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Assessing Drift and Dispersion in Models of the St. Lawrence Estuary

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– By Donovan Allum –

1. Introduction

The largest estuary in the world is the St. Lawrence Estuary and connects the - aptly named - St. Lawrence River to the Gulf of St. Lawrence and then the Atlantic Ocean. The river begins at Lake Ontario, passing important landmarks such as Kingston, Montreal, Trois-Rivières and Quebec City before emptying into the Gulf of St. Lawrence near the Gaspé Peninsula.

In 2020, 227 surface drifters (no deeper than 5 m) were released in the St. Lawrence Estuary, north of Rimouski, Quebec (Figure 2(a)) and continued downstream into the gulf of St. Lawrence, past Anticosti Island (Figure 2(b)). Most of the drifters were supplied by The Marine Environmental Observation, Prediction and Response Network (MEOPAR) and Réseau Québec Maritime (RQM). Additional drifters were provided by the Department of Fisheries and Oceans (DFO). The main goal of this experiment was to produce data to enable researchers to study drift and dispersion in the estuary for particles suspended at or near the surface with applications to search and rescue and environmental disturbances (like oil spills). There are approximately 2000 search and rescue incidents per year in the Maritime Rescue Sub-Centre (which includes the St. Lawrence Estuary). CBC also reports 334 oil spoils between 2002 and 2012 in the St. Lawrence River. As such, understanding drift and dispersion is of practical importance to the region.

Figure 1: Photo of several drifters just after they were dropped into the St. Lawrence Estuary during the 2020 release experiment. Photo provided by Cédric Chavanne, Oceanographer at UQAR.

The drifters tracked location versus time data, producing a large data set of particle trajectories freely floating down the estuary. Figure 2(b) shows the observed drifter paths of all 227 drifter trajectories that we used in our research. It would be ideal to release the drifters at or near the same time, but a project of this size on the estuary made this goal unfeasible. As a result, the bulk of the drifters were released gradually over 20 days, with several released even up to 50 days after the initial drop. This naturally complicates the project because we will be comparing drifters with different release positions and times.

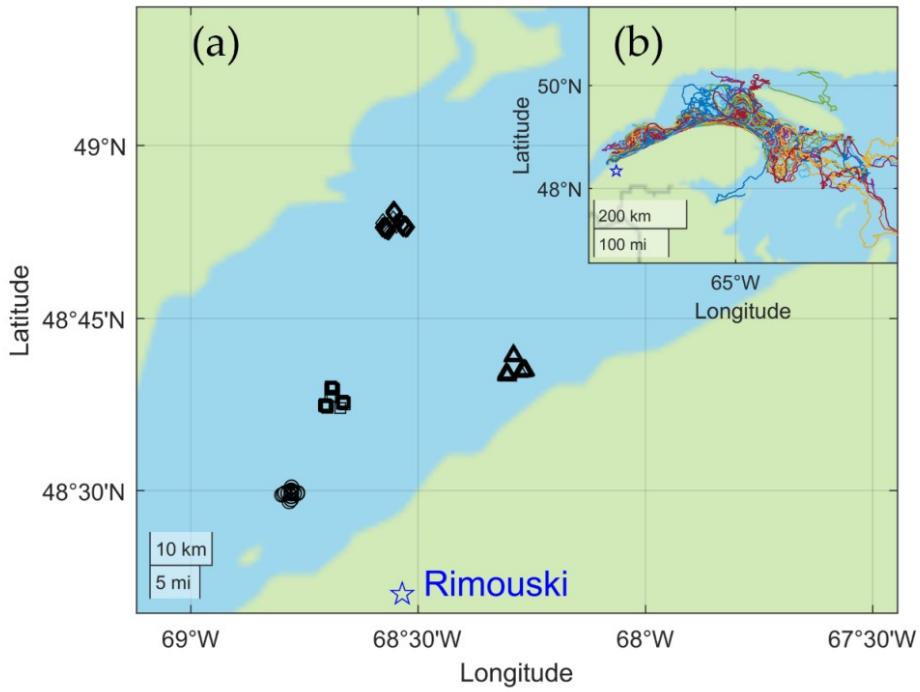

Figure 2: Preliminary data of the 227 drifters released as a part of the 2020 TReX project. (a) Initial drifter release position and configuration. (b) All 277 observed drifter paths in the St. Lawrence Estuary and into the Gulf of St. Lawrence.

My personal main area of research is the study of high-resolution simulations of hydrodynamics in cold water (i.e., water near the density maximum). This research seeks to create simulations that resolve all the scales of motion, from the largest to those at which dissipation takes place. Any study of a geographic region like the Gulf of St-Lawrence, cannot hope to resolve all scales of motion. Processes that occur below or near the grid scale are known as subgrid scale processes and they require parameterization to approximate their effect of these processes at the larger, resolved scales.

Due to the necessarily coarse resolution of these models, along with the probably imperfect parameterizations, modellers are always looking for methods to verify the accuracy of their models. Thanks to funding from MEOPAR and RQM, I was able to work on a project on field scales, more or less tangentially to my main area of research. The main goal of this project is to evaluate a particular measure of particle dispersion and assess the ability for models currently in use by the Government of Canada to predict drift and dispersion in the St. Lawrence Estuary.

Along with my PhD Supervisor Marek Stastna, we collaborated on this project with four employees of the Federal Government of Canada. Nancy Soontiens and Simon St. Onge-Drouin from Fisheries and Oceans Canada, and Christopher Subich and Graig Sutherland from Environment and Climate Change Canada. Regular meetings and discussions, both philosophical and practical, were instrumental to the success of this research.

2. Methods Used

There are many approaches and quantities that researchers use to attempt to quantify dispersion on different length scales. The simplest starting point considers single particle statistics, but this has two key drawbacks: (1) it cannot deal with particles released at different times, and (2) it does a poor job to quantify the spread of many particles, like in an oil spill. For this reason, the bulk of our work concentrated on the evolution of particle pairs.

The most natural quantity for studying particle pairs is known as the relative dispersion. If x_i is the position of the i'th particle at time t, then the relative dispersion is

$D(t) = \langle (x_i - x_j)^2 \rangle (t)$ **(1)**

where the angled brackets indicate an average over all particle pairs. In layman's terms, we quantify dispersion by analyzing the average, squared (so that it remains positive) particle-pair separation distance as a function of time. This measure is imperfect as well because it is an average over time and hence does not consider whether two particle pairs may be experiencing very different features of the flow, such as an eddy near a headland, that may be systematically moving particles.

Nevertheless, a similar quantity allows for a mathematical algorithm that quantifies separation across scales by averaging times at fixed distances instead of distances at fixed times. The process begins by setting a smallest separation distance, and defining larger and larger distances, each time multiplying by a scaling factor r. The algorithm computes what are called exit times (labelled T_i), or the times it takes for the separation distance to increase from one value to the next larger value. This is done for each particle pair, for each pair of separation distances and the exit time is averaged over all relevant particle pairs.

Of course, not all particle pairs achieve the largest distances, but the large number particles in our study made this a robust calculation. Finally, the so-called Finite Scale Lyapunov Exponent (FSLE) is defined

$\lambda_i = [\ln \ln (r)] / [\langle T_i \rangle]$ **(3)**

The FSLE, λ_i, is a unique measure of dispersion because it can take discrete modelled or physical particle trajectory data and produce effective exponential separation rates. Even further, this quantity is useful to researchers because if λ_i obeys a power law according to $D^{-\alpha}$ (where D is the separation in km and α>0 is a constant), it can be argued that the relative dispersion scales as $2t^{-\alpha}$, where the parameter can depend on the separation scale. If i can be divided into regimes where α must take on different values, then it is often used to define dispersion regimes, where different phenomenon dominate separation on different scales.

The results from two numerical models were considered for this project. The first is the Coastal Ice-Ocean Prediction System (CIOPS-E). This model is a 1/36-degree model (2.5 km is a representative value) which extends from the St. Lawrence Estuary to the North Atlantic Ocean. The second model is the Gulf of St. Lawrence Ocean model (GSL). This model has a resolution of 500 m. Both models are coupled with an atmosphere model which interacts with ocean model to determine the modelled ocean currents.

Model particle trajectories starting in the same positions as in the TReX project (Figure 2(a)) were produced by collaborators Soontiens and Sutherland. These were subsequently used to compute FSLE.

3. What We Found

For each model and the observed drifter paths, we calculated the FSLE over length scales of 0.1 km to 100 km with *r*=1.5 (Figure 3). It is presented in this Figure on a log-log scale because if the FSLE behaves as a power-law like $D^{-\alpha}$, then the FSLE will be a straight line on a log-log scale. Different slopes define different dispersion regimes. There are three main observations to make about Figure 3: (1) the FSLE of the observations is approximately constantly in slope, (2) both models produce smaller FSLE in magnitude and shallower slopes than the observed FSLE at small length scales, and (3) both models produce similar slopes and magnitude compared to the observations at large length scales.

The consistent slope of the observations suggests that the separation rate is consistent on all scales considered and the entire estuary - over the scales considered - is in a single dispersion regime. In other words, the average drifter pair at a length scale of 0.1 km is separating in a similar manner to the average drifter pair separated by 50 km. This is a surprising statement for two reasons. Firstly, many features of the flow are wildly different on 0.1 km and 100 km separation scales. Secondly, unlike in the open ocean - where the FSLE is most often used – the estuary is bounded by the shore at ~40-50 km. We expected changes to the FSLE to occur at length scales corresponding to features in the estuary currents and near the estuary width.

Both numerical models exhibit smaller FSLE - and hence, longer exit times - at small length scales compared to the observed FSLE. The slopes are consistent between models and shallower than their observed counterparts. The GSL model produces larger FSLE in magnitude than the CIOPS-E model. This is a really interesting difference between the two models which is likely caused by the difference in resolution. Determining the source of this difference could be an interesting avenue for future research.

The standard interpretation of the shallower slope in both models is that dispersion is different at small scales in the models than it is for physical drifter pairs. This is unsurprising that there is a difference in some kind, in part because some of these length scales are below the grid resolution of the models. It is, however, surprising that the models systematically produce smaller FSLE, and hence longer separation times. Due to some complicated details about how the modelled trajectories were obtained, it is possible for modelled drifters to occupy space between grid points allowing for separations below the grid spacing (indicated by the vertical dashed lines in Figure 3 for each model).

Information about how the models will handle dispersion at length scales below the grid resolution is important because real phenomenon like oil spills or search and rescue situations happen on scales below 1 km. According to the FSLE in Figure 3, the models significantly underestimate the separation rates at small scales. This would be especially problematic in a search and rescue operation where it is imperative to define a search region based on a theoretical maximum distance that a floating object could have drifted following an accident or crash.

At large length scales, the FSLE of the models behave very similarly, matching the observed FSLE in slope and magnitude quite well. Except for the dip near 70 km. It is not surprising that the dispersion would behave similarly at larger length scales. It is generally agreed that at large enough length scales, ocean models should accurately reproduce reality. This is known as an "effective resolution", distinct from the true resolution which is determined by the grid spacing. An effective resolution depends on the phenomenon being measured.

Where the comparison between models is most interesting is between the smallest and largest length scales, and how the two models transition from disagreement to near agreement with the observations at large scales. The GSL model transitions to match the observations - in slope and magnitude - at a smaller separation scale than the CIOPS-E model. It may be possible to use the FSLE to estimate an effective resolution of each model for dispersion. From Figure 3, a reasonable estimate of the effective resolution would be 2-3 km for the GSL model and 10-20 km for the CIOPS-E model. By this measure, the GSL model requires 2-3 km separations before dispersion is accurately captured. Similarly, for the CIOPS-E model.

Figure 3 also includes 99% confidence intervals for each data set which shows the robustness of this measure applied to this data set.

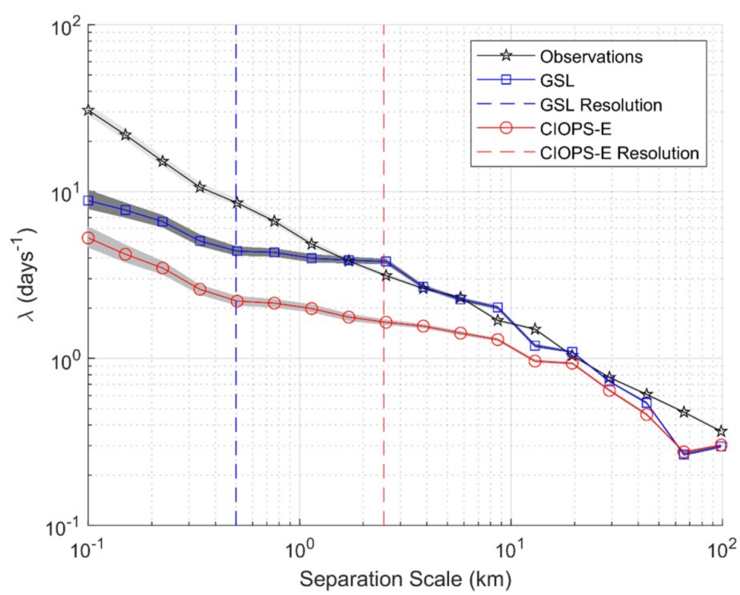

Figure 3: The FSLE calculated from the observed drifter paths, the GSL model paths and the CIOPS-E model paths. The grid spacing (smallest directly resolved length scale) for each model is indicated by vertical dashed lines, identified in the legend. Shaded regions define the 99% bootstrapped confidence intervals.

4. Conclusions

We were able to take the observed particle trajectories and compress them into a single line plot using the FSLE algorithm that converted separation distances between particle pairs into effective exponential separation rates. Through the use of a 99% bootstrapped confidence interval, we demonstrated that this calculation is robust despite the fact that drifters were released over a long period (as long as 50 days) and non-uniformly about the estuary.

We then calculated the FSLE for the GSL and CIOPS-E models with drifters released from the same locations as the observed drifters. We found that at small length scales, the modelled FSLE differed from the observed FSLE with a small magnitude and shallower slope. At larger length scales both models more accurately with the observations.

What does this mean for search and rescue or oil spill response teams who use these models? Real drifters are separating from each other more rapidly than modelled equivalent. It is unsurprising that there would be differences at length scales below the modelled resolution, but this result specifically argues that the models are predicting dispersion that is significantly slower than reality at small length scales which are most relevant immediately after a spill or crash. For a more complete and technical analysis of these results, our team is currently working on a paper which will be submitted this year.

Donovan Allum *is a 3rd year PhD student at the University of Waterloo in Applied Math. His main area of research is high resolution fluid mechanical simulations below the temperature of maximum density. He started work on this project in May 2021 and hopes to publish this research soon.*

Ship with a soul: a brief history of CSS/CCGS Hudson (1963-2022)

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– By Donald Gordon –

After serving the Canadian oceanographic community with distinction for almost sixty years, the CSS/CCGS *Hudson* is being retired. Her history and that of the Bedford Institute of Oceanography (BIO) are closely intertwined and in many ways *Hudson* has been an international symbol for marine research in Canada.

After World War II, there was a growing interest in oceanography around the world and it soon became a high priority of the Canadian federal government. In 1958, plans were announced by the Department of Mines and Technical Services (DMTS) to create BIO in Dartmouth, NS. Soon after, plans were also announced by DMTS to build a new oceanographic research vessel to be based at BIO. The driving force behind both these undertakings was Dr. William E. van Steenburgh.

The new vessel was designed by the marine engineering firm of Gilmore, German and Milne in Montreal with the capability of working in the North Atlantic and adjacent arctic waters. It was only the second oceanographic ship designed and built in Canada, the first being CSS *Baffin* launched in 1956. She was built by Saint John Shipbuilding and Drydock, Ltd. in Saint John, NB, at a cost of $7,500,000, and named after the early arctic explorer Henry Hudson. *Hudson* was launched in May 1963 and, after sea trials, arrived at BIO in December 1963, a wonderful Christmas present. She was formally commissioned in February 1964 by the Honourable Paul Benedickson, Minister of DMTS.

Hudson arriving at the Bedford Institute of Oceanography for the first time in December 1963.

Upon arrival at BIO she joined the existing fleet of research vessels which consisted of CSS *Acadia*, CSS *Kapuskasing*, CSS *Baffin*, CSS *Maxwell* and CNAV *Sackville*. Most of these were hydrographic vessels and only the CNAV *Sackville* was devoted to oceanographic research. At that time, BIO had only about fifty professional and technical staff belonging to the Canadian Hydrographic Service (CHS), the Atlantic Oceanographic Group (AOG) of the Fisheries Research Board (FRB) and the newly created Marine Sciences Branch (MSB). They were thrilled to have a brand new state-of-the–art oceanographic vessel available for their use. This was a period of growth and both staff and programs at BIO expanded rapidly over the ensuing decade.

Hudson was well designed for her purpose. Her many features included a diesel electric propulsion system with two fixed blade propellers and bow thruster, an antiroll system for stability, numerous wet and dry laboratories, open deck working areas fore and aft, numerous winches and cranes for handling all kinds of oceanographic equipment while underway and on station, a helicopter deck with hanger and hydrographic launches. Many improvements were made over the years as programs and equipment evolved. In addition, *Hudson* provided excellent accommodations for 28 scientific staff which allowed multidisciplinary programs to be carried out on a single cruise. She was also well served over her entire career by excellent officers and crew. With the exception of some possible seasickness the first few days out, going to sea on *Hudson* was a pleasure for Canadian oceanographers.

It soon became evident that *Hudson* possessed outstanding sea kindliness and station keeping ability. She was able to operate effectively under extreme conditions, including in ice, and was ideally suited for winter work in the North Atlantic. This was partly due to the curved shape of her hull that afforded a more gentle passage over steep waves. With her extensive cruising range, she was capable of working anywhere in the world's oceans. She quickly developed the reputation of being one of the best oceanographic vessels in the world and became the envy of other oceanographic institutions.

From 1963 to 1996, Hudson was managed by the BIO Ships Division under the responsibility of the science director. She was designated as the Canadian Science Ship (CSS) *Hudson* and painted white, the traditional colour of oceanographic research vessels. She was operated by a single crew who were at sea most of the time between April and December. Then, as the result of a major DFO reorganization in 1996, the operation of *Hudson* was transferred to the Canadian Coast Guard and she became known as the Canadian Coast Guard Ship (CCGS) *Hudson*. She was subsequently painted red like other Coast Guard vessels but was still programed exclusively for oceanographic research. This transfer resulted in the introduction of the layday system for crewing. There were now two crews who served a month on followed by a month off which resulted in a significant boost to shipboard morale.

Although based at BIO, *Hudson* was used throughout her career by the entire Canadian oceanographic community. Principal non-BIO users included the DFO Maurice-Lamontagne Institute, the DFO Northwest Atlantic Fisheries Centre, Dalhousie University, McGill University and the University of Quebec. Many cruises included international collaborators. Except for the last few years, she spent an average of 200 days at sea each year and over her entire career carried out over 500 research cruises. It is estimated that she steamed approximately 1,700,000 nautical miles in support of science which is equivalent to about 78 times around the world! While most of her work was done in the North Atlantic and Canadian Arctic, she also worked in the Caribbean Sea, South Atlantic, Antarctic and North and South Pacific. In her travels she made port calls in 17 other countries. During the Hudson 70 expedition, she became the first ship to circumnavigate the Americas and, in 1981, she circumnavigated North America which included traversing the Panama Canal. Hence, she made two successful passages through the Northwest Passage, each by a different route. Except for her later years, she was very much an international traveller.

Over her lengthy career, *Hudson* supported research in all the major oceanographic disciplines in Canada's three oceans. Her work initially focused on understanding basic properties and processes of the ocean and underlying seabed/bedrock. In later years, it expanded as Canadian research priorities evolved to include more applied topics such as marine resource development, the impacts of human activities on marine ecosystems, ocean monitoring and marine management.

Hudson somewhere up north in the ice

Marine engineering projects focused on testing a wide range of new oceanographic equipment under development at BIO which when proven was extensively used on subsequent cruises. Although designed primarily for oceanography, *Hudson* was also well suited for hydrography and in her early years conducted numerous hydrographic surveys in Canadian waters in support of navigational chart production. While traversing international waters, she routinely collected bathymetric data for the General Bathymetric Chart of the Oceans program (GEBCO). In more recent years she also was used to collect hydrographic data in support of efforts to extend Canadian territorial limits under the United Nations Convention on the Law of the Sea (UNCLOS).

Hudson was well used by geophysicists and geologists. Extensive geophysical surveys of oceanic crust measuring bathymetry, gravity, magnetism and seismic properties were conducted in many locations but with particular focus on the Mid-Atlantic Ridge, off Atlantic Canada and in the eastern Arctic. The results had many applications including understanding the dynamics of plate tectonics and continental drift and helping to pave the way for the development of the Canadian offshore oil and gas industry. Geologists used *Hudson* to study the seabed and subsurface in environments ranging from coastal bays to abyssal depths using a wide variety of sampling and observation tools. This information was used to develop detailed maps of seabed properties and processes and contributed to increasing the understanding of geological history, sediment transport, seabed stability and geohazards. The results, including numerous maps, had many important applications and were used extensively by industry and government.

Hudson was also extensively used by physical oceanographers to make fundamental contributions to the understanding of ocean circulation in Canadian waters and the global ocean. Much of this work concentrated in the North Atlantic and the Labrador Sea which is an important site for deep water formation during the winter months. Early work used bathythermographs and Knudsen bottles with reversing thermometers to measure water properties at discrete depths but these were later replaced by electronic instrumentation which measured conductivity and temperature with depth (CTDs), thereby allowing the profiling of the entire water column. Over her career, *Hudson* was used to deploy and retrieve an extensive number of current meter moorings in both shallow and deep water. She made major contributions to the World Ocean Circulation Experiment (WOCE) and was used to deploy numerous profiling floats as part of the international Argo program. The results of this research had many important applications including global climate studies, offshore industries and fisheries management. *Hudson* was also used to study the properties and dynamics of ice.

Hudson with new Coast Guard colours after transfer

Chemical oceanographers also made good use of *Hudson* to measure the concentration, distribution and dynamics of important chemicals in seawater and sediments in environments ranging from coastal waters to abyssal depths. These included hydrocarbons, nutrients, trace metals, organic carbon and components of the carbonate system. The results contributed to increasing the understanding of marine pollution and the impacts of human activities on ocean chemistry over time, including ocean acidification.

Hudson was also well used by biological oceanographers to study phytoplankton, zooplankton and benthic organisms in a wide variety of environments. A diverse array of sampling equipment was used to determine the species diversity, abundance, distribution and productivity of marine organisms. This work included the first biological oceanographic observations in the eastern arctic and the assessment of benthic communities in previously unstudied regions. Major contributions were made to international programs such as the Joint Global Ocean Flux Study (JGOFS). *Hudson* was also used to study the distribution of seabirds and whale migration. The results of this research had many applications, including understanding the effects of changes in ocean climate on marine ecosystems, fisheries and environmental management. Her work identifying sensitive seabed ecosystems played a major role in the creation of numerous protected areas closed to fishing activities such as The Gully Marine Protected Area (MPA), the coral closures in the Northeast Channel and the Stone Fence at the mouth of the Laurentian Channel and the closures in NAFO areas outside Canadian jurisdiction.

Numerous programs were run using *Hudson* to measure the impact of human activities on the ocean environment. One international study examined the feasibility of disposing radioactive wastes in deep water sediments on the Sohm Abyssal Plain and the results clearly indicated that this was not advisable, so the idea was dropped. Considerable effort was devoted to studying the fate and effects of operational wastes (drilling muds, cuttings and produced water) released from offshore oil and gas platforms on the Grand Banks and Sable Island Bank. These results were used to improve environmental monitoring programs and operational regulations. *Hudson* was also involved in carrying out large-scale field experiments with fishing vessels to determine the impacts of otter trawls and hydraulic clam dredges on benthic habitat and communities.

Beginning in 1998, *Hudson* was the principal vessel used in support of the Atlantic Zone Monitoring Program (AZMP), a major initiative involving all four Atlantic regions of DFO. Two cruises a year have collected physical, chemical and biological data along sixteen transects off Newfoundland and Labrador, Nova Scotia and in the Gulf of St. Lawrence to characterize oceanic variability at seasonal, interannual and decadal time scales. This extensive database has been used in assessing the impacts of climate change, validation of remote sensing data and oceanographic numerical models and the ecosystem management of fisheries.


Hudson at Hibernia oil field on the Grand Banks

Hudson made many valuable contributions beyond serving as a platform for oceanographic research. While at sea, she was always on call for search and rescue missions and responding to environmental emergencies. In 1976, she rescued the crew of the *Cape Freels* who had taken to lifeboats after their fisheries patrol vessel caught fire and sank off Newfoundland. In 1979, she responded to the breakup of the oil tanker *Kurdistan* in the Cabot Strait. In 1982, she was the first to arrive on the scene when the *Ocean Ranger* capsized and sank in a severe storm on the Grand Banks. All hands were lost but she did recover some bodies and took them into St. John's. In 1987, *Hudson* rescued all 24 crewmembers of the MV *Skipper I*, a large bulk-carrier which foundered off the Grand Banks in hurricane-force winds and took them into St. John's. Then, in 1988, *Hudson* found the burning wreckage of the *Athenian Venture*, a Greek oil tanker which exploded and broke into two off Cape Race, Newfoundland. A daylong search found only one body of the twenty-nine people believed to be on board. In 1988 she was involved in recovering wreckage from the crash of Swiss Air Flight 111 off Peggy's Cove and, in 2006, she suffered considerable damage when steaming to assist a stranded sailing vessel under hurricane conditions on the Grand Banks .

Over her career, *Hudson* suffered several mishaps of her own. For example, there were engine room fires in 1966 and 1974 with the latter leaving her dead in the water for several hours in the Sargasso Sea off Bermuda. Severe winter weather in the Labrador Sea in 1976 resulted in heavy seas smashing some windows and flooding the officer's lounge. That same year she lost a propeller in Lancaster Sound and had to finish her program and limp home under half power. Perhaps the potentially most threatening incident occurred in 1993 when she collided with an iceberg in Kangelugsuuak Fjord on the west coast of Greenland and ruptured her hull. Fortunately, there was a Danish research vessel with a helicopter and divers nearby which came to her rescue and escorted her safely to Iceland for repairs.

Whenever possible, *Hudson* was open to the public. In 1967, she steamed to Montreal and welcomed over 20,000 visitors in just one week at Expo 67. She was frequently opened for public tours when visiting foreign ports and was always a popular attraction at BIO open houses. In addition, she also hosted many distinguished visitors both at home and away, including a visit of The Right Honourable Roland Michener, the Governor-General of Canada, in 1968.

In the mid 1990s, it was well recognized that *Hudson* would not last forever and discussions began on obtaining a suitable successor. While some early consultations on vessel design had occurred, it was not until 2017 that plans were finally announced to build a new Offshore Oceanographic Science Vessel (OOSV) as part of Canada's National Ship Building Strategy. This vessel is now under construction in Vancouver and expected to arrive at BIO about 2025. This new vessel, yet unnamed, has specifications very similar to *Hudson* but will have a quite different deck layout and be equipped with new features including a dynamic positioning system for station keeping and multibeam sounding systems. While she appears on paper to be a suitable successor, it remains to be seen how well she will perform at sea under adverse conditions.

The Hudson arriving at BIO for the last time in January 2022.

Near the end of her career, *Hudson* suffered numerous breakdowns which reduced her sea time considerably and unfortunately disrupted important time series of data collection. Several refits were carried out to extend her lifetime until her successor was available. However, this strategy turned out not to be feasible and in early 2022 the Coast Guard announced that *Hudson* would be retired. She returned to BIO for the last time in January, a farewell open house for crew and staff was held in May and a formal decommissioning event took place in July. It is anticipated that she will be towed to a shipyard and broken up. Until the new Offshore Oceanographic Science Vessel arrives, east coast oceanographic cruises will reply on other vessels in the Coast Guard fleet or commercial charters.

Her longevity of 59 years is quite exceptional for research vessel, three years longer than the venerable CSS *Acadia*. However, it falls short of the 76 years that RV *Atlantis* served the Woods Hole Oceanographic Institution and the Argentinian Navy.

In summary, due to her size, facilities, crew and sea kindliness, *Hudson* was an exceptional oceanographic vessel. She went where few research ships could go and could work safely under extreme conditions. As a result, she supported groundbreaking multidisciplinary research throughout the world's ocean's. She was an important factor in making BIO one of the top oceanographic institutes in the world. She became the queen of the Canadian oceanographic fleet and an icon for BIO. Both scientists and crew became very attached to her. In retrospect, the initial investment in building *Hudson*, $7,500,000, has paid huge dividends for Canada. She will be sadly missed but a similar successor is on the horizon. Her legacy of Canadian oceanographic research has provided a fundamental understanding of the waters and seabed surrounding Canada like no other ship and that will serve as a benchmark for the future generation of studies.

