. Because of these connections to the ocean and land, sea level height at any point in the Strait is affected by tides, offshore events in the Pacific Ocean and precipitation over land. All of these elements must be taken into account in order for sea surface heights in the region to be well simulated. Accounting for these, Soontiens et al. use a wide variety of observational data and model output to drive their ocean model over this domain (Figure 1). These include both measured and calculated tides and river runoff, as well as observed temperature and salinity. The authors also use output from a weather forecast model to get values for atmospheric pressure and precipitation, in addition to wind, heat and solar input at the ocean's surface.

In comparing output from their model with observations, they begin by examining the ability of their model to simulate the spatial pattern generated by tides. Tides on Earth are driven by the gravitational forces exerted on the Earth's oceans by the moon and the sun[4]. As the Earth and the moon progress on their respective orbits, the resulting positions of the sun and moon relative to the Earth cause the resulting tides to have a series of cyclical components, called tidal constituents. At many locations, such as most of the west coast of North America, the two strongest components have to do with the position of the moon relative to given spots on the Earth's surface. One of these

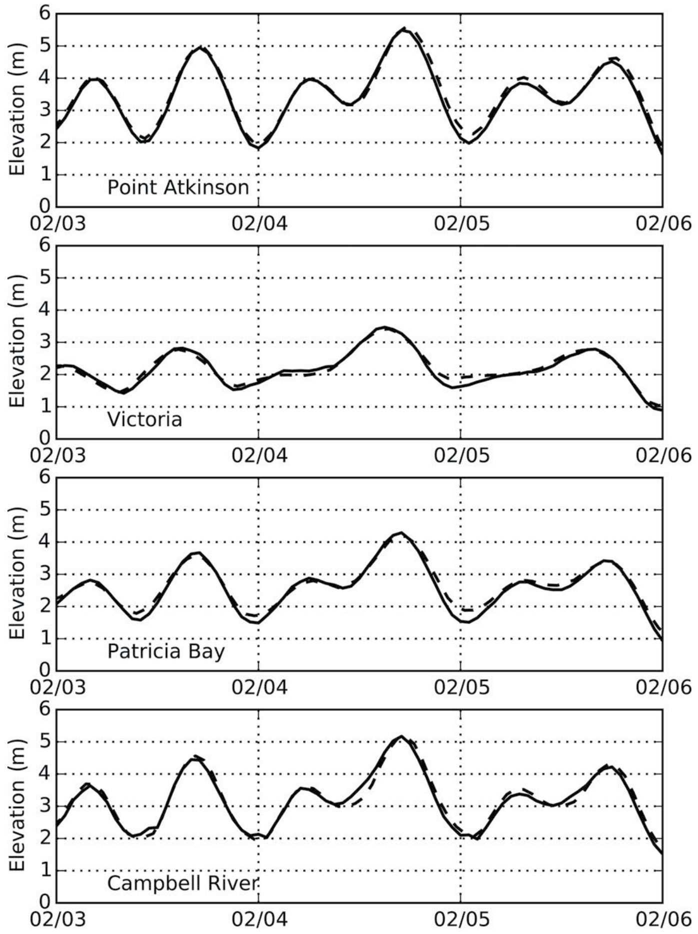

Figure 2: Simulated and observed sea level heights from the February 4th 2006 storm surge event, from Soontiens et al. (2016).

The figure above show observed (solid) and simulated (dashed) sea level elevations at four locations for a storm surge event that occurred on the BC coast on February 4th, 2006.

