Canada's Three Oceans (C3O): A Canadian Contribution to the International Polar Year

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Introduction

The purpose of climate monitoring is to collect relevant, inter-comparable data over sustained periods of time so as to allow quantification of change within a system for decision-making purposes. This is the motivation of the "Canada's Three Oceans" (C3O) project, a Canadian contribution to the International Polar Year (IPY: 2007–2009). C3O aims to (1) build an integrated, consilient view of the physical, chemical and biological oceanic structure of subarctic and arctic waters around Canada; and (2) use this information to establish a sound scientific basis for a long-term arctic and subarctic ocean monitoring strategy. By this strategy C3O will address change within ocean domains, identify gateways and barriers, and investigate the causal mechanisms, consequences and stability of frontal boundaries separating juxtaposed ocean domains. C3O will thus establish a 'climate change fence' around all of Canada's three oceans that will allow scientists and policy-makers alike to have the data and understanding upon which to practice good governance, and to deal with emerging issues such as warming, species invasion, hypoxia and acidification.

The challenge of keeping watch on the waters around Canada is as immense as it is pressing; Canada has the longest national coastline (~230,000 km) in the world, over half of which (140,000 km) lies in the Arctic. Changes within the ice-cover, water column and ecosystems of Arctic Canada are inextricably linked to the global system in general and to the bordering subarctic Pacific and Atlantic in particular. It is within this high-latitude domain that the consequences of global change and climate variability are expected to be biggest and fastest.

Two facts, however, provide a toehold for meeting the C3O goals. First, the three oceans that border Canada are inter-connected by water masses flowing from the subarctic Pacific to the Arctic and then into the subarctic Atlantic, and this ocean 'continuum' offers a conceptual framework for integrated, climate-scale observations. Second, two science-capable icebreakers of the Canadian Coast Guard already carry out programs that, together, encircle Canada and follow these through-flowing water masses and their associated biogeography. These existing missions offer a logistical framework to support ancillary science programs. Spatial variability can be observed along ship transits (totalling more than 12,000 km in length) that serve to integrate measurements on climatic and macro-ecological scales, while temporal variability is then recorded by year-round moorings at key sites. The basic concept has been tested over the past decade, and the value of repeat hydrography is proven (*e.g.*, Grebmeier *et al*., 2006).

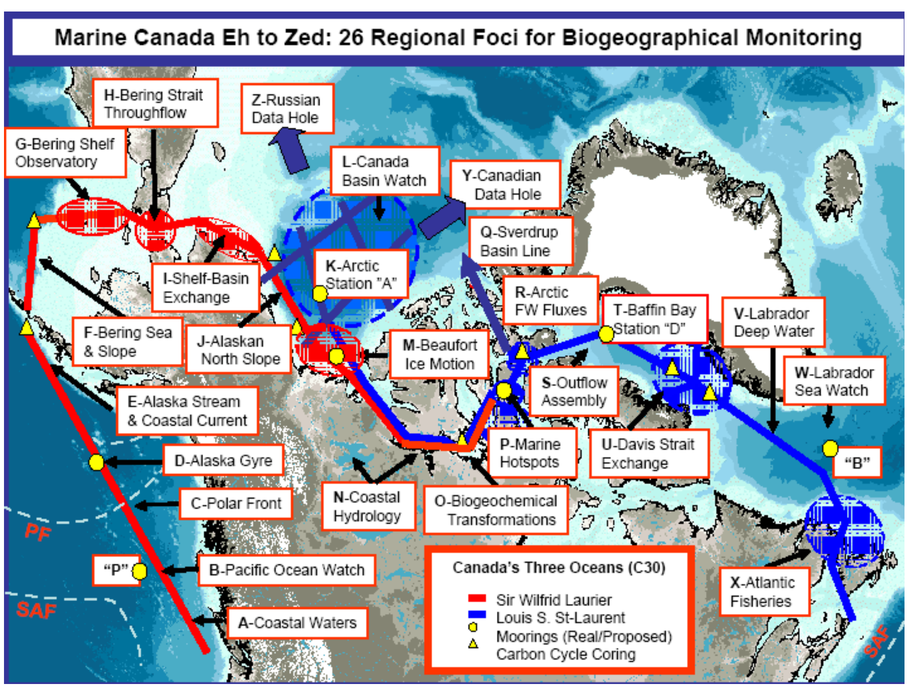

Fig. 1 Map of oceanographic stations occupied by C3O in 2007 by the CCGS Sir Wilfrid Laurier *departing from Victoria in the west and CCGS* Louis S. St-Laurent *departing from Dartmouth in the east. Letters are explained in the text.*