Don Gordon *completed his PhD at Dalhousie University, then spent two years at the University of Hawaii as a chemical oceanographer. In 1970, he returned to Canada to begin a long career as a research scientist and manager at the Bedford Institute of Oceanography. Retired in 2005, he continues to serve as an emeritus scientist with a special interest in documenting oceanographic history. He is the veteran of many Hudson cruises.*

Cities drive global warming, but change is possible

WRITTEN BY CMOS BULLETIN SCMO ON JULY 18, 2022. POSTED IN CLIMATE, MEMBERS, NEWS & EVENTS, WHAT'S CURRENT.

-By Hind Al-Abadleh-

Urban areas around the world are responsible for more than two-thirds of global greenhouse gases. At the same time, the impacts of climate change are becoming increasingly dire. What can cities do to effect long-lasting, sustainable transformation?

This article was first published on De Gruyter Conversations *on 5 July 2022.*

Earlier this year, the Intergovernmental Panel on Climate Change (IPCC) released its latest assessment, which makes it clear that humans are the primary cause of global climate change. The report also states that no region in the world will be spared from its impacts: more intense and frequent weather extremes, wildfires, floods, and droughts.

One specific chapter in the report, "Linking global to regional climate change," emphasizes the contributions that cities are making to climate change. In fact, metropolitan regions around the world consume two-thirds of the world's energy despite occupying only 2% of its landmass, which translates to more than 70% of global CO_2 emissions. That's why climate change solutions must begin in cities with engagement from citizens and local governments.

Engagement and Partnership

Dr. Hind Al-Abadleh

In May 2022, I participated as a speaker and panelist in the Cities as an Engine for Environmental Change symposium at the Forum for Global Challenges, organized by the University of Birmingham. The invited speakers and panelists shared their insights into this theme, addressing topics such as strategies to improve air quality, approaches to achieving net-zero carbon emissions, the drivers of urban health, and ideas from economics that link environmental health improvements with wealth creation.

The sessions demonstrated that cities have the tools to address the challenges they are facing in the post COVID-19 world. Scientific evidence, policies, regulations, and investments from the public and private sectors matter immensely. Governments at all levels need to invest in complex systems thinking to manage crises and learn from their own responses to the COVID-19 pandemic. Overall, the cost of not taking any action to mitigate and adapt to climate change will be much higher than the cost of action at all levels.

Another important takeaway from attending this forum was that we can no longer afford to work in silos. For cities to benefit from their investments in climate action, they must enter into partnerships and engage the community as soon as possible. We need to create new funding ecosystems at the city level that incentivize collaboration on evidence-based projects between scientists from different disciplines, industry, and local governments. These projects must be designed to have significant and tangible social, economic, environmental, and health impacts. They also need to engage with community members and address their experiences in their neighborhoods.

For example, several studies have shown that racialized and low-income communities are often disproportionately exposed to environmental risks and are located in neighborhoods with fewer green spaces. When poor health and low income are major stressors in people’s lives, those people are less likely to be open to participating in climate action initiatives. Therefore, engaging them in meaningful and respectful ways that acknowledge their immediate concerns becomes crucial in order to clarify the connections between air quality, green spaces, human health, the green economy, consumer behavior, the government’s role, and carbon emissions.

When engaging with communities from different social groups, experts need to learn from the members of low income and marginalized communities to be able to foster proactiveness, support, and optimism in adapting to the impacts of climate change and enhancing their resilience.

Education is key

Dr. Hind Al-Abadleh speaking at her current institution, Wilfrid Laurier University.

As an academic scientist, my lab research and teaching experience in environmental chemistry is motivated by scientific measurements and modeling of the impact of human activities on natural systems and human health. As an educator, I care about creating and passing on technical knowledge to future generations of scientists. In this context, I supervise student research projects that demonstrate how chemistry is key to solving environmental challenges related to air and water pollution, and the impacts of climate change.

It is also important to me to communicate scientific knowledge to the public in a timely manner. In the past, I have given presentations to children and seniors to raise awareness of air quality, environmental issues, and misconceptions about chemistry, and to encourage behavioral change at the individual and community levels. Educating people about these issues and what each one of us can do to reduce our carbon footprint is the first step in creating scientifically literate citizens prepared to address this existential threat to our civilization.

Today, I'd like you to make a resolution to educate yourself about where we are now as a human civilization and where we need to go.

The last two years have shown the world how effectively scientists can work together. In the shortest time, they developed new vaccines and designed new tools and technologies to detect airborne pathogens, purify indoor air, and quantify outdoor air quality improvements because of the lockdowns. We have also seen decision-makers at various government levels implement evidence-based policies and regulations that acknowledge the latest scientific findings on issues with societal impact.

Equipped with the science of which we are aware at this point in history, coupled with educated citizens and political leaders, our generation has unique opportunities to build a new future for humanity that is just, resilient, and more in harmony with nature. Let's not let this opportunity pass us by.

Dr. Al-Abadleh *is a Full Professor in the Department of Chemistry and Biochemistry and Research Ambassador for the Environments and Sustainability at Wilfrid Laurier University. She is currently the Chair of Atmosphere-Related Research in Canadian Universities (ARRCU), a special interests group of CMOS.*

Lab webpage
Linkedin

Monitoring climate change with the support of local communities in the Northwest Territories

WRITTEN BY CMOS BULLETIN SCMO ON JULY 26, 2022. POSTED IN ARCTIC, CLIMATE, NEWS & EVENTS, WHAT'S CURRENT.

– By Andy Vicente-Luis, Emma Riley, Elyn Humphreys, Philip Marsh, William Quinton, Oliver Sonnentag –

Arctic-boreal regions are warming rapidly, with increases in surface air temperatures over double the global average (Meredith et al., 2019). This warming leads to cascading effects on Arctic ecosystems, including loss of seasonal snow cover (Derksen & Brown, 2012), the melting of glaciers and ice sheets (Noël et al., 2018; Onarheim et al., 2018), changes in hydrologic regimes (Beel et al., 2021), shifts in vegetation dynamics (Kolk et al., 2016) and permafrost thaw (Jorgenson et al., 2006; Schuur et al., 2008). Permafrost in Canada's Arctic (McGuire et al., 2009; Tarnocai et al., 2009) and boreal landscapes (Walker et al., 2019; Moore et al., 2003) constitutes one of the largest stores of soil organic carbon in the world. Once thawed, previously frozen soil organic carbon becomes available for decomposition, releasing potent greenhouse gases such as carbon dioxide and methane to the atmosphere (Schuur et al., 2015). Most climate models do not take into account greenhouse gas emissions potentially released to the atmosphere by permafrost thaw, omitting a large part of the global carbon cycle. Due to the variability of greenhouse gas exchange across the Canadian Arctic-boreal region, it remains uncertain whether these vast landscapes will either enhance or mitigate the effects of climate change in the future (Schuur et al., 2015).

Continued monitoring of greenhouse gas emissions is required to understand how permafrost thaw and associated changes in forest, taiga, peatland, and tundra ecosystem composition, structure and functioning are contributing to the regional and global carbon budget. Related impacts on the hydrological cycle, local water resources and regional climate are equally important to monitor in order to better understand the interconnected response of these ecosystems to further climate change.

Over the past 15 years, Oliver Sonnentag (Université de Montréal) and collaborators Phil Marsh, William Quinton (Wilfrid-Laurier University) and Elyn Humphreys (Carleton University) have developed a network of ten micrometeorological towers worth several millions of dollars across the Northwest Territories (NT). At each tower site, we use the eddy covariance (EC) technique to quasi-continuously measure ecosystem-scale net exchange of carbon dioxide, methane, water and energy. Examining how these variables change over space and time can be used to determine how the northern land surface is interacting with the atmosphere and responding to climate change.

With the onset of the pandemic two years ago, Covid-19 disrupted critical climate change research around the world. Sonnentag and his collaborators realised how fragile their access to research infrastructure was. Travel restrictions in NT, although necessary to curb the spread of the coronavirus and protect local communities, threatened the operation of this research infrastructure and the data record used for territorial government and Indigenous community decision-making on climate change adaptation.

Figure 1. Inuvik residents Troy Tumma and Trevor Kaglik chat with Gabriel Hould Gosselin about eddy covariance instrumentation (left). Alex Mavrovic, Troy Tumma and Paul Mann go over snow gas measurement techniques near Inuvik, NT (right).

The continued operation of an EC tower requires regular visits by trained staff, ideally monthly, to ensure the proper functioning of the system including power supply and state-of-the-art micrometeorological instrumentation. The existing EC tower network was reliant on university researchers and technicians who had to travel to NT from southern Canada several times per year. To address these issues, a training network was developed with the help and support of academia, industry, the federal and territorial governments, and local communities across NT. This project aims to train a team of local community members living near the research sites to help maintain the micrometeorological towers. This 2-year project is supported by the Future Skills Centre (www.fsc-ccf.ca), which has a mandate to strengthen skills development networks and career opportunities in Canada.

Sonnentag and his collaborators anticipate that the training network will lead to similar local capacity-building efforts through current and future collaborations with other research projects. Local capacity-building through knowledge co-creation and co-management between communities and subject-matter experts will increase infrastructure resilience but also increase non-expert awareness and understanding of how human activities shape ecosystem health and services in an ever more complex world.

Since the project began in March 2021, we have been building the local monitoring network in NT in stages. First, a research coordinator based in Yellowknife was hired to lead the hiring efforts for 8 local community members across NT to participate in training and tower maintenance trips at research sites closest to their community.

Five fieldwork campaigns have taken place since July 2021, with varying degrees of local involvement depending on fieldwork location, weather conditions, availability and Covid-19 guidelines. These fieldwork campaigns introduced the new project members to the research site infrastructure, specifically site instrumentation, some of the procedures used for tower maintenance, as well as other climate change monitoring techniques.

Figure 2. Workshop participants gather at a peatland site outside of Yellowknife, NT.

Project members have participated in several training opportunities both online and in-person. A virtual course including pre-recorded videos was created to cover topics related to EC theory, EC instrumentation, fieldwork safety and other relevant topics. These videos include interviews with project members and partners, including William Quinton, Elyn Humphreys, Philip Marsh and numerous students, technicians and research associates. This material remains available to existing and new project members to help with preparation before performing fieldwork-related activities.

Figure 3. Participants gather at a trailhead outside Yellowknife as part of an optional weekend excursion.

In-person training took place during a two-week workshop held in Yellowknife in May 2022. The first week of this workshop included safety certifications for wilderness first aid, fall protection and wildlife awareness. The second week included an introduction to various scientific techniques and theories related to EC flux measurements, scientific instrument maintenance and climate change monitoring in general. Presentations and discussions were led by industry, academic, territorial government, non-governmental organisations and Indigenous government representatives.

Community-led maintenance of the NT network of micrometeorological towers is intended to continue until March 2023 through organised site visits. Future site visits will continue to develop the scientific and technical skills of project members working towards future contract maintenance work within this network of EC towers. The success of this project is measured not only through the effective maintenance of the NT micrometeorological tower network but also through the strengthening of community partnerships, knowledge co-creation, support of the local economy and skill development in NT.

Dr. Oliver Sonnentag *(he/him) is an Associate Professor and Canada Research Chair 2 in the Département de géographie (Atmosbios lab) at the Université de Montréal.*

Sonnentag's research interests are in atmospheric biogeosciences in high latitudes: understanding changes in land surface – atmosphere interactions in response to rapidly changing climate and permafrost conditions, and biophysical parameter monitoring and mapping to study changes in ecosystem composition, structure and functioning. Dr. Sonnentag leads the Future Skills Centre-funded training network project.

Emma Riley *(she/her) is a research coordinator in the Atmosbios lab at the Université de Montréal based in Yellowknife, NT. Riley develops and coordinates activities related to the Future Skills Centre-funded project "Climate Change Monitoring in NT" to build local micrometeorological capacity led by Dr. Oliver Sonnentag.*

Andy Vicente-Luis *(he/him) is a research coordinator in the Atmosbios lab at the Université de Montréal based in Montréal, QC. Vicente-Luis is responsible for the administration and science logistics in Dr. Oliver Sonnentag's research group including the Future Skills Centre project.*

Dr. Elyn Humphreys *(she/her) is a Professor in the Department of Geography and Environmental Studies at Carleton University, ON. Humphreys studies the exchange of trace gases such as carbon dioxide and methane, and energy between ecosystems and the atmosphere. Her research is currently focused on the impacts of climate change and other disturbances on the carbon and energy budgets of peatland ecosystems in temperate and Arctic regions.*

Dr. Philip Marsh *(he/him) is a Professor and Canada Research Chair in Cold Regions Water Science in the Department of Geography and Environmental Studies at Wilfrid Laurier University, ON. The goal of Dr. Philip Marsh's research project is to make significant advances in both the understanding of, and ability to predict, Arctic water resources at the local scale of interest to northerners. Marsh's project uses a combination of novel field observations and experiments, remote sensing, and multiscale modelling, to provide robust scenarios of future changes in the western Canadian Arctic.*

Dr. William Quinton *(he/him) is an Associate Professor and Canada Research Chair in Cold Regions Hydrology in the Department of Geography and Environmental Studies at Wilfrid Laurier University, ON. Dr. Quinton also served as Director of the Cold Regions Research Centre and was a founding member of the Laurier-GNWT Partnership Agreement initiated in 2010. He has worked in the Northwest Territories since 1987 and in the Dehcho region since 1999. His research area is in hydrology of cold regions, permafrost and peatlands.*

Thermal stratification in lakes determines where fish are, but also modifies how well acoustic telemetry can detect them

WRITTEN BY CMOS BULLETIN SCMO ON JULY 31, 2022. POSTED IN MEMBERS, WHAT'S CURRENT.

– By Mathew Wells, Yulong Kuai, and Yulu Shi –

The habitat usage of fish in large lakes and the coastal ocean is in part determined by thermal stratification, whereby fish choose regions that match their thermal preferences. The density stratification implied by a stratification of warm water above cold water also controls the dissolved oxygen profiles and the location of plankton and prey species, which also determine fish habitat usage.

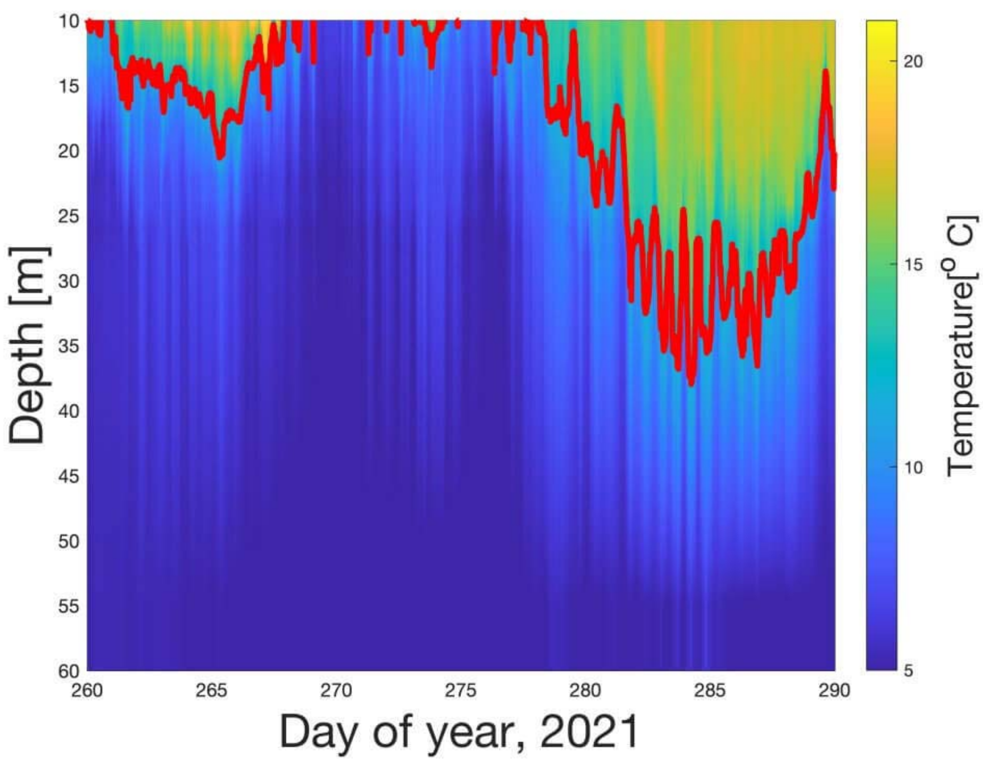

Figure 1: A time series of temperature as a function of depth in western Lake Ontario, 15 km offshore from Toronto in early summer 2021. The 12oC isotherm is marked as a red line, and displays considerable variability due to low frequency upwelling and downwellings, and higher frequency 17 hour Poincare waves. Cold water upwells to the surface from days 270-280, while a change of wind direction pushes thermocline down to 35 m depth on day 280-285.

However, this layering is not stable, and the thermocline of a large lake is always in constant motion due to wind forcing. This means fish must also constantly adjust depth to stay within their thermal preferences. Scientists use a range of acoustic detection technology to monitor fish habitat usage. The speed of sound propagation in water is mainly a function of density, and in freshwater lakes, density is mainly a function of temperature, so the speed of sound gradients across thermoclines can potentially focus or defocus sound signals and change how efficiently fish can be detected. Thus, if the thermocline is rapidly changing depth in an aquatic system, fish are likely to be changing positions at the same time as the efficiency of detecting them changes. This complicates our understanding of fish habitat usage in systems with dynamic thermoclines.

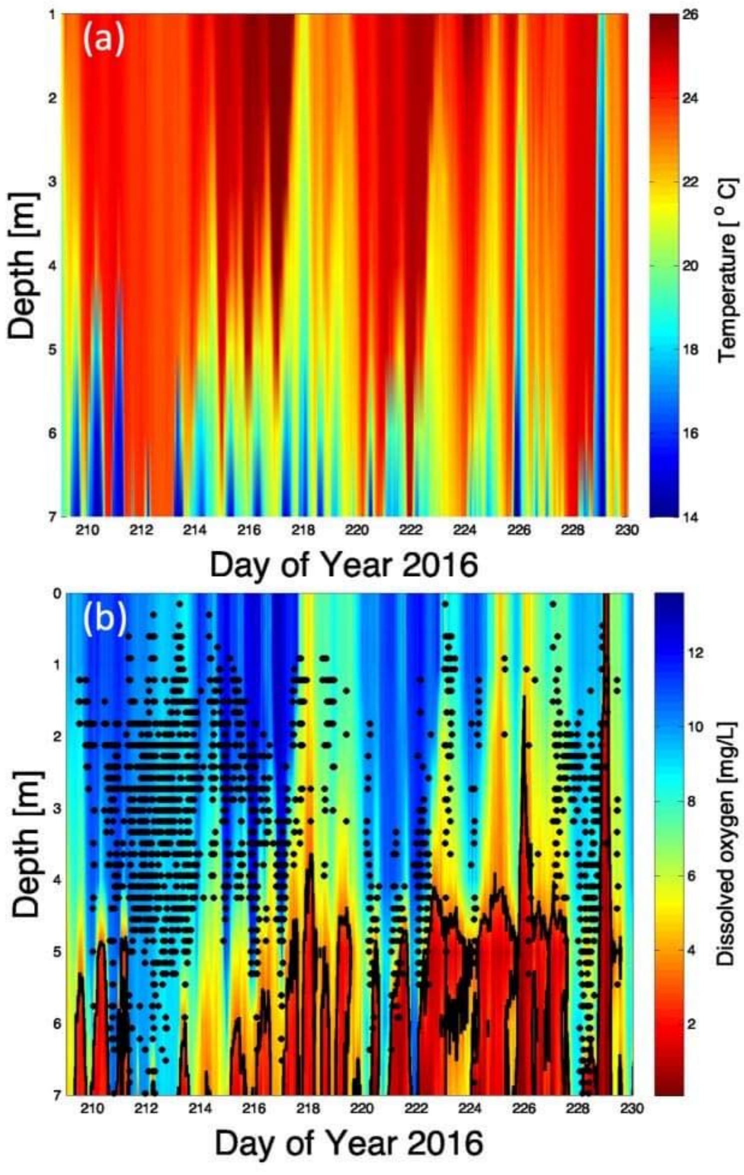

Figure 2. (a) Interpolated temperature and (b) dissolved oxygen values (mg/L) at depth (m) at the west end of Hamilton Harbour, Ontario, between days 208 and 230 of 2016

(26 July and 17 August). A strong internal seiche is driven by diurnal winds, which results in frequent upwelling of cold low oxygen water. In (b) the black circles indicate an individual walleye position in the water column, detected on the acoustic receiver at that time. Black line indicates the interpolated 3 mg/L oxycline position in the water. (Figure modified from Brooks et al. 2022).

In Figure 1 we show thermal data we collected in Lake Ontario near Toronto in early summer 2021. The surface of the lakes was as warm as 22oC, while the deepest waters were near 5oC. The red line is the 12oC isotherm and its depth can move over 20 m a day, which would influence the depth usage of cold water fish like trout or cisco. There is evidence for both 17 hour Poincare waves and 1-3 day Kelvin waves driving the large thermocline movements in Lake Ontario. The amplitude of such internal waves is greatest in large lakes which have a long fetch. In large lakes, such as the 50 km wide Lake Simcoe, these waves can be modified by Coriolis forces (Flood et al 2020). Even in smaller lakes, such as the 7 km long Hamilton Harbour, diurnal winds can lead to vertical movements of the thermocline of 5-10 m (Flood et al. 2021a).

When a fish's preferred temperature range coincides with the thermocline, the fish responds to internal waves by changing depth (Flood et al. 2021b). For instance, in Lake Simcoe, cold water Cisco stayed in colder deeper waters and tracked the moving 12oC isotherm (Flood et al. 2021b). Thermoclines in productive lakes often coincide with oxyclines, as the thermocline represents a barrier to mixing and supply of oxygen to deeper waters. In lakes with anoxic conditions at depth, fish may avoid the low oxygen zones and only use warm oxygenated water above the thermocline. Such behaviour was seen in Bass in Hamilton Harbour, where winds drove a 12 hour internal seiche that lead to extreme variability in dissolved oxygen in the littoral regions of the 7 km long harbour (Brooks et al. 2021). These fish were observed to adjust their position in response to the variable thermocline depth to stay above the thermocline in the warmer oxygenated waters (Figure 2).

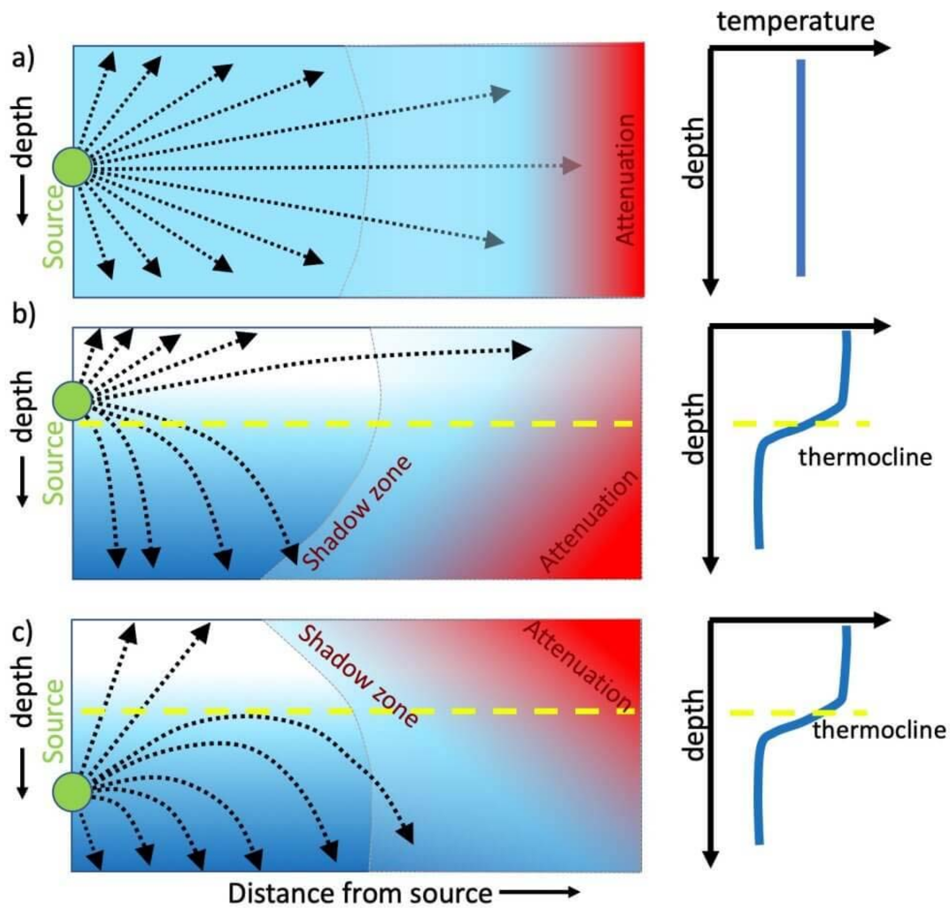

Figure 3. Illustration of how acoustic signals propagate in isothermal (a) and thermally stratified waters (b and c). In isothermal water the signal loss is mainly through three-dimensional spreading of sound (a). The presence of sound speed gradients due to thermal gradients refracts sound waves leads to defocusing and enhanced signal loss, so that three-dimensional spreading of acoustic rays is amplified by refraction when the source is on the opposite side of thermocline than the acoustic receiver (b,c). Thus while in isothermal conditions (a) the attenuation of acoustic signal is just a function of the distance from the source, acoustic "shadow zones" of reduced sound intensity forms when acoustic receivers are placed on the other side of the thermocline (b,c), which can reduce the effective detection range. In these figures, the green circle represents the acoustic source (i.e. the tag inside the fish), the gradients of blue shading represent speed-of-sound gradients, and red shading represent attenuation of sound intensity. In all sketches, the dashed gray line represents a threshold value of sound intensity below which detection efficiency is poor. (Figure modified from Kuai et al. 2021).

A recent technical revolution in fisheries research is the use of acoustic tags to directly track fish positions. A small tag is surgically implanted in a representative sample of the fish population and their location is then monitored through an array of bottom-mounted receivers. The presence of thermal stratification directly influences where fish will be in the water column, and thermal stratification also impacts how the acoustic transmissions propagate. In particular, the associated speed of sound gradients induced by temperature gradients have implications for the detection efficiency of acoustic telemetry devices and detection range. Detection efficiency can be influenced by thermal stratification, because of that, sound waves from an acoustic tag can refract and bend as they move from the warmer waters to a receiver on the lake bed, where water is usually cooler. Thus it leads to greater divergence of acoustic signals, and hence causes more sound attenuation that influences the overall performance of fish monitoring using acoustic tags. Depending on how pronounced the speed of sound gradients are, and the relative vertical locations of tagged fish and receivers, detection range may be significantly impacted in thermally stratified systems (Figure 3). According to the study carried out by Kuai et al. (2021), found that the steepest speed of sound gradient could reach 10.38 m/s m^{-1} across the thermocline of Lake Ontario, which led to the speed of sound difference between top and bottom of the water column reaching 60 m/s. The detection range of various Vemco transmitters could reach above 650 m when the water was isothermal, and it decreased to 350 - 450 m, when the water was stratified and the transmitters and receivers were situated at different sides of thermocline (Kuai et al. 2021). Thus, understanding the influence of thermal stratification to designing acoustic telemetry studies can increase the detection efficiency and detection range, and hence, improving the performance of acoustic tags.

One prominent example of a major fisheries telemetry project is GLATOS, the Great Lakes Acoustic Telemetry Observation System (Krueger et al. 2018), which now has placed acoustic tags in over 10,000 fish, with their locations recorded at over 1000 receiver stations, resulting in over 300 million position reports. Going forward, in Lake Ontario alone there are >100 bottom receivers, 300-500 active transmitters (fish), and 5-10 million potential detections over the next 3 years. Both transmitters and receivers usually record temperature as well, representing an untapped physical record of water temperatures. The strong seasonal thermal stratification in the Great Lakes represents some of the steepest sound speed gradients in any aquatic system. So far the influence of thermal stratification variability has not been considered as part of the acoustic detection array design, nor has the role of variability of thermal stratification been considered in driving some of the variability in fish habitat usage, even though we know different parts of Lake Ontario have strikingly different variability in thermocline depth (Stewart and Robertson, 1990). In order to understand how internal waves might structure the location of fish in lakes, it is first important to understand how variable thermocline movements are around the Great Lakes. Key questions are 1) What locations around the perimeter of large lakes have the largest internal waves? 2) Can the distributed receiver network give extra insight into internal wave dynamics in the Great Lakes? 3) How can we best mine the big data of GLATOS fish telemetry records to correlate fish movements with thermocline motions?

