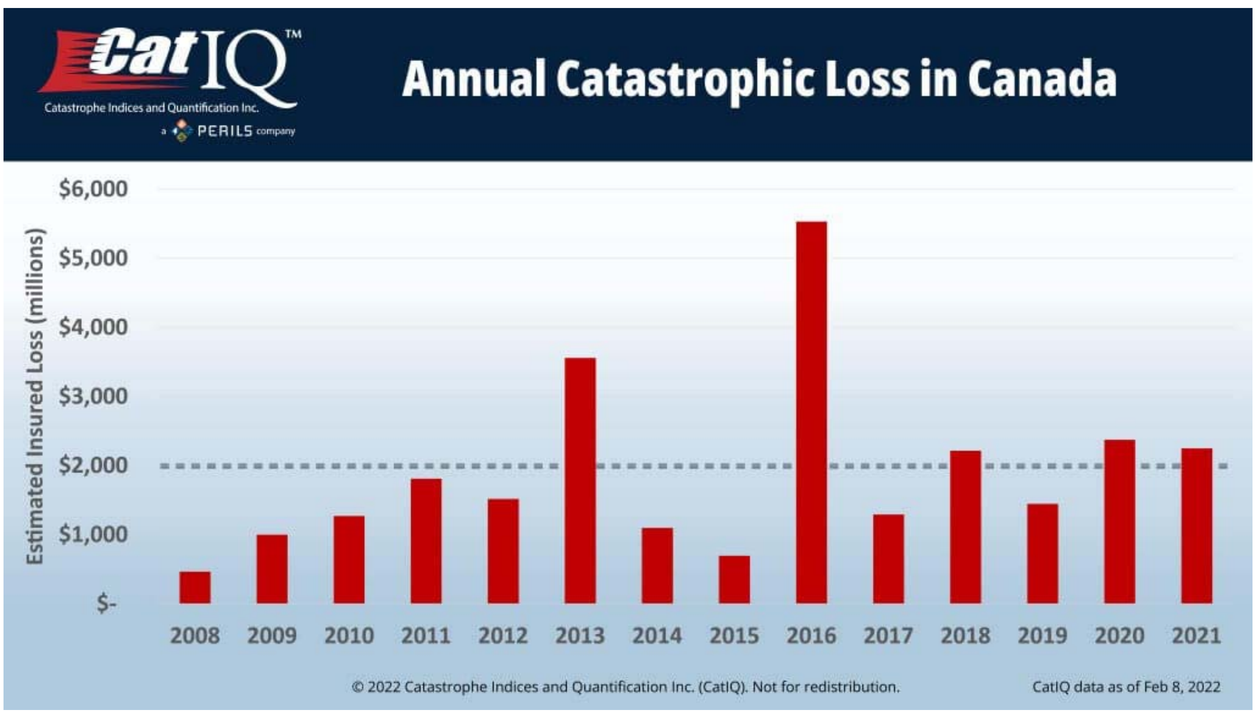
Archives CMOS Bulletin SCMO archives
Table of contents / Table de matières
January – June / 2023 / janvier – juin

Collaborating to Support Canadian Resiliency at CatIQ Connect

WRITTEN BY CMOS BULLETIN SCMO ON JANUARY 9, 2023. POSTED IN ATMOSPHERE,CLIMATE, NEWS & EVENTS, OCEANS, WEATHER.

-By Caroline Floyd-

Hurricane Fiona, flooding in British Columbia, massive hailstorms in Calgary – catastrophic events have increasingly captured Canadian headlines in recent years. Insured losses to natural disasters in Canada now routinely exceed CAD 2 billion each year, and the frequency and severity of wide-reaching disasters is expected to increase amid a shifting climate.



Long-term community resiliency is a complex problem, and one that requires cross-sector cooperation on a grand scale. The public relies on the government and private industries, like insurance and restoration, to work together before, during, and after catastrophic events. And, in turn, industry and government rely on academia to understand the scope of physical and social challenges posed by natural and human-caused disasters. In concert, the sectors must work together to develop proactive solutions and plans for action that prevent loss, increase risk awareness, and provide stability and security for Canadians.

In addition to its role as Canada's loss and exposure indices provider, Catastrophe Indices and Quantification Inc. (CatIQ), in partnership with MSA Research, organizes a conference to foster such collaboration in Canada.

CatIQ Connect – Canada's Catastrophe Conference – hosts content-driven discussions to foster collaboration before, during, and after catastrophic events. Overall themes include preparedness and resiliency, available tools, and impacted stakeholders and policymakers working together for the great good of all Canadians.

Who comes to CatIQ Connect?

- Academics, Researchers, and Students in physical and social sciences
- Government representatives
- Insurance/Reinsurance professionals
- Emergency Managers
- Engineers
- Risk Consultants & Risk Managers
- Urban Planners

Since our inaugural event in 2016, topics presented at CatIQ Connect have run the gamut of risk management and resilience issues, from the financial implications of climate change adaptation to the availability of natural hazard data for Canada, to risk communication strategies and decision science. A sample of panel discussions from our 2020 event include:

- Bringing adaptation home: Household engagements with climate change in Ottawa and Halifax
- Leadership and Financial Solutions to Climate Change
- A National Earthquake Early Warning (EEW) System for Canada
- Thoughts on the Role of Standards in Flood Resilient Stormwater Management

At our upcoming event, taking place February 7 and 8 at the Metro Toronto Convention Centre, CatIQ Connect returns in person for the first time since February 2020, welcoming back old friends and greeting new attendees as we #ReConnect the catastrophe community.

What kinds of discussions are planned for CatIQ Connect 2023?

- 2022 Catastrophes in Review
- BC Floods – Local and Insurance Perspectives
- Indigenous Communities and Insurance
- Innovations in Canadian Flood Modelling
- Managed Retreat
- Meteorology 101 – Atmospheric Rivers, Derechos, and Other Scary Things
- Modelling Risk in the Future Climate
- The Lytton Recovery
- West Coast Earthquake – The Known Unknowns

The full agenda is available online at connect.catiq.com.

In addition, we're pleased to welcome members of Canada's talented post-graduate community via our Student Delegate Program. Each year, CatIQ Connect welcomes representatives from universities across the country to give presentations on their work relating to catastrophes, providing them with important networking opportunities with those who will benefit from their research efforts.

If you have questions about CatIQ Connect or you're interested in joining your peers at the event, visit connect.catiq.com for more information, or contact Caroline Floyd at caroline.floyd[at]catiq.com.

Caroline Floyd (she/her) has a background in operational meteorology and science communication, with more than 20 years of experience in forecasting and talking about the weirdest things weather has to offer. She joined CatIQ in 2020 and currently serves as Director.

Twitter: @CatIQ_Inc

Tornadoes on the Canadian Prairies: 1826-1939–Part 1, Project Overview

WRITTEN BY CMOS BULLETIN SCMO ON JANUARY 17, 2023. POSTED IN MEMBERS, WEATHER, WHAT'S CURRENT.
-By Patrick McCarthy and Jay Anderson-

Abstract

Our project was to develop the most comprehensive and accurate database of Canadian prairie tornadoes. We have completed the period from 1826 to 1939. How this was accomplished is presented here.

Previous efforts

The systematic collection of Canadian prairie tornado events began with A.B. Lowe and G.A. McKay (1960). Brad Shannon (1976) extended that database to 1973. During the 1970s, the Prairie Weather Centre (PrWC) in Winnipeg established the Meteorological Service of Canada's (MSC) first summer severe weather program. It was supported by the Regina Weather Office and was expanded to the Alberta Weather Centre. For verification and case study purposes, severe weather events, including tornadoes, were collected and archived for the three Prairie Provinces. These reports were often very incomplete, relying on informal contacts and phone calls to weather observers. At the time it was thought that sightings of only about 1/3rd of the tornadoes reached the weather office. In collaboration with the Ontario Weather Centre, damage surveys became a part of the PrWC records. Weather spotters were added to improve event detection and description. While the collection of annual events was ongoing, the archiving of historic occurrences remained very limited.

In the early 1980s, Dr. Keith Hage, at the University of Alberta, began an extensive study to identify historic Alberta and Saskatchewan tornado and windstorm occurrences. Michael Newark (1984) developed the first Canada-wide tornado database. His work would eventually include events as far back as the 18th century. Thomas Grazulis (1993) published an extensive American tornado dataset that included a few events that straddled the U.S.—Canada border. Hage (1994) published a second database for historic Alberta tornadoes, windstorms, and lightning fatalities. Dr. Alexander Paul (1995), at the University of Regina, produced a Saskatchewan tornado chronology from 1906 to

1991 (690 tornadoes). Grazulis (2000) published a compilation of Canadian “killer” tornadoes. Hage (2001) published his compilation of Saskatchewan tornadoes (720), windstorms, and lightning fatalities from 1880 to 1984.

While employed at the MSC office in Winnipeg, we began consolidating and correcting these sources, beginning in the early 1990s and continuing to the present. This effort formed the basis of the current MSC Prairie Severe Weather archive, and which is updated annually. Eventually, a formal version was made available to the public and researchers (McCarthy, 2010). The database contained roughly 19,000 severe convective events, including 3100 reported tornadoes dating back to 1826.

Figure 1. Part of the tornado damage associated with the June 30, 1912, Regina F4 tornado. (Public domain: image provided by the City of Regina Archives – CORA-RPL-A-0905)

Methodology

We noted many problems in the 2010 database. These included vague reports, data gaps, unverified assumptions, missing and inaccurate dates and times, possible duplications, and conflicting death and injury totals. We undertook a project to review and update all the tornado reports in the archive and to add previously undiscovered events to the record.

We worked independently to take advantage of our unique but overlapping research approaches. In 2019, our two datasets were merged and differences in our records were resolved. This 1826-1939 portion of the review took about five years to complete. A small amount of new information has since been added; something that will likely occur on an ongoing basis.

The data-collection phase of the project had many challenges. Prior to 1940, there were no damage surveys, no video evidence, damage and tornado photographs were rare, eyewitness accounts were limited, and construction practices were varied. We are both experienced storm-damage surveyors and we used our experience to assess damage reports, leading to a subjective damage rating when sufficient evidence was available.

A multitude of sources, mostly unofficial and difficult to unearth, were used in the research. These included digital databases, particularly newspapers, books, historic school sources, community/rural municipality/county histories, historical societies, and obituaries. Most events appeared in newspapers, though there was typically little follow-up after the initial reports. Downed telephone and telegraph lines and poor roads often delayed the reports, leading to inaccurate dates in the record. Delayed information seldom made it into the newspapers, allowing initially bad information to linger in articles for weeks. To account for these issues, we searched for descriptions of events for up to a month after their occurrence, and in a few instances, much later.

Figure 2. This is photo of a tornado near Vulcan, Alberta on July 8, 1927; one of a number of tornadoes that day. [Public domain, photographer: McDermid Photo Laboratories, Calgary]

Eyewitnesses have an expansive view across the open prairie. Tornadoes could be seen from long distances and reports often resulted in misplaced locations. The “highways” of the prairie were the railroads. Railway station names were often referenced, further misplacing the tornado’s position. Many stations and some communities have disappeared over time. We controlled many of these difficulties by triangulating available reports to narrow the location error. On days with multiple events, the information was plotted using eyewitness accounts, storm information, and damage characteristics, to identify storm damage swaths and potential tornado tracks. The numerical NOAA-CIRES 20th Century Reanalysis (V2c) (https://psl.noaa.gov), displayed via the (https://meteocentre.com/) website, was also used to help assess storm types, potential storm motion, and storm potential. To validate a tornado occurrence, the authors used a decision-tree approach, similar to Sills, et al (2003).

A hybrid version of the Fujita (https://www.spc.noaa.gov/faq/tornado/f-scale.html) and Enhanced-Fujita Scales (https://www.spc.noaa.gov/faq/tornado/ef-scale.html) was used to rate tornado damage. The EFScale is too modern for most early events, which lack the necessary details in their descriptions. The FScale rating, which allows for a broader interpretation, was primarily used for the database. For events that crossed the U.S. – Canada border, the rating is for damage on the Canadian side, only.

The 1826-1939 timeframe was a period of immigration, spreading from east to west across the Northern Plains. There was a slow growth in population, communities, roads, railways, newspapers, etc., which affected the availability of data. For example, most cemeteries did not appear until after 1910 in Saskatchewan and Alberta.

One of our major goals was to provide a more complete account of the number of deaths and injuries. To make accurate casualty totals, a rigorous effort was made to identify the names of victims. This included victims who may have succumbed to the injuries well after the event. We used cemetery records, obituaries, ancestry/genealogy records, church records, provincial/state censuses, and death records to track down these victims.

Our effort has culminated in the most complete and descriptive archive of Prairie tornadoes and a record for researchers to build on. Some of our findings from this early compilation are presented in Part 2 of this series.

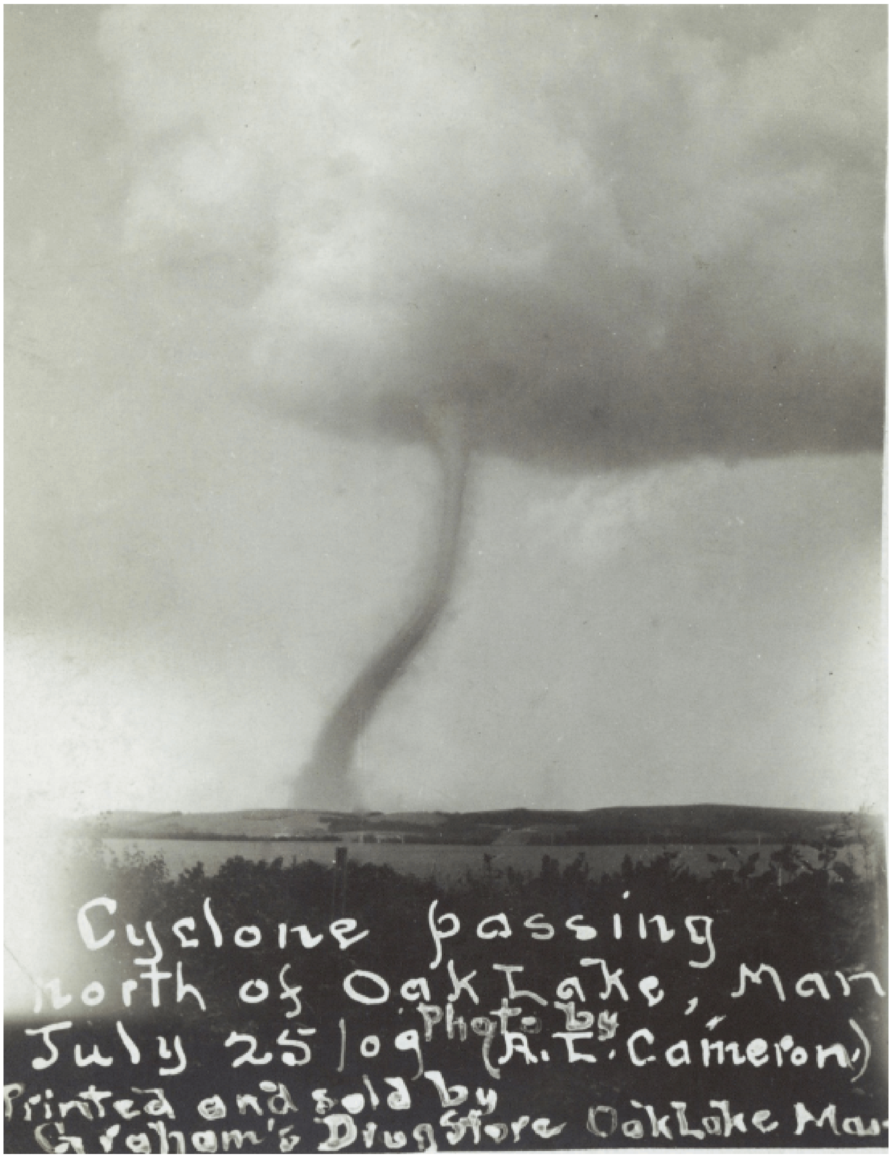


Figure 3. Tornado near Oak Lake and Kenton, Manitoba, July 25, 1909. [Public Domain: photo by A. L. Cameron].