The scientific basis

Two lines of logic underpin the C3O effort. The first is that both observational and modelling results suggest that the major impact of climate change on the marine system will be the re-distribution of oceanic boundaries and habitats/biomes, and this dictates the need to carry out times series observations over very broad spatial domains. The scientific basis for this statement is laid out in the seminal work of Sarmiento *et al*. (2004) who used satellite data and coupled models to classify the major biomes of the global ocean, to identify their diagnostic properties, and to predict the consequences of climate warming. The second line of logic supporting the C3O strategy is that the oceans surrounding Canada are both geographically and dynamically inter-connected, and they share the common trait of permanent salinity stratification. The statement comes out of work of Carmack (2007) who noted that the global patterns of moisture transport and ocean circulation result in thermohaline distributions that force a 'downhill journey' of low salinity waters from the North Pacific to the Arctic and then into the North Atlantic. The Arctic Ocean – itself – acts as a double estuary, whereby waters entering from the North Atlantic become either denser through cooling (negative estuary) or lighter by freshening (positive estuary) as they circulate within the basin and then return to the North Atlantic as a variety of components of the ocean's thermohaline circulation (Aagaard and Carmack, 1989; Yamamoto-Kawai *et al*., 2006).

Study components

C3O is comprised of repeat transects to collect data along sections spanning the subarctic Pacific, Arctic and subarctic Atlantic (**Fig. 1**). The need for observations of contiguous domains that link to the climate scale is discussed briefly in Carmack and McLaughlin (2001). Along these tracks, specific sites or benchmarks are identified to address specific eco-domains and emerging issues. Special focus is placed on quantifying ice and ocean changes in the Canada Basin through a joint U.S./Canada/Japan study called the Beaufort Gyre Exploration Project (BGEP; see McLaughlin *et al*., 2004).

Conceptually, transects are divided into three parts: subarctic Pacific, Arctic and subarctic Atlantic (**Fig. 2**). The CCGS *Sir Wilfrid Laurier* carries out the subarctic Pacific line, the CCGS *Louis S. St-Laurent* carries out the subarctic Atlantic line, and both ships share Arctic assignments. Measurements include: (1) CTD/Rosette casts (with sensors for temperature (T), salinity (S), transmissivity, fluorescence, nitrate, oxygen and photosynthetically-available radiation); (2) water sampling for salinity, dissolved oxygen (O_2), nutrients (NO_3, NH_4, PO_4, and SiO_3), the dissolved and particulate carbon, dissolved and particulate nitrogen, ^{18}O, barium, CFCs and a suite of geochemical tracers, including ^{129}I and ^{137}Cs; (3) Rosette-mounted 300-kHz Lowered Acoustic Doppler Current Profiler (LADCP); (4) Lowered Deep-Sea Camera; (5) underway seawater pumping to obtain continuous observations of near surface (~5 m) water properties, including T, S, O_2, N_2, CO_2, CH_4 and fluorescence; (6) underway dual frequency (100 and 200 kHz) acoustic backscatter system; (7) an Underway Acoustic Doppler Current Profiler (UADCP); (8) expendable (X) profiling sensors (XBTs and XCTDs) and/or Underway (U) UCTD deployments are made at ~20 km spacing to increase resolution; (9) discrete sampling for abundance, bio-diversity and phylogeography of prokaryotes (virus and bacteria), picoplankton, nanoplankton and phytoplankton; (10) phytoplankton distributions by taxonomy and estimates of primary production and nutrient uptake dynamics by on-board incubation; (11) descriptions (distribution, taxonomy, abundance, stable isotope signatures, fatty acid content, genetics and growth rate) of zooplankton using vertical net hauls; (12) sampling of macrobenthic communities on the Canadian Arctic seafloor by benthic sampling and still and video photography; (13) underway observations of marine birds and mammals; (14) ship-based sampling; mooring deployments have been carried by partners WHOI, JAMSTEC, and CRREL.

Core observations in 2007: Marine Canada from A to Z

Over 120 CTD/R stations along approximately 15,000 km of ship track were occupied in 2007 during five separate legs involving the two ships and over 90 science personnel. In 2007, the Food Web Team worked aboard the CCGS *Louis S. St-Laurent*, while box coring was done aboard the CCGS *Sir Wilfrid Laurier*; the reverse is planned for 2008. Northern community consultation and outreach was carried out under the direction of DFO's National Centre for Arctic Aquatic Research Excellence (N-CAARE) [Schimnowski and Williams, leads].