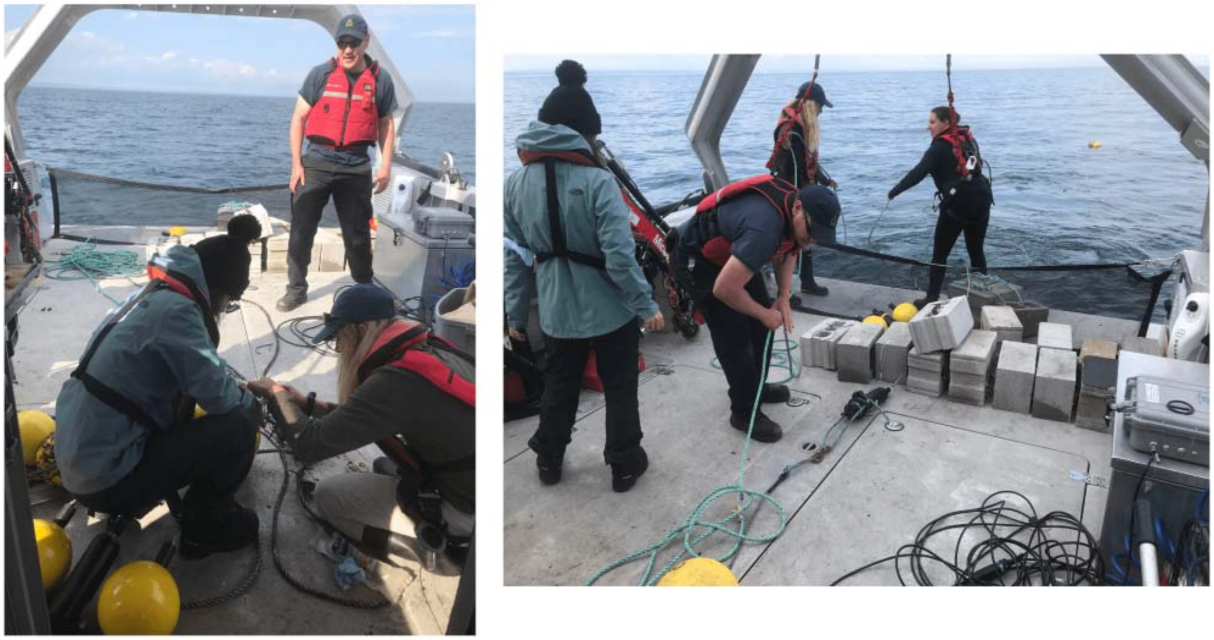

Figure 4. Photos of field crew from the Department of Fisheries and Oceans redeploying a thermistor chain and acoustic receiver in eastern Lake Ontario in June 2022. This is part of an array to understand how thermal structure influences fish habitat and is a large collaborative project involving DFO, OMNRF, USGS and others, and funded in part by GLOS.

Dr. Mathew Wells *is a Professor in the Department of Physical and Environmental Sciences at the University of Toronto Scarborough. His Environmental Fluid Dynamics group studies flows in lakes, rivers and the coastal ocean, in order to understand the transport and distribution of biology, sediment and chemicals.*

Yulong Kuai *is a PhD student in the Environmental Science program at the University of Toronto. For his Masters degree he studied quantifying the potential impacts of temperature and dissolved oxygen variability on fish habitat during the summer stratified period in Hamilton Harbour, Ontario. His current doctoral research on western Lake Erie investigates the correlation among physical drivers that triggers hypoxia and potential algal bloom in this large polymictic basin.*

Yulu Shi *is a fourth year undergraduate in the Specialist co-op program in Geoscience at the University of Toronto Scarborough. For her fourth year research project she will quantify the thermal stratification patterns across Lake Ontario and the dynamics of the thermocline depth as a function of wind patterns and bathymetry.*

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An overview of field work conducted on high-latitude mineral dust aerosol in the Ä'äy Chù Valley in Kluane National Park, Yukon

WRITTEN BY CMOS BULLETIN SCMO ON AUGUST 7, 2022. POSTED IN AIR QUALITY, ATMOSPHERE, WHAT'S CURRENT.

– By Arnold Downey –

Mineral Dust Aerosol (MDA) is known to have an important influence on several environmental topics. Like all aerosol, MDA plays a role in the radiative balance of the atmosphere, as it scatters and absorbs solar and terrestrial radiation. It also has a secondary effect on radiative forcing, as it acts as cloud condensation and ice nuclei. <!--more--> With estimated global yearly dust fluxes being on the order of petagrams (trillions of kilograms), the impact it has on climate as an atmospheric constituent cannot be overlooked. MDA also influences local air quality. Dust storms may introduce concentrations of particulate matter to regions that exceed regulatory health limits. The World Health Organization (WHO) places 24-hour guidelines for $PM_{2.5}$ concentrations (that is, the concentration of particulate matter with a diameter of less than 2.5 μm) at 15 $\mu g/m^3$, while that for PM_{10} is 45 $\mu g/m^3$. MDA affects atmospheric visibility, and its transport is part of the geochemical cycling of nutrients important for biogeochemistry, among other notable environmental effects.

Image 1: A dust storm rages in the Ä'äy Chù Valley, Kluane National Park, Yukon

With the barrage of roles that MDA plays in the environment, an understanding of its chemical and physical properties across the globe serves as valuable information to scientists across many disciplines. Although a substantial amount of research is committed to MDA as a whole, little is known about high-latitude MDA specifically. There are many reasons for this. Performing dust studies, or any study in high latitudes, is logistically difficult with population density and the resources of urban centers dropping off rapidly as one moves north of the 49th parallel. Northern environmental conditions can be harsh also, in terms of meteorology, wildlife, and natural hazards. High latitudes are nonetheless a significant source of MDA and with high latitudes experiencing some of the most pronounced effects of climate change, the conditions for dust emissions could possibly change as well. It is for this reason that the Patrick Hayes' group at the University of Montreal holds high-latitude MDA as one of their core research topics. The group has spent many of the recent late springs/early summers conducting field campaigns centered around the Ä'äy Chù Valley in Kluane National Park, Yukon, located north of the Kaskawulsh Glacier. This region is an important case study for understanding the impacts of climate change. The recession of the Kaskawulsh Glacier over the past decades has caused the Ä'äy Chù River to reroute, converting the former river to a much drier valley and replacing the river with a surface of sediment. This sediment is subject to strong glacial winds and a subarctic climate punctuated by dry, cool summers in the Kluane region. These conditions are ideal for dust storms, and so more frequent and severe dust events have been observed.

Image 2: A grizzly bear walks along the Alaska Highway near the Ä'äy Chù Valley

As mentioned above, another important impact that the dust has is on the radiative forcing of the atmosphere. MDA tends to have a cooling effect on the climate, as it primarily scatters atmospheric radiation and has been reported to cause globally a decrease of the net surface radiative forcing of about 1 W/m^2. Although, MDA possesses a small, but measurable, imaginary refractive index, indicating that it also absorbs radiation, unlike some other types of aerosols like sea salt (NaCl) and sand (SiO_2) that have no imaginary refractive index component. The 2022 Kluane campaign was focused on directly measuring the optical propertied of the MDA by means of Photoacoustic Extinctiometer (PAX) instruments. PAX instruments can measure the scattering coefficient and the absorption coefficient of aerosol particles in real time, using the collection of scattered laser light by a detector for the scattering coefficient determination, and a sensitive microphone to detect sound waves produced by the aerosol when it is heated from absorbing the same laser beam. This data is currently being processed with the goal of assessing the optical properties of the MDA directly, as well as relating these properties to the dust composition.

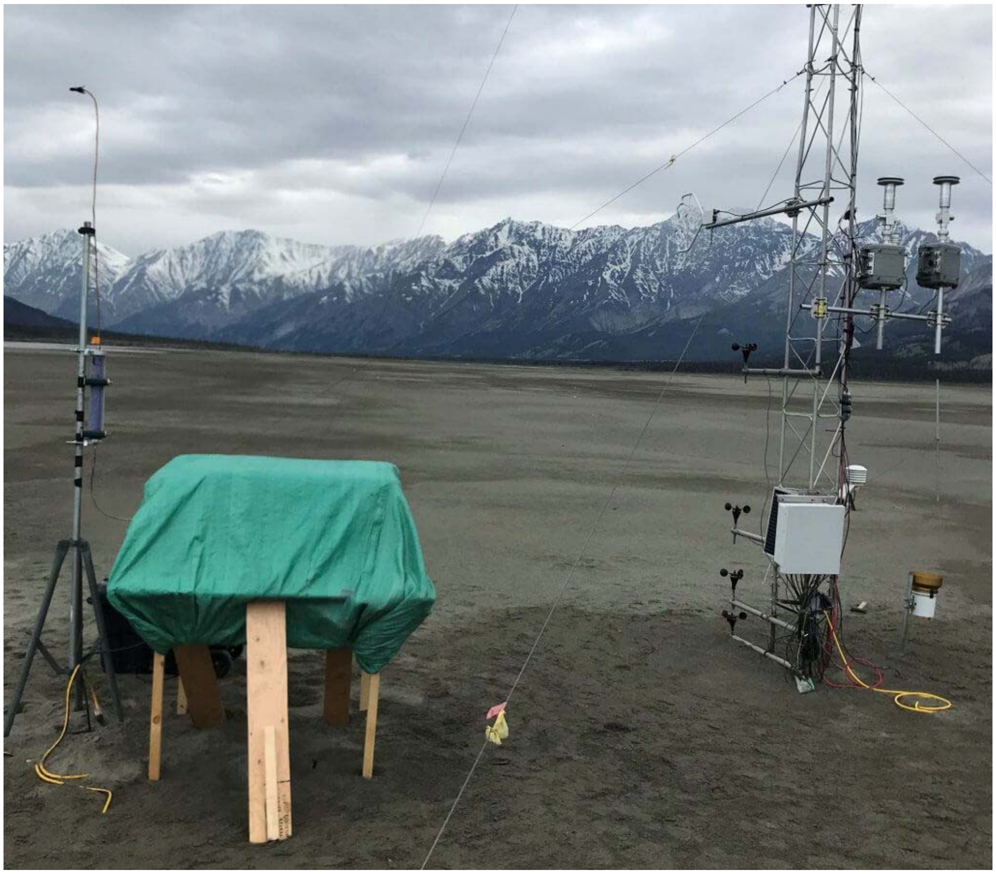

Image 3: A view of the experimental set-up for measuring aerosol optical properties in the Ä'äy Chù Valley using a PAX instrument (covered by a green tarp)

Regarding air quality, results from the 2019 Kluane campaign conducted by Jill Bachelder of the Hayes Group showed that WHO air quality guidelines were indeed surpassed as a result of the elevated dust activity in the Ä'äy Chù Valley. 24-hour PM_{10} concentrations above 1000 µg/m^3 and $PM_{2.5}$ concentrations above 250 µg/m^3 were recorded in the Ä'äy Chù Valley and near Kluane Lake. PM_{10} and $PM_{2.5}$ guidelines were also surpassed several times at the Parks Canada Visitor's Center for the Ä'äy Chù Valley. A study like this serves as an important basis for considering the effect that climate change is expected to have due to increased mineral dust activity. While this study did assess the concentrations of various metals of interest to human health in the dust, including lead and arsenic, the bio-accessibility of these metals from the dust was not assessed. This is one of the next steps to be taken for this project to further our understanding of the air quality impact. To accomplish this, an inhalation-ingestion bioassay method developed by Dr. Farzana Kastury at the University of South Australia will be implemented on MDA samples collected during the 2021 Kluane campaign. This method is designed to provide a conservative estimate of the bio-accessibility of metals and metalloids in PM_{10} to the pulmonary and gastro-intestinal system. Involving the gastro-intestinal system is an important factor to consider, as a most PM_{10} inhaled is transported to the gastro-intestinal track after about 24 hours in the lungs.

Understanding the implications that the evolving dust emissions have in the Kluane region is especially important for assessing the impact that climate-driven environmental changes will have on populations that inhabit the region. The Kluane Lake area is home

to Kluane First Nation and is the traditional territory of the Lù’àn Män Ku Dän, (which means Kluane Lake People in the Southern Tutchone language). Their traditional territory stretches in all directions from Łù’àn Mǟn (Kluane Lake) to the Ruby and Nisling mountain ranges to the northeast and the St. Elias Mountains to the southwest. The region is shared also by two other first nations; the Champagne Aishihik and the White River First Nation.

High-latitude MDA, specifically in the Kluane region, is endlessly intriguing from an atmospheric chemistry perspective. The Hayes Group is privileged to conduct this research while being able to see and explore such a beautiful part of the world. As researchers, we hold a deep appreciation for Kluane First Nation as well as the other First Nations in the Yukon, the original stewards and occupants of the land, which permit the realization of projects such as these. The Hayes Group would also like to acknowledge the massive contributions from Professor James King and his research group in the Geography Department at the University of Montreal, as this work would not be possible without this collaboration. The Hayes Group would also like to acknowledge the financial contributions of the major sponsors on the project, The Canadian Mountain Network, Polar Knowledge Canada, and the Natural Sciences and Engineering Research Council (NSERC).


Image 4: A view of Kluane Lake from the top of Sheep Mountain

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Arnold Downey *is a doctoral student at the University of Montreal (UdeM) under the supervision of Professor Patrick Hayes. Arnold obtained his Bachelor of Science degree with a major in Chemistry and a minor in Atmospheric Science from McGill University in 2018. Before beginning a master's degree at UdeM that would be fast-tracked into a doctoral program, he spent time gaining experience while working in industry, working as an analytical chemist at AGAT Laboratories in Montreal, Quebec and Canadian Nuclear Laboratories in Chalk River, Ontario.*

Questions concerning the article or research by the Hayes group in general can be sent directly to the author at arnold.downey@umontreal.ca.

Early Exploration of the High Latitude Stratosphere Part I: Pre-World War II Era

WRITTEN BY CMOS BULLETIN SCMO ON AUGUST 18, 2022. POSTED IN ATMOSPHERE, PAST ISSUES, WHAT'S CURRENT.

– BY KEVIN HAMILTON –

Introduction

In 1960 McGill professor Ken Hare wrote a notable paper reviewing recent and ongoing research in stratospheric meteorology. In his paper Hare used example synoptic charts over North America (including the Canadian Arctic) to illustrate the basic features of the circulation in the lower and middle stratosphere. This paper came at the end of a period of fruitful discovery demonstrating that the winter stratosphere was a very dynamic environment and identifying the polar night jet stream and the sudden stratospheric warming phenomenon. Hare did not know of the equatorial quasibiennial oscillation (whose discovery was first published in 1961), but otherwise Hare's paper describes what is still the modern paradigm for the stratospheric general circulation. Workers in the field of stratospheric dynamics would spend the next decades explaining and attempting to numerically simulate the key aspects of the circulation identified in Hare's paper.

In a 1962 paper Hare put recent progress in context:

"Until 1950 it was generally assumed that the stratosphere was dull and uninteresting: it was dry and very stable with no weather […] The ascents that penetrated the tropopause confirmed this view. The winds were observed to decrease rapidly with height as the balloons climbed into the stratosphere…"

While this statement accurately emphasizes the rapid pace of discovery in the 1950's, it oversimplifies the history. I have undertaken to delve deeper into the history of the scientific developments that led by about 1960 to the modern view of the extratropical stratospheric general circulation. This paper reviews some key developments up to about 1940, while Part II will examine the postwar investigations that led to the discovery and characterization of the "polar night jet stream" in the winter stratosphere.

Fig. 1 shows the DJF climatological zonal-mean temperature and zonal wind determined from modern observations plotted up to the 1 hPa (~50 km) level. The temperature plot includes blue shading for areas with temperatures below 210oK and red shading for regions in the stratosphere with temperature greater than 230oK.

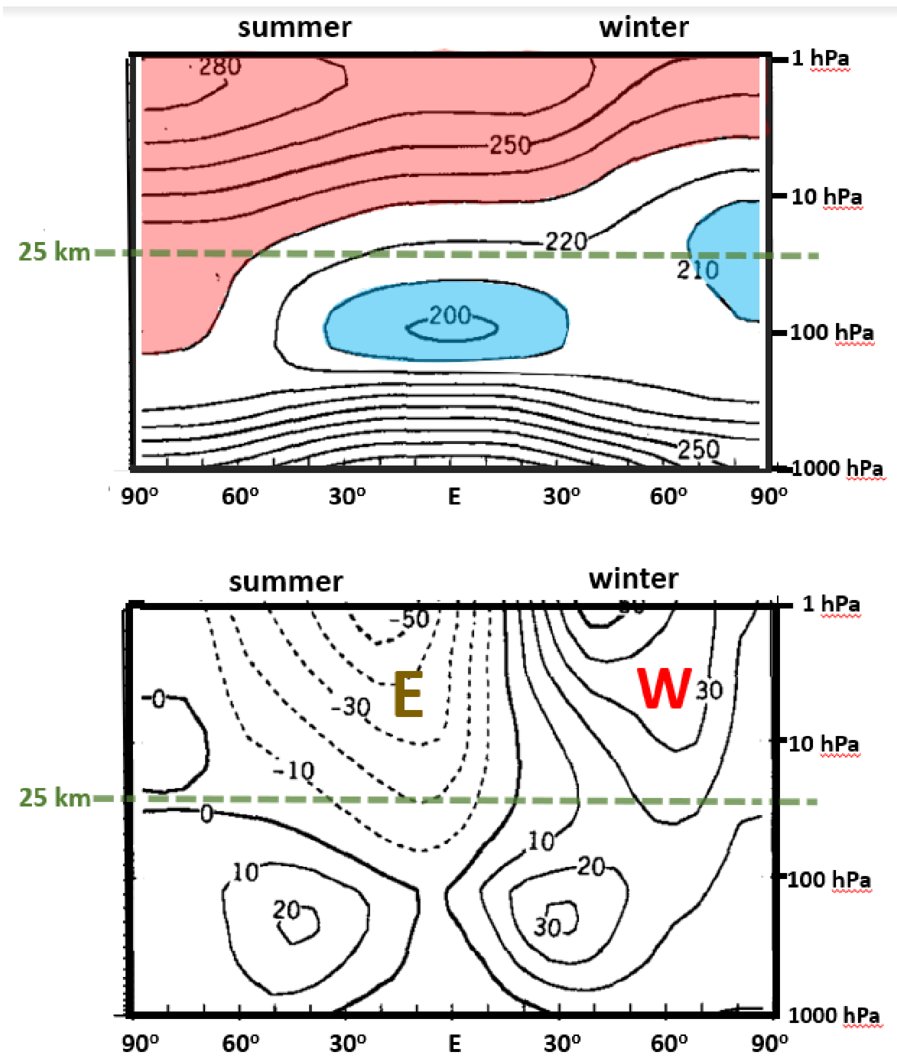


Figure 1. Multiyear average of the December-February mean zonal mean temperature (top) and zonal wind (bottom). Contours are labelled in oK and m-s-1, with dashed contours denoting easterly mean winds. Modified from Hamilton et al. (1995). Copyright American Meteorological Society. Used with permission.

The most notable feature of the lower stratosphere is the cold equatorial tropopause and temperatures that increase poleward along isobaric surfaces at least out to midlatitudes. The behavior of the lower stratosphere at high latitudes differs between the summer and winter hemispheres: in summer the temperature increases poleward all the way to the pole, while in winter the temperature reaches a maximum in midlatitudes and drops towards the very cold winter pole. This temperature structure is geostrophically consistent with the mean zonal winds seen in Fig. 1, with the wind speeds in the tropospheric jets dropping off above the tropopause in both hemispheres, but increasing again in a westerly polar stratospheric vortex in the winter and in an easterly polar vortex in the summer.

The Thermal Structure of the High-Latitude Stratosphere

Efforts to observe the atmospheric temperature above the surface using manned balloons began as early as the late 18th century. However, the systematic study of the atmosphere greatly advanced with the invention and deployment of unmanned balloon sondes beginning in the 1890's, initially at some European locations. In 1902 Léon Teisserenc de Bort announced the discovery of a "zone isotherme" beginning between 8 and 12 km altitude in 25 soundings near Paris and similar results were announced for soundings near Berlin by Richard Assmann. Even after this first discovery of the tropopause the now-familiar features of the stratosphere, notably the enormous annual cycle in the circumpolar circulation from winter westerlies to summer easterlies were completely unknown and unanticipated by scientists.

Over the next two decades a more detailed picture emerged as unmanned soundings began to be taken at more locations. These early measurements were made with "registering sondes" which recorded the temperature, pressure and humidity on physical media, requiring that the sonde be recovered and returned to the investigator by members of the public. Overall this procedure worked surprisingly well and in some cases significant fractions of the sondes were returned. For example, the first such observations in Canada, at Toronto during 1911-1915, deployed 94 sondes, 53 of which were recovered (47 reached the stratosphere). By 1908 the fact that the tropical tropopause is much higher and colder than at higher latitudes had been discovered. This showed that, at least in a belt from the equator to midlatitudes, the temperature along a horizontal surface in the stratosphere increased poleward, a finding that was counter to the intuition based on the familiar behaviour of the atmosphere near ground. Still left open was the question of whether the temperature gradients continued all the way to the poles (in both winter and summer).

In 1927 the leading British meteorologist Sir William Napier Shaw published what seems to be the first attempt at a meridional-height climatology of atmospheric temperature, which he shows up to 20 km in "summer" and "winter". His figure is somewhat startling to a modern meteorologist as it shows the temperature above the tropopause as exactly isothermal at each latitude and a temperature in the winter lower stratosphere that increases from about 60o latitude to the pole. Shaw's result is reproduced here as Figure 2 with my own added labeling and color shading for clarity.

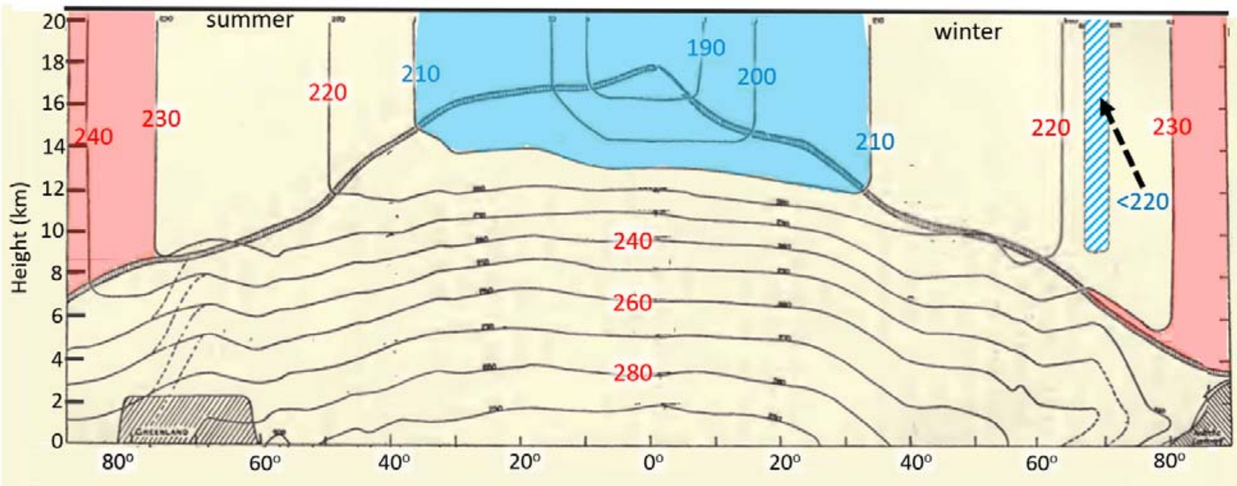


Figure 2. A cross-section of the near solstice temperature climatology, slightly modified from Shaw (1927). The red and blue continuous shading is as in Fig. 1. The striped blue shading denotes an isolated region with temperature below 220oK. The shaded regions near the ground show rough topographic representation of Greenland (left hemisphere) and Antarctica (right hemisphere). Despite the topography shown, there actually was no attempt by Shaw to distinguish the stratospheric temperature climatology in the Northern vs Southern hemispheres, and the temperature data used are mainly from the Northern Hemisphere.

Unfortunately, Shaw seems to have discounted credible, if indirect, evidence that the temperatures must rise substantially with height in the stratosphere. Shaw's picture was soon criticized by Charles Normand, the Director-General of meteorological observatories in India, who noted that in the stratosphere Shaw had depicted "*conditions that may be described as isothermal in the vertical.*" Normand noted balloon measurements at low and midlatitude sites that suggested there is an actual inversion in the lower stratosphere, including measurements at his own observatory in Agra in India (27oN) which were then being analyzed by the young Indian meteorologist K.R. Ramanathan. In 1929 Ramanathan produced an improved temperature climatology extending to 25 km. His result is reproduced here in Figure 3. Ramanathan's result compares much better with the modern climatology (Fig. 1). However, his depiction of the temperature climatology in the low stratosphere as being nearly symmetric between the summer and winter hemispheres stands out as an obvious deficiency.

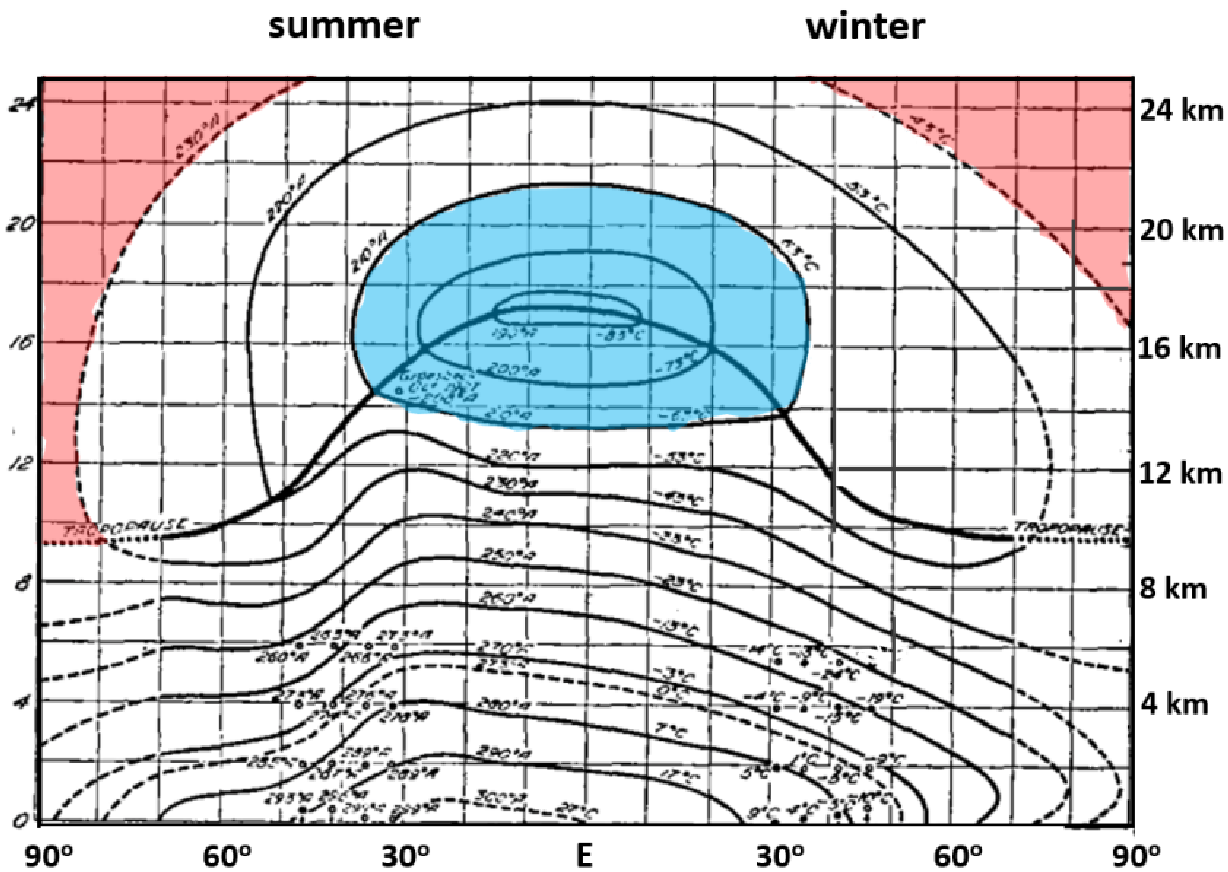


Figure 3. A cross-section of the near solstice temperature climatology as advanced by Ramanathan (1929). This figure is modified from a slightly derived version published in 1929 Monthly Weather Review. Red and blue shading as in Fig. 1.

These old diagrams of stratospheric climatology have something of the charm of antique world maps made when substantial imagination was still needed to complete the outlines of the continents. Ramanathan did not follow the custom of old mapmakers and depict dragons in his unknown polar regions, but contented himself with completely filling in his figure using dashed contours in the regions where he felt less confidence!

Both these early attempts by Shaw and Ramanathan completely missed the very cold winter pole and consequent increasing westerly flow with height in the circumpolar region that we now expect as the usual state of the high latitude winter stratosphere. Indeed Shaw was aware of the surprising implications of his temperature model for the stratospheric zonal wind, writing in 1928 that:

"above the level of 20 km we may expect a continuous gradient [of pressure] from the equator to the poles, increasing with height, and consequently a general circulation from

East to West over the whole globe, […] equivalent to a lag of the atmosphere behind the rotation of the solid earth."

The Need for More High Latitude Observations

Shaw responded very constructively to Normand and Ramanathan's criticisms and wrote later in 1929:

"It is with much pleasure that I notice … Dr. Ramanathan's amplification and correction of the tropical portion of my diagram of … temperature in a vertical section of the atmosphere of the globe from the summer pole to the winter pole. I hope the time is not far distant when some other enterprising meteorologist will render a like service for the polar regions of that diagram. It is badly needed."