References

Grazulis, T.P., 1993. Significant Tornadoes, 1880-1991. Volume II: A Chronology of Events. Environmental Films, St. Johnsbury, VT. https://books.google.ca/books?id=yW5NAQAAIAAJ&printsec=frontcover&source=gbs_ge_summary_r& cad=0#v=onepage&q&f=false

Grazulis, T.P., 2000. Canadian Killer Tornadoes. The Tornado Project, St. Johnsbury, VT.

Hage, K.D., 1994. Alberta Tornadoes, Other Destructive Windstorms and Lightning Fatalities: 1879-1984. Self-published, Spruce Grove, Alberta, Canada.

Kendrew, Wilfrid George, and Balfour W. Currie, 1955. The climate of central Canada–Manitoba, Saskatchewan, Alberta and the Districts of Mackenzie and Keewatin. E. Cloutier, Queen's Printer, Ottawa, 152.

McCarthy, P. (ed), 2011. Prairie and Northern Region 1826-2010 Severe Weather Event Database. Prairie and Arctic Storm Prediction Centre, Meteorological Service of Canada, Environment Canada, CD-ROM CD_095.

McKay, G.A., A.B. Lowe, 1960. The tornadoes of western Canada. Bull. Amer. Meteor. Soc., 41, No. 1, pp. 1-8. https://doi.org/10.1175/1520-0477-41.1.1

Newark, M. J., 1984: Canadian Tornadoes, 1950- 1979. Atmos.-Ocean, 22, 343-353.

Paul, A.H., 1995. The Saskatchewan Tornado Project. University of Regina, Department of Geography Internal Report.

Raddatz, R.L., R.R. Tortorelli, M.J. Newark, 1983. Manitoba and Saskatchewan Tornado days 1960 to 1982. Environment Canada, Atmospheric Environment Service, Canada Climate Centre, Downsview, ON, CLI-683, 57 pp.

Raddatz, R.L., J.M. Hanesiak, 1991. Climatology of Tornado Days 1960-1989 for Manitoba and Saskatchewan. Climatological Bulletin. 1991, 25, Num 1, pp. 47-59.

Shannon, T.B., 1976: Manitoba Tornadoes 1960-1973. Atmospheric Environment Service, Meteorological Applications Branch,

Environment Canada, Project Report No. 29.
https://publications.gc.ca/collections/collection_2020/eccc/En57-46-29-eng.pdf

Sills, D.M.L., Scriver, S.J., and King, P.W.S. 2004. The tornadoes in Ontario project (TOP). Preprints, 22nd AMS Conference on Severe Local Storms, Hyannis, Mass., American Meteorological Society, CD-ROM 7B.5.
http://www.yorku.ca/pat/research/dsills/papers/SLS22/SLS22_TOP_AMS.pdf

---

Patrick McCarthy is a retired Meteorological Service of Canada meteorologist and former Head of the Prairie and Arctic Storm Prediction Centre. He is an active weather history buff, storm chaser, and the Chair of the CMOS Winnipeg Centre.

Jay Anderson is a meteorologist, formerly with Environment Canada, where he worked primarily in Winnipeg and Vancouver over a 34-year career. Since his retirement, he has been working casually as a consultant, primarily in the travel industry, and teaching storm chasing at the University of Manitoba

Tornadoes on the Canadian Prairies: 1826-1939– Part 2, Project Results

WRITTEN BY CMOS BULLETIN SCMO ON JANUARY 17, 2023. POSTED IN MEMBERS, WEATHER, WHAT'S CURRENT.
-By Patrick McCarthy and Jay Anderson-

Abstract

Kendrew and Currie (1955) commented on prairie tornadoes in their 1955 publication The Climate of Central Canada: "…they probably occur in Alberta and Manitoba but there is no definite evidence," while noting that Saskatchewan averaged only about one per year. After an exhaustive effort, we have compiled the most complete historical database of Canadian prairie tornadoes before 1940. This included a total of 589 rated tornadoes, with 152 having a damage track. The project also yielded a more complete account of tornado deaths and injured for the period.

Results

Most early events occurred in the more-populated eastern prairies. Beginning in the 1880s, agricultural farms and communities grew along the railway lines that were being laid westward across the plains. By 1900, there began a significant increase in tornado reports in Saskatchewan and Alberta (Figure 1).

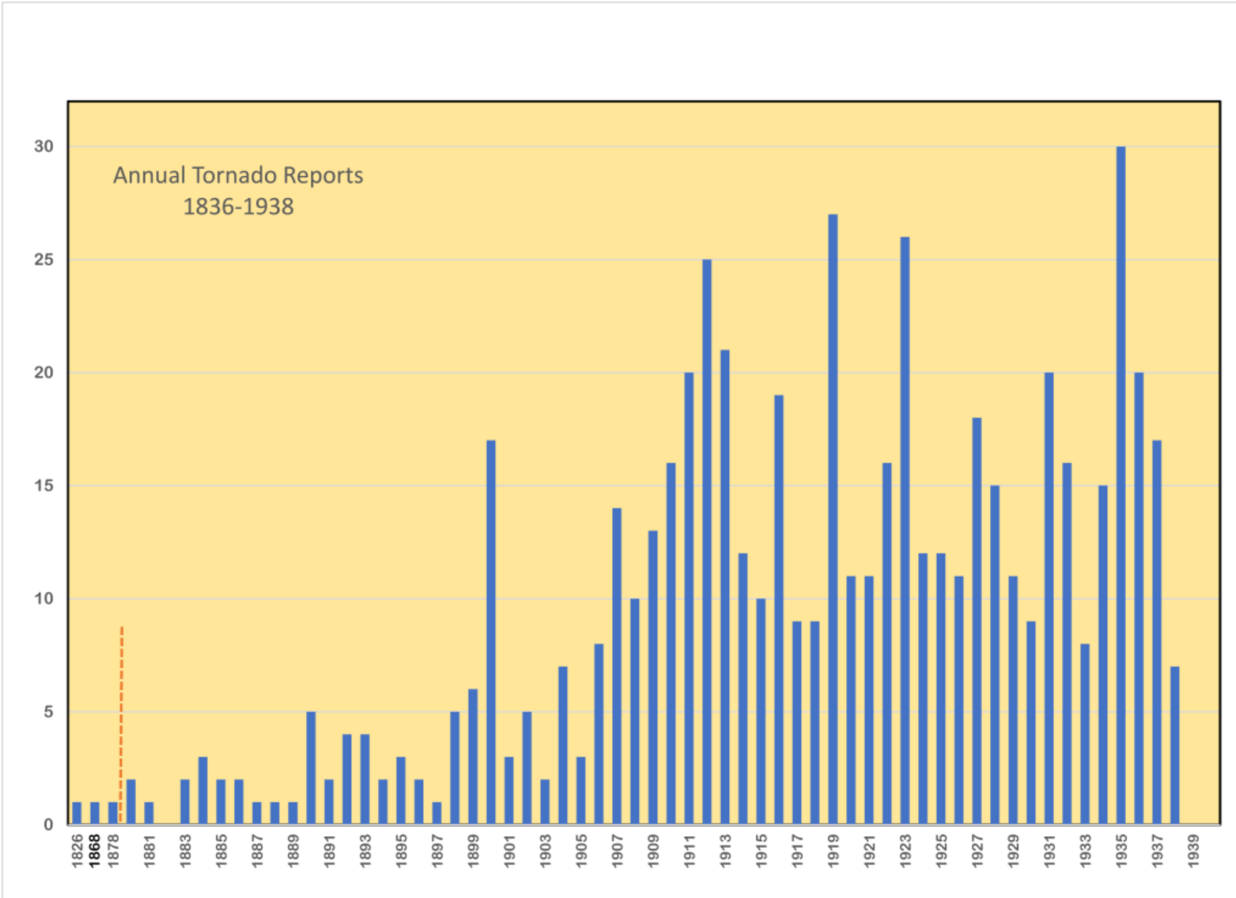


Figure 1: Graph showing the number of tornado reports per year in the three prairie Provinces from 1826 to 1939. The vertical dashed line indicates a break in the yearly sequence. There are no reports in 1939.

The 1826-1939 tornado occurrences are mostly south of the tree line, spread across the prairie region (Figure 2). Tornado reports often trace out those railway lines. This artifact is due to tornado reports being associated with a nearby town, village, or rail station, even though the tornado may have been quite distant. These are well-known distributions to Environment Canada’s forecasters, though highways have replaced railways as the alignment axis. The broad climatological characteristics of Prairie tornadoes were evident from a very early stage.

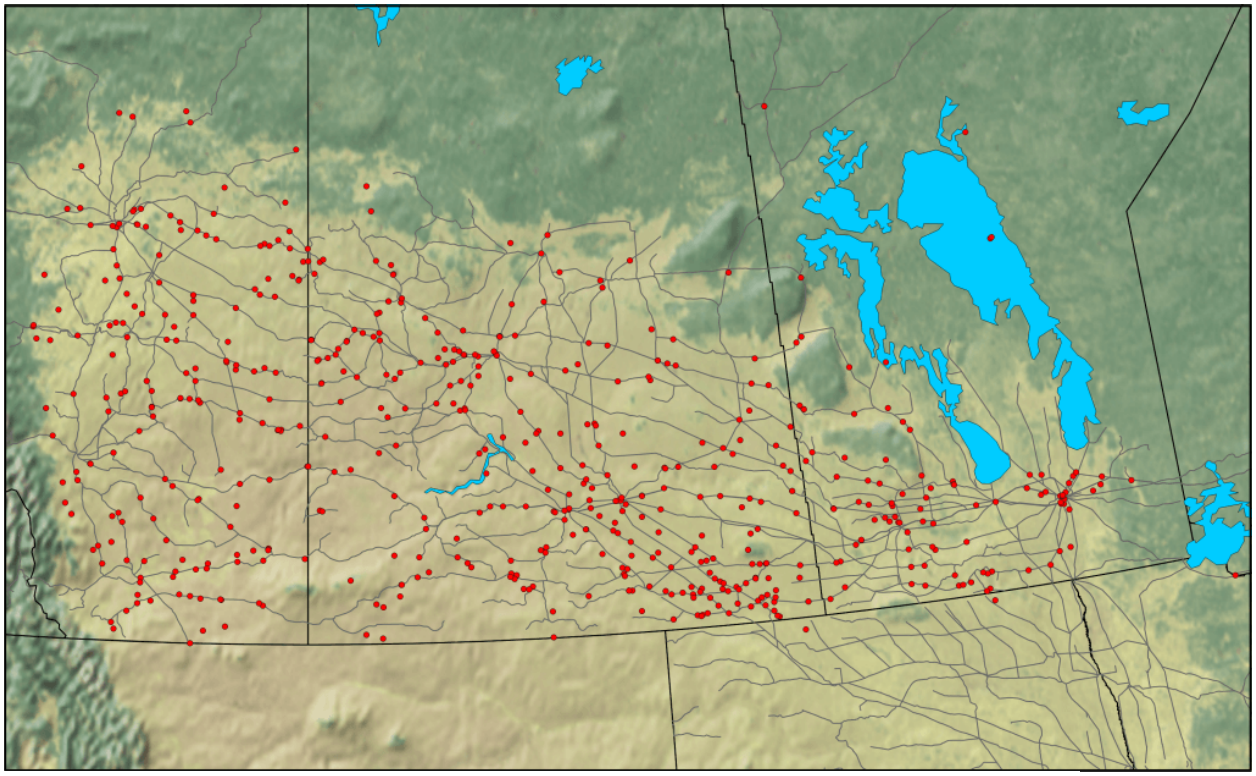


Figure 2: the distribution of recorded tornadoes between 1826 and 1939. The present-day railway network underlies the tornado data.

Figure 3 shows that the largest number of tornadoes occurred from mid-June to mid-July. Observations of late evening and overnight tornadoes are limited by darkness, a bias that we attempted to overcome by examination of the synoptic situation and the reported damage tracks. The northern latitude of the region means that civil twilight ends at 10:30 pm and begins at 4:30 am in late June leaving only a six-hour period of darkness at the height of summer. This period for observable tornadoes is among the longest in North America.

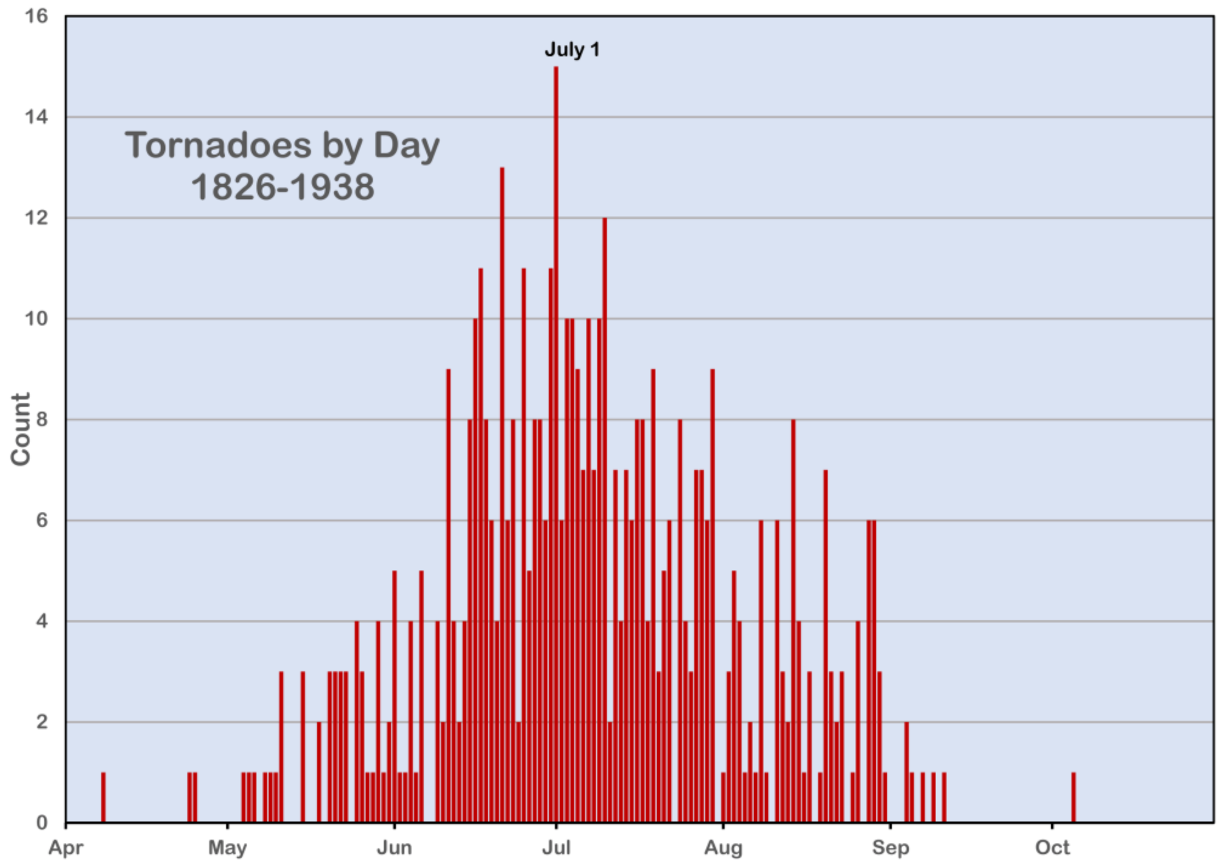


Figure 3: Number of tornadoes for each day of the year, 1826-1939.

It is the nature of the Prairie tornado that there are significant stochastic variations in reported events from year to year, ranging from zero to 30 in our sample. This may or may not represent differences in climatological conditions in individual years, as we cannot know how complete our sample is. It is only recently, with the popularity of storm chasing, cell phone cameras, and social media that annual tornado counts have begun to reflect the actual frequency of events closely enough to derive a useful climatology. Recently, the Northern Tornadoes Project (2020) has demonstrated that intensive damage surveying can reveal a more complete account of tornadoes and their tracks.