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1. For most of the Twentieth Century, sea level rise proceeded at about two millimetres per year, since the early 1990s it has accelerated to about three millimetres per year. Projected future sea level rise depends on the emissions scenario used and ranges from 0.26-0.54 metres by 2100 for aggressive emissions reduction scenarios to 0.57-0.97 metres for scenarios that assume business as usual emissions. For more information, see Church et al. (2013).
2. With the exception of the ocean's tides, the circulation of the atmosphere and ocean is driven almost entirely by incoming solar radiation. The distribution of incoming solar radiation and outgoing longwave radiation determines the temperature gradient between the equator and the poles and most of the large-scale features of the atmosphere's circulation. As atmospheric greenhouse gas emissions change the overall balance of radiation in the atmosphere, atmospheric temperature gradients will change, possibly affecting atmospheric circulation.
3. The maximum amount of water vapour that the atmosphere can "hold" increases rapidly (almost exponentially) with temperature according to a physics relationship known as the Clausius-Clapeyron relation. As the temperature of the troposphere (the lowest layer of the Earth's atmosphere) has increased, we have observed a corresponding increase in the amount of water vapour in the troposphere. For example, see: Hartmann et al. (2013).
4. The ocean's tides are generated by the difference in the gravitational forces experienced at different places on the Earth. For example, the ocean on the side of the Earth closest to the moon experiences a stronger gravitational force from the moon than the ocean on the side of the Earth farthest from the moon does. This difference in gravitational force experienced from one side of our planet to the other is roughly twice as great for the moon as it is for the sun, because the moon is much closer. Other celestial bodies also exert tidal forces on the Earth, but they are so small as to be negligible. For instance, the next largest tidal force experienced by the Earth is exerted by Venus and is about one ten-thousandth that of the tidal force due to the Sun.

is due to the Earth rotating about its axis Each day, causing a tidal constituent with a period of about 12 hours. The other is due to the angle of the moon relative to (i.e. “above” or “below”) the equator, causing a tidal constituent with a period of about 24 hours. The authors find that the model captures the amplitude and timing of these two major constituents of the tides quite well at most of the locations tested, except Seymour Narrows, owing to the narrowing of the landscape that occurs there, which is not well represented in the model.

Soontiens et al. also test their model’s ability to simulate past storm surge events, examining six events from 2006 to 2012. The model perfoms well in simulating all tested storm surge events (Figure 2), both in terms of the overall sea surface height and the component of height due to residuals, which are the contributions of things other than tides and rivers to sea level height, primarily the wind.

The authors also use their model to tease apart the factors that contribute to storm surge events by simulating an event that occurred in February 2006 and driving their model with different combinations of factors that are known to influence such events, including ocean height at the boundary where the Pacific meets the Georgia Strait, atmospheric pressure, winds and tides. They find that the height of the Pacific Ocean is by far the dominant factor, accounting for around 85% of the height of the surge. Winds alone are responsible for only a few percent at most locations. Changes in atmospheric pressure alone can account for up to a third of the total surge height at some locations, but this effect is only large when combined with the external influence of the Pacific Ocean.

The next paper, by Hagos et al., examines projected changes to atmospheric river events over western North America using a global climate model. Driving the model with a high-emissions, business-as-usual scenario (RCP 8.5[5]) Hagos et al. examine model biases in atmospheric circulation patterns, simulated landfalling atmospheric river days and extreme precipitation days over the 21st Century.

Atmospheric river events arise when strong midlatitude cyclones draw up long, narrow streams of moist air from the tropics. Atmospheric rivers are responsible for most of the poleward transport of water vapour in the atmosphere and can cause intense precipitation when they make land fall along the west coast. The amount of precipitation delivered by a given event depends on a number of factors, including the topography of the landscape that it passes over, its duration, the moisture it carries and their ability to release moisture as rain (which depends on the temperature, atmospheric stability, wind direction and wind speed within the storm). In addition, the latitude at which they make landfall is important because this determines where the precipitation and impacts occur.

Hagos et al. first note two biases in the climate model. One of these is that the subtropical jet stream, a meandering westward current of fast-moving air aloft at about 30° north latitude, occurs at a more southerly latitude in the simulations they use. This may artificially increase the atmospheric river count by increasing the speed at which winds move at height. The other is a slight cool bias in the model’s middle and upper troposphere when compared to reanalysis products[6]. The authors correct for these biases by adjusting the threshold windspeed used to identify atmospheric river events and the percentile threshold used for defining extreme precipitation days. They then examine what projections produced with the model show for landfalling atmospheric river days and extreme precipitation days. They define atmospheric river days as days in which an atmospheric river makes contact with at least one land cell in the model’s grid, between 32° and 60° north and west of 110° west. They define extreme precipitation days as days in which one of these land grid points experiences precipitation amounts greater than the 97.8th percentile of simulated daily precipitation values over the 1980-1999 period.