Here Shaw put his finger on the key remaining uncertainty for mapping the basic climatology of the lower stratosphere, namely whether in the winter and summer hemispheres the temperature continues to increase poleward. The lack of high latitude stratospheric observations is not surprising as the registering sonde approach was particularly challenging in remote regions. For example, a British team launched 450 registering sondes from Ft. Rae (modern day Behchokǫ̀) in northern Canada (63oN, 110oW) during the 2nd International Polar Year (1932-33), but only 2 were recovered.

The 1930's marked the beginning of a revolution in atmospheric monitoring with the development and deployment of radiosondes. After earlier pioneering experiments by American and French scientists, the first practical radiosonde had been invented by the Soviet meteorologist Pavel Molchanov in 1930. This enabled temperature data to be gathered as the balloon rose through the atmosphere and opened up a new vista for real time weather forecasting. The radiosonde technique was still experimental in the early 1930's and, for example, it was not until 1937 that a network of operational radiosonde stations was established in the US. In Canada the first regular radiosonde profiling began in 1941 at Toronto and Edmonton, while daily radiosonde profiling in the Canadian north began at some stations starting in 1942.

In 1931 the exploration of the polar stratosphere took an important and colourful step forward with a unique scientific expedition that combined two cutting-edge technologies of the day: the newly-invented radiosonde and enormous dirigible airships capable of very long range flights, as described in the next section.

The *Graf Zeppelin* and the 1931 *Polarfahrt* ("Polar Journey")

Figure 4. A German stamp issued to commemorate the 1931 polar expedition of the *Graf Zeppelin*.

The early 20th century was an era of polar exploration notable for famous land and sea expeditions aiming to reach the North and South Poles. Then the 1920's saw polar explorations by fixed wing aircraft and dirigible balloons. At the end of the decade an international polar exploration society devised a plan to use the world's largest dirigible airship – the 236 m long *LZ127 Graf Zeppelin* – for an Arctic journey of geographical discovery and scientific investigation. The key participants would be German, Soviet and US scientists and polar explorers. The *Graf Zeppelin* had been constructed in 1928 and normally was used for luxurious commercial passenger transportation. The costs of chartering the *Graf Zeppelin* and the other expenses of the *Polarfahrt* would be largely covered by the sale of franked postcards carried aboard that had stamps specially issued by the postal authorities of Germany and the Soviet Union (Figure 4). The flight was documented on film with newsreel style narration.

Notable among the scientists in the crew was Molchanov who brought his newly-invented radiosondes to profile the Arctic atmosphere from the dirigible platform.

Figure 5. Pavel Molchanov and colleagues prepare to launch a sounding balloon from the *Graf Zeppelin*. Photo from the Radiosonde Museum of North America.

The flight began in Germany and stopped briefly in Lenningrad before lifting off on July 26, heading northward over the Barents Sea, passing 80oN and beyond the northern coast of the islands of Franz Josef Land. The *Graf Zeppelin* stayed aloft until July 30 when it landed in Berlin. For the aims of the *Polarfahrt* the dirigible had two notable advantages over fixed-wing aircraft: (i) it could move very slowly for long durations which greatly facilitated the mapping of the land and ocean surface below, and (ii) its large size and slow speed made it possible to serve as a platform to launch radiosonde balloons. The process was complicated because the cabins and other access points were on the bottom of the dirigible. The solution was to release the balloons with a weight that caused them to initially descend. After a short period the weight dropped off and the balloon could rise freely (see Figures 5 and 6). Molchanov made three successful soundings (near 66, 77.5 and 81oN) that penetrated the stratosphere up to ~16 km altitude. The temperature data collected in these soundings would get star billing in the next important paper on stratospheric climatology which I discuss below.

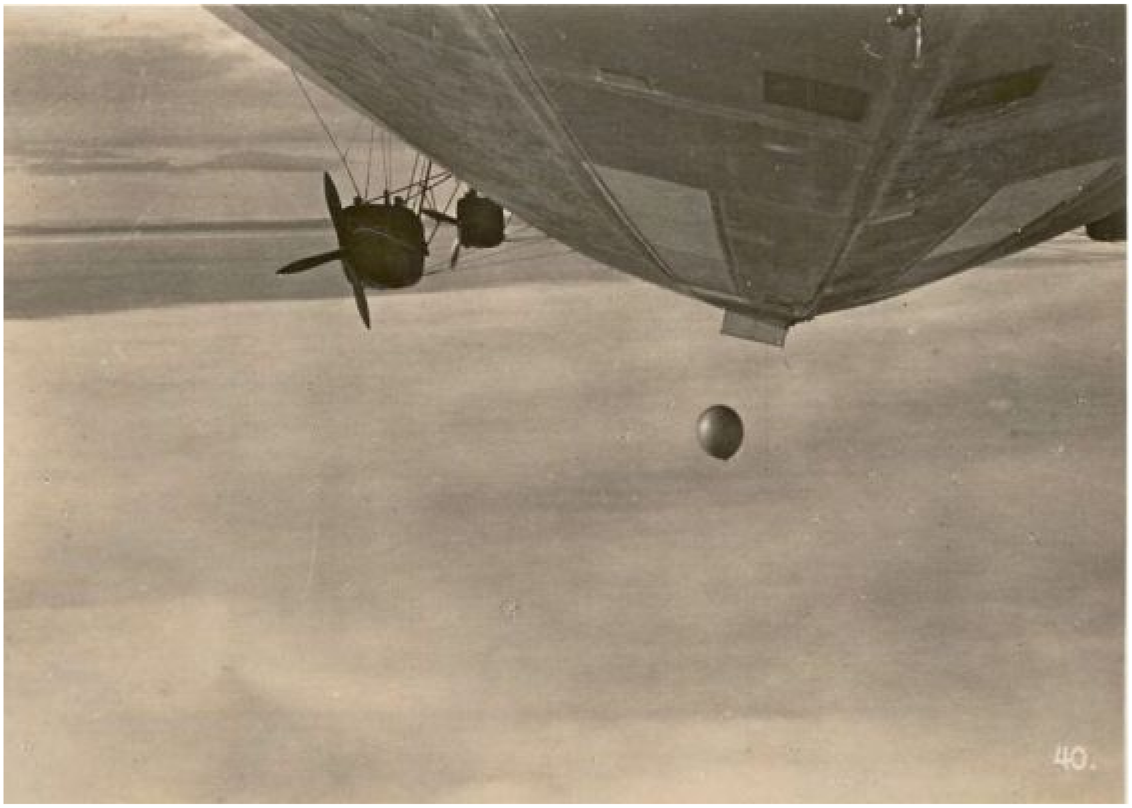


Figure 6. A sounding balloon dropped from the bottom of the *Graf Zeppelin* during the *Polarfahrt* expedition of 1931. The balloon was initially weighted and sank but the weight was designed to drop off, allowing the balloon to later rise. Photo from the Radiosonde Museum of North America.

The Climatology of Palmén (1934)

In 1934 Finnish meteorologist Erik Palmén reported on his new assessment of the temperature climatology in the stratosphere. Palmén's paper in the *Meterologische Zeitschrift* is not currently available online (the full citation is reference #32 on this list). Below I will quote Palmén's paper in my own machine assisted translation from the German.

Notably Palmén reviewed results of a successful multiyear series of registering balloon sondes at Abisko in northern Sweden (68oN) which he felt forced a complete revision of earlier ideas about the high latitude temperature in the stratosphere:

"With the temperature results of these registering balloons […] significant progress has been made in our knowledge of the temperature over the polar regions. There is no

doubt that these new temperature data must essentially modify our view of stratospheric dynamics."

Specifically he notes that a comparison of the Abisko observations in winter with observations from other European locations was consistent with stratospheric temperatures in winter decreasing poleward, rather than increasing *"as was previously generally assumed"*.

Palmén obtained confirmation of his contention of a cold winter polar region by obtaining

"…indirect evidence for the low stratospheric temperature in the Arctic by analyzing ascents in more southern regions during powerful intrusions of Arctic air masses".

As an example he discussed a case in southern Norway (60oN) on February 2-3, 1933 and the analysis of:

" … a series of six registration balloons sent […] to study the stratospheric processes in a deep cyclone whose center was already filled with Arctic air masses."

And finding that

"the stratospheric temperature was conspicuously low, amounting to 207oK at the highest altitude observed (about 15.3 km)."

In summer, by contrast, Palmén found that the Abisko observations supported the idea of a warm pole, indeed

"…the polar-directed increase in temperature in summer is much more powerful than was previously believed".

Palmén emphasized that this contention was supported by Molchanov's *Polarfahrt* measurements:

"Further evidence of the extraordinarily high summer stratospheric temperature in the Arctic was provided by the soundings during the polar voyage of the Graf Zeppelin in July 1931."

Specifically he quotes the temperatures measured by Molchanov's three radiosondes at the highest point in each profile (all near 16 km altitude) 230oK, 234oK and 240oK at 66oN, 77.5oN and 81oN, respectively. Palmén speculated that the temperature increase would continue all the way to the pole so that:

"An average temperature of about 243oK 15 km above the North Pole therefore seems very likely for the months of June and July."

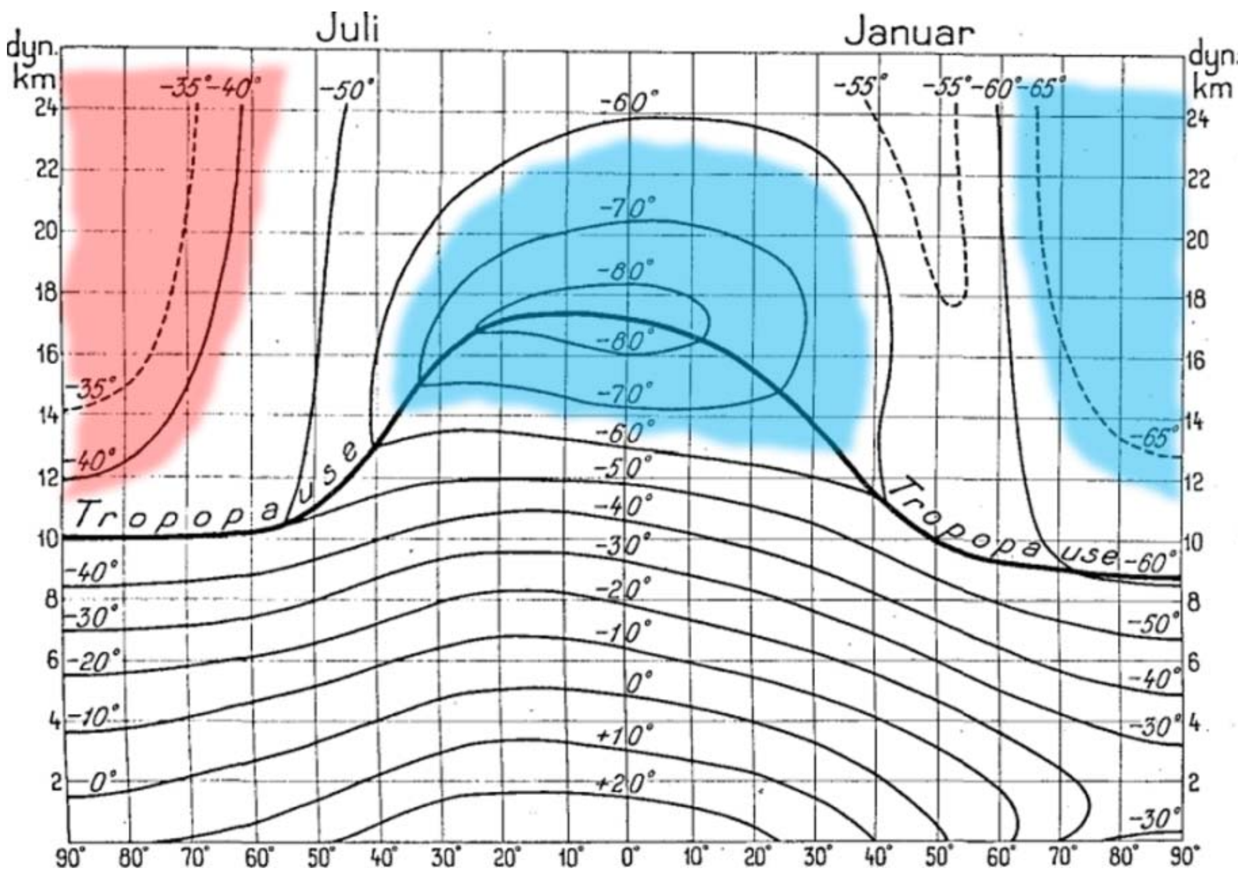


Figure 7. Palmén's representation of the climatological temperature in the Northern Hemisphere in July (left half) and January (right half). The contours are labeled in oC. I have added blue and red shading with the same meaning as in earlier figures, but I subjectively estimated the locations of the 210oK (-63oC) and 230oK (-43oC) boundaries. Reproduced by permission, see www.borntraeger-cramer.de/journals/metz.

Palmén used his insights on the high latitude stratospheric temperature to construct a height-latitude section of temperature appropriate for the Northern Hemisphere in July and January (Figure 7). While the earlier climatology presented by Shaw shocks modern meteorologists by its unrealistic stratosphere, Fig. 7 is actually surprising in its rather realistic depiction of the stratospheric temperature structure.

Palmén's work influenced a key contemporary work. The height-latitude climatology of the atmosphere was addressed in the landmark comprehensive (797 page) meteorology textbook Physikalische Hydrodynamik: Mit Anwendung auf die Dynamische Meteorologie (Physical Hydrodynamics Applied to Dynamical Meteorology) published in 1933 by an all star group of authors including Vilhelm and Jacob Bjerknes and Tor Bergeron. They (figures 112 and 113) show February and August zonal mean temperatures for the Northern Hemisphere up to 17 km, but poleward of 60° only include results up to about 8 km. However in their discussion they write

"The polar stratosphere has been virtually unexplored so far, but based on the recently published preliminary communication on the results of the registration balloon ascents in Abisko, we can conclude that in summer the stratospheric temperature also continues to increase polewards from 60°N, while in winter it decreases again from 60°N."

In 1937 the Japanese meteorologist Hidetaka Futi published a more complete climatology of stratospheric temperature. He shows diagrams with his best estimate of the climatological temperature for each calendar month, from the North Pole to 30°S (he used data from Pretoria at 26°S) and from the ground to 30 km altitude (although the actual observed soundings he used seem to have rarely extended above ~25 km). Futi's results throughout the year are quite realistic compared with modern climatologies.

Conclusion

The results of Palmén and Futi represented a beginning step, but a very important step, towards understanding the dynamics of the stratosphere. Notably they identified the correct meridional temperature gradients in both the summer and winter hemispheres and thus proved that there should be a mean westerly stratospheric winter circumpolar vortex, definitively disproving Shaw's model of mean easterlies at all latitudes. This set the scene for the more detailed understanding that would develop over the next two decades as determinations of the stratospheric winds became increasingly available – a story which I will relate in Part II.

Kevin Hamilton is Emeritus Professor of Atmospheric Sciences and retired Director of the International Pacific Research Center (IPRC) at the University of Hawaii. He has had a long career in academia and government including stints at McGill and the University of British Columbia in the 1980's. His main research interests have been in stratospheric dynamics and climate modeling, but he has also investigated aspects of the history of meteorology. He currently serves as an Editor of the journal History of Geo- and Space Sciences.

Early Exploration of the High Latitude Stratosphere Part II: Discovery of the Polar Night Jet Stream

WRITTEN BY CMOS BULLETIN SCMO ON AUGUST 23, 2022. POSTED IN ATMOSPHERE, PAST ISSUES, WHAT'S CURRENT.

– BY KEVIN HAMILTON –

Introduction

As shown in Part I, by the mid-1930's the basic climatology of stratospheric temperature up to ~30 km was understood. In the lower stratosphere a strong seasonal cycle of temperature at high latitudes was found, notably with a cold winter pole consistent with a westerly mean vertical shear and a circumpolar westerly vortex.

In his 1935 Symons Memorial Lecture English mathematician and physicist Francis Whipple noted a consequence of the newly found understanding of the temperature climatology, specifically that the horizontal pressure difference at 20 km between "England" and "Lapland" reversed in summer and winter, leading to expectation of mean geostrophic flow in the latitude band ~50o-70oN at this level that is easterly in summer and westerly in winter. He noted that this was consistent with observations during World War I that the sounds of battle in France were heard far to the west, near London, only in summer. Such long-distance propagation involves sound wave fronts that have refracted upward into the stratosphere and then back downward from the stratosphere to the ground; their propagation is sensitive to the stratospheric temperature and wind.

Over the next quarter-century this early insight would be refined into a detailed picture of the typical wind structure in the stratosphere through the annual cycle. This paper is devoted to a review of this progress in observing the stratospheric wind field, with a focus on the discovery of the polar night jet stream.

Very Early Direct Wind Observations in the Stratosphere

Before radio tracking techniques were developed, measurements of the wind high above the ground depended on optical theodolite tracking of balloons, and this only rarely allowed winds to be observed up to stratospheric levels. The English meteorologist Gordon Dobson (1920) seems to have been the first to systematically investigate the stratospheric winds. Dobson analyzed a total of 70 soundings from several European stations during the period 1904-1912 that featured (i) recovery of the registering sonde (and hence observation of the temperature profile and the location of the tropopause), and (ii) penetration above the tropopause, and (iii) theodolite tracking of the winds into the stratosphere. Dobson's result is reproduced here as Figure 1. Only 4 of these profiles extended above 22 km and almost all the profiles display peak winds near the tropopause and a rapid drop off with height in the first few km of the stratosphere.

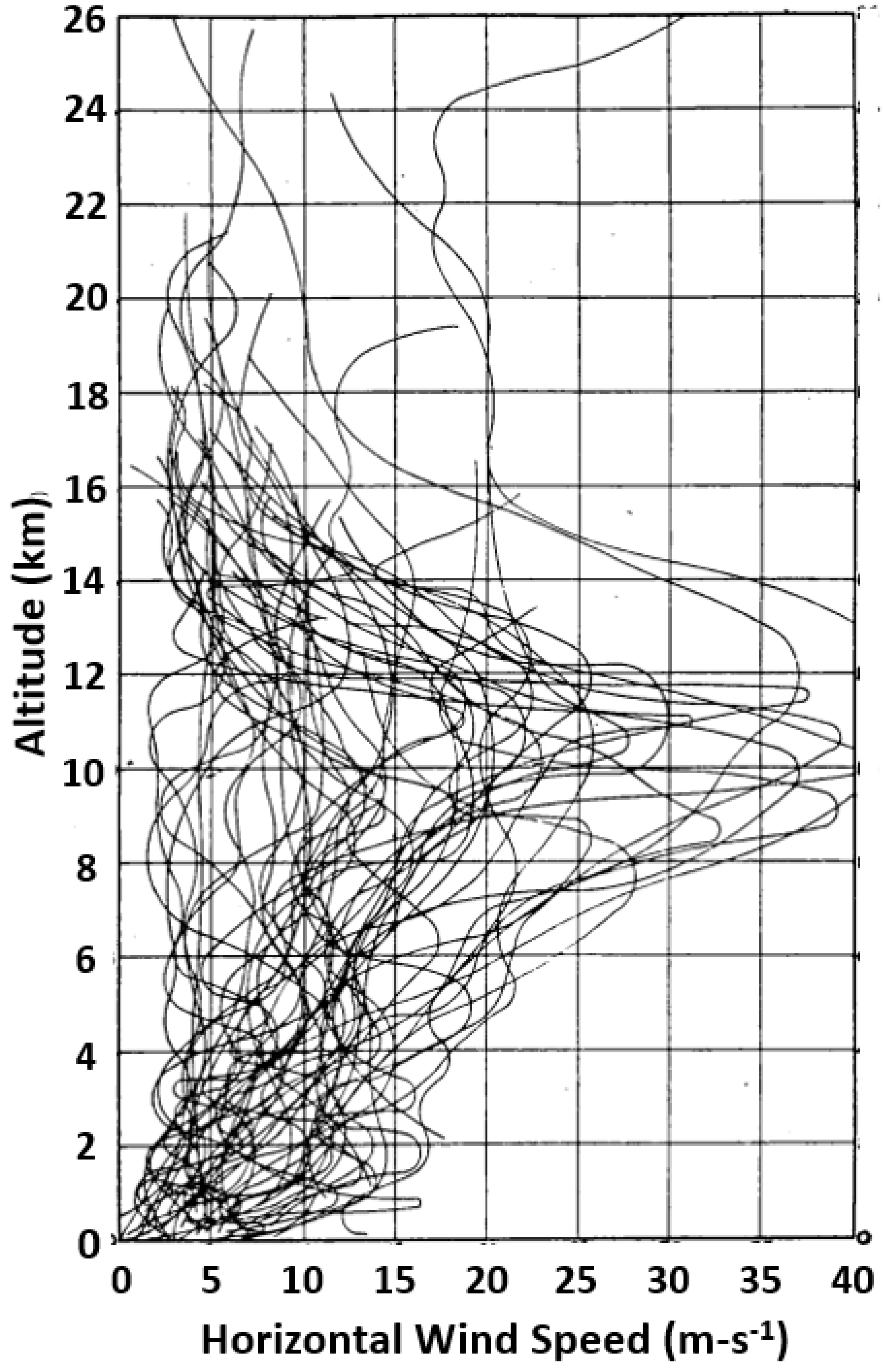


Figure 1. Individual profiles of horizontal wind speed as a function of height from 70 tracked sounding balloons at European locations during 1904-1912. Slightly modified from Dobson (1920).

Jet Streams

Today we are familiar with the idea that the large-scale atmospheric circulation typically features intense narrow currents or “jet streams” primarily aligned in the zonal direction. The recognition of the existence and significance of various jet streams in the atmosphere emerged over time. The atmospheric aerosol after the 1883 Krakatoa eruption in Indonesia was tracked as it circled the earth in a narrow region around the equator. An amateur scientist from Hawaii named Sereno Bishop within a year had coined the term “smoke stream” for this phenomenon. Today we know that this jet-like wind is characteristic of the equatorial stratosphere and Bishop arguably deserves credit for discovering the first “jet stream” in the atmosphere.

In the early decades of the 20th century there were scattered reports of strong midlatitude winds near tropopause levels measured by pilot balloons. Particularly notable were pilot balloon observations taken near Tokyo (36oN) by the Japanese meteorologist Wasuburo Ooishi in the early and mid-1920’s. He found that the winds near 10 km in winter were typically very strong westerlies, with one notable sounding in December 1924 showing a westerly wind of more than 70 m-s-1 at 9 km.

In the 1930’s knowledge of the winds in the upper troposphere began accumulating from observations during high altitude aircraft flights. In 1934 and 1935 the pioneer high-altitude aviator (and inventor of the pressurized flight suit) Wiley Post experienced wind speeds in excess of about 50 m-s-1 when flying in the upper troposphere over the US. In 1939 the German meteorologist Seilkopf noted strong winds measured around midtroposphere by aircraft in Europe and coined the term *strahlströmmung* (“jet flow”). In World War II the US military were surprised by the strong headwinds encountered by B-29 bombers as they flew high altitude missions to Japan. It appears that Rossby, then at the University of Chicago, originated the English language term “jet stream” for these very strong winds. During WWII Herbert Riehl, later a leader in the study of tropical meteorology, was a graduate student at the University of Chicago and a meteorology instructor for the US military. He later recalled that

“… we were most impressed by the news that B-29s sent westward to Tokyo became almost stationary over the target. [the term “jet stream”] first was used tentatively but soon was taken seriously, as it indicated not only the speed of the current but also the narrowness..[…].Once the word was out, of course, everyone started to calculate the geostrophic winds through the troposphere”.

Early Radiosonde Network at High Latitudes

Indeed the discovery of tropospheric jet streams in the early 1940’s drove much research in dynamical meteorology in the following years. For this purpose researchers could now use temperature soundings from the growing network of radiosonde stations supporting the international weather forecasting enterprise. As discussed in Part I the practical radiosonde was invented in 1930 but was not widely deployed for operational sounding until the late 1930's and 1940's. In the US, for example, an operational radiosonde network of roughly 20 stations was established in 1937.

Upon the entry of the US into World War II in 1941 there was a sudden interest on the part of the US military in aviation and weather forecasting in the Arctic. The US used airfields in Canada to support busy air routes through the eastern Canadian Arctic and then across the North Atlantic to Europe, and also through the western Canadian Arctic to connect the continental US with Alaska. Several upper air sounding stations were established in northern Canada and operated by either the Canadian Department of Transport or the US military. A list of stations and a summary of the data from these stations through 1947 was published as a Canadian government report by Henry and Armstrong in 1949. Twelve radiosonde stations were established at various times during 1942-1944, stretching meridionally from Churchill (59oN) to Arctic Bay (74oN). Pilot balloon observations of the wind were taken at most of these stations as well as at five additional Arctic stations. Almost none of the optically tracked pilot balloons provided data above 8 km and almost all the radiosonde temperature profiles terminated below 20 km. Despite the limited vertical coverage, data from these wartime stations would be critical for the next advances in establishing the climatology of the high latitude atmosphere as discussed below.

After the war the Canadian government took over the high latitude stations and most continued to collect data. Interest from the US military in the Canadian Arctic grew again in the early "cold war" years and in 1947 an agreement between the US and Canada was reached to establish an extended network of Arctic weather stations, a story told in detail by Heidt and Lackenbauer (2022). Quoting their book:

"Twice daily, for more than a quarter century, personnel at each of five Joint Arctic Weather Stations (JAWS) …[performed]… upper air observations. […] These isolated stations in Canada's High Arctic, established by the American and Canadian civilian weather bureaus in the decade after the Second World War, were jointly operated by both governments until the early 1970s."

The newly established JAWS stations were designed to cover very high latitudes and notably included Alert (82.5oN) on Ellesmere Island which, even today, remains the world's most northerly permanently inhabited settlement.

Geostrophic Wind Climatologies

Multiple years of wartime radiosonde temperature soundings at twelve stations near 80oW, stretching from Salinas, Equador (2oS) to Coral Harbour (64oN) and Arctic Bay (74oN), were used by the American meteorologist Seymour Hess (1948) to construct climatological meridional cross-sections of temperature and geostrophic zonal wind. His result for the geostrophic wind in winter is reproduced here as Figure 2. Most striking is the westerly maximum near 12 km altitude and 35oN. This showed that, while the tropospheric subtropical jet stream has significant day-to-day variability, it still manifests as a very clear localized wind speed maximum even in a long term mean. Hess apparently felt that poleward of 50oN his data supported plotting the geostrophic wind only up to about 15 or 16 km. With this restricted view one can discern only a hint of vertical shear consistent with a stratospheric high latitude westerly jet.

Also in 1948 Erik Palmén published a similar cross-section based on radiosonde results from stations in Cuba, eastern North America and Greenland.

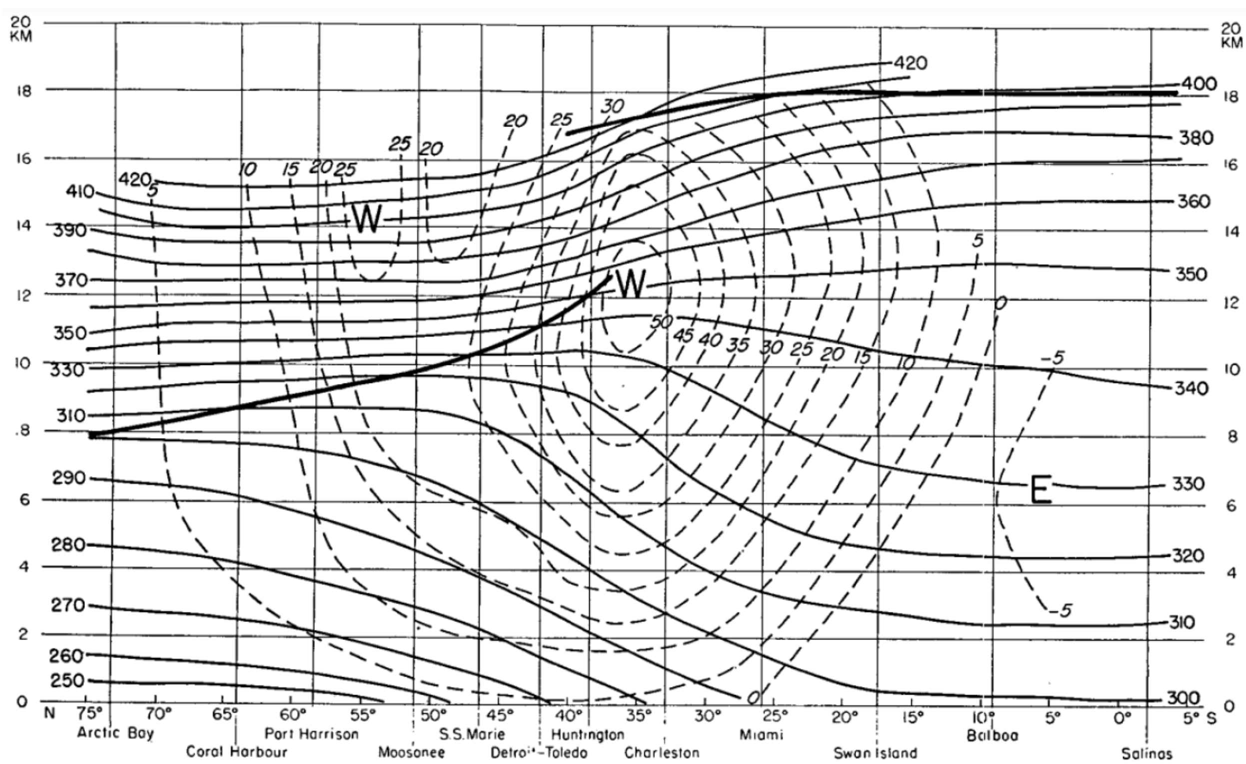


Figure 2. The January-February 1942-1945 mean potential temperature (solid contours) and geostrophic zonal wind (dashed contours, labeled in m-s-1). Results based on radiosonde temperature data at stations near 80oW and stretching between 2oS and 74oN. Reproduced from Hess (1948). American Meteorological Society by permission.

