PCIC SCIENCE BRIEF: A MODEL SIMULATION OF FUTURE OCEANIC CONDITIONS ALONG THE BRITISH COLUMBIA CONTINENTAL SHELF

Recent research, published in the journal *Atmosphere-Ocean*, by Foreman et al. (2014) and Morrison et al. (2014), uses an ocean circulation model for the BC continental shelf to make projections of future ocean conditions for the 2065-2078 period relative to the period of 1995-2008. The authors project that surface temperatures may increase by 0.5 to 2.0 °C, seasonal surface salinity may drop by up to 2 PSS[1] in some areas, and that Haida Eddies will strengthen, as will the Vancouver Island Coastal Current and freshwater discharges into coastal waters.

British Columbia's (BC) coast is a diverse region where the majority of large rivers pour freshwater into fjords, and upwelling deep water from the continental shelf brings nutrients from deep in the ocean that increase the productivity of plankton and, in turn, a variety of other marine organisms. The coast is subject to the heaviest precipitation in the province, as weather systems from the North Pacific Ocean meet the Coast Mountains. Island channels and inshore waters, such as inlets, offer regions that are sheltered from the intense wind and waves that affect the western edges of Haida Gwaii and Vancouver Island. The coast is home to a diverse set of ecosystems, fisheries and more than 70% of BC's population.

The authors of two recent papers in *Atmosphere-Ocean* use a newly developed ocean circulation model for BC's continental shelf to explore how the ocean conditions along the shelf may differ in the 2065-2078 period as compared to 1995-2008. The authors work from an earlier hindcast by Masson and Fine (2012) and use it as a contemporary reference against which the projected changes are com-

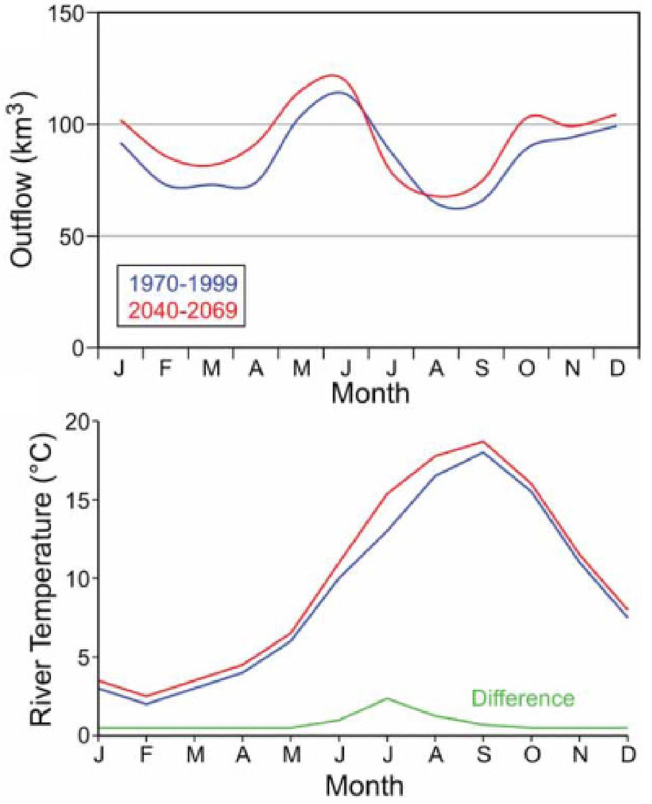

Figure 1: Monthly average freshwater discharge, taken from Morrison et al. (2014).
The above figure shows the monthly average freshwater discharge for the twenty-one watersheds that impact coastal BC waters, from Morrison et al. (2014). The upper panel is the monthly average total outflow for the entire BC coast and the lower panel is the monthly average river discharge temperature.

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1. The Practical Salinity Scale (PSS) employed here uses the ability of sea water to conduct electrical currents (at a given temperature and pressure) as a measure of salinity. Conductivity is used because other methods of measuring dissolved material in sea water, such as evaporating a sample until it dries or chemical tests for the amount of chlorine, are less accurate and more difficult to carry out. On this scale, ocean surface salinity ranges from 0 at river mouths to about 39, with an average of 35. (PSS values lack units because the PSS is based upon a ratio of the conductivity of the ocean water sample to the conductivity of a potassium chloride sample—i.e. the units "cancel out.")
2. For more information on the North America Regional Climate Change Assessment Program, see: http://narccap.ucar.edu.
3. 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, but here a Limited Area Model that is run in a hindcast mode. For more information on the North American Regional Reanalysis, see: http://www.emc.ncep.noaa.gov/mmb/rreanl/.
4. For more information on the Simple Ocean Data Assimilation, see: http://www.atmos.umd.edu/~ocean/.