A cartoon, corresponding to the map in Figure 1, depicts the 26 regional benchmarks *en route* clockwise around northern North America from Victoria to Halifax (**Fig. 2**). The matching sections of temperature, salinity, dissolved oxygen and chlorophyll fluorescence are shown in **Fig. 3**. Benchmarks are as follows: **A** identifies British Columbia coastal waters, an important habitat for Pacific salmon; **B** passes near Ocean Station "P", an icon of long-term time series; **C** crosses the Polar Front into **D**–the Gulf of Alaska gyre, characterized by a shallowing of the pycnocline, nutricline and hypoxic waters; **E** crosses the Alaskan Stream (AS) and Alaska Coastal Current (ACC), major freshwater (FW) transport corridors; **F** follows the flux of FW from the Pacific into the Bering Sea and the upwelling of nutrient-rich waters onto the slope and shelf; **G** crosses the Bering Sea shelf and near-bottom 'cold pool'; **H** is Bering Strait, the gateway of low salinity Pacific water into the Arctic Ocean; **I** is the Chukchi Sea, a site for production of cold halocline waters (HC) that drain into the Arctic Ocean via Barrow Canyon; **J** is the Alaskan North Slope coastal current connecting U.S. and Canadian coastal ecosystems; **K** is Arctic Ocean Station “A”, a times series maintained off and on since 1987; **L** is the Beaufort Gyre, the FW flywheel of the Arctic Ocean, in support of the Beaufort Gyre Exploration Project (BGEP); **M** denotes the ongoing monitoring of ice thickness and drift on the Canadian Beaufort Shelf; **N** is the coastal hydrology of the Canadian Beaufort Shelf and Arctic Archipelago, including lake and river characteris-tics; **O** represents physical and biogeochemical changes as ice and seawater (residence time ~ 5–10 years) transit the Canadian Arctic Archipelago; **P** represent various biological ‘hotspots’ *en route*, such as Bellot Strait, Gulf of Boothia and Barrow Strait, where physical processes produce and concentrate food for top predators; **Q** is the transit north across the poorly explored Sverdrup Basin; **R** is Arctic FW outflow through northern archipelago passages in support of CATS (Canadian Archipelago Through-flow Study) and ASOF (Arctic–Subarctic Ocean Fluxes) objectives; **S** is the “assembly” in northern Baffin Bay of Arctic outflow waters from Nares Strait (NS), Lancaster Sound (LS) and the West Greenland Current (WGC); **T** is Baffin Bay and its isolated deep water; **U** is Davis Strait and the

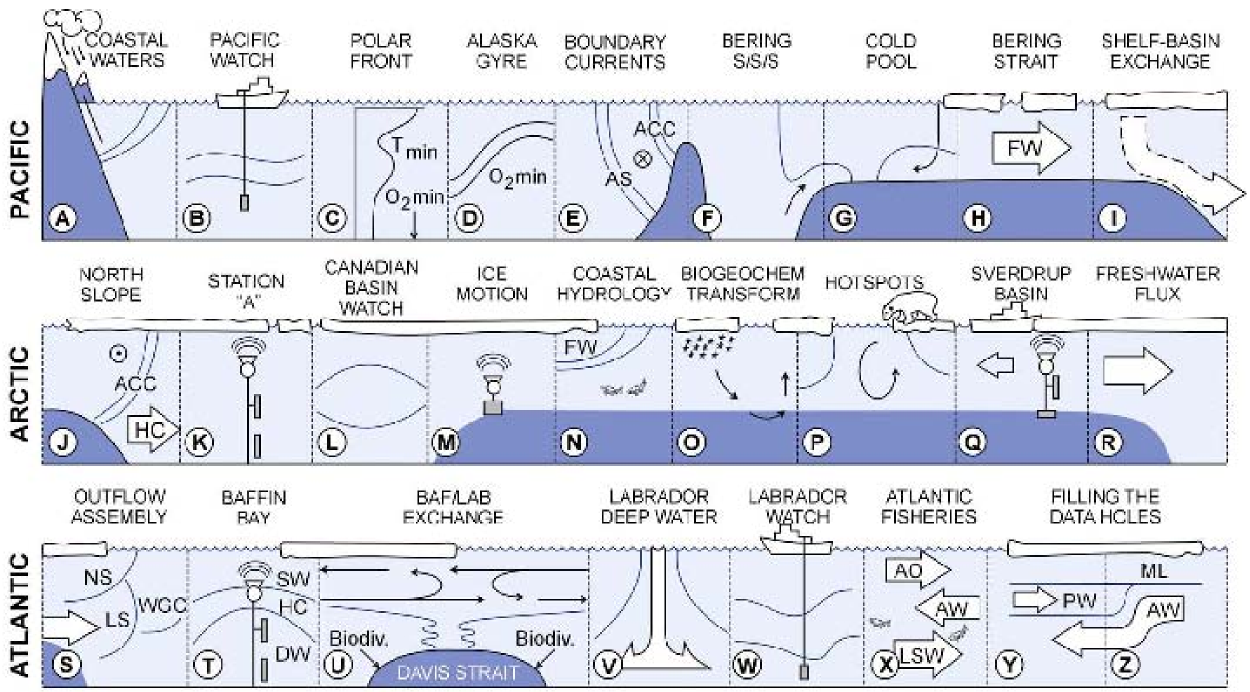

Fig. 2 *Cartoon showing regional benchmarks along the C3O transect from the Pacific to the Atlantic via the Arctic. Letters and abbreviations are explained in the text.*