Henry and Armstrong's 1949 report on high latitude Canadian observations notes that *"the overwhelming majority of the upper wind observations in this report are pilot-balloon ascents. In a few years time when a sufficient quantity of radio-wind data is available, it should be possible to obtain a better picture of wind […] at the higher levels."* Here they reference an important revolution then occurring in the technology of balloon meteorological measurements. The use of steerable directional antennas to track balloon borne radiosondes allowed balloon temperature and pressure data to be obtained up to higher altitudes as well as for the balloon elevation and azimuth to be observed to higher levels (and even during poor visibility conditions). The winds measured in this manner became known as “rawinds” and the measuring system a ”rawinsonde”.

The improved geographical and altitude coverage of the radiosonde network particularly beginning in the late 1940’s allowed the American meteorologist Adam Kochanski (1955) to revisit the 80oW meridional section using data from 1948-1951. For this period Kochanski notes that data from 17 stations stretching from Panama (9oN) to Alert (82.5oN) were available. Kochanski’s result for the January climatology of geostrophic zonal wind is shown here as Figure 3. This represents an improvement over Hess’s earlier results, particularly in the high latitude stratosphere where the climatology is provided up to 30 km and all the way to the pole. Noteworthy was the clear indication of a strong westerly climatological jet peaking at or above 30 km with maximum speed of more than 80 knots (~41 m-s-1). Kochanski referred to this as the *“polar-night maximum […] in the middle stratosphere”*.

While his high latitude results are fairly realistic, Kochanski’s plot for the tropical and subtropical stratosphere agrees rather poorly with more modern determinations of the zonal wind climatology in the winter hemisphere. Kochanski was at a disadvantage back in 1955, of course, as the equatorial quasibiennial oscillation would not be discovered until 1961.

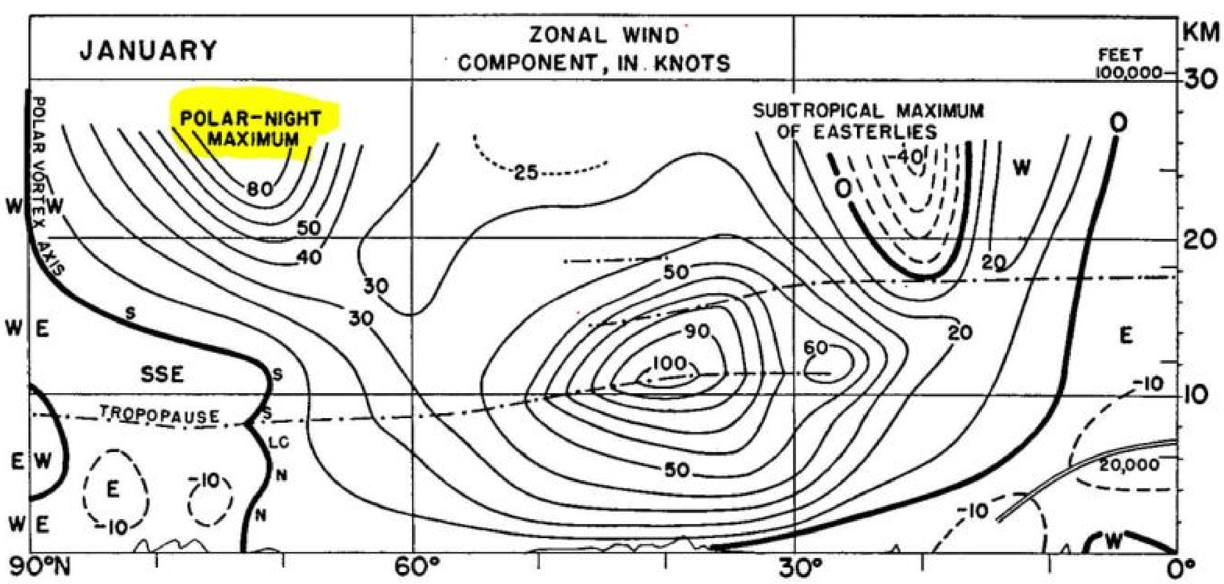


Figure 3. The four year (1949-1952) climatological January mean geostropic zonal wind in the Northern Hemisphere. Reproduced from Kochanski (1955). American Meteorological Society by permission.

Using Radio Wind Data

The US military led the development of the technology of radio-tracked weather balloons. Key developments in the late 1940’s were made at the US Army Signal Corps Laboratory in New Jersey. Notably by 1948 they had working versions of the steerable parabolic antenna system later known as GMD-1. Over the next decade GMD-1 would become a standard for most US military and civilian systems and it was confirmed that it produced quite accurate wind determinations. In 1950 C.J. Brasefield of the Signal Corps Laboratory wrote a paper reporting on 20 radiosonde flights using their new technology to measure winds and temperatures up to as high as 35 km at Belmar, New Jersey (42oN) during July 1948-April 1949. He notes that between ~17 and 35 km the prevailing winds displayed a notable seasonal cycle:

“Between 60,000 ft and 120,000 ft, the winds were easterly during the summer and westerly during the winter. […] Usually the wind speed was still increasing at the bursting altitude of the balloon. These results are consistent with the existence of a stratospheric circumpolar vortex which is cyclonic in winter, anticyclonic in summer. The fragmentary wind data obtained from these flights at high altitudes suggest the possible existence of a stratospheric jet stream in middle latitudes.”

Although Brasefield had very limited data just from just one midlatitude site he successfully intuited key features of the circulation of the extratropical stratosphere, notably suggesting that the circulation might feature a “stratospheric jet stream”.

With a growing network of weather stations featuring radio-tracked rawinsonde measurements, it became practical to characterize the stratospheric circulation using direct wind observations. Warren Godson of the Canadian Meteorological Service and his colleague Roy Lee analysed the Canadian wind observations at high latitudes. They published their results in two important papers: Lee and Godson (1957) and a 1958 paper by Godson and Lee (which is not currently available online) titled “High level fields of wind and temperature over the Canadian Arctic” (volume 31 of the journal *Beiträge zur Physik der Atmosphäre*).

Lee and Godson (1957) describe their project in their abstract:

“The existence of an Arctic stratospheric jet stream in winter, hitherto largely inferred from mean geostrophic wind sections, is considered on the basis of actual winds for the Canadian Arctic area during the winter of 1955-1956.”

Lee and Godson examined the instantaneous winds on a few selected days during the winter. They noted that the jets that they saw were not aligned exactly zonally and they used the available data to characterize the component of the wind parallel to the jet axis. Figure 4 shows an example from their 1957 paper. The contours are for the north-west component of the wind plotted as a function of distance along the chain of stations shown from Alert (82.5oN, 62oW) at the left to Norman Wells (65oN, 127oW) on the right, i.e. on a rough northeast-southwest section stretching 2500 km. Here I have combined a map identifying the individual stations with the contour plot of the wind. I have added shading to distinguish regions with north-west winds greater than 40 knots and greater than 100 knots (deep shading). This approach allowed Godson to depict the winds in the core of the jet stream as they appear in an instantaneous snapshot.

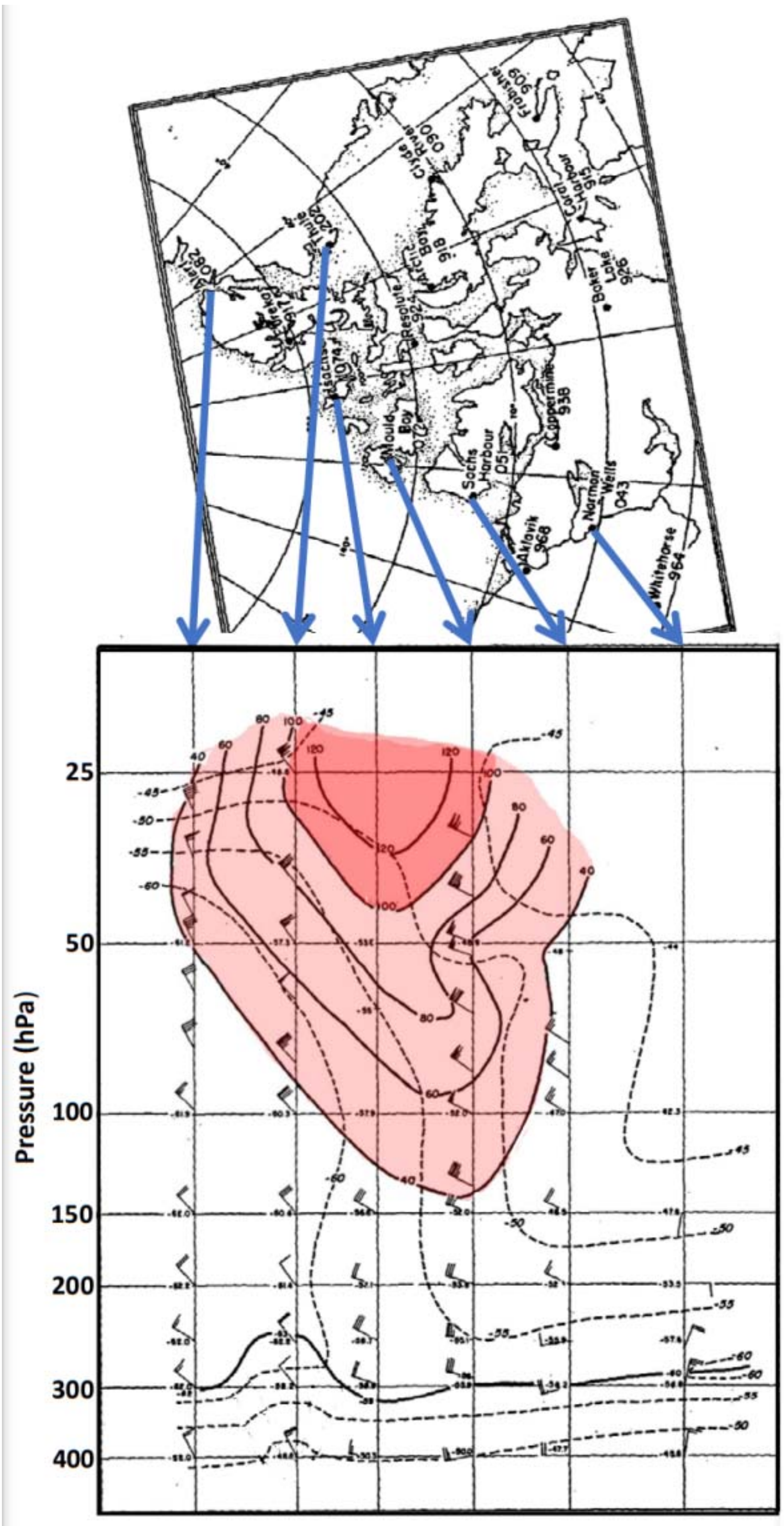


Figure 4. The solid contours in the lower panel show the north-west component of the wind observed at 0300 GMT on March 26, 1957. The contours are based on radio tracked balloon

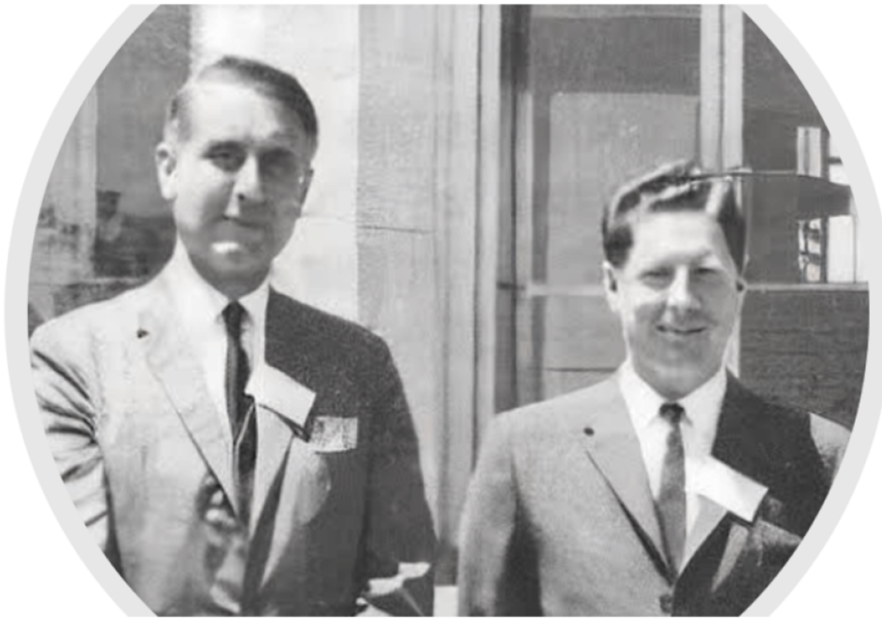
rawinds at six stations in the Canadian Arctic as shown on the map in the upper panel and aligned roughly northeast (left) to southwest (right). The colour shading shows regions with north-west winds exceeding 40 knots (100 knots for the deeper shading). Also shown are dashed temperature contours. Adapted from Lee and Godson (1957). American Meteorological Society by permission.

In the second paper Godson and Lee (1958) extended their analysis over three winters. They focused on both describing the typical structure of the jet revealed in their data as well as the intraseasonal and interannual variability that is apparent. Quoting their conclusions:

“Vertical cross-sections of the Arctic stratospheric jet stream are presented to show its vertical structure. It is generally found at around 70-75oN although pronounced meridional movements result in its occurrence as far south as 50oN. Maximum wind speeds occur above 50 mb and occasionally exceed 230 kt. The rapid-warming epoch in 1957 was the most spectacular at very high levels (Frobisher reported an increase in 25 mb temperature of 34oC in 24 hours). Vertical time-sections of temperature have revealed major differences in the structure of these warming periods, whose dynamic processes are undoubtedly exceedingly complex”.

The Godson and Lee (1958) paper refers to Richard Scherhag’s pioneering 1952 work on sudden midwinter stratospheric warming which Scherhag saw in Berlin radiosondes, and which he had named the “Berlin phenomenon”. However, Godson and Lee went well beyond Scherhag’s work in characterizing the warmings and the associated changes in the polar vortex. It is noteworthy that the earlier Lee and Godson (1957) paper is cited in a well known and somewhat parallel 1958 analysis of the sudden warming phenomenon by US Weather Bureau scientists Sidney Teweles and Fred Finger.

The papers of Godson and Lee were cited as motivation in several interesting papers that appeared in the next couple of years. Krishnamurti (1959) wrote a paper titled “A vertical cross section through the “polar-night” jet stream” showing a similar analysis as in the Godson papers, but based on data in a 4-day period (December 31, 1957-January 3, 1958) and presenting more detailed analysis, including a plot of the potential vorticity in a section across the jet axis. Palmer (1959) wrote a paper on observations the winter polar stratospheric vortex including a comparison of the situation in the Arctic and Antarctic. The question of whether the polar night jet is baroclinically unstable was addressed by Murray (1960), and Murray’s paper helped inspire one of the all-time most famous papers in the field of geophysical fluid dynamics, namely the study of the necessary conditions for baroclinic instability by Charney and Stern (1962).



Left: F. Kenneth "Ken" Hare (1919-2002). Right: Byron W. "Barney" Boville (1921-2001). Photo from 1961 courtesy of the McGill Department of Atmospheric and Oceanic Sciences

Blooming Interest in Polar Stratosphere Research

The initial papers on the polar night jet opened an era of enhanced interest in the dynamics of the polar stratosphere and Canadian scientists and institutions would take the lead. Notably McGill University's researchers led by professors Ken Hare and Byron W. Boville would continue with observational studies of the circulation in the polar stratosphere. McGill's biennial "Stanstead Seminar" series, founded by Hare in 1955, would become a leading venue for discussing developments in stratospheric research. The 1963 Seminar was titled "The Stratosphere and Mesosphere and Polar Meteorology" and attracted an international group of outstanding researchers. The 1965 Stanstead Seminar was titled "The Middle Atmosphere". Hare's introduction to the 1963 proceedings volume included his perspective on recent history:

"In 1959 when we first devoted the Seminar in part to stratospheric questions, research at such levels was something of a novelty. The McGill group felt itself to be among pioneers. Four years later all is changed. Stratospheric and mesospheric problems occupy the centre of the stage."

The research at McGill in the early 1960's would provide important empirical input into seminal work on stratospheric dynamics over the subsequent decade. I will mention here two notable examples. First the classic 1970 paper of Taroh Matsuno formulating a numerical model of stationary Rossby waves in the extratropical stratosphere includes as motivation references to three of Boville's observational papers (1960, 1963, 1966). In 1971 Matsuno generalized his 1970 model and made the fundamental discovery of the mechanism of stratospheric sudden warmings. Then Jim Holton in his 1975 pioneering monograph *The Dynamic Meteorology of the Stratosphere and Mesosphere* includes a version of a figure prepared by Hare showing a polar projection of the long term mean January and July 30 hPa heights (reproduced here as Figure 5). This served as the fundamental observational background to Holton’s discussion of stratospheric quasi-stationary Rossby waves.

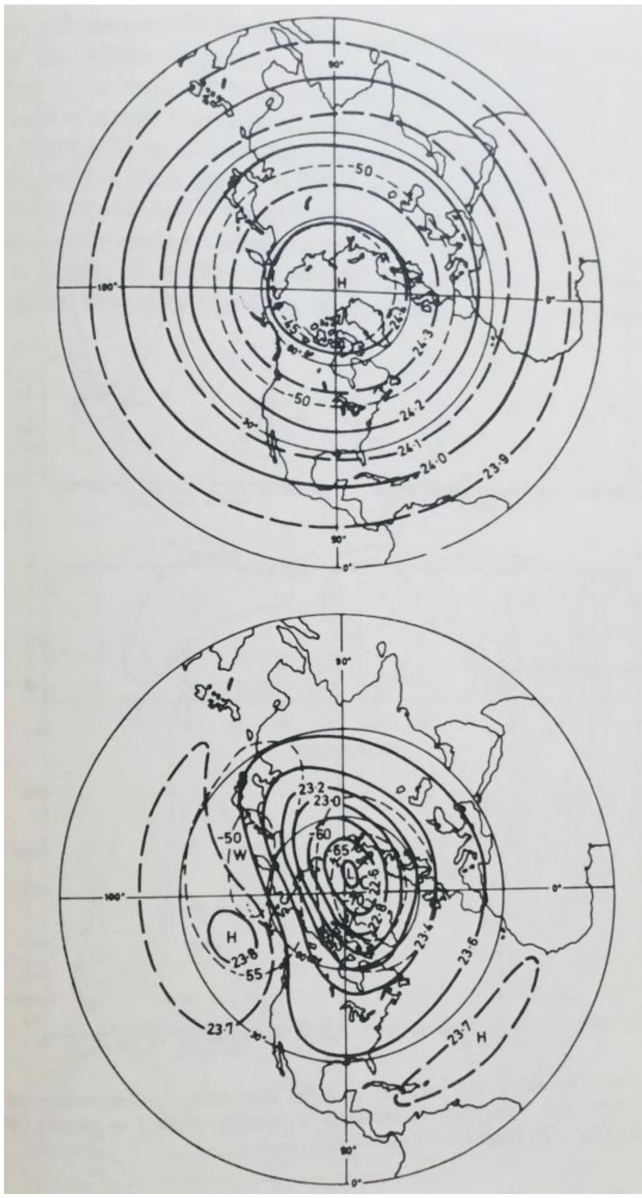


Figure 5. The long-term July (top) and January (bottom) mean 30 hPa geopotential heights over the Northern Hemisphere based on results from Ken Hare. Contours labelled in km. Reproduced from Holton (1975). American Meteorological Society by permission.

The term “Polar Night Jet (Stream)”

It is difficult to identify a precise moment of discovery for the stratospheric polar night jet stream phenomenon. But what about the name “polar night jet/polar night jet stream”? My survey of the literature shows that the term was probably unknown before about 1957 but quickly became popular, so that by 1960 it had become a standard piece of meteorological nomenclature and had even appeared in the popular media. As noted earlier, the two key pioneering papers of 1955-1957 did not use the term: Kochanski (1955) referring to a “polar night maximum” and Lee and Godson (1957) referring to the “Arctic stratospheric jet stream”. Krishnamurti (1959) may be the first journal article with “polar-night jet stream” in the title.

Remarkably, the newly discovered phenomenon was referred to in an article meant for the general public in the April 1958 issue of Popular Mechanics. The article discussed recent developments in weather forecasting and mainly focused on tropospheric jet streams. However it also notes that *“the most recently discovered planetary wind band, dubbed the polar night jet, flows around earth 80,000 feet above the Arctic circle”* and even displayed a schematic diagram of the Northern Hemisphere atmosphere including a depiction of the polar night jet.

I evaluated the evolving popularity of the term “polar night jet (stream)” using the google “ngram viewer” application. The ngram and its application to studying the history of science is described in more detail here. The ngram viewer analyzes the entirety of the digitized documents available to Google Books and determines the frequency of use for any given phrase in individual calendar years. Specifically ngram produces a measure of the ratio of pages containing the phrase to the total number of pages of text available in that year. Figure 6 shows the yearly ngram measures for the phrase “polar night jet”. The ngram viewer results are known to have issues with errors in the optical character recognition procedures and with misdating of documents – and so the results can be noisy. In any event Fig. 6 shows vividly the growth in popularity of the concept of the polar night jet in the late 1950’s and early 1960’s.

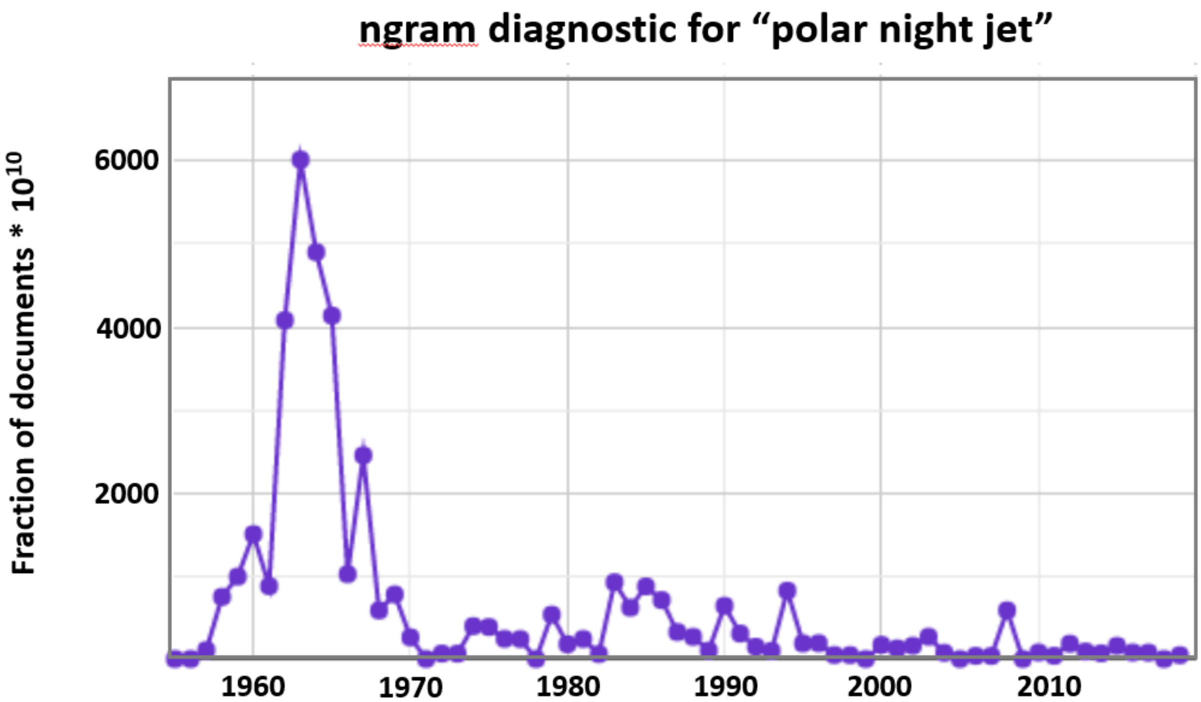


Figure 6. The Google ngram measure of the frequency of the occurrence of the character string "polar night jet" in all the documents in Google Books each year from 1955 through 2019.

To the Present Day

The term "polar night jet" or "polar night jet stream" is still widely used and is introduced to students in today's standard textbook of stratospheric meteorology. The term may seem slightly dated or potentially misleading for some students, however, as it may suggest a jet that is anchored to the edge of the polar night, while the real jet is, of course, much more dynamic. Indeed the declining word count (Fig. 6) may reflect a modern tendency to consider the stratospheric polar vortex as a whole as a region of high potential vorticity, rather than focusing on the jet-like wind maximum. However, the term "polar night jet" is still quite evocative – one readily imagines a ring of powerful winds streaming high above the ground in the polar darkness – and in 2020 it even inspired an electronic music composition by the Estonian musician Lauri-Dag Tüür.

Kevin Hamilton is Emeritus Professor of Atmospheric Sciences and retired Director of the International Pacific Research Center (IPRC) at the University of Hawaii. He has had a long career in academia and government including stints at McGill and the University of British Columbia in the 1980's. His main research interests have been in stratospheric *dynamics and climate modeling, but he has also investigated aspects of the history of meteorology. He currently serves as an Editor of the journal History of Geo- and Space Sciences.*

Recap: PRODIGY field school on Quadra Island

WRITTEN BY CMOS BULLETIN SCMO ON SEPTEMBER 1, 2022. POSTED IN NEWS & EVENTS, OCEANS, WHAT'S CURRENT.

– By Isabelle Lao –

In May 2022, leading faculty from the University of British Columbia (UBC), Victoria (UVic), and Waterloo (UWaterloo) held a weeklong field school at the Hakai Coastal Ecological Observatory on Quadra Island as a part of the Pacific Rim Ocean Data Mobilization and Technology (PRODIGY) field school.

Image 1: Becca Beutel from UBC working on her team's sensor.

PRODIGY is a joint program led by 11 principal investigators with expertise ranging from geophysics to oceanography, statistics, and computer science. As Program Director, Dr. Philippe Tortell, describes, "PRODIGY's purpose is to provide students with unique, value-added training and research opportunities, not just in academia but also within industry, government and NGO sectors." Through the Natural Sciences and Engineering

Research Council of Canada Collaborative Research and Training Experience (NSERC-CREATE) program, PRODIGY provides training to graduate students across the entire ocean-data life cycle: deploying and testing new ocean sensors, data analysis and assimilation, numerical modeling and forecasting, and engaging decision-makers and stakeholders to drive data-informed ocean policy and management.

Leading up to the field school, students participated in a semester-long ocean data course with a different thematic focus and instructor each week. While most of the topics concerned data analysis techniques, the field school was an opportunity to explore an area that most students did not have a lot of experience in: instrumentation.

Image 2: Carmen Holmes-smith from UVic deploying her group's home-made wave measurement buoy using a kayak.

Led by Dr. Rich Pawlowicz from UBC, students explored the ocean data life cycle from acquisition to analysis and communication. Working in groups, students began by proposing a sensor then programmed them using Arduinos to deploy in the field. As noted by Dr. Susan Allen, "what you want to measure is different from what you're actually measuring" for many of the sensors, posing a challenge to students. As an example, seawater salinity measurements are actually based on direct measurement of electrical conductivity. This requires appropriate calibration and quality-control measures. Each student group had to address these complexities, disentangling the influence of measurement noise and calibration issues against true environmental variability. For example, a group that made a seismograph picked up a lot of noise from incoming ferries.

The group projects ranged from measuring the height of waves to the turbidity of water. Ocean Light Group member, Birgit Rogalla, says that she enjoyed working with her hands, and learned a lot about troubleshooting sensors when they calibrated their nephelometer. Her group was successfully able to submerge their home-made nephelometer 8 meters into the water, with design help from Sam Stevens. PhD student Shumin Li designed a wave buoy with his group to measure wave height and frequency using accelerometer sensors and a lab drifter. He recalls encountering significant challenges with a similar project in his undergraduate studies, and was excited by his group's success this time around due to the collaboration and guidance from his group members and instructors.