We estimated the strength of tornadoes according to a hybrid Fujita – Enhanced Fujita Scale, as described in our Part 1 article. The ability to come up with a definitive value is limited when information is sparse. Table 1 shows the distribution of our F-value estimates. The deficiency in F0 values is most likely due to their weak and transient nature, which makes them less likely to be observed, reported, or newsworthy. The data also suggests that deaths and injuries are more likely with stronger tornadoes.

Fujita Scale	Events	Injured	Deaths
F0	181	18	3
F1	243	97	14
F2	127	194	32
F3	29	105	32
F4	9	390	44
F5	0	0	0

Table 1: Frequency of Fujita Scale values for events (1826-1939) with associated injuries and deaths.

Most early tornado reports contained only a single observation. Typically, only the more severe events included comments about the path location and length. Individual reports also tended to be limited by reference to a single nearby community. We endeavoured to be more precise by finding additional eyewitness accounts of each event that would allow a track to be established and by triangulating reports to obtain a more accurate position. From this improved dataset, we were able to estimate the tracks of 152 tornadoes in the pre-1940 era. In the case of the 1912 Regina tornado (Figure 4), we were able to find seven tornado tracks in the outbreak that day—a result that is comparable to the 1987 Edmonton tornado event.

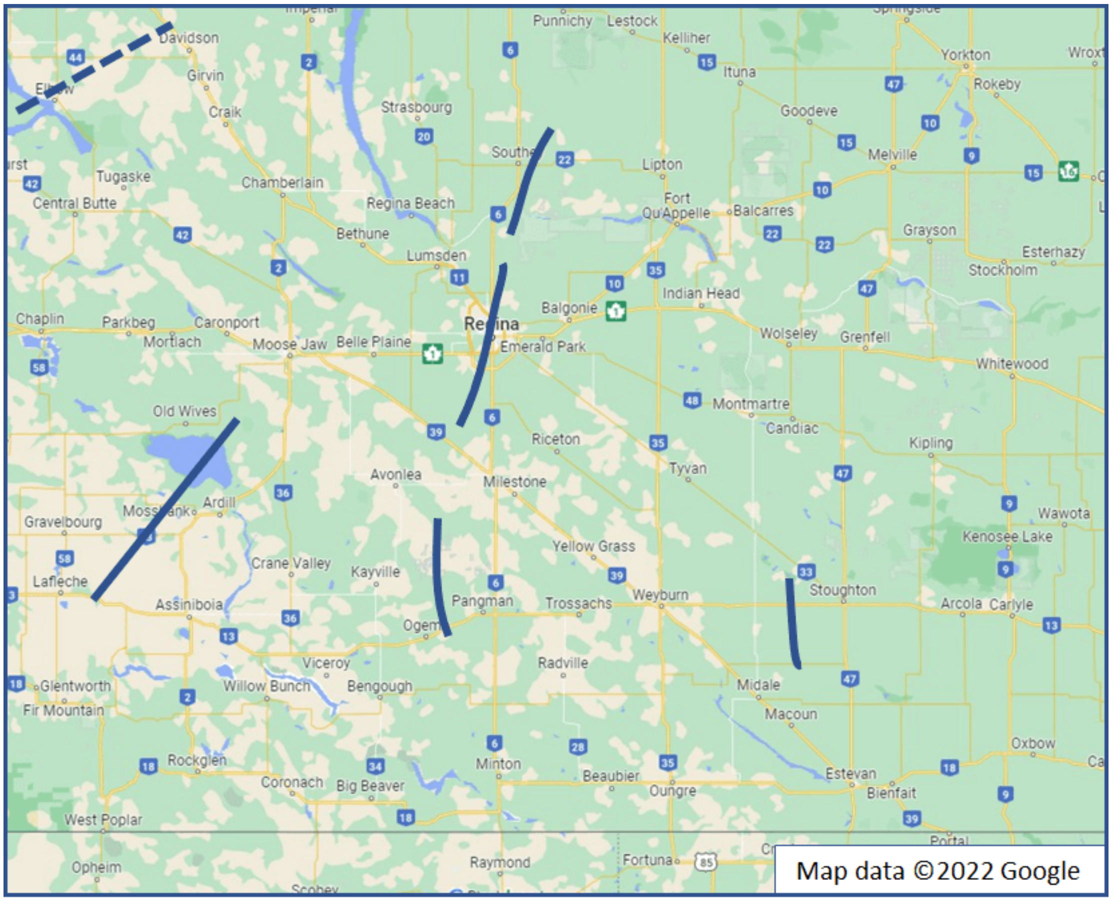


Figure 4: Approximated tornado tracks on the day of the June 30, 1912 Regina Tornado. The tornadoes generally moved from south to north, much like the 1987 Edmonton Tornado storms. The underlying Google map is for 2022.

One consequence of the research was the uncovering of additional events for inclusion into the severe weather database, including elements such as deaths due to lightning, major hail events, and unusual phenomena such as raining frogs and fish falling from the sky. In a few exceptional cases, a detailed assessment of extreme non-tornadic wind events, such as the 1922 Manitoba derecho, was constructed. These mesoscale convective systems often have embedded and difficult-to-detect tornadic circulations.

Ongoing work

As online digital databases continue to grow, we will likely see further adjustments to this early dataset. Moving forward, we are now examining the period from 1940 to 1979. The current database for this time frame contains over 900 possible tornado events. The goal is to have a comprehensive, reliable, accurate, and public dataset of tornadoes from the first reports on the Canadian Prairies to the present.

References

Kendrew, Wilfrid George, and Balfour W. Currie, 1955. The climate of central Canada–Manitoba, Saskatchewan, Alberta and the Districts of Mackenzie and Keewatin. E. Cloutier, Queen's Printer, Ottawa, 152.

Sills, D. M. L., Kopp, G. A., Elliott, L., Jaffe, A. L., Sutherland, L., Miller, C. S., Kunkel, J. M., Hong, E., Stevenson, S. A., & Wang, W. (2020). The Northern Tornadoes Project: Uncovering Canada's True Tornado Climatology, Bulletin of the American Meteorological Society, 101(12), E2113-E2132. Retrieved Oct 7, 2022, from https://journals.ametsoc.org/view/journals/bams/101/12/BAMS-D-20-0012.1.xml

---

Patrick McCarthy is a retired Meteorological Service of Canada meteorologist and former Head of the Prairie and Arctic Storm Prediction Centre. He is an active weather history buff, storm chaser, and the Chair of the CMOS Winnipeg Centre.

Jay Anderson is a meteorologist, formerly with Environment Canada, where he worked primarily in Winnipeg and Vancouver over a 34-year career. Since his retirement, he has been working casually as a consultant, primarily in the travel industry, and teaching storm chasing at the University of Manitoba

Bias Correcting Surface Snow Water Equivalent Estimates using Machine Learning

WRITTEN BY CMOS BULLETIN SCMO ON JANUARY 22, 2023. POSTED IN CLIMATE, WHAT'S CURRENT.

-By Fraser King-

During Canada's cold winters, snowpacks that aren't consistently plowed or hovelled slowly grow in size and density. From a water-balance perspective, these snowpacks act as ephemeral water towers, waiting for spring temperatures to eventually warm them enough to melt en masse. This snowmelt-derived water is a critical contributor to local water budgets as it refills aquifers, and feeds nearby rivers and lakes. However, rapid snowmelt periods can quickly saturate the soil, leading to surface runoff and flooding. Snowmelt-derived flooding has become increasingly problematic across much of Canada in recent decades as global temperatures continue to rise, leading to millions of dollars in damage to local communities, and disruptions to regional ecosystem development and sustainability.

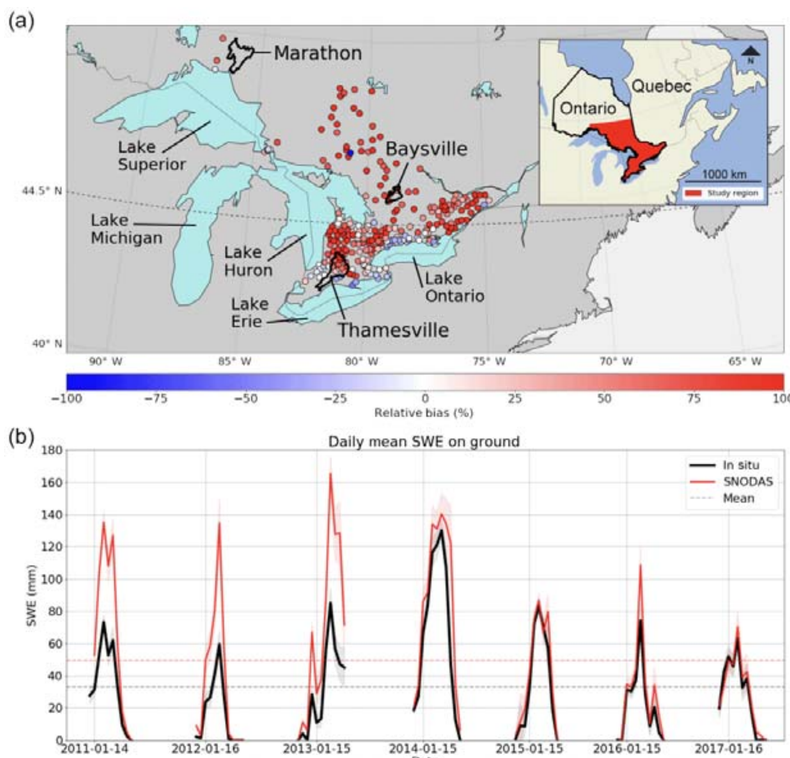


Figure 1: a) Relative bias in SNODAS SWE estimates when compared to in situ estimates from ECCC; and b) 7 year timeseries of SWE on ground estimates from SNODAS and ECCC.

The ability to accurately quantify the amount of water stored in snow on the ground is therefore an important component in flood forecasting, allowing local governments to better prepare for, and mitigate, damages caused by future rapid snowmelt events. As discussed in another recent CMOS bulletin from Ross D. Brown, the number of snow-observing sites across Canada has dropped by over 50% since 1995, leaving large unobserved gaps across much of the country. Climate models and reanalysis products are powerful tools which can be used to fill these spatiotemporal gaps in observations, however no model is without bias, error and uncertainty, which limits our estimates of the true water content in a given snowpack.

In a paper submitted to Hydrology and Earth System Science in 2020, we address some of the aforementioned concerns surrounding model error by bias correcting snow water equivalent (SWE) estimates from the SNOw Data Assimilation System (SNODAS) gridded SWE product. SNODAS is a daily, 1 km modelling and data assimilation dataset produced by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service's Operational Hydrologic Remote Sensing Center. While this product was primarily developed for use across the continental United States, the northern portion of SNODAS overlaps with southern Ontario. Through a combination of the many sources of observations assimilated by SNODAS, and its complex, physically-based internal model, SNODAS produces some of the highest quality estimates of surface SWE across the region.

However, when compared with independent in situ measurements recorded by the Climate Research Division of Environment and Climate Change Canada (ECCC), SNODAS displays clear spatiotemporal biases in its SWE estimates across much of southern Ontario (Figure 1). Temporally, SNODAS exhibits a strong positive bias pre-2014 (a period which marks a distinct change in the known assimilated datasets), along with strong positive spatial biases as we move further inland, away from the US border.

To address these biases, we explored a suite of increasingly sophisticated statistical bias-correction methods, culminating in the application of a nonlinear machine learning (ML) technique which displayed the best overall skill. Instead of jumping directly into ML, we followed an "Occam's razor" methodological approach by starting with simple, well validated and interpretable methods of bias correction like mean bias subtraction (MBS) and linear regression to develop a performance baseline. The idea being that if a simple method does nearly as well as a more sophisticated ML-based method, we should use the simpler, more explainable technique.

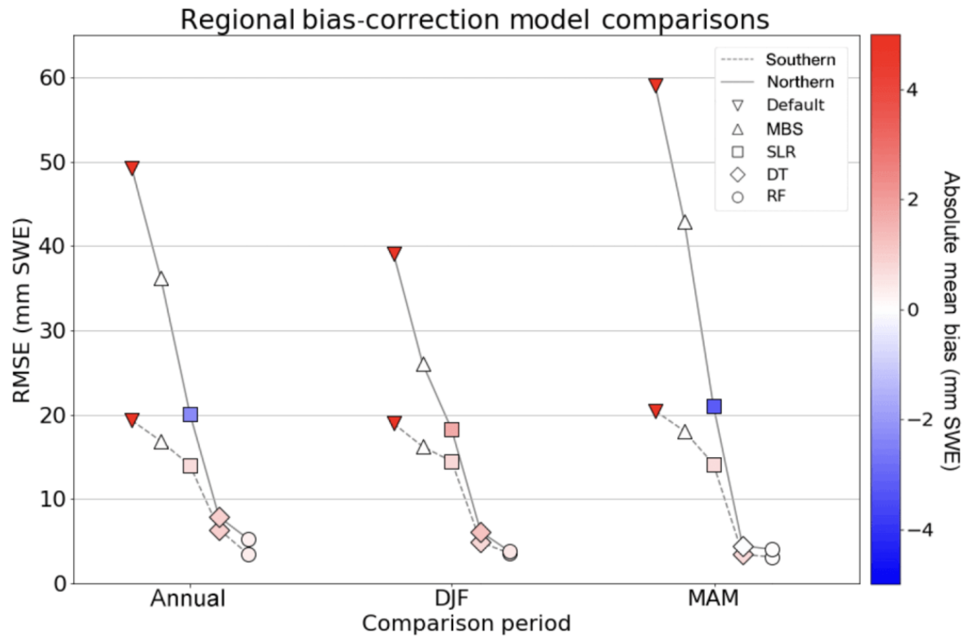


Figure 2: RMSE and absolute mean bias for each model trained and tested using different spatiotemporal partitions of the full training dataset.

We evaluated four different models including the aforementioned MBS, a simple linear regression (SLR) model, decision tree (DT), and finally a random forest (RF). Each of these models were fit using the same training datasets over three periods

1. December, January, February (DJF)
2. March, April, May (MAM)
3. DJF MAM (i.e. annual)

across two spatial domains (northern vs. southern Ontario). Each model was fit using a set of climate predictor variables (SNODAS SWE on ground, precipitation biases, surface temperature, elevation, year, and day of year) to model ECCC SWE on ground at 391 sites.

Our results indicated that the RF continually demonstrated the lowest overall RMSE and absolute mean bias over each period and across all regions (Figure 2). The overly simplistic MBS did an excellent job at removing the mean bias (by construction), however this was accomplished by overcorrecting the bias in some regions and under correcting it in others (resulting in the high RMSE for this method in Figure 2). The SLR fared better with a slightly lower overall RMSE, however these linear methods were unable to fully account for the nonlinear spatiotemporal bias from Figure 1. The best performing methods were the ML-based DT and RF, with the RF demonstrating improved performance annually (improved robustness).