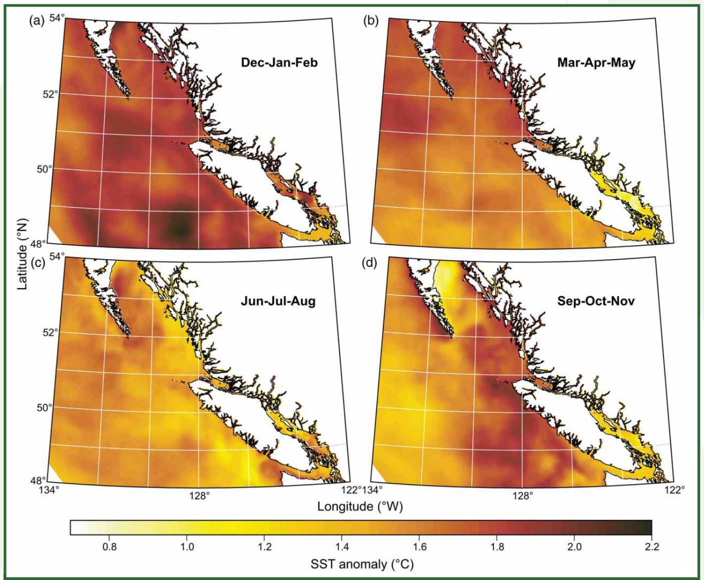

Figure 2: Projected seasonally-averaged sea surface temperature differences (2065-2078 as compared to 1995-2008), from Foreman et al. (2014).

The above figure shows the projected seasonally-averaged sea surface temperature differences for four seasons. For reference, the average sea surface temperature in the region varies from about 11 °C in the Strait of Georgia to 9 °C in the North Coast region.

pared. To run their ocean model, the authors use projections of future climate from a Regional Climate Model-Global Climate Model (RCM-GCM) pairing from the North American Regional Climate Change Assessment Program[2] (NARCCAP), wind data from the North American Regional Reanalysis[3] (NARR), ocean data from the Simple Ocean Data Assimilation[4] (SODA) and tides from the tidal model in Foreman et al. (2000). They also present the differences in the projections for 2040-2069 versus the 1970-1999 period (the time periods used for NARCCAP) for a number of climate variables.

After testing the RCM-GCM pairing from NARCCAP chosen for this research, to make sure that it is representative of the larger ensemble of RCM-GCM pairs available, the authors use a combination of RCM-GCM output and hindcast values from their ocean model as the initial conditions for their experiment. They demonstrate that the RCM-GCM trends over 1970-2069 can be extended to 2078 and then use average RCM-GCM output differences between the 2040-2069 and 1970-1999 time periods to create the future forcings for their 2065-2078 simulation. The authors make this extension to 2078 because they use Masson and Fine's 1995-2008 hindcast as their contemporary baseline.

Surface air temperatures are projected to warm for all seasons and average precipitation increases in winter and decreases in summer. This is mirrored in freshwater discharge, which decreases by up to 10% in June through August, and increases by about 10% for all other months (Figure 1). When the authors' results for the freshwater discharge of the Fraser river watershed are compared with PCIC hydrological modeling results, we find that PCIC's results show changes in discharge in all seasons, whereas Morrison et al.'s results show changes primarily in spring (March-June). Both sets of future projections show an increased snowmelt-driven spring flow. River temperatures are also projected to increase. When compared to the 1995-2008 average, sea surface temperatures for the 2065-2078 period are 0.5 °C to 2.0 °C higher, with less warming during summer months (Figure 2). Projected summer sea surface temperatures do not display cooling from an upwelling of colder subsurface water.

The authors project an overall decrease in surface salinity in the study region. The largest decrease is at the mouth of the Fraser river, where surface salinity is reduced by up to 2 PSS[1], although parts of the west coast of Vancouver Island and the Salish Sea show salinity increases in some seasons. Foremen et al. attribute these increases to changes in the distribution of freshwater plumes[5]. Projected changes to surface density show greater stratification[6] in the winter, which the authors suggest may indicate that mixing from stronger winter winds cannot overcome the stratification from warmer, generally fresher, near-surface waters.

Foreman et al. find that the northward flowing Vancouver Island Coastal Current, which is driven by horizontal differences in water density, shows an increase in strength over the June to August period. The authors attribute this to greater discharge from the Juan de Fuca Strait. The size—and hence, energy—of eddies[7] off the west coast of Haida Gwaii are projected to increase, due to increases in winter winds. Because these Haida Eddies carry nutrients and larvae away from the coast, the authors note that these changes may have ecosystem consequences. Foreman et al. also note that projected increases in wind strength cause increases to the northwesterly component of surface flows over the December to February period. No appreciable changes to the Juan de Fuca Eddy, a large eddy that forms west of the Strait of Juan de Fuca in the summer, are projected.