Image 3: Team working together on the design and programming of a home-made seismometer.

The week culminated in presentations from each group where they demonstrated their findings: what worked, what didn't work, and most importantly what they learned. As one of the first field school undertakings after the pandemic, many participants commented on the excitement and energy of working with people in person. Dr. Allen recalls watching the students communicate patiently with one another, collaborate, and build relationships, all while having fun.

With all the learnings of the first field school, PRODIGY is still only a new program with five years still to go in the project timeline. Additionally, this project includes a formal collaboration with faculty and students at the Universidad de Concepción in Chile, working to examine similar processes in the coastal features of British Columbia andChile, including deoxygenation, acidification and seismic hazards. In January, a second field school will be conducted at the Millenium Institute of Oceanography in Chile with members of the Quadra cohort as well as the second cohort. As Dr. Tortell summarizes very succinctly, ‘To use ocean resources properly, we need people who are high level objective thinkers’ and this is exactly what PRODIGY has set out to do, by equipping students with the ability to conceptualize the data they need, design and deploy appropriate sensors to collect observations, and then use the data and associated models to support sustainable use of ocean resources.

Image 4: Group photo of PRODIGY instructors and participants.

This article was written by Isabelle Lao with interviews and input from Dr. Philippe Tortell, Dr. Susan Allen, Dr. Rich Pawlowicz, Birgit Rogalla, and Shumin Li.

***Isabelle Lao** is the Bulletin Editor for the Canadian Meteorological and Oceanographic Society. She received her BSc from the University of British Columbia in 2021 with a degree in Chemistry and Oceanography. She currently works at the Pacific Climate Impacts Consortium as a Climate Data Analyst.*

Ocean Decade Community of Practice

WRITTEN BY CMOS BULLETIN SCMO ON SEPTEMBER 6, 2022. POSTED IN CLIMATE, MEMBERS, NEWS & EVENTS, OCEANS, WHAT'S CURRENT.

– By Jia Yi Fan –

The United Nations Decade of Ocean Science for Sustainable Development (referred to as Ocean Decade) is an effort to catalyze action and innovation in order to achieve "the science we need for the ocean we want." Marine Environmental Observation, Prediction and Response Network (MEOPAR) responded to this need in early 2021 by working with partners to mobilize a Community of Practice dedicated to supporting Canadian action under the Ocean Decade, starting with focusing on improving access to information and stimulating collaboration.

What We Do

- Help connect networks as well as individual researchers and marine science practitioners
- Initiate unique and innovative activities to address Decade Outcome and Challenge Areas
- Support leadership and organization, to recruit & attract membership

Who Can Join?

- Institutions
- University-based research centers
- Industry

- Non-profit organizations
- Government/community/individual researchers at all stages of their careers and education

Current activities

Science-Art Symbiosis

This CoP has been exploring the practice of science-art to inspire future creations by the network, to be showcased at the MEOPAR Annual Meeting on November 24, 2022, and beyond. Developed by interdisciplinary scientist Samantha Jones, these activities aim to engage diverse participation across the network and center the science-art practices of diverse folks. No previous experience with art is necessary.

These endorsed Ocean Decade activities align with the UN Decade of Ocean Science for Sustainable Development Challenge 10: Change humanity's relationship with the ocean and Outcome 7: An inspiring and engaging ocean. Ocean literacy and communicating the value of the oceans is important for knowledge mobilization and to inspire people to get involved.

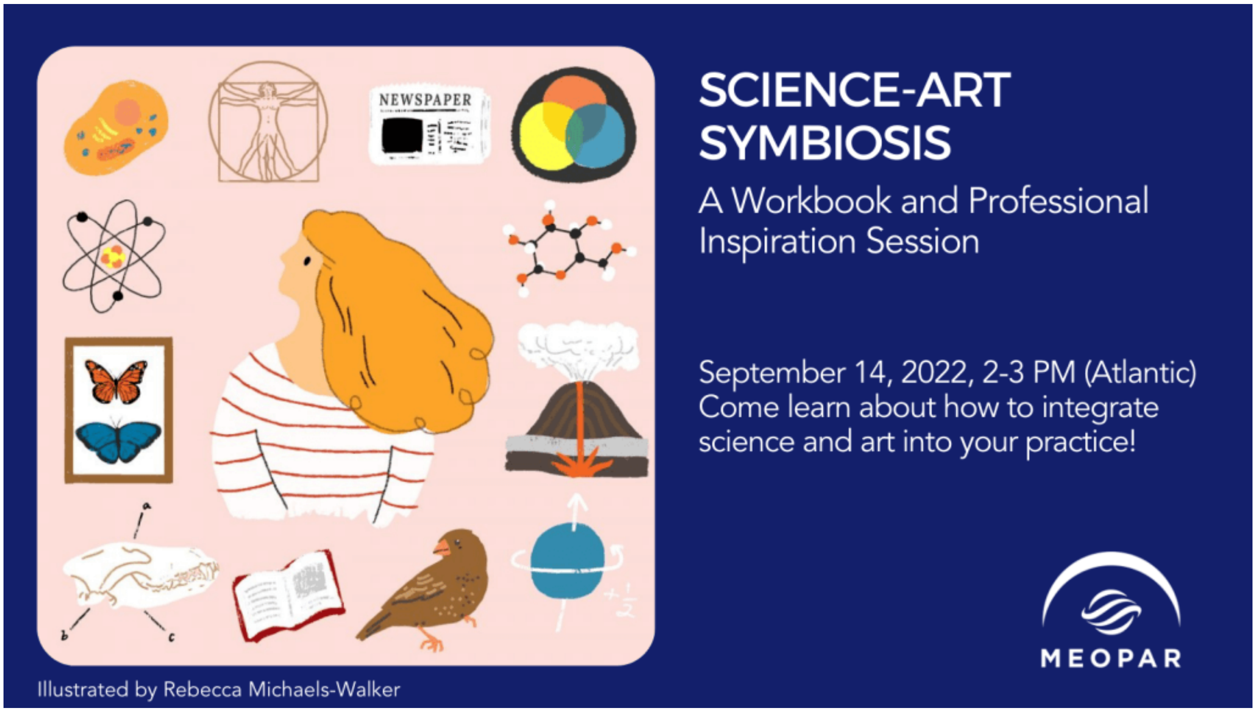
Important dates

- August 16, 2022: Workbook released
- September 14, 2022, 2-3 PM AT: Professional Inspiration Session

Science-Art Showcase

- September 30, 2022: Deadline for expression of interest
- October 31, 2022: Deadline for artwork submission

- November 24, 2022, 3:30-5:00PM AT: Artworks revealed



Ocean Decade Inventory

Following two Town Halls held to engage Canadian researchers and practitioners on the Ocean Decade, one issue stood out: there is too much to be done in a decade to duplicate efforts, but how do we know who is working on what?

In response to this need, the Ocean Decade Community of Practice is building an accessible inventory to help connect individuals and organizations working in similar fields, with similar needs, or similar projects under the Ocean Decade. The searchable database will be a one-stop shop, allowing people to query projects, organizations and individuals and filter results by location, challenge, outcome addressed, etc. This is a foundational step towards breaking down silos, addressing gaps and forming actionable solutions for the ocean we want.

This tool will lend a hand in driving Fisheries and Oceans Canada's (DFO) National Ocean Decade Implementation Strategy and support the Outcome Area Champions in forming strong networks of networks.

Are you working on Ocean Decade-related projects or know someone who is? Are you looking to get involved on Ocean Decade projects? Or have an idea of your own, but are unsure where to start? The Ocean Decade CoP wants to add you to our contact's inventory! You can help by completing this 5-minute survey.

Want to shape the future of this CoP? Consider joining the Steering Committee as a Member or a Co-lead. Applications are accepted on a rolling-basis until all positions are filled.

Stay updated on news and engagement opportunities with the Ocean Decade Community of Practice by joining our mailing list here.

Questions? Contact Jia Yi, the Ocean Decade CoP Coordinator at jiayi.fan[at]meopar.ca

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***Jia Yi Fan** (she/her) is the Ocean Decade Community of Practice (CoP) Coordinator and Research Associate - CoPs at the Marine Environmental Observation Prediction & Response Network (MEOPAR). Jia Yi is an Environmental Science professional with experience in GIS & Remote Sensing, fieldwork and social justice. She holds a BSc (Hons) in Environment from McGill and a MEnvSc from the University of Toronto. She is passionate about mapping, biogeochemistry, and ecotoxicology.*

Cold fingers: A potential new salt transport process under lake ice

WRITTEN BY CMOS BULLETIN SCMO ON SEPTEMBER 12, 2022. POSTED IN WHAT'S CURRENT.

– By Jason Olsthoorn –

Introduction

The more we look under lake ice, the more unexpected things we find. Recent field campaigns have shown that photoplankton levels under lake ice can be almost as high as their peak summer values! Similarly, sunlight penetrating through ice and snow can cause thermal plumes that mix down to the bottom of even large lakes. What other unexpected processes are happening below the ice during winter?

The water under ice is usually density stratified. This stratification determines how much oxygen and other nutrients transport to the bottom of lakes, possibly controlling if the bottom water becomes hypoxic. The *thermal* stratification present before ice formation sets the stage for the rest of winter. In addition, *salinity* **can also contribute to the density stratification. While most Canadian lakes are fresh ($S \approx 0.2$ g / kg), a small amount of salt can have a big effect on the stratification, especially in deep lakes.**

If the salt stratification is large enough, it can prevent complete mixing of the lake each year.

During the winter, there are few processes that specifically transport salt. Sediment respiration, proposed by Mortimer and Mackereth (1958), would increase the salinity at the lake bottom, forming gravity currents that flow towards the deepest part of the lake. This is a *bottom-up* process. Are there other salt-transport processes and how important are they?

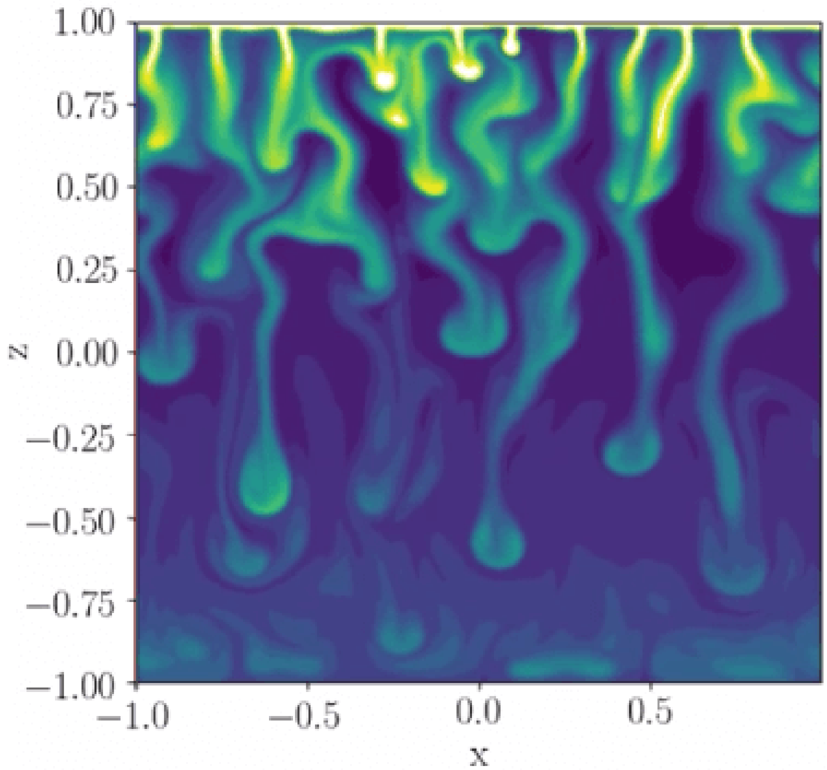

Figure 1 -- Saline plumes resulting from a surface salt flux and a stable temperature stratification.

Our Model

When lake ice forms, it will reject contaminants, such as salts, into the water below. In collaboration with Dr. Cynthia Bluteau (U. Rimouski), Dr. Ted Tedford (UBC), and Dr. Greg Lawrence (UBC), we have shown that salt exclusion will lead to an increase in salinity under ice. This is a *top-down* process where salinity increases at the ice-water interface.

Both temperature and salinity affect the density under ice. The ice-rejected salt increases the fluid density, and, independent of anything else, would drive downward convection. However, temperature under the ice is stably stratified, meaning it can compensate for the extra mass of the salts. In this case, salt and temperature have opposing contributions to the fluid density. If there is enough salt in the water, and the lake-ice forms quickly enough, the water salinity will overwhelm the temperature stratification and the salt-exclusion will result in under-ice convection. However, most Canadian lakes are not very salty. What happens if temperature dominates the water density?

It turns out that heat and salt diffuse at different rates. These different diffusion rates can result
in what are known as Double Diffusive Instabilities. Using a simple numerical model and assuming a fixed salt flux from the ice, we showed that salt-exclusion forms double-

diffusive plumes that are able to transport the saline water from the ice to the lake bottom, even if the sable temperature stratification controls the density. Our model predicted what these model plumes would look like and their effect on the vertical transport of heat.

To show that these saline plumes would happen in a real system, we performed laboratory experiments in a walk-in freezer, using a tank that was filled with 50cm× 50cm × 20cm of water. If the water we used was distilled, we did not observe any salt plumes forming under the growing surface ice. However, even for salinities as low as S = 0.02 g / kg, we were able to visualize salt fingers growing after a few hours. Because of the relatively small volume of water, the water did freeze faster than natural lake ice would grow, but controlling for the relevant parameters, we predict that we would find similar salt plumes in most Canadian lakes.

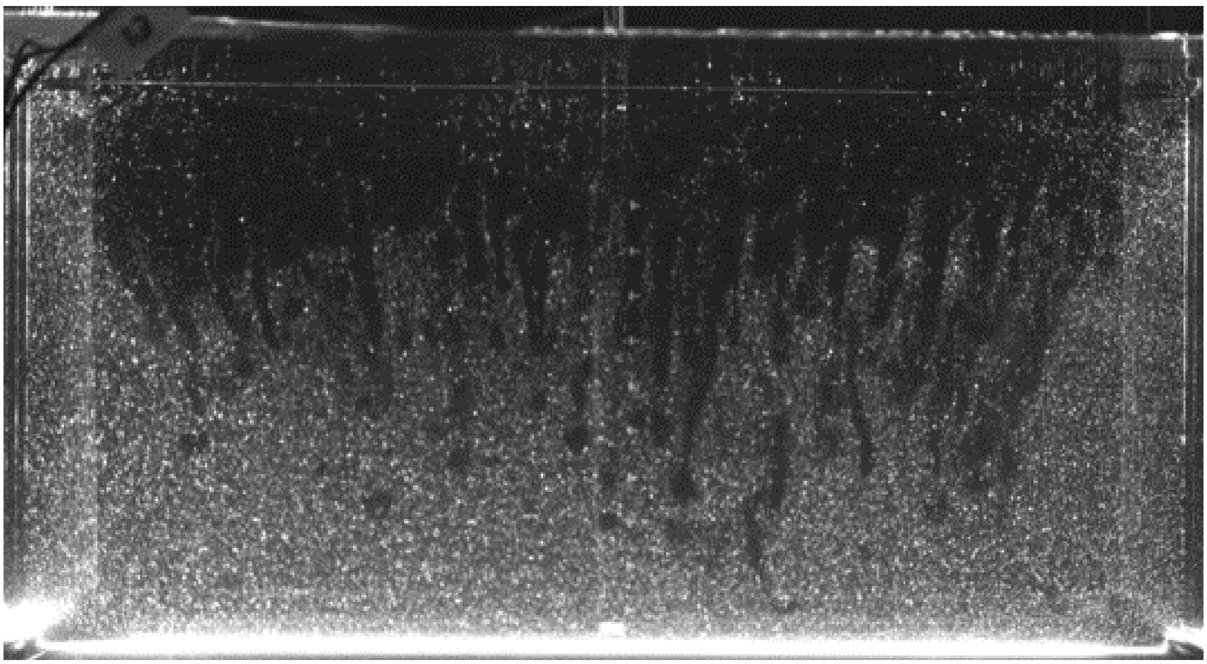

Figure 2 -- Raw camera image of the saline plumes forming under ice in a laboratory experiment. Light reflecting particles were added for computing the velocity.

Does this happen in real lakes?

To our knowledge, no one has yet found salt plumes under lake ice. But this is not necessarily surprising given the complexities and sparseness of under-ice field measurements. In addition, these saline plumes transport salt, but they do not significantly mix the under-ice temperature stratification.

That said, we can estimate the mean ice growth for an average Boreal lake (50cm / Winter). Combining this with a global estimate for lake salinity and a guess at the under-ice temperature stratification, we estimate that most lakes are susceptible to these saline plumes for some portion of the year. This is particularly true at the start of the year, when ice grows quickest.

We can measure the salinity under lake ice, and we can show that it often increases over the winter. Is that a result of salt-exclusion, sediment respiration, or some other process that hasn't yet been discovered? The verdict is still out, but I have a preference.

Relevant Papers

Olsthoorn, J., Bluteau, C.E. and Lawrence, G.A. (2020), Under-ice salinity transport in low-salinity waterbodies. Limnol Oceanogr, 65: 247-259. https://doi.org/10.1002/lno.11295

Olsthoorn, J., Tedford, E.W.. and Lawrence, G.A. Salt-fingering in seasonally ice-covered lakes. GRL. Under Review.

Dr. Jason Olsthoorn *is an Assistant Professor at Queen's University, where he models mixing and transport processes that occur in Canadian lakes. He recently completed his Killam Postdoctoral Fellowship at UBC, after completing his PhD at the University of Cambridge. He loves to cook, which may explain his fascination with salt.*

Future ocean changes: What can ecosystem models tell us?

WRITTEN BY CMOS BULLETIN SCMO ON SEPTEMBER 26, 2022. POSTED IN CLIMATE, OCEANS, WHAT'S CURRENT.

– By Andrea Bryndum-Buchholz –

Climate change is impacting all aspects of life across the globe. Oceans are becoming warmer and more acidic causing a cascade of consequences for marine life — heightened mortality, reduced calcification, and shifts in the distribution of species are just some of the major changes that are already being observed. For example, the survival of calcifying species such as mussels, corals, even some plankton species is threatened because with increasing ocean acidity these species are less and less able to build their shells or skeletons. Other, more mobile species, such as pelagic fish or whales are moving towards habitats that are more suitable for their survival, changing overall species biomass and abundance patterns. This, in turn, can affect fisheries catches and revenue, leading to negative consequences for coastal livelihoods and well-being.

The global nature of climate change requires a global overview and understanding of future ocean responses and consequences for human livelihoods and well-being. Ecosystem models can be one tool to do just that. Ecosystem models can help to explore future responses in marine ecosystems and fisheries, from local to global scales, to ongoing climate change which can guide decision-making in ocean resource management and conservation.

By definition, an ecosystem model, is "a mathematical representation of an ecological system. It is a simplified form of a highly complex ecosystem in the real world. The ecological system can range in scale from an individual population to an ecological community, or even an entire biome." Not all aspects can be included in models, thus each model represents only specific aspects of the ecosystem and does not capture all processes present within the system. In other words, individual ecosystem models consist of model-specific building blocks, such as species types (e.g., plankton, crabs, fish, mammals), species size classes (e.g., small, medium, large species), or functional groups (e.g., pelagic, benthic, demersal, consumers, producers). This is why each ecosystem model vary in their response to changing environmental conditions.

Combining multiple ecosystem models into an ensemble can provide a more comprehensive picture of ecosystem processes; it also allows for model advancements because individual models, which are driven by standardized input data, can be compared and assessed in terms of why projections differ due to e.g., model structure, parameters, and ecosystem processes. The Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, Image 1), an international network of more than 40 marine ecosystem modellers, is spearheading ensemble modelling of marine ecosystems to shed light on the long-term impacts on climate change on fisheries and marine ecosystems, on regional and global scales.

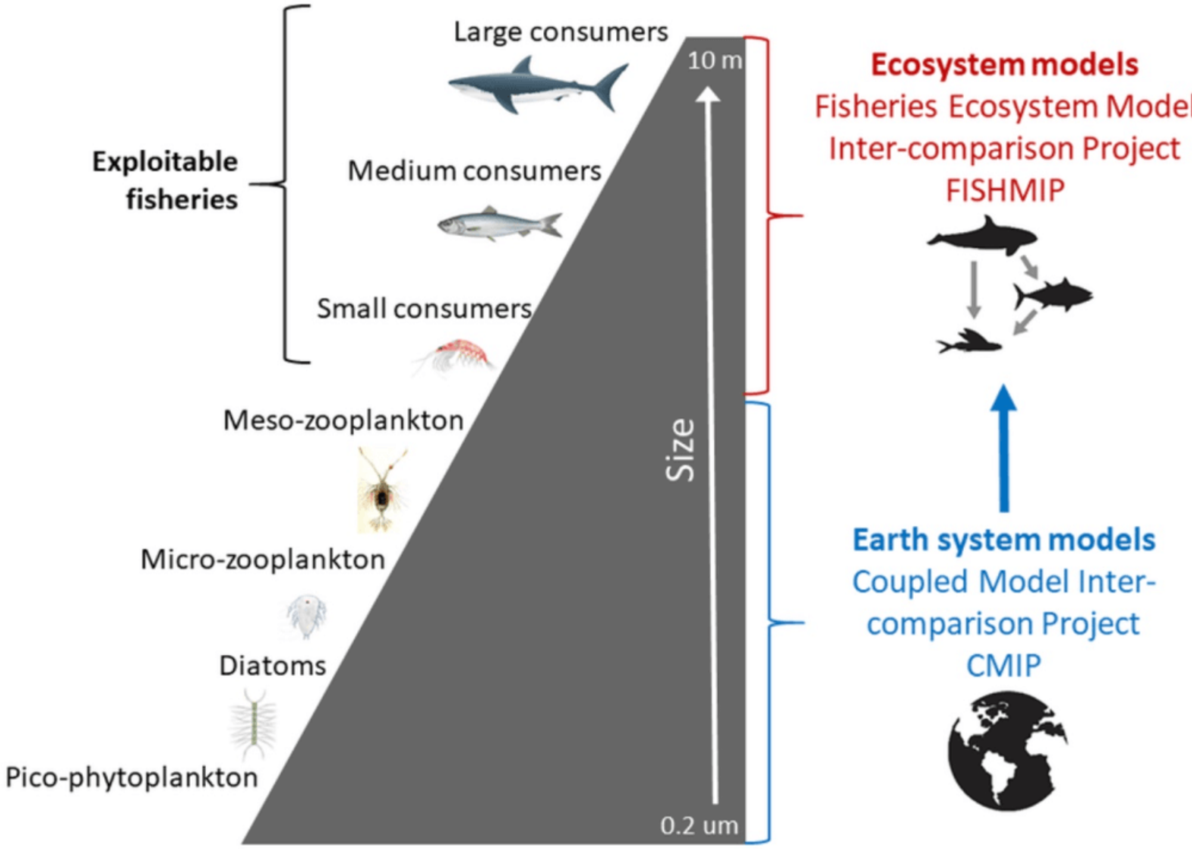

Image 1. Conceptual overview of marine ecosystem projections under climate change as done in the Fisheries and Marine Ecosystem Model Inter-comparison Project (Fish-MIP; Image from Daniel G. Boyce).

Fish-MIP results are used to help inform climate and environmental policy, such as through the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate; the UN IPCC Sixth Assessment Report; and the UN Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) Global Assessment Summary for Policy Makers. Here, Fish-MIP provided information on e.g., how the abundance of marine animals across the global ocean may change under ongoing climate change; how marine ecosystem responses differ depending on the ocean basin under climate change, where changes in the Indian Ocean differed substantially from projected changes in the Arctic Ocean (Image 2).

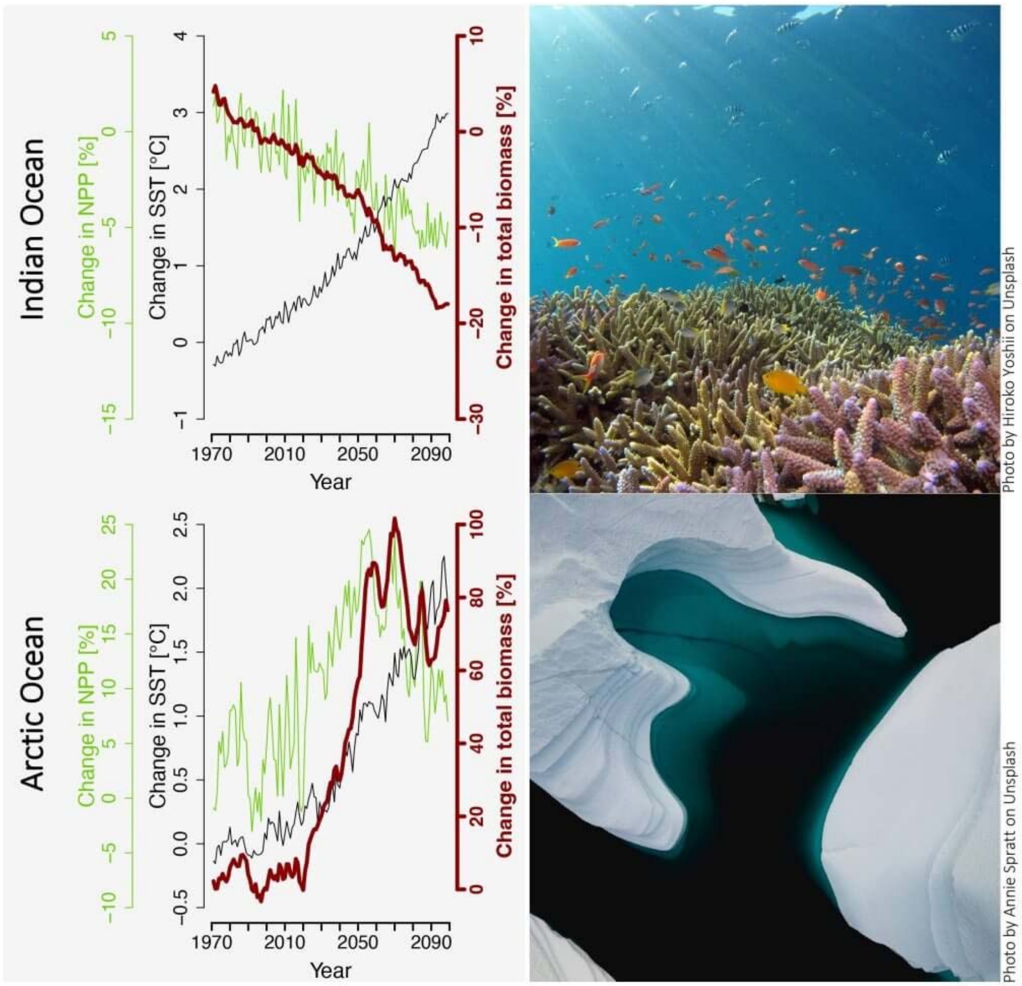

Image 2. Model projections of primary production (NPP; green), surface water temperature (SST, black) and total marine animal abundance (TCB, red) under the scenario of unabated climate change in the Indian and Arctic Ocean. Graphs modified from Bryndum-Buchholz et al. 2019.

While these ensemble projections help to understand future trajectories of ocean changes, the underlying uncertainties in the projections and limitations that exist often hold back policy development and on the ground decision-making. One of the main limitations being spatial resolution of model projections, that do often not match the scale of ocean policy or management.

Nevertheless, decades of climate-impact research have highlighted, documented, and discussed climate change impacts on our planet to be certain enough about the consequences of inaction on humanity. A shift in the global mindset and political will to act on climate change is required to avoid increasingly catastrophic events such as floodings, wildfires, hurricanes, or heatwaves. This shift is needed now despite of the uncertainty in what the future might bring, despite of the uncertainty in model projections. Acknowledging the uncertainty in the science, can still provide science-based advice and science-informed decision-making.

Ecosystem models will continue to advance and will continue to inform climate and environmental policy. Increasing computing power will allow for higher complexity in model structures and hence a higher complexity in the representation of ecosystem components. Underlying model uncertainty will likely not disappear, but as model results are communicated in effective ways that focus on climate risks instead of uncertainty, climate action will hopefully become stronger and more immediate.

Andrea *(She/Her) is a Postdoctoral Fellow at the Fisheries & Marine Institute, Memorial University of Newfoundland, with the Ocean Frontier Institute (OFI) and Marine Environmental Observation Prediction & Response Network (MEOPAR). She is interested in understanding future changes in marine ecosystems due to ongoing climate change, assessing consequences and finding solutions for fisheries management and marine biodiversity conservation in a changing ocean. Andrea is interested in science communication and is a passionate writer.*

Twitter: @AndreaBBuchholz

Cold Arctic outflow winds cool and reoxygenate coastal waters in Bute Inlet, British Columbia

WRITTEN BY CMOS BULLETIN SCMO ON OCTOBER 5, 2022. POSTED IN OCEANS, WHAT'S CURRENT.