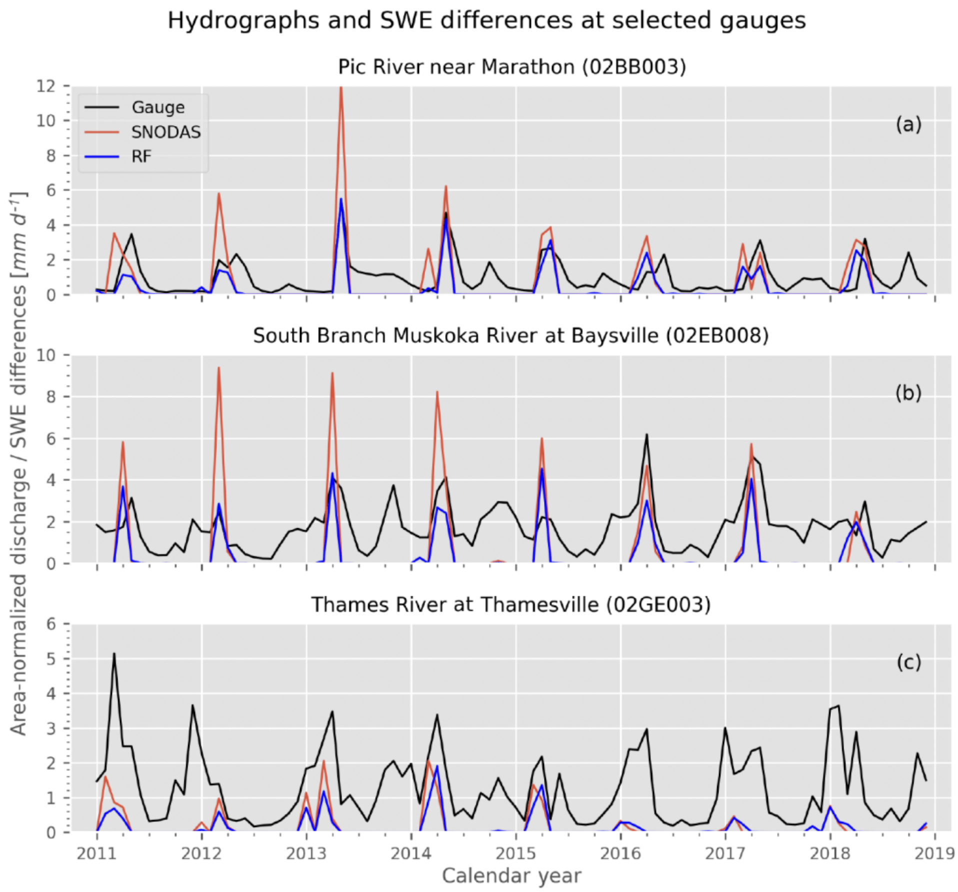


Figure 3: Timeseries comparisons of monthly area-normalized discharge from SNODAS and the bias corrected SWE melt estimates at three river gauges in Ontario.

To further quantify the differences between bias-corrected and uncorrected SWE estimates, we also performed a simple water balance analysis across three watersheds in southern Ontario, anticipating that reductions in mean SWE would produce a more physically consistent fit with in situ melt measurements. Comparing monthly snow melt estimates (i.e. the negative SWE differences between consecutive monthly means from bias corrected and uncorrected SWE datasets) with area-normalized discharge across each basin (Figure 3), we found that the bias corrected RF-derived melt estimates were much closer in magnitude to in situ, and did not display the unphysical overestimation which was typical of SNODAS. These types of follow-up comparisons are incredibly useful methods for further validating the robustness of bias correction models like those explored in this work, and can be used to identify deficiencies which may be hidden upon first glance (e.g. preserving physical laws which are unknown to the ML model).

While the ML-based bias correction techniques applied here demonstrate good skill and a general robustness throughout the region, there are other options to choose from in the ML toolbox. In an upcoming study, we plan on evaluating some of these tools through a daily, ten-year Canada-wide bias correction of temperature, precipitation and radiation fields from the fifth-generation Canadian Regional Climate Model (CRCM5) (biases shown in Figure 4). With a much larger available sample in this follow-up project, we are able to experiment with more sophisticated neural network (NN) approaches for spatiotemporally bias correcting each climate variable. These bias corrected fields can then be used to drive land surface models and, in turn, bias correct surface snow estimates via a proxy correction of associated climate variables. When trained on the billions of available data points, early results suggest that NN approaches strongly outperform linear methods, and even beat out RF techniques for nonlinear biases like those present in surface temperature.

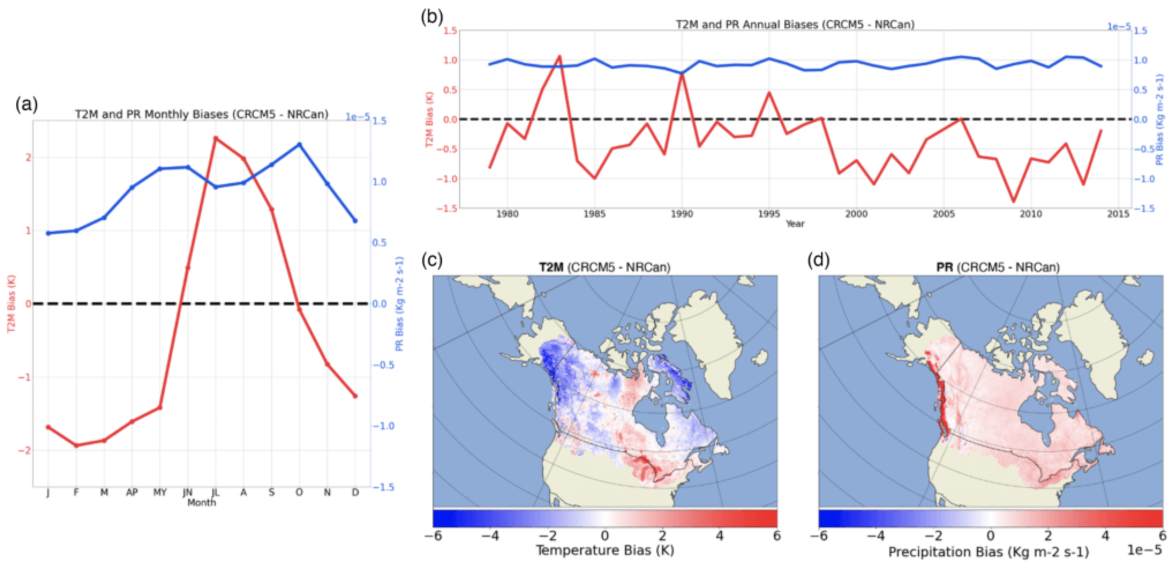


Figure 4: CRCM5 surface temperature (T2M) and precipitation (PR) biases at a) monthly and b) annual timescales; along with their corresponding climatological mean biases across Canada in c) and d).

ML has been used across the Geosciences for decades, however, rapid advancements in computing resources, combined with petabytes of now easily accessible observational data, has allowed this field of research to flourish in recent years. While it can be appealing to immediately jump to ML for problems like downscaling or bias correction, we argue that this mindset may be problematic. The Occam’s razor approach to problems such as these provide researchers with additional opportunities to save on computational costs (i.e. avoid expensive model training/hyperparameterization phases), and to develop a more interpretable and explainable model. While we are incredibly optimistic about the future of ML (and especially deep learning) in the Geosciences, we also recommend that future researchers take care by starting with simple methods before digging into their respective machine learning toolboxes.

Fraser King completed his PhD in remote sensing and machine learning of precipitation at the University of Waterloo in December, 2022. He is now a post doctoral research fellow at the University of Michigan, developing machine learning-based snowfall retrieval algorithms and using surface and spaceborne radars to improve our understanding of hydrometeor particle microphysics.

Will Greenland be really ‘Green’ after losing its ice mass?

WRITTEN BY CMOS BULLETIN SCMO ON JANUARY 30, 2023. POSTED IN ARCTIC, CLIMATE, WHAT'S CURRENT.

-By Xander Wang, Pelin Kinay, Aminur Shah, and Quan Dau-

Many people believe that, due to global warming, a longstanding myth about Greenland might be the reality – a ‘green’ land, resembling its name – ‘Green’, instead of the snowwhite ice-covered land that exists now. Recent scientific evidence suggests the ice sheets in Greenland are melting quickly because of rising air temperature and warm ocean waters, which is causing sea level rise and threatening coastal areas. UN Climate Actions are aimed at limiting global warming by lowering carbon emissions, which would eventually lead to less ice melting in the polar areas, including Greenland. Greenland’s potential future, on the other hand, is unknown. The key question remains: is it possible to stabilize Greenland’s ice cover, or will it be a completely “Green” continent in the future if the Paris Agreement’s (2015) carbon reduction goals are not met?

While past evidence of melting ice sheets in Greenland has been studied, predicting the future of the huge ice cover is also of significant interest to scientists. Establishing a direct relationship between ice retreat and a warming climate could assist prove the ‘carbon emission – rising temperature – melting ice covers – sea level rise’ pathways.


An image of Greenland Ice Sheet – towards an unpredictable future

Credit: Wikimedia Commons

A recent study published in Earth's Future explored how the spatial breadth of the Greenland ice sheet might change in the context of global warming, using a regional climate model to quantify future changes in the Greenland ice sheet covering various emission scenarios.

Due to the poor performance of climate models in simulating precipitation (including the PRECIS model used in this study), the team only addressed this subject using future temperature estimates. The study, in particular, employed the idea of ice cap climate to estimate whether or not an area will be covered by an ice sheet.

According to the authors, ice cap climatic coverage of Greenland would diminish steadily throughout the century under both RCP8.5 and RCP4.5, meaning that the spatial area of the ice sheet would fall by 15% (RCP4.5) and 25% (RCP8.5) by the end of the century. In comparison, the low-emission scenario (RCP2.6) has the possibility of limiting the loss of Greenland ice sheet coverage to less than 10% by the middle of this century, with no more loss expected after that. Though various surface variables influence the evolution of Greenland's ice surface mass balance process, the researchers decided to use the temperature projections only to investigate if it is possible to stabilize the Greenland ice sheet given that the PRECIS does perform reasonably well in simulating near-surface air temperature over Greenland.

Compared with the baseline period of 1970-2000, the study projects future ice coverage over Greenland for three periods – 2020s, 2050s, and 2080s under three emission scenarios. "The low-emission scenario of RCP2.6 does have the potential to stabilize the warming climate in Greenland after 2050s and prevent further loss to its ice sheet coverage", the authors conclude. Ice covering only 65.5% of the country estimated in the baseline period could reduce to 56% in the 2050s and then increase to 57% in the 2080s under a low emission scenario. Hence, low emissions could potentially limit the warming in Greenland below 1°C within the next 30 years and constrain its loss of ice sheet coverage below 10%.

By contrast, ice coverage will continuously decline throughout this century as the local climate in Greenland is likely to warm up continuously under both medium and high emission scenarios. The worst could be expected in the 2080s under a high-emission scenario, with only around 40% of the country covered by ice caps.

The findings of this study are critical for understanding the consequences of various carbon emission scenarios on stabilizing or limiting warming in Greenland and thus the loss of ice sheet coverage, which is connected to rising sea levels. The results of the study imply that both the high- and medium-emission scenarios would result in ongoing warming in Greenland and thus major ice sheet loss. However, the low-emission scenario has a high potential for reducing local climate warming and ice sheet loss before the 2050s. Most notably, assuming the low-emission scenario is satisfied, no significant changes are projected after the 2050s.

The findings are significant not just for giving climate activists optimism that the Greenland ice sheet will be preserved and coastal populations would be protected from rising sea levels, but also for pressing all nations to take immediate action to decrease carbon emissions. It is fair to expect that the ice sheet covered by the ice cap climate will remain in place indefinitely, but it is difficult to predict when the ice sheet beyond the ice cap climate coverage will begin to melt and eventually disappear, authors highlight.

It goes without saying that the real 'Green' land is on the horizon if we do not take any action to reduce GHG emissions and global warming, and the greatest consequences are obvious. Greenland might envy the beauty of a lush green landscape; however, the rest of the world will suffer from the worst impacts of sea level rise and coastal flooding.

Changes in the Greenland and Antarctic ice sheets have a significant societal impact because they have a direct impact on world sea levels, as glaciers and ice sheets melt, more water enters the ocean. Fortunately, there are some climate policies and actions in place at the global and local scales. So, there is hope! Yet, effective actions are urgently needed to reduce carbon emissions so that we can slow down the disappearance of the ice sheet over Greenland and save our coastal communities from big disasters.

News on the following published article:

Wang, X., Fenech, A., & Farooque, A. A. (2021). Possibility of stabilizing the Greenland ice sheet. Earth's Future, 9(7), e2021EF002152.
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021EF002152

Dr. Xander Wang is an Associate Professor in the School of Climate Change and Adaptation at the University of Prince Edward Island (UPEI). He is also the Director of Climate Smart Lab in the Canadian Centre for Climate Change and Adaptation. Dr. Wang has been recently elected as a member of the Royal Society of Canada (RSC) College of New Scholars. Dr. Wang has served as the Associate Dean (Interim) in the School of Climate Change and Adaptation and is a core member leading the development of the Canadian Centre for Climate Change and Adaptation at UPEI, which is a world-leading research and teaching cluster in climate change impacts and adaptation. Before joining UPEI, Dr. Wang worked as an Assistant Professor in the School of Geosciences at the University of Louisiana at Lafayette, US.

Dr. Pelin Kinay is a postdoctoral fellow of the Climate Smart Lab in the Canadian Centre for Climate Change and Adaptation at UPEI. Her research interest focuses on climate change adaptation and its associated impacts on human health, as well as the natural and human-caused variables that influence climate change.

Dr. Aminur Shah is a postdoctoral fellow of the Climate Smart Lab in the Canadian Centre for Climate Change and Adaptation at UPEI. His research interest focuses on vulnerability and risk assessment of social-ecological systems to natural hazards, sustainable flood risk management, sustainability assessment, climate change impacts and adaptation, community risk reduction, and nature-based solutions.

Dr. Quan Dau is a postdoctoral fellow of the Climate Smart Lab in the Canadian Centre for Climate Change and Adaptation at UPEI. His research interest focuses on water science and global climate change, including but not limited to, hydrological cycle, water resources planning and management, remote sensing, artificial intelligence, climate change adaptation, irrigation water management, socio-economic projection, and reservoir operating management.

Keeping Watch Over Prince Edward Island's Coastline

WRITTEN BY CMOS BULLETIN SCMO ON FEBRUARY 21, 2023. POSTED IN CLIMATE, OCEANS, WHAT'S CURRENT.

– UPEI Climate Lab team led by Dr. Adam Fenech, and including Dr. Xander Wang, Don Jardine, Ross Dwyer, Andy MacDonald, Luke Meloche, and Catherine Kennedy –

Coastal erosion is the primary challenge that climate change presents to Prince Edward Island through storm surges, sea level rise, and high water levels. The sensitive sand and sandstone shorelines across Prince Edward Island often experience a wearing away by water, waves, ice, and wind. Sea level rise measured at Charlottetown, Prince Edward Island has increased by 36 centimetres over the past century (1911-2011 from Daigle, 2012) and is anticipated to increase by a further 100 centimetres over the next 100 years (IPCC, 2021). In terms of damaging storms, the Intergovernmental Panel on Climate Change (IPCC), the global community's scientific authority on climate matters, concluded that they were "virtually certain" that there had been an increase in intense tropical cyclone activity in the North Atlantic since the 1970s, and "more likely than not," these intense tropical cyclones would increase in the North Atlantic in the late 21st Century (IPCC, 2013). As a result of these anticipated ocean, geological, and storm changes, coastal erosion is expected to continue and likely become more severe, threatening public and private infrastructure at great economic cost to the 1,260 kilometres of coastline on Prince Edward (ACZISC, 2005).

The most recent study examining the rates of coastal erosion for every metre of coastline on Prince Edward Island (Webster and Brydon, 2012) by interpreting aerial photographs of Prince Edward Island's coastline for the years 1968 and 2010 using orthorectification and coastline delineation techniques calculated an annual coastal erosion rate of 0.28 metres per year.

A quantitative risk assessment of coastal residences (homes, cottages), safety and security infrastructure (roads, bridges, water treatment plants, hospitals, fire departments, etc.) and heritage (churches, graveyards, lighthouses, archaeological sites, parks, etc.) was conducted by the UPEI Climate Lab to determine what Prince Edward Island infrastructure is at risk to coastal erosion, concluding that over 1000 residences (houses and cottages), over 40 garages, 8 barns, and almost 450 outbuildings are vulnerable to coastal erosion. Even 17 lighthouses, those maritime cultural icons, were deemed to be at risk. Such scientific results were significant but were threatened to sit on a shelf in a scientific report unless communicated sufficiently to the organizations and communities of Prince Edward Island. But how best to do this?

CoastaL Impacts Visualization Environment (CLIVE)

CLIVE is a geovisual interface that combines available coastal data, historical records, and climate change predictions, and translates them into a 3-Dimensional geovisual information tool allowing users to “fly” over Prince Edward Island, raising and lowering sea levels and clicking on and off coastal erosion rates. Programmed in the UNITY shareware, CLIVE combines data from an extensive provincewide archive of aerial photographs documenting coastline erosion as far back historically as 1968, and the latest highresolution digital elevation data derived from laser surveys known as LiDAR, a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light.