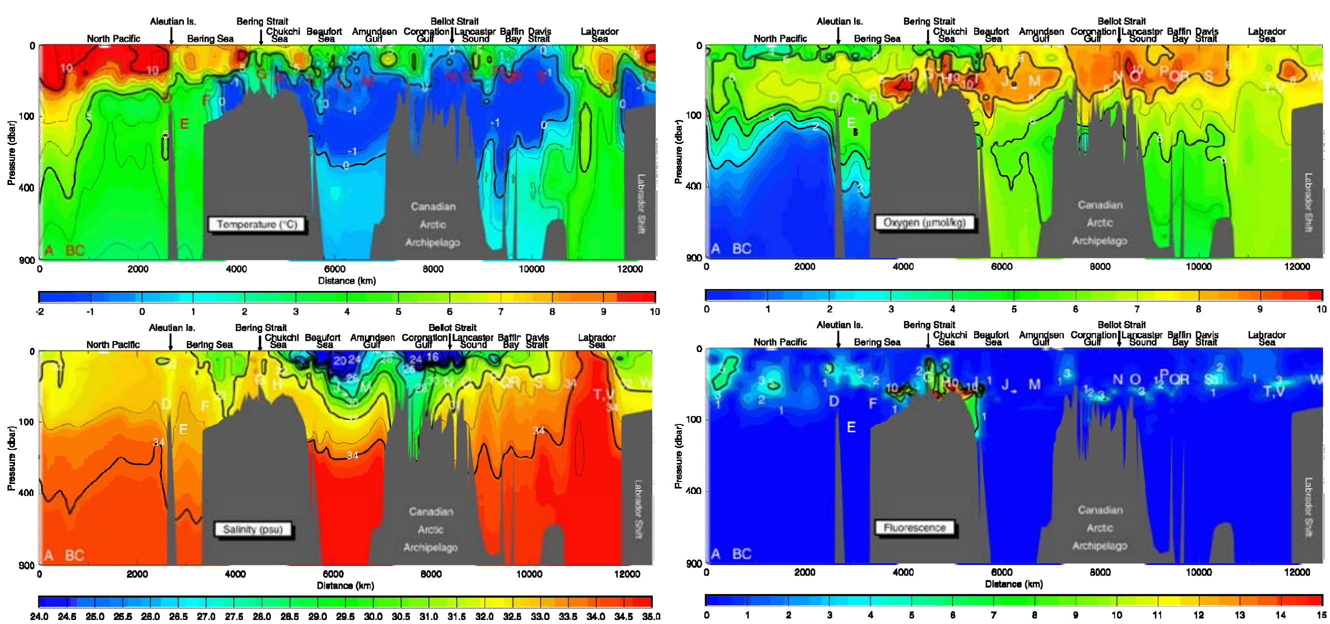

Fig. 3 *Sections of temperature (top left), salinity (bottom left), dissolved oxygen (top right) and fluorescence (bottom right) along the C3O section from Victoria to Halifax (left to right). Letters are defined in the text.*

bifurcations in the Baffin/Labrador and West Greenland currents, and the export of Arctic outflow waters; **V** is deep convection in the Labrador Sea; **W** passes near Ocean Station "B", another time-series icon; **X** represents the influence of arctic-derived waters on the physical habitat of the North Atlantic fisheries. Not shown above, but proposed, are hydrographic lines extending into the Canadian Hole (**Y**) and the Russian Hole (**Z**) of the Canada Basin where very little data exist and where the ice is quickly melting.

Summary

In 2007, C3O explored marine Canada from the surface to the seabed, from the smallest (virus) to the largest (whales) organisms, and from the Pacific to the Arctic to the Atlantic. Further, C3O is the only observationally-driven IPY project that shows the inter-connectedness of arctic and subarctic domains and how such domain boundaries may be affected by a changing climate. And while C3O is an IPY effort (2007–2011), its full scientific and social value will be realized when extended into the future – to 2050 and beyond – the time scales of social relevance as seen by international panels such as the Intergovernmental Panel on Climate Change and the Arctic Climate Impact Assessment. The requirement for a national commitment to a sustained, observationally-based ocean climate program is demonstrated by the uncertainties in climate model predictions, and a program to continually gauge, refine and update the real progress of change is urgently needed. Within the decade Northern Communities must be empowered to conduct as much marine monitoring as is possible. It is thus hoped that a major fraction of C3O monitoring methods will be turned over to local coastal communities and carried out by northern residents, following a community-based scientific franchise model.

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