– By Jennifer Jackson, Jody Klymak, Keith Holmes, Wiley Evans, Alex Hare, Charles Hannah, Bill Floyd, Laura Bianucci, Di Wan–

Anthropogenic climate change has led to the warming (Johnson et Lumpkin, 2022) and loss of oxygen (Breitburg et al., 2018) in the world's oceans. In British Columbia, temperature and oxygen data have been collected in fjords since 1951 (Pickard, 1961). Between 1951 and 2020, deep (Jackson et al., 2021) and intermediate (Jackson et al., 2022) waters warmed and lost oxygen. Despite these long-term trends of warming and deoxygenation, there are regional mechanisms in some areas of the coastal waters that cause cooling and reventilation; identifying and understanding these mechanisms and their spatial variability is important to assess the complexity of change in the coastal oceans.

Arctic outflow winds are defined as the transport of cold, dry air from the continent to the coast through a mountain pass (Overland and Walter, 1981). Given the complexity of the British Columbia coastline, the impact of Arctic outflow winds is variable, and inlets that have an unimpeded connection to the continent can transport less modified, colder air to the coast (Bakri et al., 2017). Bute Inlet, within the traditional territory of the Homalco Nation (Figure 1), is an example, where the valley between the continent and the coast is not blocked by mountains (MacNeil, 1974). Bute Inlet is a fjord that is about 80 km long and up to 700 m deep, with one sill that is about 355 m deep (Pickard, 1961).

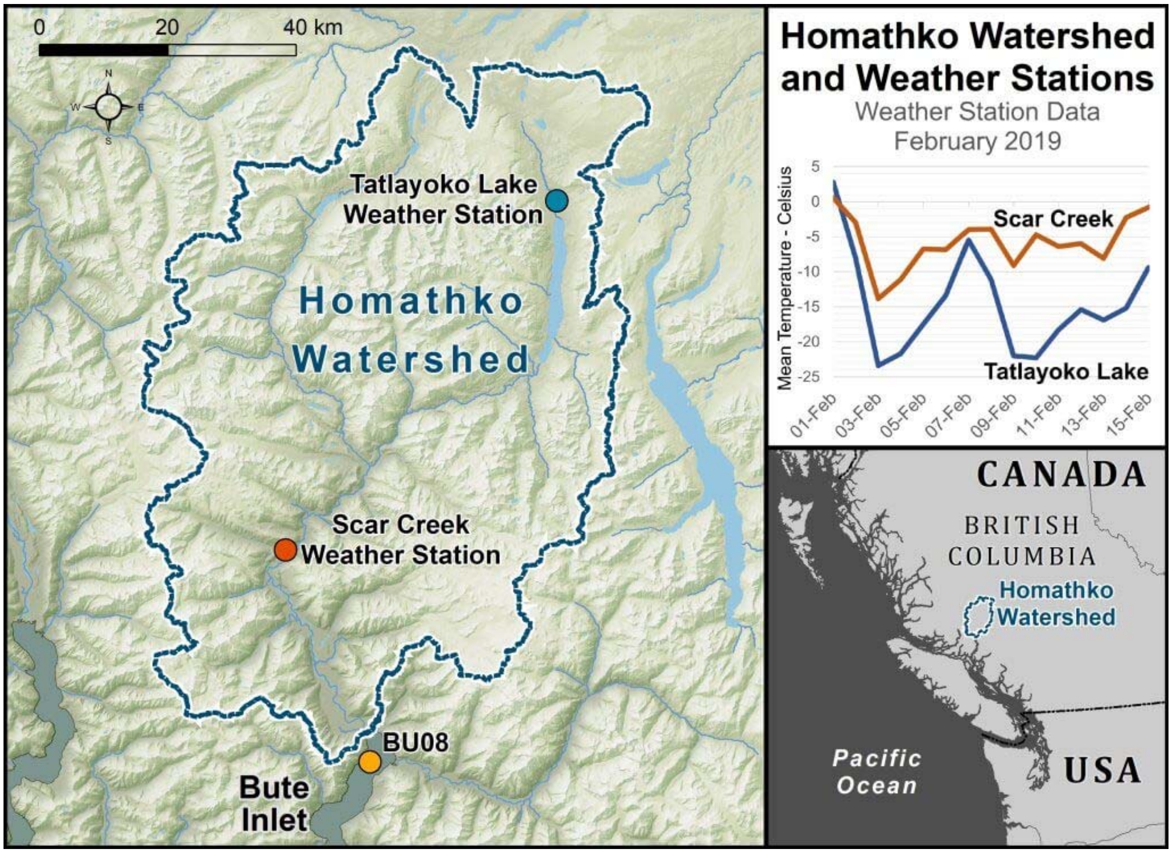

Figure 1: Map of Homathko Watershed and the head of Bute Inlet in relation to its location in western Canada (map inset). Daily mean temperature data from Tatlayoko Lake (elevation 875 m; blue line) and Scar Creek (elevation 50 m; orange line) weather stations during the Arctic outflow wind events from February 1 to 15, 2019 are shown in the upper right-hand corner.

Temperature, salinity and oxygen data have been collected at eight stations in Bute Inlet since 1951 by the University of British Columbia (1951 to 1987), Fisheries and Oceans Canada (1989 to 2014), and the Hakai Institute (2017 to present). Atmospheric data have been collected on the continental plateau at Tatlayoko Lake since 1928. In total, more than 800 oceanographic profiles have been collected in Bute Inlet and these data are available online at www.cioos.ca. For this research, we use air temperature to identify an Arctic outflow event in February 2019, and use oceanographic observations and a 2-D model to investigate the impact of the Arctic outflow winds on Bute Inlet.

The Arctic outflow event lasted from February 1 to 15, 2019, with daily average air temperatures at Tatlayoko Lake ranging from -5 to -24°C. Oceanographic data were collected on January 24 and March 26, 2019. Between those dates, the upper ~100 m of the water column cooled by more than 1.5°C and gained more than 3 mL/L of oxygen (Figure 2). A model simulation forced by realistic atmospheric conditions (winds spun up over 1 day that reached a maximum of 15 m/s for 4 days) recreated this cooling and reoxygenation, confirming that Arctic outflow events can cause mixing to 100 m in Bute Inlet.

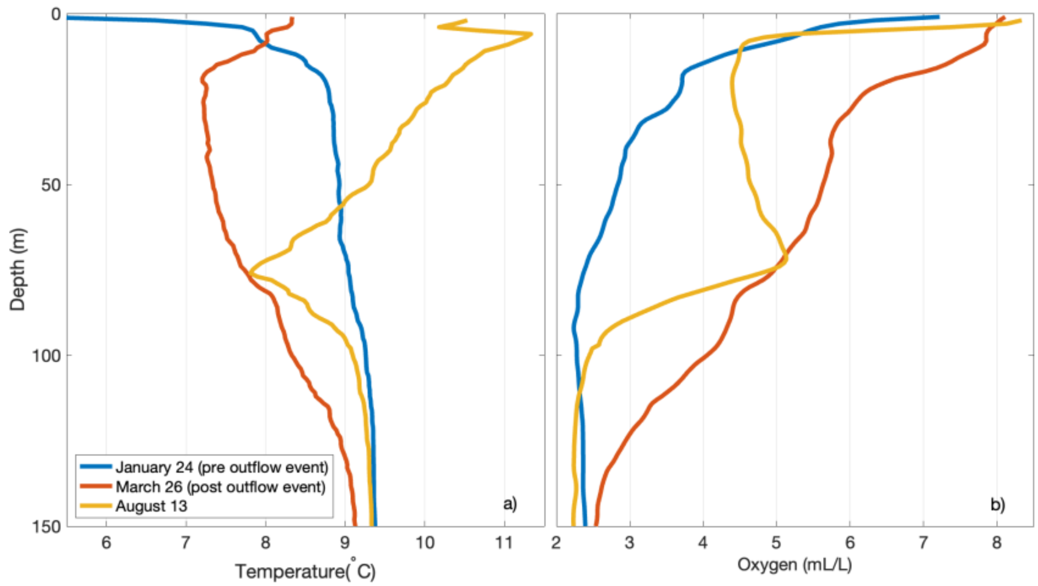

Figure 2: (a) Temperature and (b) oxygen profiles from station BU8 (Figure 1) for the time period January 24 to August 13, 2019. Each coloured line represents one date when in situ data were collected.

Future studies are to extend this study in space in time, specifically i) to examine what other British Columbia inlets are impacted by Arctic outflow winds and ii) to examine how Arctic outflow winds have been impacted by climate change. In addition, an important area of future research is to determine how the marine ecosystem is impacted by Arctic outflow winds.

***Jennifer Jackson** is a research scientist in at the Hakai Institute who currently studies warming and deoxygenation in coastal British Columbia waters. She has also studied water mass formation and the impact of ocean warming on sea ice melt in the Arctic Ocean and the impact of the Agulhas Current on South African coastal waters. Jennifer co-founded the British Columbia Environmental Film Festival in 2021.*

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Retrospective: Robie W. Macdonald, OC, FRSC (1947-2022)

WRITTEN BY CMOS BULLETIN SCMO ON OCTOBER 24, 2022. POSTED IN MEMBERS, NEWS & EVENTS, OCEANS, WHAT'S CURRENT.

-By Sophia C. Johannessen and Jules M. Blais-

This retrospective was first published on FACETS on 22 September 2022.

Robie (Rob) Macdonald studied large-scale ocean systems, including the global carbon cycle, climate change and contaminants, in the Arctic and Pacific Oceans. He was recognized internationally as one of the country's primary experts on the behaviour of contaminants in the marine environment, and he brought new insight and a broad perspective to every project.

Among his many accomplishments, Rob was a leader in the international effort to ban the "dirty dozen" of persistent, organic, bioaccumulative pollutants, as well as in the ban on polybrominated diphenyl ethers in Canada. Although his contaminant work was highly influential on national and international policy, Rob preferred to study contaminants as tracers of natural pathways. He wanted to understand how systems worked and how they were changing as a result of climate change.

The originality and excellence of his work were widely recognized, but it was his generosity and wisdom in mentoring others that made the greatest difference to the people who knew him.

Education, employment, recognition

Rob received a Ph.D. in Chemistry from Dalhousie University in 1972, with a thesis on the oxidation of ethylene. After working as a post-doctoral fellow for three years, he became a Research Scientist for Fisheries and Oceans Canada in 1975. When the Institute of Ocean Sciences opened in 1978, Rob moved into an office there, where he remained for the rest of his career. On retiring in 2013, he continued his research as an Emeritus scientist.

Rob wrote or co-authored 280 peer-reviewed articles, as well as numerous book chapters and reports. Even during the last year of his life, he submitted five articles and a book chapter.

The excellence of his work was widely recognized (Table 1). He held Fellowships in the Royal Society of Canada (2004), the American Geophysical Union, the Chemical Institute of Canada, the Explorers Club and the Royal Canadian Geographical Society. He received numerous awards, culminating in his being named an Officer of the Order of Canada in 2019.

As a federal government scientist, Rob's expertise was recognized within government as well as in academia. He was promoted to the highest classification of Research Scientist, and in 2002 he received the Head of the Public Service of Canada Award. In 2015 he received the Prix d'Excellence, Fisheries and Oceans Canada's most prestigious award.

Scientific approach and major contributions

Rob brought a broad perspective to his work. He liked to stand back from the details to see the larger picture. To that end, he often constructed regional box model budgets, including budgets for organic and inorganic carbon (e.g. Capelle et al., 2020) and several contaminants (e.g. polyaromatic hydrocarbons, Yunker et al., 1999). He looked for the levers that could effect change in a system, in order to determine which processes actually mattered. He then applied this understanding to evaluate the sensitivity of particular systems to climate change (e.g. McGuire et al., 2009).

He built a deep understanding of the environment, brick by brick, first laying a solid foundation of budget and pathway studies, before applying that understanding to topical applied questions. For example, he used his basic work in freshwater budgets and oxygen stable isotopes (Macdonald et al., 1995) to develop a method to assist fisheries officers to identify whether salmon had been caught legally in the ocean or illegally in a river. He used a similar approach to assess the footprint of Victoria's controversial sewage discharge in a regional context, based on a set of foundational geochemical studies (Johannessen et al., 2015).

His broad knowledge enabled him to bring insight from one field to inform another. For example, earlier research had focused on contaminants or climate change, but rarely both simultaneously. With his knowledge of climate change and its effects on the carbon cycle, Rob showed that not all changes in contaminants in the environment or in food webs were related to changes in contaminant discharge. He linked the two fields in a way that produced a new understanding of contaminant trends, particularly in the Arctic (e.g. Macdonald et al. 2003).

Rob's perspective on ocean and atmospheric pathways proved essential for integrating the state of knowledge on arctic contaminants, as part of the Arctic Monitoring and Assessment Programme and the Canadian Northern Contaminants Program. He led a 140-page synthesis of Canadian Arctic contaminant pathways (Macdonald et al. 2000), which was one of the most comprehensive analyses of contaminants in the Arctic for its time, an accomplishment for which he was awarded the Canadian Meteorological and Oceanographic Society President's Prize (2000).

While his studies and syntheses led to new perspectives on the anthropogenic contamination of the Arctic, they have perhaps even more importantly illuminated the biogeochemical systems into which the contaminants enter. Working, as always, with colleagues, Rob used the patterns in stable and radioactive lead isotopes in sediment to map major Arctic water circulation patterns (Gobeil et al., 2001). His work also led to an improved understanding of the processes that lead to amplification of contaminants in the environment (e.g. Macdonald et al. 2002). He also showed how large-scale animal migrations, like those of Pacific salmon or seabirds, are efficient vectors for contaminants (e.g. Blais et al. 2007).

In his research Rob emphasized the importance of timescale. On the small scale this meant recognizing that biological mixing of surface sediment could smear together years or even thousands of years of accumulated sediment. He developed a method that could unmix core records mathematically, to show what the original history must have been (Macdonald et al., 1992). On the global scale, he explained that no matter how carbon is distributed among compartments in the modern carbon cycle, the continued addition of ancient fossil fuels increases the total amount of carbon in the modern environment; there is no mechanism to remove it on a timescale relevant to humans.

Rob believed that peer-review represented the best form of quality control for science and that the science wasn't done until it had been reviewed and published. He said that papers published in good journals represented the platform of a researcher's expertise and credibility. He also believed that – regardless of the political culture of the time – it was a government scientist's responsibility to build such a platform of expertise, based on reviewed and published science, so that they could offer the best possible advice to government.

He stressed the importance of field work, as well. He pointed out that the word autopsy came from "seeing for oneself." He believed that there was no substitute for getting out and seeing the environment first-hand. To this end, he spent substantial time in the field, including approximately 40 sampling cruises on ships and many other expeditions by small boat, airplane, helicopter and snowmobile.

Advice on science and life

Rob thought deeply about science and life. He formulated these ideas into advice, which he shared freely with students, colleagues and even managers. Here are just a few of his conclusions:

- Find what you're passionate about, and do that.
- Take the science seriously, but not yourself.
- Don't do things for rewards. It is not a *quid pro quo* world when it comes to things of true, deep value.
- Take advantage of luck by doing the work ahead of time to be ready when an opportunity arises.
- Wear the "right hat" for the situation.
- Include and appreciate people, particularly technical and graphics support staff.
- Support new researchers who have no track record (and then continue to support them if they produce).
- Surround yourself with people you like to work with.
- Give away ideas.
- The secret to a happy life is gratitude. If you have eyes to see, life gives us much and yet it owes us nothing.

Finally, Rob said that the most important conversations about oneself happen when one is out of the room. Those conversations are guided by one's behaviour, compassion, and choices. In the months since Rob's death, there have been a great number of conversations about him. He made significant and lasting contributions to science, and more than that, he made a real difference to people.

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High-resolution ocean modelling of British Colombia's fjords

WRITTEN BY CMOS BULLETIN SCMO ON NOVEMBER 1, 2022. POSTED IN CLIMATE, WHAT'S CURRENT.

-By Krysten Rutherford and Laura Bianucci-

The nearshore and coastal ocean is an important region, acting as a buffer between the land and the open ocean. As a result, it experiences climate change impacts from the open ocean and also absorbs impacts from the land and land-use changes. Moreover, it is often the most utilized by humans for recreational, economic, and traditional activities, which can subsequently lead to impacts from, for example, oil spills and aquaculture operations. Scientists across the globe have therefore set out to better understand these regions. One tool at their disposal is high-resolution ocean modelling.

Dr. Laura Bianucci, who currently works for Fisheries and Oceans Canada at the Institute of Ocean Science (Sidney, BC), is one such researcher studying the coastal areas of British Columbia. She has always been interested in understanding coastal ocean processes ranging from continental shelf to nearshore scales, and has been working with related numerical ocean models since graduate school. Initially, her work focused on high-resolution regional models, but it has evolved over the years to focus more and more on questions regarding nearshore processes. She believes that the type of high-resolution models she employs help us to better understand parts of the coastal ocean that are so important to us as a society and for the ecosystem.

Figure 1: Fish farms in Clayoquot Sound along the west coast of Vancouver Island (photo credit: Glenn Cooper).

As Dr. Bianucci points out, high-resolution models are not necessarily new, but increasing computer power has meant that the ability of these models has significantly increased in recent years. The term “high-resolution” can mean many things when it comes to numerical ocean models since there are many different types of applications for this scientific tool. Here, we are referring to a model’s spatial resolution, which is similar to pixels in a photograph – the resolution of a photograph (or model) depends on the size of the pixels (or size of the model grid cells), with a higher resolution photograph (model) having smaller pixels (grid cells) to capture more detail. Finding a model’s optimal spatial resolution depends largely on balancing its computational expense with the scientific questions being asked and processes being modelled. Large model domains and/or high-resolution models require more computer power and more storage; in other words they are more computationally expensive. However, processes or regions cannot be accurately resolved if they are on scales smaller than the model grid cell width (i.e. resolution), which must be taken into consideration when developing models for specific applications.

For Dr. Bianucci, who studies the intricate nature of the many inlets and fjords of British Columbia’s coastline, high-resolution often means a model grid cell width ranging in size from 10 to 100 m. These coastal areas are made up of narrow channels that often cannot be resolved with models that have a resolution of >1km. For reference, some high-resolution regional ocean models have a resolution of 2-10km and global Earth System Models (ESMs) often have a resolution of ~100 km. With her models having such high spatial resolution, they often need to cover a smaller area to limit the computational expense. As such, Dr. Bianucci develops model applications for specific inlet and fjord systems. Currently, she is working on 4 different high-resolution models which encompass Queen Charlotte Strait, Discovery Islands, West Coast of Vancouver Island, and Quatsino Sound (see Figure 2).

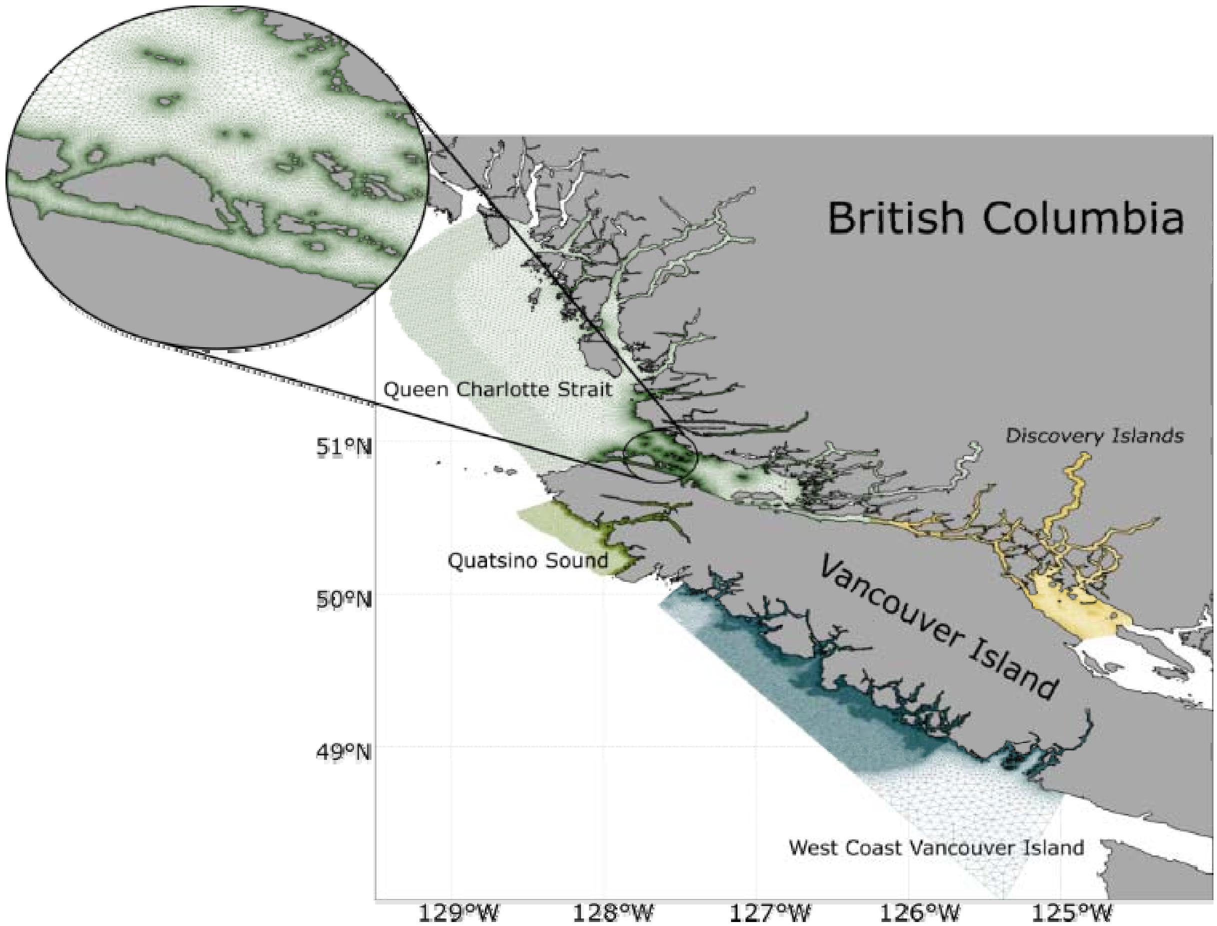

Figure 2: Four model domains: Discovery Islands, West Coast Vancouver Island, Quatsino Sound and Queen Charlotte Strait. Inset shows zoomed in model grid for Queen Charlotte Strait as an example of the model resolution (credit: Krysten Rutherford).

The questions that Dr. Bianucci tries to tackle with her projects are multidisciplinary in nature. As such, she often brings together a diverse team of individuals. “Ocean science today is in deep need of interdisciplinary research and, most importantly, interdisciplinary teams. Siloed research is not the right approach when facing a multifaceted challenge like climate change,” Dr. Bianucci comments. Given that the regions Dr. Bianucci studies are highly utilized by humans, she additionally tries to involve as many stakeholders as possible in her projects. She works closely with fisheries managers as well as with First Nation partners who are interested in finding out more about the resilience of their systems that are changing very rapidly due to climate change. She keeps them up to date on the modelling side, but also integrates them into the implementation of monitoring plans of the various fjords she is studying. Many of these fjords are lacking in observations because it is difficult to visit them frequently and sample in high enough spatial resolution to constrain the system. The implementation of these monitoring plans, particularly when combined with high-resolution modelling, is therefore crucial to better understanding these systems.

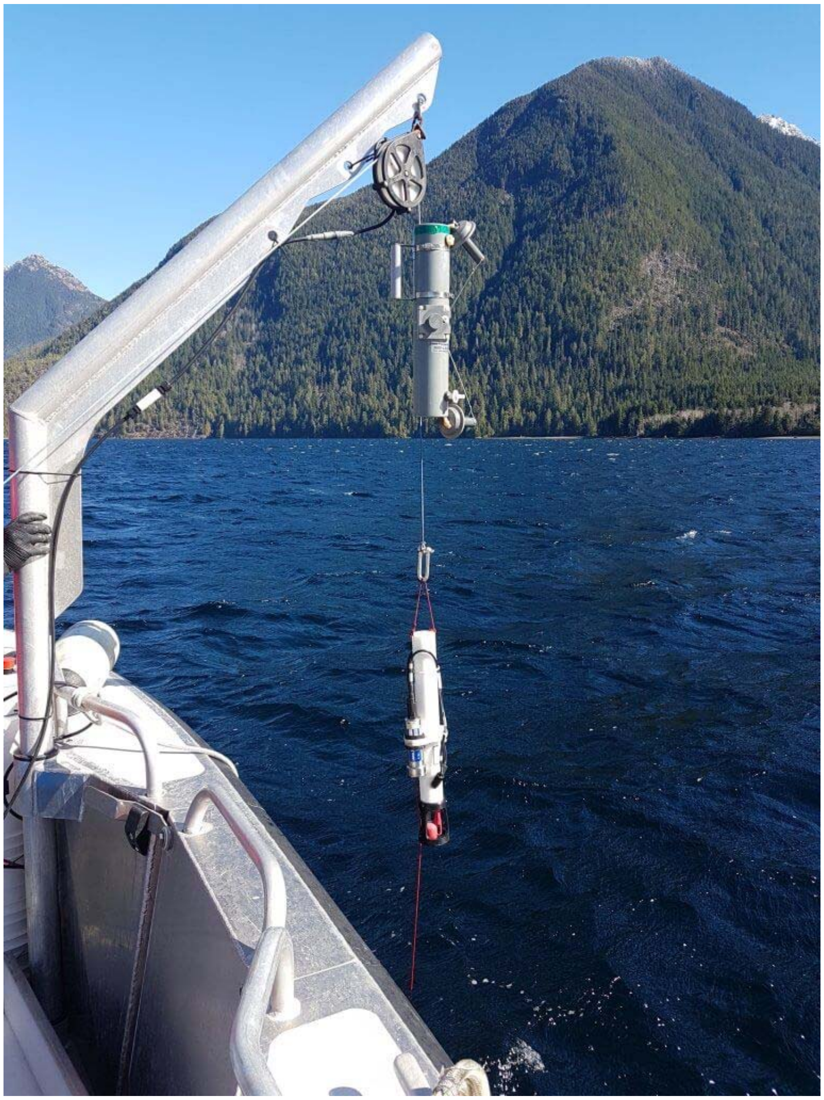

Figure 3: CTD and Niskin deployment off the CME Anderson in Quatsino Sound (photo credit: Glenn Cooper).

Models in general are great tools that can be used to investigate the inner workings of the ocean without altering the real ocean, both at present-day and under future conditions, Dr. Bianucci argues. They are powerful tools that help us interpret sparse observations, and allow scientists to test mechanisms and hypotheses that can be hard to observe in the real ocean. Given the many uses of numerical ocean models, there are many different types of modelling systems available. Currently, Dr. Bianucci specifically uses one called Finite Volume Community Ocean Model (FVCOM). This type of model is unstructured, which means that the grid cell size can vary throughout the model. This feature is beneficial for the type of modelling that Dr. Bianucci is doing since it allows her to represent different types of areas, which may need different resolution, within the same model (e.g. continental shelf vs. fjords).

British Columbia's inlets are often home to many aquaculture operators. The development of these inlet-specific models can help operators and regulators in a variety of ways, such as by helping them plan best management practices and for potential future changes. For example, Dr. Bianucci and her team have implemented particle tracking in her models, which can simulate the dispersal of pathogens or contaminants from aquaculture farms (DFO 2021). Her current work is also focused on hypoxia and deoxygenation since this is what many fjords along the British Columbia coastline are experiencing. A couple of her recent collaborative studies have found long-term deoxygenation and warming trends in four BC fjords (Jackson et al. 2021), and have explored the seasonal occurrence of near-surface hypoxia in another inlet based on recent measurements (Rosen et al. 2022). She aims to use her models to improve the understanding of the dynamics behind these observed low oxygen events as well as how these events and dynamics may change under future climate scenarios. Furthermore, by studying several inlets and fjords, Dr. Bianucci hopes to address the spatial diversity of coastal hypoxia in these geomorphologically complex regions. For example, it is not yet fully understood why a subset of the inlets along the West Coast of Vancouver Island experience hypoxia while some do not. Dr. Bianucci believes that differences in the bathymetry and sill locations, how the inlets are aligned with the main winds, and the type of freshwater forcing reaching the fjords are likely some of the key drivers in setting inlet biogeochemical properties. This work is still in progress, but Dr. Bianucci is very much looking forward to seeing the outcomes of her modelling work in this region.

Over the coming years, Dr. Bianucci hopes to expand her models to include even more coastal areas. These models can be used to see the impacts on and from any given aquaculture farm, and help to establish the best management practices. She also hopes to use these models to understand how extremes and climate change as a whole will impact the important near shore regions of British Columbia, in terms of hypoxia, acidification, and temperature. It will be incredibly important over the coming years to get a firm grasp on these stressors and how they will affect the local fish stocks and aquaculture farms; high-resolution ocean modelling is a formidable tool for the task.