A public engagement tour at sixteen towns across Prince Edward Island was held in 2014 and 2018 with each session presenting an introduction to Prince Edward Island’s vulnerability to coastal erosion and sea level rise, introduced CLIVE, examined the vulnerability of local communities and answered questions. Each session was also preceded and concluded with a written survey to gauge attendee’s knowledge, concern and willingness to adapt to coastal erosion and sea level rise. The concern for coastal erosion of each participant was high, and, in most cases, increased after being introduced to CLIVE. Most importantly, these sessions motivated coastal home or cottage owners to respond to their vulnerability by increasing their resilience to the anticipated sea level rise and coastal erosion.

CLIVE has garnered national and international attention including national text journalism from the Globe and Mail (19 February 2014); national Canadian broadcast coverage from the Canadian Broadcasting Corporation (World Report radio on 11 February 2014), international journal coverage (National Geographic, 16 December 2015) and international television coverage from Al Jazeera media. CLIVE won an international award in 2014 from the Massachusetts Institute of Technology for communicating coastal risk and resilience. The CLIVE technology has been exported to the City of Los Angeles, and implemented in several counties in Nova Scotia and New Brunswick, as well as across Canada.

This raised awareness of coastal issues prompted the Prince Edward Island government to support the Climate Lab at the University of Prince Edward Island to build a coastal surveillance system to act as an early warning system for coastal erosion. This system includes peg-line measurements, drone surveys, tidal gauges and climate stations.

Coastal Surveillance System

Figure 1: UPEI Climate Lab cap on peg for measuring coastal erosion year-to-year.

Every summer, one lucky student working at the Climate Lab at the University of Prince Edward Island has the best job on the Island because they get to visit 200 sites across the province (many with beaches) and take peg-line measurements. This coastline surveillance approach involves physically hammering two 1 metre (m) lengths of 15 millimetre (mm) diameter metal rebar “pins” into the ground in a line spaced 10 m and 20 m roughly normal to the coast; and then manually taking a measurement to the coastal indicator feature (e.g. cliff or bluff edge) using a measuring tape. Metal caps are hammered on the ends of the rebar using a rubber mallet just before the desired depth is achieved (Figure 1). GPS locations of each pin are taken using a Garmin eTrex recreation grade Global Positioning System (GPS) for general site mapping and locating pins year-to-year. Visiting year-to-year provides an early warning system to coastal erosion. Our results show that the average coastal erosion at these pin sites varies year-to-year, but the “usual suspects” show annual erosion rates ranging from 1 to 5 metres. And our preliminary analysis of the coastal impacts from Hurricane Fiona of September 23-24, 2022 show erosion rates at individual locations of over 10 metres.

Figure 2: A DJI Phantom 4 RTK drone flown by the Climate Lab at the University of Prince Edward Island

To survey the full run of the coastline, the UPEI Climate Lab also flys drones to measure coastline change at 90 sites across Prince Edward Island. A DJI Phantom 4 RTK drone (see Figure 2) is flown at an altitude of 50 meters using 75% front and side flight plan overlaps, and then along the coast angling the camera at the coastline to give some depth to the imagery. Ground control points (GCPs) are laid throughout each site before flying to increase the accuracy of the resulting maps produced from the stitched imagery (known as orthomosaics), with the center of each GCP measured using a Trimble Real Time Kinematic (RTK) Global Positioning System (GPS) unit that provides an accuracy of 2 centimeters (cm). Flying drones as these sites year-to-year provides a good sense of how Prince Edward Island's coasts are changing (see Figure 3).

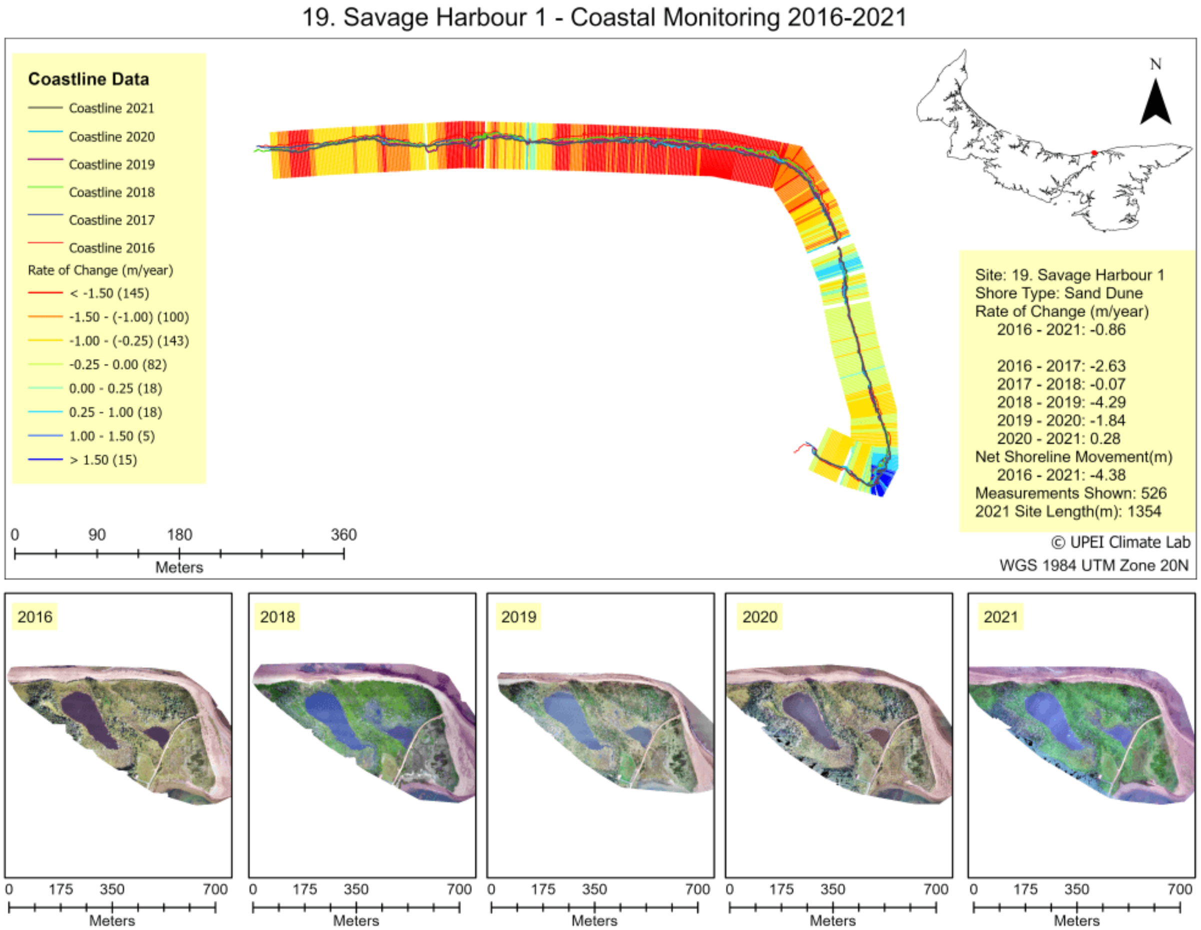


Figure 3: Coastal monitoring using drones at Savage Harbour, Prince Edward Island. This 1.3 kilometre coastline has shown a net shore erosion of 4.38 metres from 2016 to 2021. Red colours show erosion over 1.5 metres per year.

A series of fifteen real-time tidal gauges have been installed across Prince Edward Island by the UPEI Climate Lab, working with the PEI Emergency Management Office and the Mi’kmaq Confederacy of Prince Edward Island. These sites provide the Island’s only direct monitoring for an early warning system of rising tidal levels and storm surges. These tidal gauges were instrumental in alerting PEI ports of the timing and magnitude of storm surges from Hurricane Fiona in September 2022, providing the only record of the actual height of the storm surges (see Figure 4). To complement these coastal stations are a series of inland climate stations installed by the UPEI Climate Lab to measure temperature, precipitation, wind, atmospheric pressure and solar radiation every 2 to 5 minutes, 24/7 at over 70 locations across Prince Edward Island. These stations provide support research on climate vulnerability, impact and adaptation studies across the Island; support the reconstruction of extreme climate events; and support groundtruthing of high-resolution regional climate models. But most importantly, these climate stations provide detailed real-time weather/climate information to Islanders in their day-to-day needs as farmers, fishermen, tourism operators, or simply beach goers.

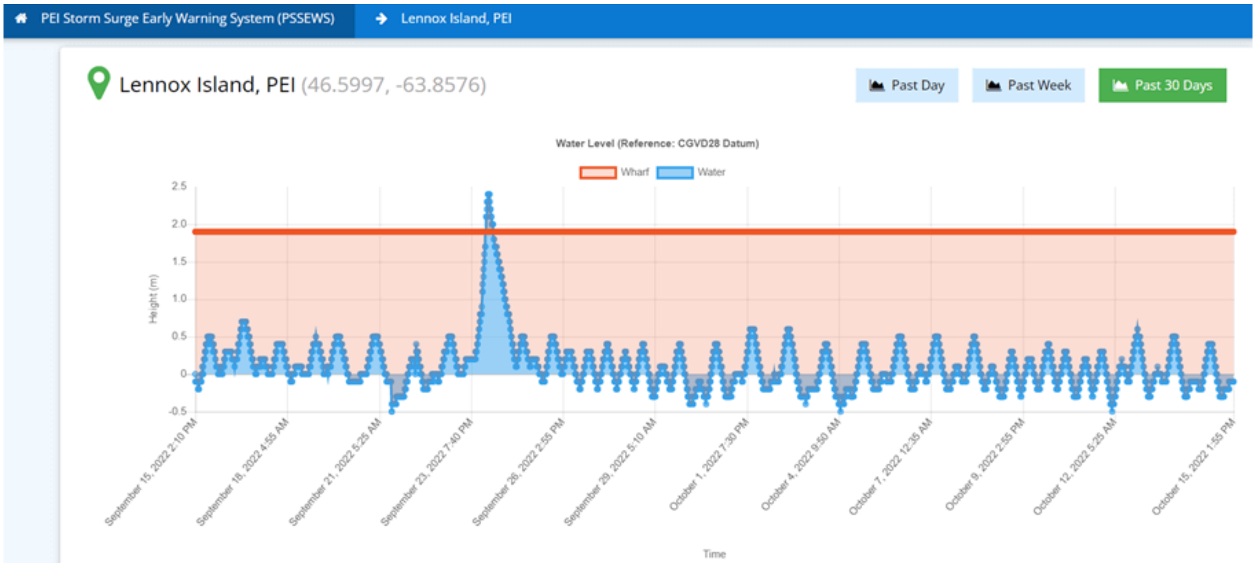


Figure 4: PEI Storm Surge Early Warning System graph of Hurricane Fiona storm surge of record 2.4 metres on September 24, 2022. This real-time 24/7 early warning system reports 15 tidal gauges from across Prince Edward Island installed and maintained by the UPEI Climate Lab in partnership with the PEI Emergency Management Office and the Mi'kmaq Confederacy of Prince Edward Island.

Final Words

Climate change is presenting greater challenges to Prince Edward Island's coasts with rising sea levels, storm surges and coastal erosion, but the Climate Lab at the University of Prince Edward Island is keeping watch over Prince Edward Island's coastlines, measuring them annually with pegs and drones as an early warning system of coastal change. The Climate Lab also installed and maintains a 24/7 surveillance over the Island's storm surges with 12 tidal gauges, and the Island's climate with over 70 climate stations, for a real-time early warning system. With such significant vulnerability to anticipated future coastal threats, the UPEI Climate Lab's climate change early warning systems need to be maintained, and could benefit from financial injections.

Dr. Adam Fenech has worked extensively in the area of climate change for thirty-five years and has edited eight books on climate change. Dr. Fenech is an Associate

Professor in the School of Climate Change and Adaptation at the University of Prince Edward Island where he developed the curriculum for the first undergraduate programme in Applied Climate Change and Adaptation. He is presently the Director of the University of Prince Edward Island’s Climate Research Lab that conducts research on the vulnerability, impacts and adaptation to climate change, where his virtual reality depiction of sea level rise has won international awards including one from MIT for communicating coastal science. He maintains the largest fleet of drones at a Canadian university including the largest drone in the country with a four metre wingspan.

Adaptation planning: an interdisciplinary approach to climate change risk reduction

WRITTEN BY CMOS BULLETIN SCMO ON FEBRUARY 28, 2023. POSTED IN ARCTIC, MEMBERS, WHAT'S CURRENT.
– By Sarah Kehler, S. Jeff Birchall-

Climate change presents a complex and unprecedented problem. As temperatures rise, the global climate is becoming increasingly unstable. Climate impacts, such as sea level rise and frequent extreme weather events, are causing acute impacts on ecological and human systems. Although climate change is a global phenomenon, unique and severe consequences occur at the local level. Uncontrollable coastal erosion, devastating overland flooding or atypical temperature extremes can easily overwhelm an unprepared community. Climate impacts are likely to be costly: in 2025, Canada is expected to see a loss of $25B due to climate change, and by 2100, annual losses could be as high as $100B (Sawyer et al, 2022). These risks underscore the importance of adaptation, the process through which communities anticipate and prepare for climate change

Unique and intensifying local climate impacts are forcing communities to adapt. With their place-based knowledge and authority, local governments, such as municipal and regional governments, are in an ideal position to facilitate this adaptation (Birchall et al., 2023). Urban planning guides local-level decision making around future land use, development and infrastructure. Adaptation planning seeks to integrate climate science into urban planning – a critical step toward preparing for climate change. Decision making that considers future projections can considerably reduce disaster risk, enhance infrastructure resilience and prepare communities for uncertainty (Davoudi et al., 2013).

Anticipatory adaptation provides security. Adaptation mitigates disaster risk and, should an event occur, can substantially reduce response costs and economic losses. In fact, every $1 spent on anticipatory adaptation will provide up to $15 benefit within 75 years (Sawyer et al, 2022). However, the benefits of adaptation go beyond economics. Adaptation, when implemented equitably, provides food and livelihood security, increases human health and well-being, and conserves biodiversity.

There are two main types of adaptation: hard adaptation and soft adaptation (Table 1). Hard adaptation is structural, focusing on updating infrastructure to withstand climate impacts. Today, most adaptation consists of hard infrastructure measures like sea walls (Kehler & Birchall, 2021). Soft adaptations are non-structural or ecosystem-based, focusing on managing risks through restricting land use and bolstering ecosystem services. Soft measures are increasingly recognized as critical aspects of adaptation; flood risk, for example, can be mitigated through wetland preservation or zoning restrictions.

Definition and classification	Examples to reduce vulnerability in practice	Benefits	Drawbacks
Structural (hard adaptations)			
An infrastructural change or improvement that is intended to increase a community's resilience to climate impacts	To physically protect against storm surge, coastal erosion, sea level rise, permafrost thaw and flood: • shoreline armoring • levees • sea walls • drainage channels • dams • dykes • elevated infrastructure (stilts) • heat insulators	• Commonly used and well understood • Quick to install • Associated with a visible sense of security	• Associated with rigidity • Capital intensive • Costly to maintain • Contribute to environmental degradation
Non-Structural (soft adaptations)			
Measures that focus on human behavior and aim to permit the continued use of vulnerable areas by managing climate risks primarily through planning, including the regulation of land use and development	To reduce exposure to storm surge, coastal erosion, permafrost thaw, sea level rise and flood: • planned relocation or retreat • altered land use and building controls • elevated floor requirements • increased setbacks • emergency management • insurance	• Greater flexibility in responding to climate threats • More cost effective than structural adaptations	• Social barriers challenge implementation • Subject to institutional and political constraints
Ecosystem-Based (soft adaptations)			
Protective strategies that leverage the adaptive opportunities associated with ecosystem services	To reduce the impacts of storm surge, coastal erosion, sea level rise, and flood: • beach nourishment • sand dune restoration • wetland preservation • rain gardens	• Unobtrusive in nature • Potential to enhance ecosystem health • Additional recreation and aesthetic opportunities	• Limited understanding of how to value ecosystem services in monetary metrics

Table 1: Adaptation approaches. Structural, non-structural and ecosystem-based approaches are defined and classified with examples provided according to climate vulnerabilities. Benefits and drawbacks are presented for each approach. Adapted from: Bonnett & Birchall (2020).