5. Freshwater plumes are columns of fresh water that flow out over the continental shelf from estuaries and rivers.
6. Stratification refers to the tendency of ocean water to form layers of differing density. Generally, less dense (generally warmer and less salty) water form layers that sit on top of more dense (generally cooler and saltier) water layers in what is known as "stable stratification."
7. Ocean eddies are swirling, circular ocean currents.

The authors find that changes to sea surface levels are higher on the shelf in the winter and spring and lower over the summer. However, thermal expansion effects, global glacial melt contributions and geological processes, such as subsidence are not accounted for in this study. Because of this, figures from the study cannot be taken as projected changes for the BC coast. Instead, they can be seen as the projected contributions that regional changes in ocean circulation may make to future sea level heights.

Methodology

The authors use the output of the Canadian Regional Climate Model[8] (CRCM), which was used to downscale output from the Third Generation Canadian Coupled Global Climate Model[9] (CGCM3). The models are run under the Intergovernmental Panel on Climate Change's A2 emissions scenario[10]. For observational data, the authors use NARR wind data and ocean temperature and salinity data from SODA. The ocean shelf model itself is an application of the Regional Ocean Modeling System[11] (ROMS) model, with a horizontal resolution of 3 km and a vertical resolution that varies with depth and terrain. The authors use Masson and Fine's (2012) ROMS hindcast for the period of 1995-2008 to develop their companion future projection for the period of 2065-2078.

The authors first examine the monthly average surface air temperature and precipitation for the RCM-GCM combination that they choose, in order to confirm that it is representative of the larger NARCCAP ensemble. Then, in order to get the initial conditions, boundary conditions and atmospheric forcing, the authors calculate the differences between the current and future periods, and use these anomalies to determine the trends in all the required forcing and initial fields. They use these trends to arrive at values for the 2065-2078 period and add this to their ocean model's 1995-2008 hindcast values. For monthly winds, the authors examine the RCM-GCM pair's output and determine that, while the wind magnitudes match observations, the wind direction does not. Because the wind direction does not match, the RCM-GCM output would not be able to accurately capture seasonal upwelling. Foreman and colleagues instead use NARR winds and add to them the changes projected by the RCM-GCM combination. This anomaly approach is then used for all forcing and initial condition fields (precipitation, shortwave radiation, cloud cover, etc. as well as temperature and winds) for the ocean model, except tides, for which the tidal model described in Foreman et al. (2000) is used.

Because the ocean model has a higher spatial resolution than the RCM, there are regions which are defined as land in one and ocean in the other. In order to calculate ocean fields at these locations, the authors use a modern statistical analysis method that employs Empirical Orthogonal Functions to generate values for humidity, air pressure and air temperature that are needed to drive the ocean model. Freshwater discharge is calculated from precipitation, temperature and snowpack estimates following Morrison et al. (2011). For the ocean model's western, northern and southern boundaries, ocean conditions were interpolated directly from CGCM3 output.

Finally, the authors compare RCM-GCM output for the 2040-2069 period versus the 1970-1999 period and ocean model output for the 2065-2078 period versus the period of 1995-2008.

Foreman, M.G.G., W. Callendar, D. Masson, J. Morrison, and I. Fine, 2014: A model simulation of future oceanic conditions along the British Columbia continental shelf, Part II: Results and analyses. *Atmosphere-Ocean*, **52**, 1, 20-38, doi:10.1080/07055900;2013.873014.

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Morrison, J., M.G.G. Foreman, and Masson, D., 2011: A method for estimating monthly freshwater discharge affecting British Columbia coastal waters. *Atmosphere-Ocean*, **50**, 1, 1-8, doi:10.1080/07055900.2011.637667.

[8] For more information on the Canadian Regional Climate Model see: http://www.ouranos.ca/fr/programmation-scientifique/science-du-climat/simulations-climatiques/MRCC/eng/crcm.html.

[9] More information on the Canadian Coupled Global Climate Model is available from the Canadian Centre for Climate Modelling and Analysis, here: http://ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=1299529F-1.

[10] The Intergovernmental Panel on Climate Change published a set of emissions scenarios known as the Special Report on Emission Scenarios (SRES) in 2000, in order to provide input for evaluating the consequences of various trajectories of future greenhouse gas emissions. For more information on the these emissions scenarios, see here: http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=23

[11] For more information on the Regional Ocean Modeling System, see: https://www.myroms.org/.