Hagos and colleagues find that (Figure 3) the model projects significant increases in both atmospheric river days and extreme precipitation days on the west coast of North America. To quantify this, the authors compare the last two decades of the twentieth century and the last two decades of the twenty-first century. They find an increase of 35%±8% in atmospheric river days by the end of the twenty-first century and a corresponding increase of 28%±7% in the number of extreme precipitation days. The extreme precipitation days do not increase quite as dramatically as the atmospheric river days. The authors attribute this to greater atmospheric stability[7] in the warmer climate, which partially offsets the impact of the greater number of atmospheric river days. Hagos et al. also note that the projected increase will not necessarily be uniform along the west coast.

What do the results of these papers mean for British Columbia? First, regarding storm surge events, the primary

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5. The Intergovernmental Panel on Climate Chance 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, e.g. RCP 8.5 would result in an increase of 8.5 Watts per square meter as compared to the preindustrial period (taken to be the year 1750). For more information on CMIP5 and 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.

driver of sea level height is the height of the Pacific Ocean on the boundaries of the Strait of Georgia. Second, it seems that storm surges in this region can be simulated with a high degree of skill. The same model is now being used by researchers to generate forecasts of storm surge events in the region[8], which are available in their preliminary form for research purposes. The model will also be used will be used for risk assessment along the coast.

Regarding atmospheric rivers, the projections discussed here suggest that the west coast may see an increase in the number of atmospheric river days it sees each year. The projections also suggest that these atmospheric river events may come with an increase in the number of extreme precipitation days. However, there are several important points to note. First, the uncertainties here are still quite large. Second, the model used by Hagos et al. displays some unusual behaviour in its simulations of subtropical jet streams, which may affect projections of atmospheric rivers9. Third, there are potential issues with using the same classification of atmospheric rivers between different time periods10. Fourth, Hagos et al. examine the west coast of North America as a whole. While these results are suggestive, their implications for British Columbia are limited. Further research is required to provide a robust, detailed assessment of how atmospheric rivers might affect BC in the future.

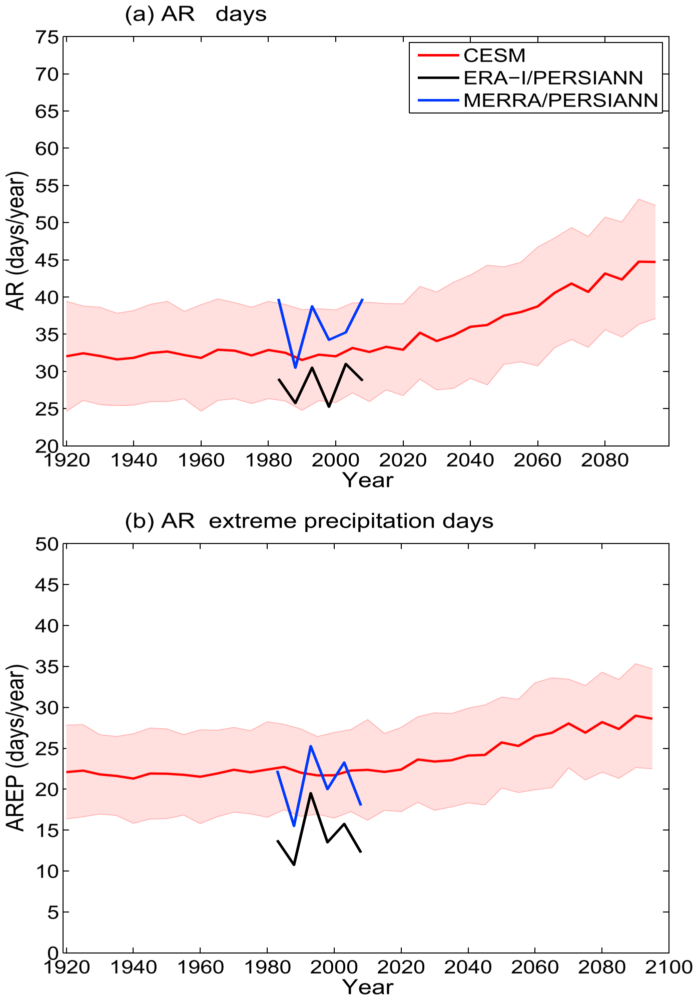

Figure 3: Atmospheric river days and associated extreme precipitation days on the west coast of North America, from Hagos et al. (2016).