This article was written by Dr. Krysten Rutherford based on an interview with and input from Dr. Laura Bianucci and images from Glenn Cooper.

Krysten Rutherford *(she/her) is a postdoctoral fellow at the Institute of Ocean Science in Sidney, BC, and completed her PhD in 2021 at Dalhousie University. She implements and develops high-resolution models to better understand present-day processes and the potential future impacts of climate change on coastal systems.*

Laura Bianucci *(she/her) is a research scientist at the Institute of Ocean Science in Sidney, BC. Before joining Fisheries and Oceans Canada in 2017, she was a scientist at Pacific Northwest National Laboratory (Seattle, WA, USA) and a postdoc at Dalhousie University. She holds a PhD from the University of Victoria (2010).*

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The birth of the HAWC

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-By Hind Al-Abadleh, Jean-Pierre Blanchet, Adam Bourassa, and Kaley Walker-

On October 18, 2022, The Honourable François-Philippe Champagne, Federal Minister of Innovation, Science and Industry announced that Canada will contribute more than $200 million to the High-altitude Aerosols, Water vapour and Clouds (HAWC) mission to be part of the Atmosphere Observing System (AOS) mission led by NASA. The AOS mission is an international and major multi-satellite mission that also include Japan, France, and Germany. Led by the Canadian Space Agency (CSA), the HAWC mission consists of two Canadian instruments on a Canadian satellite and a third instrument on a NASA satellite, all planned for launch in 2031.

The HAWC mission is an intrinsically collaborative project. The HAWC team consists of the CSA, a consortium of thirteen universities, Environment and Climate Change Canada, Natural Resources Canada, and the National Research Council of Canada. Canadian aerospace companies with international expertise in optics and satellite technology were also partners on the innovative instruments designed and developed in Canadian university labs. The three Canadian-made scientific instruments (sensors) that work in a synchronized fashion from orbit are ALI (Aerosol Limb Imager) – satellite imager for aerosol profiling (USask-developed), SHOW (Spatial Heterodyne Observations of Water) — satellite imager for water vapor (USaskdeveloped), and TICFIRE (Thin Ice Cloud and Far InfraRed Emissions) — far infrared imager for ice clouds and radiation (UQAM-developed). TICFIRE will fly on the polar orbiting element main observatory of the NASA AOS with a suite of active and passive nadir looking instruments, and ALI and SHOW will fly on a Canadian satellite in a synchronized orbit to make coordinated limb observations of the same air mass as TICFIRE. The key project elements for HAWC on NASA's AOS, include launching of the HAWC satellite by NASA, creation of a Canadian-built satellite platform, development of the three Canadian atmospheric sensors, and data production/computing/analysis.

The Canadian team has been hard at work over nearly two decades before HAWC was born. Early investments from the CSA enabled concept studies and technology development. The HAWC team has been advocating for federal support of the HAWC Satellite mission for over a year as a timely and tangible outcome of Canada's Strategy for Satellite Earth Observation. While HAWC is designed for a space mission time of five years, this government investment in the project would help supply of valuable data to inform the next two decades. HAWC will deliver data on atmospheric aerosol and clouds that will enable creation of evidence-based solutions for long-term, short-term and time-critical decisions for extreme weather prediction, climate modelling and air quality.

The HAWC mission is an opportunity to reposition atmosphere-related research in Canada and to build new collaborations inside and outside of the science community. By leveraging this new government investment with other research grants, HAWC will integrate the efforts ofresearchers in government, industry and universities in ways that will contribute to the training and retention of highly qualified personnel. The HAWC team aims to create collaborative educational opportunities that include specialized classes, in-person and virtual workshops, and hands-on experimental and theoretical modules to name a few. All partners on the HAWC team are committed to integrating best practices in equity, diversity, and inclusion in their training plans to capitalize on the creativity and ingenuity of diverse scientific teams.

As efforts are ramping up to tackle climate change, the HAWC team will engage in timely knowledge mobilization efforts. These efforts include working closely with Environment and Climate Change Canada's Indigenous Science Division, writing plain language op-eds for newspapers and scientific magazines, launching public outreach seminars in partnership with science communication and wider community groups.

As mitigation efforts are ongoing, albeit slowly, to reduce carbon emissions, to enhance climate adaption and minimize human suffering, humanity needs not only better environmental prediction capability but also sustained funding to new and ongoing international scientific collaborations and integration of multiple ways of knowing and informing societies of what's to come.

Professor Hind Al-Abadleh: *HAWC consortium collaborator, Wilfrid Laurier University, Department of Chemistry and Biochemistry, and Chair, Atmosphere-related Research in Canadian Universities (ARRCU).*

Professor Jean-Pierre Blanchet: *HAWC consortium co-lead, Université du Québec à Montréal, Département des sciences de la Terre et de l'atmosphère.*

Professor Adam Bourassa: *HAWC consortium co-lead, University of Saskatchewan, Institute of Space and Atmospheric Studies.*

Professor Kaley Walker: *HAWC consortium co-lead, University of Toronto, Department of Physics.*

The importance of coastal foredunes as a nature-based solution for shoreline protection: What Hurricane Fiona tells us

WRITTEN BY CMOS BULLETIN SCMO ON DECEMBER 16, 2022. POSTED IN CLIMATE, NEWS & EVENTS, OCEANS, WHAT'S CURRENT.

-By Jeff Ollerhead, Robin Davidson-Arnott, and Bernard O. Bauer-

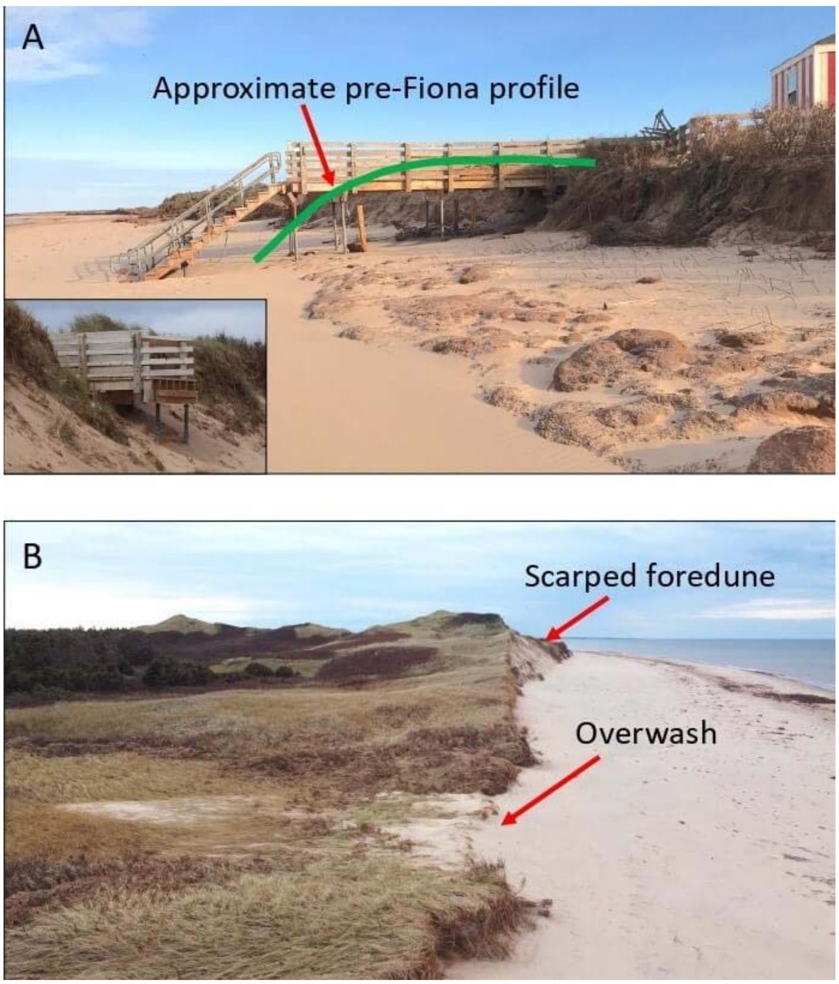

Figure 1: A) Foredune erosion at the Greenwich Dunes eastern beach access post-Fiona (photo taken west to east). The inset shows the boardwalk in May 2022, prior to the stairs being attached (photo taken east to west). B) Overwash and scarped foredune at Greenwich post-Fiona (photo taken east to west).

Introduction

Foredunes are oft-touted as a nature-based solution to preventing shoreline inundation during major storms, serving to mitigate potential damage to valuable coastal infrastructure and reducing the erosional impact of waves and storm surge. The recent destruction imparted by Hurricane Fiona (September 2022) on the north coast of Prince Edward Island (PEI) provides an ideal opportunity to validate this assertion.

Climate change and ocean warming in the near future will lead to three anticipated consequences for many Canadian coastal areas: i) an acceleration in rates of relative sea level rise, ii) an increase in the frequency and magnitude of major storms, and iii) a decrease in winter sea ice coverage. All three factors will drive increases in rates of shoreline erosion. The Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the science related to climate change, makes these consequences abundantly clear, and Fiona illustrates the trend nicely (Figure 1).

Davidson-Arnott and Bauer (2021) published a paper recently examining controls on the geomorphic response of beach-dune systems to progressive water level rise in relation to otherlong-term controls on coastal response (e.g., wind climatology, vegetation growth, geological context). Most of the evidence suggests that the beach and foredune (together with the nearshore profile) can migrate landward intact, keeping pace with current rates of relative sea- level rise (Fox-Kemper et al. 2021). This situation can be disrupted, however, if the frequency and/or severity of erosive storms increases. This will reduce or prevent the beach-dune system from re-establishing itself in a landward position via the delivery of sand from the nearshore to the dunes under fair weather wave conditions and aeolian processes.

A research program initiated more than 20 years ago at Greenwich Dunes (part of PEI National Park; Figure 2A) demonstrates that the dunes are generally evolving and migrating inland as suggested by Davidson-Arnott and Bauer (2021; Figure 2B). Our collective understanding of the processes involved is informed by multiple studies at the site, conducted at various spatial and temporal scales, from sediment transport to the dunes during individual wind events, to seasonal variability in sediment transport over the foredune, to the decadal evolution of the foredune system over the past 100 years (e.g., Walker et al. 2017; Mathew et al. 2010).

The impact of Fiona on the beach-dune system was pronounced, with a substantial portion of the stoss slope of the foredune system being eroded. The integrity of the dunes remained largely intact, however, and the dune crest was not breached. The question now is whether the foredune at Greenwich, and likely at other locations along the north coast of PEI, is likely to remain intact with a changing climate? There is hope, because we know from archival records that all of the foredune at Greenwich was eroded away during a major storm in 1923, and that complete recovery of the foredune system occurred, albeit over several decades (Mathew et al. 2010). An associated question is how the foredune system can be managed to provide the greatest likelihood of ‘surviving’ climate change? Fiona provides insight into both questions.

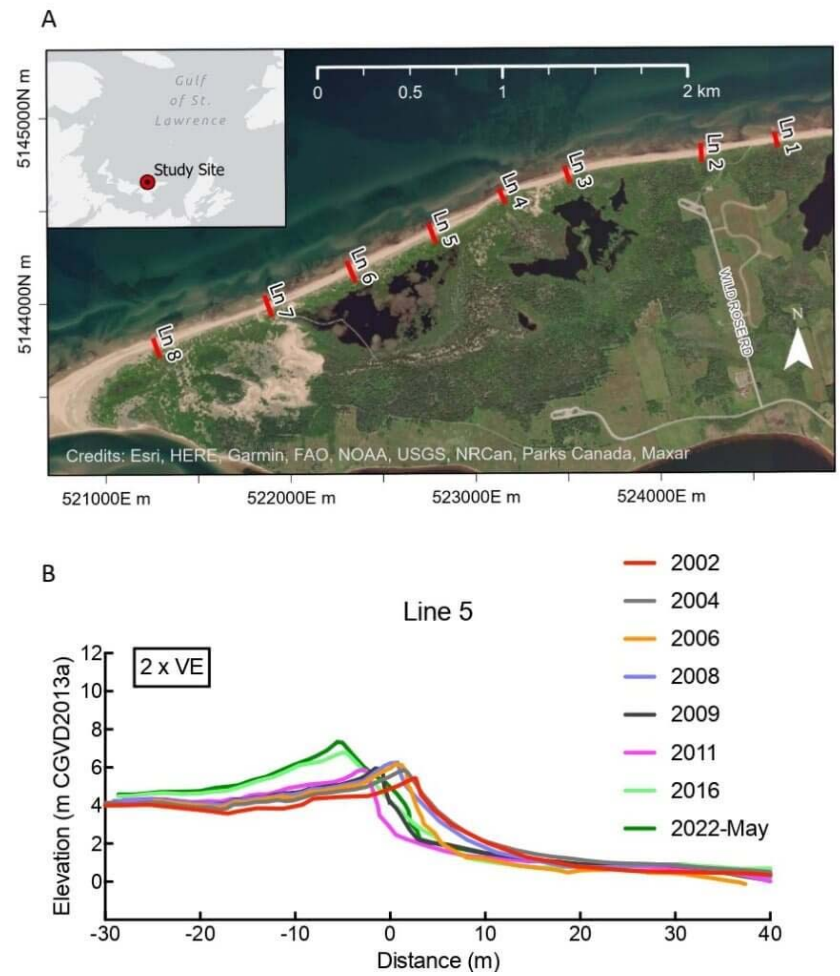

Figure 2: A) Field site at Greenwich Dunes, PEI, and locations of profile lines (Ln 1 to Ln 8). Projection is UTM (Zone 20N). B) Profile changes at line 5 over a 20-year period (2002-2022) not including the impact of Fiona. A vertical exaggeration (VE) of 2 times is used.

Hurricane Fiona – The Storm

Although Atlantic hurricanes pass over or close to PEI every few years (Table 1), they are relatively infrequent events, with periods of several years without notable impacts (e.g., 2015-2018). By the time these warm-cored storms reach PEI, they have typically transitioned from their ‘hurricane’ or ‘tropical storm’ designation into an extra-tropical configuration with significantly reduced wind speeds, unless merging with mid-latitude cyclonic disturbances travelling through the region. Hurricane Fiona was not unusual in terms of its trajectory, extra- tropical status, and reduced wind speeds in the Maritimes, but its impact on the north coast of PEI was considerably more significant than any other tropical-origin storm in recent times.

Figure 3A shows the evolution of 4 (of 5) hurricanes to impinge on PEI since 2013, which is the period of record for the Stanhope weather station (ECCC ID#8300590-6545) which is representative of conditions on the north coast of PEI. Hurricane Ida is not included because it had slower windspeeds than the other four storms and tracked across PEI twice—once from the south and then from the north on the following day—after doing a loop in the Gulf and losing energy. It is evident that Fiona was the most significant storm during this decade, with winds peaking at 89 km h^{-1} and sustained winds above 60 km h^{-1} for 7 consecutive hours. A peak wind gust was recorded at 131 km h^{-1} just before midnight on September 23. An important factor for coastal impacts is that the wind was consistently out of the north for most of the storm, which lasted approximately 24 hours.

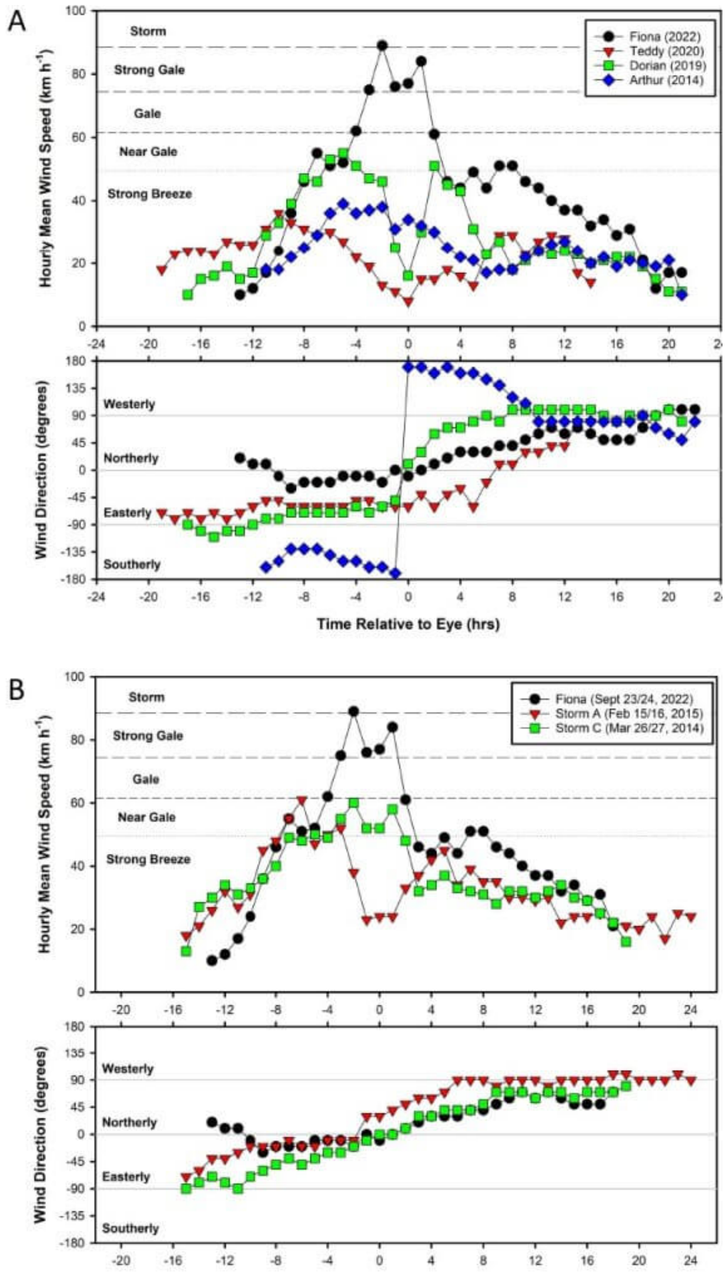

Figure 3: A) Mean hourly wind speed and direction at the Stanhope, PEI station for 4 hurricanes to impinge on PEI since 2013. B) Mean hourly wind speed and direction for Fiona relative to two of the most intense winter storms recorded at the Stanhope, PEI station since 2013. Nomenclature follows the Beaufort Scale.

In contrast, the other three hurricanes shown in Figure 3A (Teddy, Dorian, and Arthur) were much less effective in their potential to cause shoreline erosion on the north shore of PEI. Dorian, for example, never reached 'gale' status (Beaufort Scale) and at its peak, had speeds of only 55 km h^{-1}. Unlike Fiona, which tracked to the east of PEI, Dorian tracked almost directly over our field site. This meant that the wind in advance of the eye was generally from the east in the alongshore direction and then transitioned rapidly to a westerly direction (also alongshore but from the opposite direction) after the eye passed. Neither direction is conducive to wave generation or significant storm surge at Greenwich. Arthur and Teddy had greatly reduced wind speeds, never quite attaining 40 km h^{-1}, and in the case of Arthur, the wind direction was dominantly from the south, consistent with its track across the western tip of PEI.

An assessment of all Atlantic hurricanes since 1953, using data from the Charlottetown Airport (YYG) weather station (ECCC ID#8300300-6526 and ID#8300301-50621; in continuous operation since 1953) indicates that Fiona was among the most intense hurricanes to hit PEI in three decades. The barometric pressure during Fiona was the lowest recorded at 95.85 kPa and the maximum hourly windspeed of 73 km h^{-1} ranks it third in intensity behind Hurricanes Juan (Sept 29, 2003; 82 km h^{-1}; 98.55 kPa) and Arthur (Jul 5, 2014; 76 km h^{-1}; 98.1 kPa). However, the inland location of Charlottetown airport means the windspeeds experienced on the north shore of PEI are often different. As shown in Figure 4A, the records from the Stanhope station show that the windspeeds during Fiona peaked at 89 km h^{-1} rather than the 73 km h^{-1} experienced at the airport. Moreover, the Stanhope station recorded a peak of only 39 km h^{-1} during Hurricane Arthur, rather than the 76 km h^{-1} experienced at the airport, which is due to the southerly wind direction during Arthur.

Even though Fiona stands out as one of the most intense Atlantic hurricanes to impact the north shore of PEI, there are other mid-latitude frontal systems that rival its intensity. A storm on March 12/13, 2022 had barometric pressures almost as low (96.24 kPa) as during Fiona, but windspeeds were below a 'strong breeze.' Figure 4B shows the evolution of Fiona relative to two of the most intense storms recorded at the Stanhope station since 2013. Storm A (Feb 15/16, 2015) attained peak windspeeds of 61 km h^{-1}, which makes it the second-most intense wind event after Fiona. Storm C (March 26/27, 2014) was of similar intensity with peak windspeeds of 60 km h^{-1} and near gale conditions for 9 hours continuously. In the period 2014-2022, there were a total of thirteen storms that had peak windspeeds of 61 km h^{-1} or greater (based on Charlottetown data), only two of which were hurricanes (Fiona and Arthur). The other eleven storms had a mid-latitude origin and all occurred in the winter or early spring (i.e., December 15 through March 31). This is of considerable importance when assessing beach-dune interaction, because beach-dune systems on PEI are often covered by snow, and the north coast is protected from wave erosion by shore-fast ice, during this period (Figure 4). Thus, many of the most significant storms to hit PEI are incapable of forcing substantial shoreline change, despite their intensity, due to the presence of snow and shore-fast ice.

Figure 4: Photo of the beach-dune system at Line 7 taken February 15, 2008, showing snow on the foredune and shore-fast ice in the nearshore (view to east).

Hurricane Fiona – Beach-Dune Impacts

As noted above, an impact of Fiona was the erosion of a substantial portion of the stoss slope of the foredune along the Greenwich shoreline (Figures 5 and 2B). Our data also show, however, that landward retreat was less and preservation of the foredune greater at the western end of the study site, the downdrift end of the local littoral system. At the eastern end of the study site, the foredune is losing volume and retreating more rapidly.

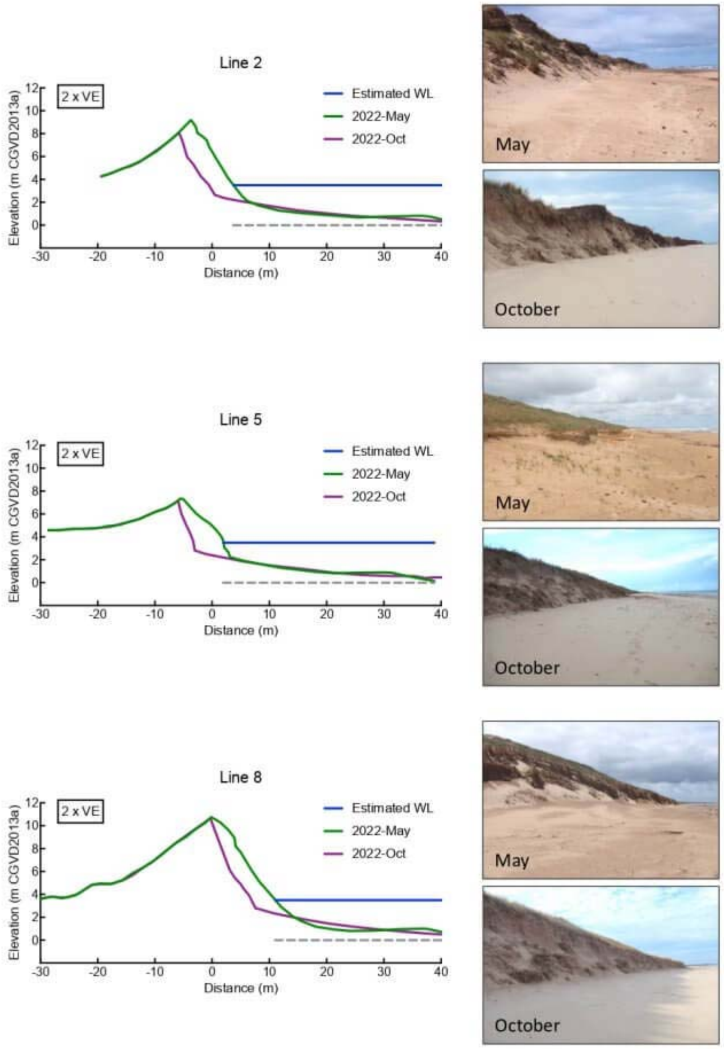

Figure 5: Profiles across the foredune at lines 2, 5, and 8 and comparative photos from May and October 2022 (before and after Fiona; taken from east to west). The dashed grey line shows mean sea level and the blue line is the estimated maximum water elevation during Fiona (storm surge + wave runup) based on measurements of wrack lines. A vertical exaggeration (VE) of 2 times is used.

Much of the eroded sand during Fiona was lost to the nearshore, but a proportion was transported over the crest and onto the lee slope. Although it cannot be seen on Figure 5 given the scale, the data show a small increase in elevation on the lee slope from May to October 2022, and freshly deposited sand was evident there when surveying post-Fiona. Where the foredune was low, some sand moved inland by overwash (Figure 1B). Much of the sand that was moved to the nearshore zone will gradually make its way back to the beach-dune system driven by fair-weather waves and aeolian processes.

One challenge we faced in assessing Fiona and its impacts, is a lack of marine data for the north shore of PEI. Fisheries and Oceans Canada does not maintain any real-time tide stations on the north shore of PEI. Water level gauges operated by the Canadian Centre for Climate Change and Adaptation (CCCCA) at the University of Prince Edward Island at North Rustico and North Lake were not working properly during Fiona. The only estimate we could obtain was from CCCCA's gauge at Red Head, which captured a peak storm surge of at least 2 m during Fiona. ECCC has no operational buoys in the Gulf of St. Lawrence to report on wind speed, wave height and period, atmospheric pressure, etc., so we are left to hindcast likely wave characteristics using terrestrial wind records. This situation is far from ideal, as researchers attempt to quantify the impacts of climate change in general, and storms in particular, in Maritime Canada.

The Future

As Figure 2 shows, over the past 20 years the foredune crest at line 5 has translated landward and grown vertically. Sand has been transported to the lee side, maintaining total dune volume. In short, the system is evolving in a manner consistent with the Davidson-Arnott and Bauer (2021) model, with the differences in erosion along the shoreline caused by Fiona explained by differing amounts of sediment available in the littoral cell. This observation highlights the need to assess beach-dune sediment balance in three dimensions along a stretch of coastal foredune (i.e., both on-offshore and alongshore) when assessing the robustness of a foredune to provide natural protection.

Based on our studies, it is anticipated that where there is sufficient sediment supply, sand ramp emplacement will take place relatively quickly and dune healing will occur. The increasing frequency and intensity of storms brought on by a warming climate may, however, disrupt the critical equilibrium between dune scarping and healing processes that have characterized this system for the last 50 years. As ocean temperatures warm, hurricanes and tropical storms will retain their intensity longer as they move north. This will likely be exacerbated by that fact that as sea ice (and particularly shore-fast ice) declines in the coming decades, winter events like Storm A (Feb 15/16, 2015) will become more effective in eroding the dunes. So, hurricanes reaching PEI will likely become more frequent and stronger (as suggested by Fiona) but the system will also be subjected to additional erosion from strong winter storms (i.e., Nor'easters) in the near future.

As Mathew et al.'s (2010) work demonstrates, the Greenwich beach-dune system can recover from even catastrophic erosion. Recovery from the storm of 1923 happened at a decadal scale, rather than at an annual scale, but it did happen. The management imperative is therefore to facilitate dune healing along this coast after major storms via natural processes by: 1) preventing human disturbance of the natural vegetation through activities such as trampling, driving of all-terrain vehicles, and construction; and 2) by providing substantial accommodation space for the foredune to migrate inland and grow upward as relative sea level rises. Management of the Greenwich Dunes by Parks Canada has employed this strategy, and our monitoring program indicates that it played an important role in the ability of the foredune there to withstand the impact of storm surge and erosion by large waves during the passage of Fiona.

Table 1: History of Atlantic Hurricanes impinging on PEI since 1999

Jeff Ollerhead is a Professor in the Geography and Environment Department at Mount Allison University in Sackville, NB. He is a coastal geomorphologist who studies beaches and salt marshes. In recent years, he has been particularly involved in designing and monitoring salt marsh restorations in the upper Bay of Fundy.

Robin Davidson-Arnott retired from the Department of Geography, Environment and Geomatics in 2009 and is now continuing research as Professor Emeritus. In addition to work on beach and nearshore sedimentation, he has carried out research on coastal salt marshes, erosion of cohesive coasts, particularly underwater erosion, beach/dune interaction, and the dynamics of coastal sand dunes. He has published extensively in book chapters and refereed journals, and his book Introduction to Coastal Processes and Geomorphology was published by Cambridge University Press in 2010 and a second edition in 2019.

Bernard Bauer is a process geomorphologist specializing in sediment transport dynamics in aeolian, nearshore, and fluvial systems. His research is primarily directed at advancing fundamental scientific understanding of Earth systems, but increasingly he is interested in ensuring that the latest scientific knowledge is used by coastal managers and environmental decision makers to inform policy development. Bauer is Emeritus Dean of Arts & Sciences at the University of British Columbia Okanagan.

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