About one quarter of the carbon dioxide (CO$_2$) produced by human activities since the start of the Industrial Revolution (anthropogenic CO$_2$, mostly from fossil fuel burning with much smaller contributions from cement production and land use change) has been taken up by the oceans.\textsuperscript{1} The oceans provide a great service to the planet by slowing down the accumulation of CO$_2$ in the atmosphere, which is the major cause of global warming. However, this additional CO$_2$ is changing the fundamental chemistry of the oceans. CO$_2$ dissolves in the surface water to form carbonic acid, which upon dissociation results in a decrease in pH and the concentration of the carbonate ion, a building block of calcium carbonate (CaCO$_3$) shells and skeletons. Ocean acidification (OA) refers to the decrease in pH and carbonate ion concentration due to the increasing anthropogenic CO$_2$ in the ocean (Figure 1). The upper ocean pH has decreased by 0.1 pH unit (approximately 30 percent increase in acidity) over the past 200 years and is expected to fall an additional 0.3 pH unit by 2100 (approximately 150 percent increase in acidity).\textsuperscript{2} Oceans have not experienced such a rapid pH change for at least the last 66 million years, and possibly the last 300 million years. This raises serious concerns about the ability of marine organisms to adapt. During some of the acidification events in the Earth’s history, selective extinction and slow recovery of some species have occurred.\textsuperscript{3}

Organisms that form CaCO$_3$ shells and skeletons will experience direct impacts because acidity increases the solubility of CaCO$_3$. Both ecologically and economically important organisms in a variety of tropic levels have CaCO$_3$ structures. Some examples of ecologically important organisms are coccolithophores, which are the basis of some marine food chains, pteropods, which are a food source for a variety of northern fish, and warm and cold water corals which provide important habitats for other organisms. Economically

\begin{flushleft}
\textsuperscript{1} C.L. Sabine et al., “The Oceanic Sink for Anthropogenic CO$_2$,” Science 305, no. 5682 (2004): 367–371, doi.org/10.1126/science.1097403.

\textsuperscript{2} K. Caldeira and M.E. Wickett, “Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean,” Journal of Geophysical Research Oceans 110, no. C9 (2005): C09S04, doi.org/10.1029/2004JC002671.

\textsuperscript{3} B. Hönisch et al., “The Geological Record of Ocean Acidification,” Science 335, no. 6072 (2012): 1058–1063, doi.org/10.1126/science.1208277.
\end{flushleft}
important organisms with CaCO$_3$ structures include shellfish such as oysters, mussels, clams, shrimp, lobsters and crabs. Studies of biological responses to OA have been an active research field over the last 10–15 years. These laboratory studies have shown malformation and dissolution of shells of organisms including coccolithophores, pteropods, and oyster and clam larvae in seawater with high CO$_2$, therefore low pH. Biological effects of OA to both CaCO$_3$ and non-CaCO$_3$ organisms have also been reported. Studies have demonstrated decreased survival, calcification, growth, development, and abundance in response to acidification, reproduction and physiology, metabolic rate, depression of immune systems, behavioral change, and taste of shrimp.

Although many organisms with CaCO$_3$ shells and skeletons showed negative effects from OA, some were not affected and others even thrived in acidified water. Given the variable responses of individual types of organisms to ocean acidity, together with other stressors such as warming, deoxygenation, and pollution, it is difficult to predict how whole marine ecosystems respond to climate change and acidification. To investigate marine ecosystem response,

---

4 K.J. Kroeker et al., “Impacts of Ocean Acidification on Marine Organisms: Quantifying Sensitivities and Interactions with Warming,” *Global Change Biology* 19, no. 6 (2013): 1884–1896.

5 S. Dupont, E. Hall, P. Calosi and B. Lundve, "First Evidence of Altered Sensory Quality in a Shellfish Exposed to Decreased pH Relevant to Ocean Acidification," *Journal of Shellfish Research* 33, no. 3 (2014): 857–861.
several studies have been conducted using mesocosms, which mimic future warm and acidified oceans, and studies using natural analogues such as underwater volcanos where CO$_2$ gas is released and natural acidification conditions are formed.

Since CaCO$_3$ shells and skeletons are more soluble at lower temperatures and higher pressures, high latitude and deep water ecosystems will be more vulnerable to the stress of OA. Also, the solubility of gases, including CO$_2$, is higher in cold water than in warm water. Thus, although OA is a global threat, cold waters in Canada may be particularly vulnerable. Ocean acidification also lowers the oceans’ capacity to absorb anthropogenic carbon directly (the solubility pump) and through changes in primary productivity and phytoplankton species composition (the biological pump), providing a negative feedback to climate change.

Ocean acidification is controlled and enhanced by various mechanisms and Canada’s three oceans have distinct drivers (Figure 2). In the Pacific, wind-driven upwelling brings the intermediate depth water, corrosive to organisms with CaCO$_3$ shells and skeletons, to the surface. This upwelling is a natural phenomenon and occurs seasonally. The intermediate water of the Pacific has inherently higher CO$_2$ than Atlantic water due to the accumulation of CO$_2$ produced by microbial respiration. The supplementary addition of anthropogenic CO$_2$ has, however, lowered the pH of this water to a critical level. In the Arctic, the first observations of corrosive surface ocean waters were reported. The Arctic Ocean receives a large amount of fresh water from rivers, seasonal ice melt, and glacial meltwater. This fresh water has little buffer capacity and effectively reduces the pH of Arctic waters. Decreasing ice cover enhances the uptake of