This figure shows model simulations of the number of atmospheric river days and associated extreme precipitation days each year for the 1920-2100 period (red line and shading) and two sets of reanalysis data for comparison (blue and black lines, as noted).

Ashouri, H., K. et al., 2015: PERSIANN-CDR: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies, *Bulletin of the American Meteorological Society*, **96**, 69–83, doi:10.1175/BAMS-D-13-00068.1.

Chang, E. K. M., Y. Guo, and X. Xia 2012: CMIP5 multimodel ensemble projection of storm track change under global warming, *Journal of Geophysical Research: Atmospheres*, **117**, D23118, doi:10.1029/2012JD018578.

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.

Hagos, S. M., et al., 2016: A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations, *Geophysical Research Letters*, **43**, 1357–1363,

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6. 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, Hagos et al. use two sets of reanalysis data, the National Aeronautic and Space Administration's Modern Era-Retrospective Analysis for Research and Applications (MERRA) and the European Centre for Medium-Range Weather Forecasts' Re-Analysis Interim (ERA-Interim). Hagos et al. also use precipitation from a multisatellite record that has been processed using an artificial intelligence method, Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN). For more information on MERRA, see Rienecker et al. (2011). For more information on ERA-Interim, see Dee et al. (2011), and see Ashouri et al. (2015) for more information on PERSIANN.
7. Stability describes how prone the atmosphere is to overturning and rising motions, which can cause or exacerbate extreme precipitation events due to feedback within clouds. (Warm, moist air can enter a cloud from near its base, rise and condense, releasing heat. This then warms the cloud and increases its updraft, pulling in more air from the base and so on.) This is less important for extreme precipitation events in British Columbia, where extreme precipitation tends to result from the lifting of air masses over local mountainous landscape features.
8. The forecasts are now offered in their preliminary form as a research tool. They can be accessed via the University of British Columbia's Storm Surge Information Portal, online, here: https://salishsea.eos.ubc.ca/storm-surge/forecast.html.

doi:10.1002/2015GL067392.

Rienecker, M.M. et al., 2011: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, **24**, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

Shields, C. A., and J. T. Kiehl, 2016a: Atmospheric river landfall-latitude changes in future climate simulations, *Geophysical Research. Letters*, **43**, doi:10.1002/2016GL070470.

Shields, C. A., and J. T. Kiehl, 2016b: Simulating the Pineapple Express in the half degree Community Climate System Model, CCSM4, *Geophysical Research. Letters*, **43**, 7767–7773, doi:10.1002/2016GL069476.

Soontiens et al., 2016: Storm Surges in the Strait of Georgia Simulated with a Regional Model. *Atmosphere-Ocean*, **54**, 1, 1-21, doi:10.1080/07055900.2015.1108899.

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.

9. It is worth noting that both the Community Earth System Model used by Hagos et al. and a subset of this model, the fourth version of the Community Climate System Model (CCSM4), exhibit unusual changes to subtropical jets when compared to other models (Chang, Guo and Xia, 2012). This in turn may affect some aspects of projected changes to atmospheric rivers. For a more in-depth look at projected changes to atmospheric rivers along the west coast using the CCSM4, see Shields and Kiehl (2016a and 2016b).
10. Atmospheric rivers are defined by the amount of moisture that they transport. This requires setting some fixed threshold for detecting an atmospheric river. In the future, as the atmosphere warms, it can hold more moisture. This means that a weaker type of atmospheric circulation event today that would not be strong enough to transport enough water vapour to qualify as an atmospheric river event may qualify as an atmospheric river event in the future. This is because, though it may not be transporting any more air, the air that it is transporting would contain more moisture. This could be expected to create an increase in atmospheric river frequency. However, such a definition can still be useful, especially if one is interested in impacts, such as flooding, that are principally due to the amount of moisture that is transported.