Adapting effectively requires sufficient adaptive capacity – the conditions that enable communities to anticipate and respond to change (Cinner et al., 2018). Local governments must be flexible, cooperate across jurisdictions, and understand the importance of adaptation (Birchall et al., 2023). They must have access to resources, such as money, technology or services, in order to initiate adaptation. Public support, stakeholder engagement and political leadership underpin adaptive capacity; without people advocating for anticipatory action, adaptation is unlikely to occur (Ford & King, 2013). There is growing awareness that implementation of adaptation is often inequitable, with wealthy areas receiving greater support, decreasing the overall adaptive capacity of the community (Kehler & Birchall, 2021).

Adaptation is not a cure-all for climate change. Both hard and soft adaptations come with limits, benefits and drawbacks (Table 1). However, over-reliance on hard adaptation has put communities at risk: Climate change will quickly outpace our capacity to adapt through hard measures alone. Despite good intentions, over the long-term hard adaptation can carry high maintenance costs and risks of failure, while providing less benefits than soft adaptation (Birchall et al., 2022). In some circumstances, the unintended consequences of expensive infrastructure and engineered adaptations can lead to maladaptation, when adaptation measures do not decrease risk, and rather increase vulnerability to climate change.

Unfortunately, many communities, overwhelmed by the sheer cost and magnitude of future adaptation demands, lack the consistent public support and bureaucratic efficiencies necessary to meet them (Birchall et al., 2023). These barriers can inhibit the planning process from undertaking effective local-level adaptation, and increase the risk of maladaptation (Kehler & Birchall, 2021). Avoiding maladaptation requires effective and equitable adaptation. To do so, planning must address adaptive capacity constraints and aim to balance hard and soft adaptations. These goals can be achieved simultaneously. For example, by exploring less expensive and minimally disruptive soft options first, communities can avoid maladaptation risks, garner public support and conserve limited resources for when hard measures are unavoidable.

Case study: The challenge of adaptation in the Canadian Arctic

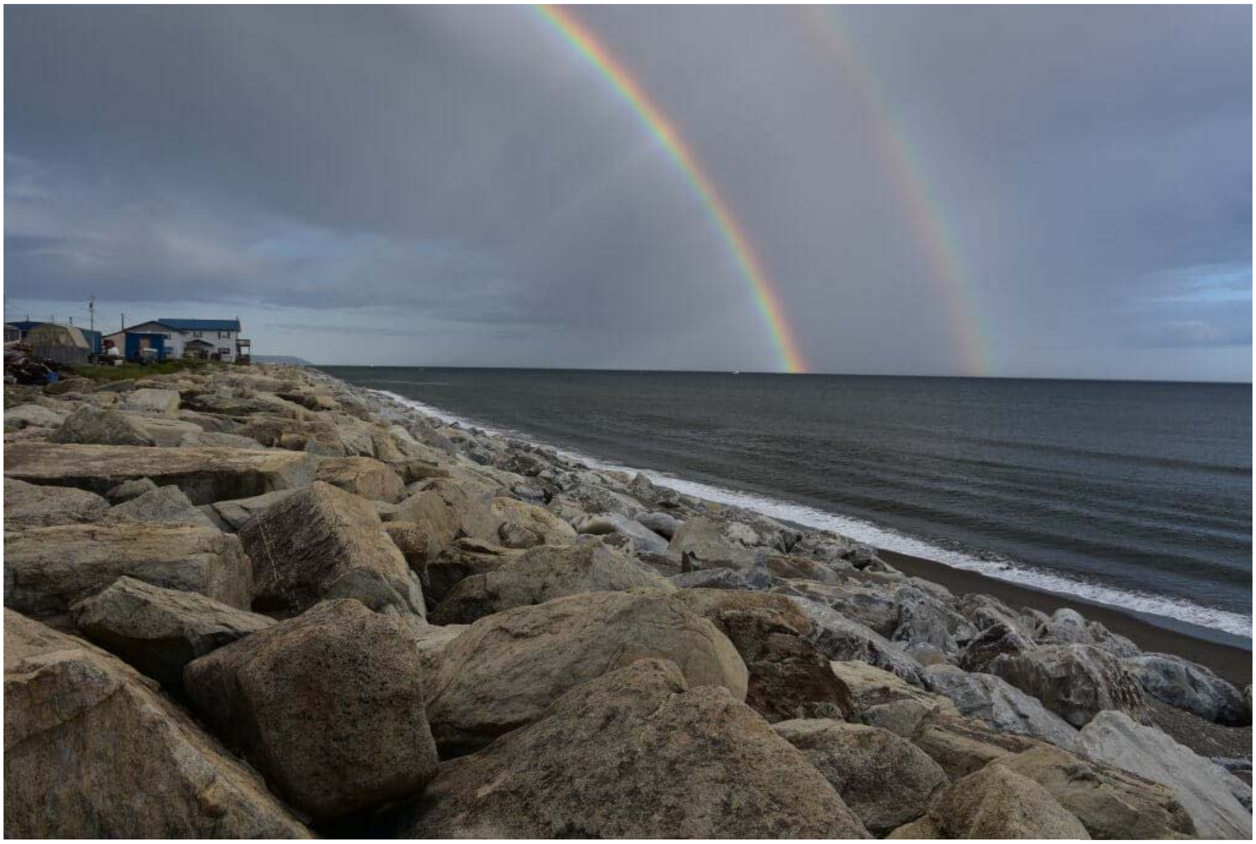


Photo 1: Seawall in Nome, Alaska. An example of a structural adaptation. Photo courtesy of S. Jeff Birchall, taken August 12, 2016, 1am.

While climate change is impacting communities across the globe, the Canadian Arctic currently experiences intensified local-level climate impacts. Recent studies find that, since 1979, arctic amplification has caused northern regions to warm nearly four times faster than the global average (Rantanen et al., 2022). This intense warming has caused substantial physical impacts, such as permafrost thaw, sea ice loss, coastal erosion and biodiversity loss. Isolation, ecological fragility and remoteness further render northern communities vulnerable to climate change.

Extreme exposure to climate impacts require intensive adaptation. However, Arctic communities face unique adaptation barriers and maladaptation risks. Many of these barriers and risks remain unknown due to lack of technical data and personnel, and inadequate public consultation. As climate change worsens, it is becoming apparent that hard and soft adaptations typically used in warmer climates have little utility in the Arctic. Extreme cold narrows ecological niches, reducing biodiversity and constraining the feasibility of ecosystem-based adaptation. Simultaneously hard infrastructure adaptation is limited by structural and ecological fragility, and maladaptation often leads to widespread environmental degradation. As a result, infrastructure maintenance and upgrades are becoming increasingly expensive, which communities struggle to afford due to low property values. When infrastructure goes unmaintained, disaster risk increases and northern communities, which tend to be isolated and reliant on a single economic industry or subsistence food production, are vulnerable to even minor disruptions (Birchall et al., 2022).

For Arctic communities adaptation is complex. Indigenous knowledge systems are crucial to effective adaptation, and may offer insight into current unknowns. However, as mindset barriers and inequality prevent collaboration, high proportions of marginalized groups can restrict effective adaptation (Kehler & Birchall, 2021). Collaboration between Indigenous communities and local governments is necessary to overcome barriers and co-create effective long-term adaptation policies (Birchall & MacDonald, 2019). Adaptation in the Canadian Arctic offers a unique opportunity to address lagging reconciliation and set an example for integrating non-western knowledge systems into disaster risk reduction.

Sarah Kehler is currently a PhD student at the University of Alberta; her general area of study is Urban and Regional Planning. She is currently a research assistant with the Climate Adaptation and Resilience Lab, focusing on barriers to achieving equitable and effective policy for adaptation and resilience to climate change.

S. Jeff Birchall, PhD, RPP, MCIP is an Associate Professor of Local-scale Climate Change Adaptation/ Resilience, in the School of Urban and Regional Planning, Department of Earth and Atmospheric Sciences, University of Alberta, where he serves as Director of the Climate Adaptation and Resilience Lab. Jeff leads the UArctic Thematic Network on Local-scale Planning, Climate Change and Resilience. Further questions regarding the article can be directed to jeff.birchall@ualberta.ca

Too far from shore– the fate of the Franklin expedition

WRITTEN BY CMOS BULLETIN SCMO ON MARCH 27, 2023. POSTED IN ARCTIC, OCEANS, WHAT'S CURRENT.

– By Robert W. Park and Douglas R. Stenton –

Background

The basic details are well-known: in May of 1845 two Royal Navy ships, HMS *Erebus* and HMS *Terror*, departed Great Britain under the command of Sir John Franklin to attempt the transit of a Northwest Passage. Two years later they reported “All well” but 11 months after that, in April of 1848, the 129 sailors who had set out from Britain had been reduced to 105 survivors departing their ships dragging boats mounted on sleds across the ice and snow in a desperate attempt to escape the Arctic. At least 25 of those survivors would perish less than 100 kilometers from the ships, and the furthest any of the survivors are known to have travelled was around 350 kilometers. The tragic outcome of the Franklin expedition has captured and held the public’s imagination for almost 180 years and the continuing importance of the Franklin story is illustrated by the very public involvement of several government agencies and some of Canada’s industrial and media elite in the 21st century search for the shipwrecks, and by the fact that Canada’s Prime Minister reserved for himself the 2014 announcement of Parks Canada’s discovery of the *Erebus*.

Beyond the excitement of the discoveries of the wrecks of both ships, there are at least two reasons why the Franklin expedition still resonates. The first and probably the most pervasive is the idea that it remains a huge mystery. If you search Google for the co-occurrence of the terms “Franklin expedition” and “mystery” you come up with almost 80,000 hits. Calling it a mystery implies that it is not yet understood, or even that it is inexplicable. The second very common rationale, sometimes implicit, is that *of course* a British naval expedition attempting to sail through the Canadian Arctic Archipelago in wooden ships late in the period known as the ‘Little Ice Age,’ overwintering one or more times along the way, would inevitably end in disaster. Viewed this way, the Franklin expedition is not a mystery but rather a case study in Eurocentric hubris and incompetence in comparison with Inuit whose ancestors had inhabited that region successfully for millennia. As researchers who have spent most of our careers learning about those 4500 years of Inuit history in Arctic Canada, that latter perspective has some appeal. However, neither of these perspectives is really correct. The ultimate cause of the catastrophe is not a mystery because, although there are many interesting details we are still learning, the overall explanation seems quite clear and well understood. Further, the disaster was not inevitable—many comparably equipped and commanded British Navy expeditions in the decades before and immediately after the Franklin expedition proved that fact by overwintering and returning home with minimal mortality.

Our own particular interest in the Franklin expedition focuses on understanding the archaeological record created after they deserted the ships. However, in order to understand and learn from that archaeological record, we needed to research the health of the Franklin crews, which is what we focus on here. Much more information on this can be found in Park and Stenton (2019).

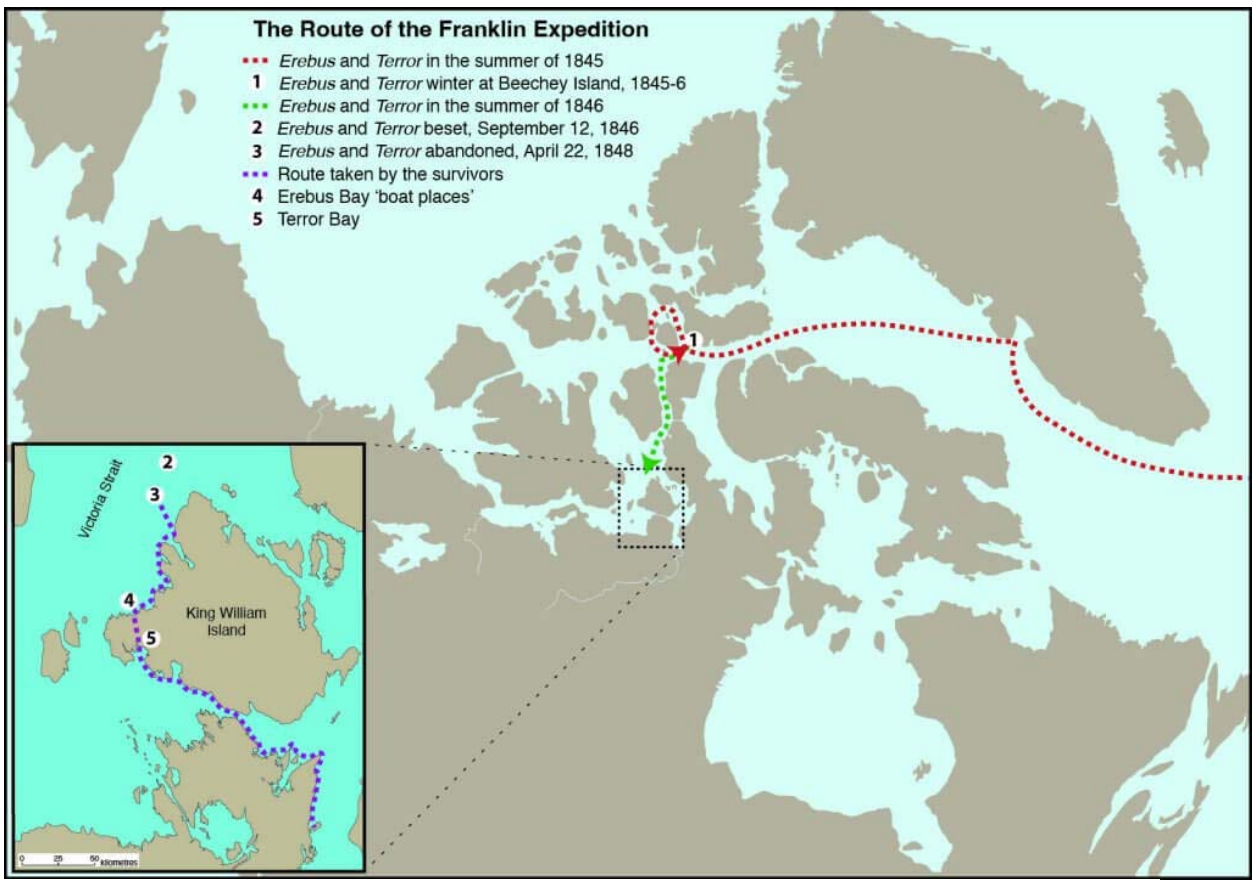


Figure 1. The route taken by the Franklin expedition, showing where they were beset in the ice far from shore between September 1846 and April 1848. The positions are the ones reported by the expedition.

Mortality in the Royal Navy

The death of some members of the Franklin expedition over its planned three-year duration would have been expected. A statistical study of health in the entire Royal Navy between 1830 and 1836 (Troubridge, 1841) found that the average yearly death rate for that period from wounds, accidents, and illness was 1.38%. Six Royal Navy Arctic expeditions between 1819 and 1855 which utilized the same basic technologies and strategies as the Franklin expedition had an average annual mortality consistent with that—1.67%—with the highest being just 2.97%. Over three years—the length of time for which the Franklin expedition was provisioned—a cumulative mortality somewhere between 4.14% and 5.01% of its 129-man complement would therefore have been expectable, or five to seven deaths. The 100% mortality on the Franklin expedition in what was probably less than three and a half years is thus clearly extraordinary, but the distinctive timing of the deaths is significant. Three died in the first year (Beattie & Geiger, 1987) but the "All well" message written at the end of the second year suggests few subsequent deaths had occurred. Franklin himself died at the beginning of the third year and by the end of that year 20 more had died, so the cumulative mortality when the ships were deserted was already 18.6%. The remainder died during the trek southwards.