6 U. Riebesell, R.G.J. Bellerby, H-P. Grossart and F. Thingstad, “Mesocosm CO$_2$ Perturbation Studies: From Organism to Community Level,” *Biogeosciences* 5 (2008): 1157–1164, doi.org/10.5194/bg-5-1157-2008.
7 J.M. Hall-Spencer et al., “Volcanic Carbon Dioxide Vents Show Ecosystem Effects of Ocean Acidification,” *Nature* 454 (2008): 96–99.
8 R.A. Feely et al., “Evidence for Upwelling of Corrosive ‘Acidified’ Water onto the Continental Shelf,” *Science* 320, no. 5882 (2008): 1490–1492, doi.org/10.1126/science.1155676.
9 M. Chierici and A. Fransson, “Calcium Carbonate Saturation in the Surface Water of the Arctic Ocean: Undersaturation in Freshwater Influenced Shelves,” *Biogeosciences* 6 (2009): 2421–2432; M. Yamamoto-Kawai et al., “Aragonite Undersaturation in the Arctic Ocean: Effects of Ocean Acidification and Sea Ice Melt,” *Science* 326, no. 5956 (2009): 1098–1100, doi.org/10.1126/science.1174196; L. Robbins et al., “Aragonite Undersaturation in Greater than 20% of Canadian Basin, Western Arctic,” *PLOS ONE* 8, no. 9 (2013): e73796, doi.org/10.1371/journal.pone.0073796.
atmospheric CO$_2$, further accelerating Arctic acidification. In the Atlantic, the effects of corrosive Arctic water, freshwater input from the St. Lawrence River, hypoxic (low oxygen) water in the Gulf of St. Lawrence, and high rates of anthropogenic CO$_2$ uptake in the deep convection region of the Labrador Sea act to enhance OA. Corrosive Arctic water can be traced southwards along the biologically and commercially active shelf region of Eastern Canada. In the St. Lawrence Estuary, acidification is closely related to hypoxia caused by the multi-decadal changes in water mass composition due to circulation. Its pH has decreased from 7.9 in the 1930s to 7.65 by the 2000s, much faster than the global average. Labrador Sea Water (LSW) is formed each year in the Labrador Sea by winter deep convection, subsequently spreading to the intermediate and deep waters of the North Atlantic. LSW is well ventilated and contains high concentrations of anthropogenic CO$_2$. As a result, the pH of the LSW is steadily decreasing.

Ocean acidification in coastal regions exhibits much higher temporal and spatial variability than in open oceans. Seasonally variable freshwater inputs

10 Arctic Monitoring and Assessment Programme (AMAP) (2013), _AMAP Assessment 2013: Arctic Ocean Acidification_ (Oslo: AMAP, 2013).

11 K. Azetsu-Scott et al., “Calcium Carbonate Saturation States in the Waters of the Canadian Arctic Archipelago and the Labrador Sea,” _Journal of Geophysical Research_ 115, no. C11 (2010): C11021, doi.org/10.1029/2009JC005917.

12 A. Mucci, M. Starr, D. Gilbert and B. Sundby, “Acidification of Lower St. Lawrence Estuary Bottom Waters,” _Atmosphere-Ocean_ 49, no. 3 (2011): 206–218, doi.org/10.1080/07055900.2011.599265.
from rivers and glacial meltwater also reflect the local geology, therefore, freshwater inputs affect each coastal region differently. Nutrient input from the land enhances coastal productivity, resulting in increased microbial respiration leading to oxygen depletion and further CO$_2$ production. As a result, ocean acidification is accelerated. In urban coastal areas, emissions of other acidifying gases, such as nitrogen oxides (NO$_x$) and sulfur oxides (SO$_x$), can also contribute to enhanced coastal acidification.

Canada is one of the first countries in the world to experience the adverse impacts of OA. Ocean acidification is likely to alter the structure and function of its marine ecosystems. Hence, fishing industries, subsistence fisheries by Indigenous communities, and tourism will be directly influenced. The results of these changes will threaten economies, especially those directly connected with fisheries, culture, and subsistence of Indigenous peoples and eco-tourism.

Beyond Canadian waters, global food security risks caused by OA and climate change, especially for developing nations, need to be emphasized. Reducing nutrient input to the coastal area, developing new aquaculture practices such as close monitoring of intake water to the hatcheries, and cutting down the emissions of acidic gases such as NO$_x$ and SO$_x$ can help to slow down the progress of local OA and thus manage risks. However, global ocean acidification will inevitably progress further unless the global emission of CO$_2$ resulting in the accumulation of CO$_2$ in the atmosphere is controlled and reduced.

13 K. Azetsu-Scott, M. Starr, Z-P. Mei and M. Granskog, “Low Calcium Carbonate Saturation State in an Arctic Inland Sea Having Large and Varying Fluvial Inputs: The Hudson Bay System,” *Journal of Geophysical Research Oceans* 119, no. 9 (2014): 6210–6220, doi.org/10.1002/2014JC009948.

14 D. Ianson et al., “Vulnerability of a Semi-enclosed Estuarine Sea to Ocean Acidification in Contrast with Hypoxia,” *Geophysical Research Letters* 43, no. 11 (2016): 5793–5801, doi.org/10.1002/2016GL068996.

15 K.A. Hunter et al., “Impacts of Anthropogenic SO$_x$, NO$_x$ and NH$_3$ on Acidification of Coastal Waters and Shipping Lanes,” *Geophysical Research Letters* 38, no. 13 (2011): L13602, doi.org/10.1029/2011GL047720.