Taking all of that into account, what was different about the Franklin expedition that could account for such massive mortality? The difference or differences must be consistent with (a) a mortality rate over the first two years similar to that in other Arctic expeditions and in the Royal Navy generally, allowing them to write "All well" at the end of that period; and (b) a mortality rate in the third year far higher than that seen in other comparable Arctic expeditions, even ones that remained in the Arctic for several more years than Franklin's.

Theories Concerning the Franklin Catastrophe

Many hypotheses have been advanced over the years to explain the Franklin catastrophe including diseases such as scurvy, tuberculosis, and trichinosis, or poisoning by lead, zinc, or botulism. Of these, lead poisoning (Beattie, 1985; Kowal et al., 1990) was the most promising but recent research showing high lead levels in Royal Navy sailors elsewhere, and no increase in lead over time in Franklin expedition sailors, has eliminated it as a primary factor (Millar et al., 2015; Swanston et al., 2018), and none of the other theories meet the criteria listed above (Park & Stenton, 2019). This brings us back to our central question: what was different about the Franklin expedition that could account for such massive mortality during its third year?

We have concluded that the one significant factor that *does* distinguish the Franklin expedition from previous and subsequent expeditions is wintering location. As each

Arctic open-water sailing season came to an end the standard procedure was to overwinter close to shore. Indeed, Franklin's orders instructed him to do this: "…you are to use your best endeavours to discover a sheltered and safe harbour, where the ships may be placed in security for the winter" (Belcher et al., 1855). The expedition did this at the end of the 1845 sailing season, wintering at Beechey Island. But in 1846 they did not, and in September *Erebus* and *Terror* were beset in Victoria Strait at least 20 kilometers from the nearest coast, King William Island. This was not immediately catastrophic, because nine months later the crews reported "All well," undoubtedly anticipating that the summer break-up would soon free them to continue their journey. But the 1847 break-up never came, and the ships spent the expedition's third year still locked in the ice far from land.

Too far from shore

The difference between wintering close to shore or 20 kilometers away turns out to be highly consequential. All British expeditions of this era set out with enough stored food to be self-sufficient for the duration of the time they anticipated spending in the Arctic, which was three years in the Franklin expedition's case. However, all were also equipped to make, and assiduous in making, efforts to acquire game and fish from autumn to spring, while they were in harbour adjacent to land. Rules were established to provide an incentive for the hunters and to ensure that the resulting fresh food was distributed throughout the entire crew, and records show some expeditions acquiring thousands of pounds of meat and fish this way. Franklin had indicated that he intended to use every available opportunity to obtain game, and we know he did so during their first winter because hunting camps were later found at Beechey Island. But during their second and third winters, when the *Erebus* and *Terror* were beset at least 20 kilometers from the nearest coastline, the logistics of acquiring game or fish would have been extremely difficult. It would have been too dangerous to traverse the pack ice to King William Island until it had frozen solid, and by the time that had happened they would have been contending with dwindling hours of daylight, increasing cold, and a seasonal scarcity or absence of terrestrial game. Out on the sea ice near the ships there would have been few opportunities for hunting, apart from the occasional polar bear. There would have been ringed seals nearby, but the techniques used by Inuit to hunt them through their breathing holes would have been quite beyond the capabilities of the British sailors (M'Clintock, 1859).

For these reasons it is probable that the crews did not acquire significant quantities of fresh food throughout the autumn and winter of 1846-7. They clearly travelled to King William Island in the spring of 1847 since that is when they left the "All well" report there. However, the long distance between the ships and shore undoubtedly precluded sending out the numbers of hunting parties dispatched by other expeditions. That inference is supported by the fact that extensive archaeological surveys of the northwest coast of King William Island have found only one Franklin expedition campsite, and not the many hunting camps that might be expected had they been using the coast repeatedly during the entire time they were beset nearby: September 1846 to April 1848. Thus, after leaving Beechey Island, the Franklin crews ate a far higher proportion of stored food than expeditions which were able to hunt near their sheltered harbours. By the time the 105 survivors left the *Erebus* and *Terror* the crews had been cut off from significant fresh supplements to their stored food for around 21 months.

Figure 2. Aerial view of part of the Erebus Bay coast. Within the area shown in this photograph the survivors abandoned two boats on sledges, and at least 22 of the original survivors perished here after travelling less than 100 kilometres from the ships (Photo: D.R. Stenton).

Stored food

The Franklin expedition's unique reliance on stored food suggests that a nutritional deficiency may lie at the root of the catastrophe. The most famous nutritional deficiency affecting the Royal Navy was ascorbic acid (vitamin C), whose lack produces the disease scurvy. However, the very limited number of fatalities from it on other expeditions would suggest that the lemon juice they all carried could be an adequately effective antiscorbutic, at least when combined with the additional ascorbic acid that they obtained from fresh game. But a less famous nutritional deficiency associated with stored food is likely more significant. The disease beriberi results from a deficiency in thiamine (vitamin B1). It produces a complicated range of symptoms but initially causes severe weakness and pain in the legs, to such an extent that walking may be difficult or impossible. Thiamine breaks down rapidly, so even stored food that started out with adequate quantities may have become deficient in it after storage in a ship's hold (Cecil & Woodruff, 1962). Further, thiamine had not yet been discovered so the expeditions did not carry appropriate supplements like the lemon juice carried to avoid scurvy.

A vivid example of beriberi caused by stored food was documented in the early 20th century in poor Newfoundland fishing communities. Their winter diets consisted of little more than tea, white flour and biscuits, salt beef, salt pork, salt cod, margarine, molasses, and berries (Aykroyd, 1930), similar to the stored foods used by the Royal Navy. By late spring each year, after several months of consuming that diet, many Newfoundlanders developed the disease. Between 11 and 20 people died of it per year but the majority recovered by early summer due to the renewed consumption of thiamine via fresh foods. From this example it is clear that thiamine deficiency over just a few months can produce debilitating symptoms which can culminate in death if thiamine is not reintroduced to the diet.

Figure 3. Archaeological investigation of one of the Erebus Bay boat places, with the flags marking find spots (Photo: D.R. Stenton).

Catastrophe in the third year

It is thus plausible that Royal Navy expeditions entered the Arctic with stored food supplies whose thiamine content soon deteriorated. But expeditions that were successful in hunting and fishing each autumn and spring were largely able to avoid the debilitating effects of beriberi whereas the crews of the *Erebus* and *Terror*, beset for almost two years far from the nearest hunting areas, would not have been able to supplement their stored supplies with fresh foodstuffs to any significant degree. The timing of the Franklin expedition mortality is consistent with the crews suffering from compounding nutritional deficiencies due to complete reliance on stored provisions commencing with their departure from Beechey Island. The effects of beriberi were probably not yet widely debilitating when the “All well” report was written almost a year later, but they undoubtedly contributed to the deaths that subsequently occurred during the winter of 1847-8. The known early symptoms of beriberi—weakness and pain in the legs, affecting the ability to walk—also provide a grim insight into the experience of the 105 who attempted to escape the Arctic by man-hauling boats on sleds in frigid Arctic spring weather. We know that two of the boats and at least 22 sailors were left behind less than 100 kilometers from the ships at a place later named Erebus Bay. Just 25 kilometers further the remains of another large group of sailors would be discovered by Inuit at a place later named Terror Bay. It may be that some of these sailors were still alive but could no longer walk, and their colleagues no longer had the strength to pull them on the sleds. Archaeological research has confirmed that these parties had firearms and lots of ammunition so if there had been game available, they would have been able to shoot it, but at that time of year there would have been little to hunt.

Thus, the ultimate cause of the catastrophe can be linked to wintering in the ice pack. We do not know why in September of 1846 Franklin allowed his ships to become frozen far out in Victoria Strait rather than following his orders to seek a safe harbour along one of the adjacent coastlines. Several scholars have speculated that it must have been inadvertent, the outcome of a failed gamble to traverse the strait ahead of the autumn freeze-up, perhaps under their cutting-edge steam power (Cyriax, 1939; Cookman, 2000). If that is the case, it is evocative that the only skeleton we have been able to identify so far is that of John Gregory, the engineer who was responsible for running *Erebus*' steam engine and who was one of the 105 who later attempted to walk out of the Arctic (Stenton et al., 2021). But someday we may learn more details of what happened in September of 1846 if Parks Canada's ongoing investigations of the wrecks of *Erebus* and *Terror* manage to recover legible ships' logs or journals.

Robert W. Park is an Associate Dean in the University of Waterloo's Faculty of Arts and a Professor in its Department of Anthropology. For four decades he has participated in archaeological fieldwork in Southern Ontario, Yukon, Northwest Territories, and especially Nunavut.

Douglas R. Stenton, CM, is the former (retired) Director of Heritage for the Government of Nunavut, and an Adjunct Assistant Professor in the Department of Anthropology at the University of Waterloo. He has conducted archaeological fieldwork in what is now Nunavut since 1980 and has led investigations of the 1845 Franklin expedition since 2008.

Acknowledgements

The fieldwork that inspired this research was funded by the Government of Nunavut Department of Culture and Heritage, Nunavut Archaeology Program. We wish to thank the Inuit Heritage Trust and the Hamlet of Gjoa Haven for their support of our research, and the officers and crew of the Canadian Coast Guard Ship *Sir Wilfrid Laurier* for providing the outstanding logistical support that made it possible for us to explore so thoroughly the region where the Franklin catastrophe unfolded.

References

Aykroyd, W. R. (1930). Beriberi and other food-deficiency diseases in Newfoundland and Labrador. Epidemiology & Infection, 30(3), 357-386. https://doi.org/10.1017/S0022172400010500

Beattie, O. (1985). Elevated bone lead levels in a crewman from the last arctic expedition of Sir John Franklin (1845-1848). In P. D. Sutherland (Ed.), The Franklin Era in Canadian Arctic History 1845–1859 (pp. 141-148). Archaeological Survey of Canada, Canadian Museum of Civilization.

Beattie, O. B., & Geiger, J. (1987). Frozen in Time. Western Producer Prairie Books.

Belcher, E., Richardson, J., Owen, R., Bell, T., Salter, J. W., & Reeve, L. (1855). The last of the Arctic voyages being a narrative of the expedition in H.M.S. Assistance under the command of Captain Sir Edward Belcher, C.B., in search of Sir John Franklin, during the years 1852-53-54. (2 vol.). L. Reeve.

Cecil, S. R., & Woodruff, J. G. (1962). Long-term storage of military rations. Dept. of the Army, Quartermaster Research and Engineering Command, Quartermaster Food and Container Institute for the Armed Forces.

Cookman, S. (2000). Ice blink: the tragic fate of Sir John Franklin's lost polar expedition. Wiley.

Cyriax, R. J. (1939). Sir John Franklin's last Arctic expedition: A chapter in the history of the Royal Navy. Methuen & Co., Ltd.

Kowal, W., Beattie, O. B., & Baadsgaard, H. (1990). Did solder kill Franklin's men? Nature, 343(25), 319-320. https://doi.org/10.1038/343319b0

M'Clintock, F. L. (1859). Discoveries by the Late Expedition in Search of Sir John Franklin and His Party. Proceedings of the Royal Geographical Society of London, 4(1), 2-14. https://doi.org/10.2307/1798820

Millar, K., Bowman, A. W., & Battersby, W. (2015). A re-analysis of the supposed role of lead poisoning in Sir John Franklin's last expedition, 1845-1848. Polar Record, 51(3), 224-238. https://doi.org/10.1017/S0032247413000867

Park, R. W., & Stenton, D. R. (2019). Use Your Best Endeavours to Discover a Sheltered and Safe Harbour. Polar Record, 55(6), 361-372. https://doi.org/10.1017/S0032247419000573

Stenton, D. R., Fratpietro, S., Keenleyside, A., & Park, R. W. (2021). DNA identification of a sailor from the 1845 Franklin northwest passage expedition. Polar Record, 57, e14. https://doi.org/10.1017/s0032247421000061

Swanston, T., Varney, T. L., Kozachuk, M., Choudhury, S., Bewer, B., Coulthard, I., Keenleyside, A., Nelson, A., Martin, R. R., Stenton, D. R., & Cooper, D. M. L. (2018). Franklin expedition lead exposure: New insights from high resolution confocal x-ray fluorescence imaging of skeletal microstructure. PLOS ONE, 13(8). https://doi.org/10.1371/journal.pone.0202983

Troubridge, T. (1841). Statistical Reports on the Health of the Navy, for the Years 1830, 1831, 1832, 1833, 1834, 1835, and 1836—Part II. House of Commons Parliamentary Papers.

Satellite SSS: A Monitoring Tool for the Gulf of St. Lawrence?

WRITTEN BY CMOS BULLETIN SCMO ON APRIL 2, 2023. POSTED IN CLIMATE, OCEANS, WHAT'S CURRENT.

– By Jacqueline Dumas, Julien Laliberté, and Denis Gilbert –

The use of satellite remote sensing technology to monitor the Gulf of St. Lawrence was first demonstrated in 1961 when TIROS-2 captured the spring ice breakup. Following this breakthrough, satellites were used increasingly to improve our understanding of ocean dynamics. In fact, satellite data have been used for half a century to monitor sea surface temperature (Minnett et al. 2019) and for over forty years to monitor ocean color (McClain et al. 2022). In addition, Sea surface salinity (SSS) satellite-based products have recently been developed to depict ocean dynamics. The available satellite data include European Space Agency’s Soil Moisture Ocean Salinity (SMOS) products since 2010 and National Aeronautics and Space Administration’s Soil Moisture Active Passive (SMAP) products since 2015. Numerous studies have used these data sets to capture SSS signals throughout the world including in the Arabian Sea (Menezes, 2020), the Bay of Bengal (Akhil et al, 2020), the Mediterranean Sea (Grodsky et al, 2019) the Indonesian Sea (Lee et al 2019), the Gulf of Mexico (Vasquez-Cuervo et al 2018) as all well as colder regions such as the Arctic ocean (Fournier et al 2019) and the Gulf of Maine (Grodksy et al. 2018). This last study also includes a promising evaluation of satellite SSS for monitoring the Gulf of Maine.

The algorithms to retrieve the satellite SSS vary amongst products, using various ancillary inputs such as wind speed and direction, sea ice masks, galactic maps and dielectric constant models. Each product also uses different correction schemes and different approaches to estimating the uncertainty in their data. Generally, satellite SSS use the sea surface temperature and brightness temperature to attribute a value to sea surface salinity. In proximity to land, radio frequency interference can lead to errors in satellite measurements. Most products omit data close to land for this reason.

The Gulf of St. Lawrence (GSL) is a dynamic semi-enclosed marine system for which salinity is closely monitored with in situ sampling programs overseen by the Department of Fisheries and Oceans Canada such as the Atlantic Zone Monitoring Program (AZMP). Since in situ sampling is punctual in space and time, Dumas and Gilbert (2023) recently sought to verify how synoptic observations of SSS satellite products could help complete our understanding of the GSL surface salinity. They compared two products from SMOS; Centre Aval de Traitement des Données SMOS (CATDS) and Barcelona Expert Center

(BEC), as well as two products from SMAP; Jet Propulsion Laboratory (JPL) and Remote Sensing Systems (RSS). The spatial resolution of these smoothed Level 3 products is approximately 60 km. They are available as monthly means or as 8 and 9-day running means for SMAP and SMOS, respectively. These four satellite products were evaluated by comparing them with in situ CTD measurements taken throughout the GSL at 2 m depth or less from the ocean surface. The satellite products were also compared to a moored CTD at 1 m depth located 40 km from the coast at the AZMP Shediac Valley Station, shown in Figure 1.

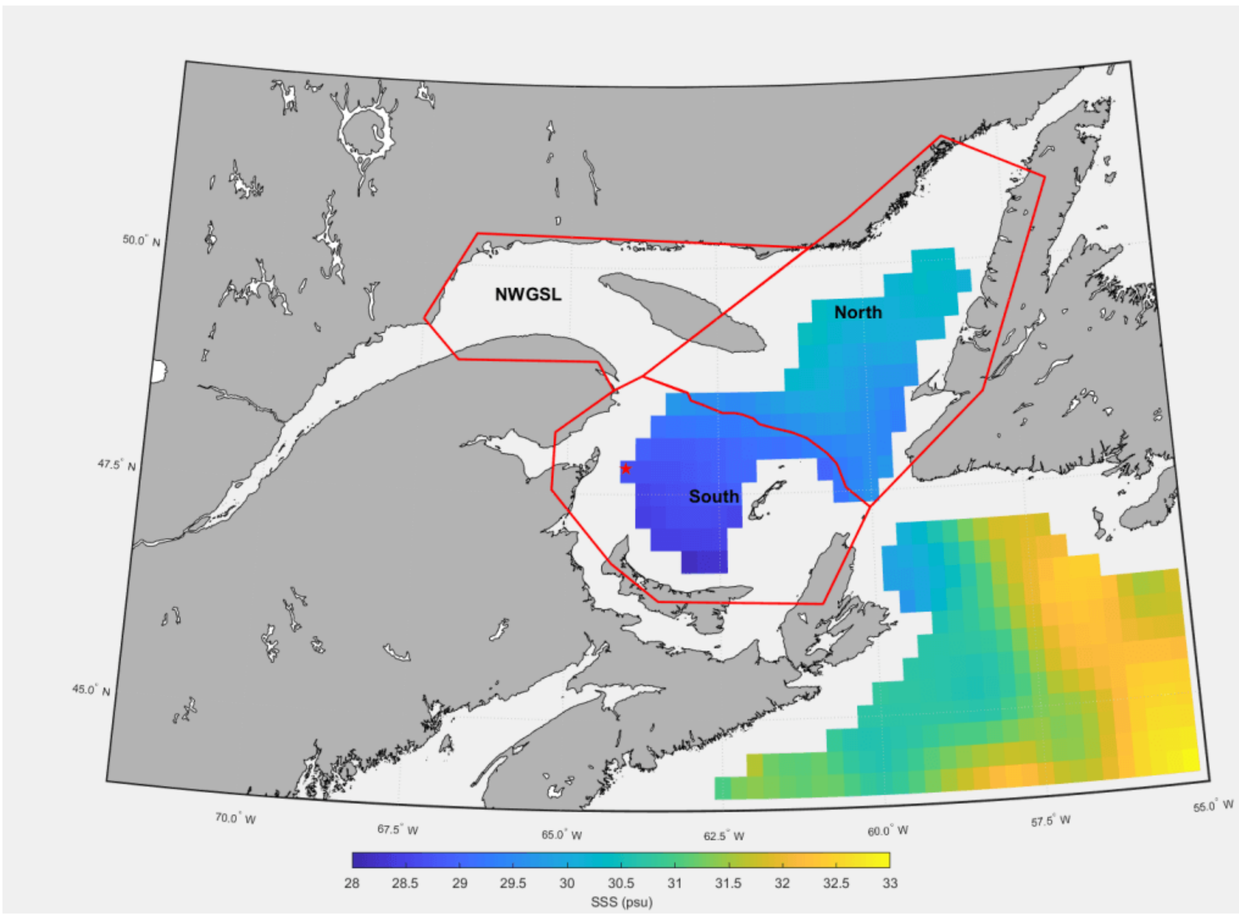


Figure 1 : August 2001 JPL monthly data with the regions used in Dumas & Gilbert (2023). The red star indicates the AZMP Shediac Valley Station.

Comparing monthly means of satellite and in situ SSS for each of the four satellite products resulted in statistically significant correlations which explained 71-81% of the variance over the whole GSL region. Three different subregions were defined (Southern GSL, Northern GSL and northwest GSL in Figure 1) due to different salinity patterns and sampling frequency. The Southern GSL had the most CTD observations, the greatest seasonal variability and the greatest variance explained (64-72%) of the three regions. JPL had the highest variance explained in this region, followed by BEC, CATDS and RSS. In the Northern region 49-59% of the variance was explained by JPL, BEC and RSS, whereas in the NWGSL region 52-56% of the variance was explained by CATDS and BEC. Note that only SMOS products had data available in the NWGSL region. More in situ CTD data will be required to confirm if the stronger variance explained in the South region is due to better data availability there. Time series of the anomaly of regional monthly means show good agreement between the interannually varying in situ and satellite SSS (Figure 2).

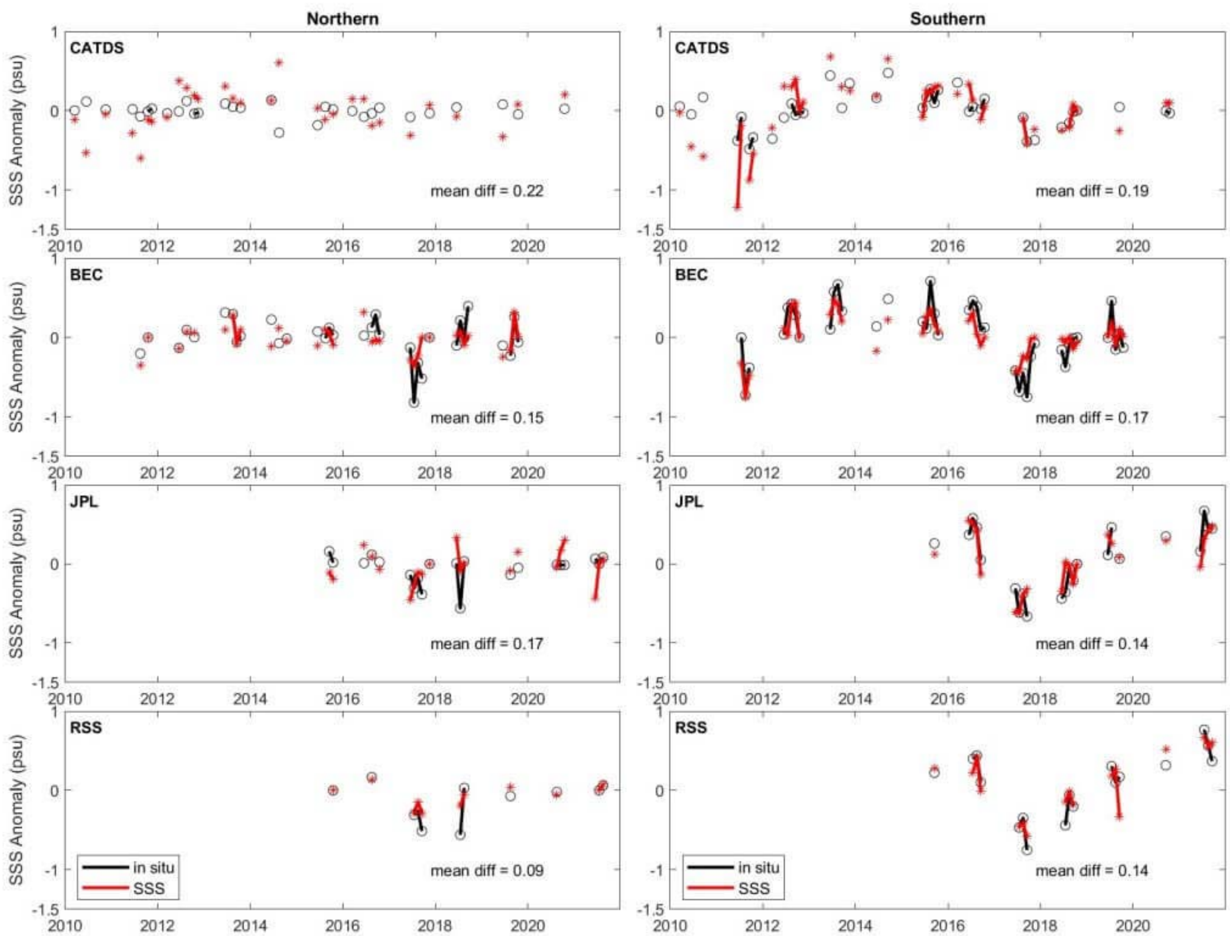


Figure 2: Anomaly of satellite and in situ SSS. The left and right columns show respectively the Northern and Southern regions' monthly means.

When comparing satellite measurements to CTD SSS at one grid point, the Shediac Valley high frequency sampling station, 48-92% of the variance was explained. At this location BEC had lower correlation coefficients than other products. 77-88% of variance in SSS was explained by JPL and 83-92% by CATDS. The mean bias for different regions is approximately 0.5 psu and 0.3 psu when evaluated at the Shediac Valley grid point.

The study concludes that, although the GSL waters are relatively cold (which poses an extra challenge to SSS retrieval) and close to land and ice, satellite data successfully capture SSS its interannual variability and annual cycle. More specifically, the study concluded that based on data availability and correlation coefficients, JPL stood out as being the best satellite product for this region.

Keeping in mind that the objective of this evaluation was to supplement the availability of salinity measurements with other sources of information, other means of deriving salinity should be considered next. For instance, a relation between ocean color and salinity is well established in the scientific literature. Colored dissolved organic matter (CDOM) generally decreases as salinity increases and, since CDOM absorbs blue sunlight, it can be monitored by ocean color satellites. Thus CDOM can be used as a proxy for salinity. A quantitative evaluation of this relationship for the GSL is already detailed in Nieke et al. (1997) and ready to be implemented along the salinity gradient. The higher spatiotemporal resolution of ocean color satellite data (typically 4 km, daily) would add considerable information about salinity to the GSL in general, but perhaps most importantly in regions not covered by SMOS and SMAP products.

Jacqueline Dumas completed her M.Sc. in Earth and Ocean Sciences at the University of Victoria, BC. Her thesis and earlier work focused on the impact of varying atmospheric forcing on the thickness of Arctic sea ice using a thermodynamic sea ice model. Presently working at Maurice Lamontagne Institute, QC, she has worked on projects involving oxygen and salinity observations and more recently she has joined the biogeochemical modelling group. She also looks after the permanent thermograph network in the GSL.

Dr. Julien Laliberté works for the Department of Fisheries and Oceans Canada where he seeks to reinforce our knowledge on phytoplankton in the Estuary and Gulf of St. Lawrence. He monitors the ecosystem using ocean color remote sensing, fieldwork, and hydrological optics.

Dr. Denis Gilbert worked as a physical oceanography research scientist for the Department of Fisheries and Oceans Canada from 1991 to 2021. He created his own company (Denis Gilbert Scientifik) in 2022 to offer science communication and climate services. Twitter handel : @dgscientifik

Bibliography

Akhil, V. P., Vialard, J., Lengaigne, M., Keerthi, M. G., Boutin, J., Vergely, J. L., & Papa, F. (2020). Bay of Bengal sea surface salinity variability using a decade of improved SMOS re-processing. Remote Sensing of Environment, 248(111964), 1–18. https://doi.org/10.1016/j.rse.2020.111964

Dumas, J., Gilbert, D. (2022): Comparison of SMOS, SMAP and In Situ Sea Surface Salinity in the Gulf of St. Lawrence, Atmosphere-Ocean, DOI: 10.1080/07055900.2022.2155103

Fournier, S., Lee, T., Tang, W., Steele, M., & Olmedo, E. (2019). Evaluation and intercomparison of SMOS, aquarius and SMAP sea surface salinity products in the Arctic ocean. Remote Sensing, 11(24), 1–19. https://doi.org/10.3390/rs11243043

Grodsky, S., Vandemark, D., & Feng, H. (2018). Assessing coastal SMAP surface salinity accuracy and its application to monitoring gulf of maine circulation dynamics. Remote Sensing, 10(8), 1–19. https://doi.org/10.3390/rs10081232

Grodsky, S. A., Reul, N., Bentamy, A., Vandemark, D., & Guimbard, S. (2019). Eastern Mediterranean salinification observed in satellite salinity from SMAP mission. Journal of Marine Systems, 198(103190) 1–11. https://doi.org/10.1016/j.jmarsys.2019.103190

Lee, T.,Gordon, S.,&Sprintall, J. (2019). Maritime continent water cycle regulates low-latitude chokepoint of global ocean circulation. Nature Communications, 10(2103), 1–13. https://doi.org/10.1038/s41467-019-10109-z

McClain C.R., Franz B.A. and Werdell P.J. (2022) Genesis and Evolution of NASA's Satellite Ocean Color Program. Front. Remote Sens. 3:938006. doi: 10.3389/frsen.2022.938006

Menezes, V. (2020). Statistical assessment of sea-surface salinity from SMAP: Arabian Sea, Bay of Bengal and a promising Red Sea application. Remote Sensing, 12(3), 1–37. https://doi.org/10.3390/rs12030447

Minnett, P. J., Alvera-Azcárate, A., Chin, T. M., Corlett, G. K., Gentemann, C. L., Karagali, I., … & Vazquez-Cuervo, J. (2019). Half a century of satellite remote sensing of sea-surface temperature. Remote Sensing of Environment, 233, 111366.

NASA, “SSS Retrieval – It’s Complicated’’, Salinity: Sea Surface Salinity from Space, https://salinity.oceansciences.org/data-salinity-02.htm. Accessed 22 January 2023.

Nieke, B., Reuter, R., Heuermann, R., Wang, H., Babin, M., & Therriault, J. C. (1997). Light absorption and fluorescence properties of chromophoric dissolved organic matter (CDOM), in the St. Lawrence Estuary (Case 2 waters). Continental Shelf Research, 17(3), 235-252.

Vazquez-Cuervo, J., Fournier, S, Dzwonkowski, B., & Reager, J. (2018). Intercomparison of in-situ and remote sensing salinity products in the Gulf of Mexico, a river-influenced system. Remote Sensing, 10(10), 1590. https:/doi.org/10.3390/rs10101590

Obituary notice for Emeritus Professor Isztar Zawadzki (1939-2023)

WRITTEN BY CMOS BULLETIN SCMO ON APRIL 9, 2023. POSTED IN MEMBERS, NEWS & EVENTS.

– By Jacques Derome, Frédéric Fabry, Henry Leighton and Man K. (Peter) Yau –

On February 11th, 2023, Emeritus Professor Isztar Zawadzki, internationally known for his ground-breaking work in radar meteorology and precipitation physics, succumbed to a stroke. With great effort, determination and much help from his life partner, Dominique, he had well recovered from a first stroke three years earlier, but this second one surpassed his resilience.

Dr. Zawadzki was born in Poland on February 9th, 1939. Fearing the mounting ravages of antisemitism and the war, his mother fled with her toddler to Russia and then departed for Argentina. It is there, at the University of Buenos Aires, that he completed a Licenciado en Ciencas Fisicas. Having developed an interest in radar meteorology and in the formation and prevention of hail, he decided to enrol in graduate studies in the Department of Meteorology (now Atmospheric and Oceanic Sciences) at McGill University, obtaining his Ph.D. in 1972 under the supervision of Professor Roddy R. Rogers.

Isztar began his academic career in the Physics Department of the recently created Université du Québec à Montréal where he was a moving force behind the creation of a graduate program in meteorology. In 1992, McGill University recruited him as Director of the Stewart Marshall Radar Observatory within the Department of Atmospheric and Oceanic Sciences, a wise move indeed, as it ushered in a period of rapid expansion of the radar activities in a leading research and operational Observatory worldwide. His warm personality and contagious enthusiasm for science made him a magnet for graduate students and led to a multitude of visitors and post-doctoral fellows to the radar lab from around the world.

Isztar published more than 117 papers. His research spanned a wide range of innovative applications of weather radar data and the study of cloud physics processes. His first research axis was to further our understanding of the complex processes involved in the formation and distribution of winter and summer precipitation: he studied drop growth, riming, secondary-ice formation and melting with vertically pointing radars and in-situ sensors, correctly interpreting results thanks to a great physics intuition, and reproducing them by numerical modeling while gathering new insights. His research on hydrometeor size distributions also led him to experiment with moment normalization. Since the distribution of drop sizes shapes the reflectivity measured by radar, some of his earlier work examined the effects of changing drop size distributions on precipitation estimation accuracy. This work was recently republished at the European Radar conference as an example of foresight, clarity of thinking, and good science. Improving rainfall measurements by radar also found important applications in hydrology. When he joined McGill, after leading the conversion of its radar to have Doppler capabilities, he developed a new line of work, how to best use the information from radar data to improve numerical modelling. He first explored how to retrieve 3D winds and later thermodynamics first from a single Doppler radar and then also using bistatic receivers. Isztar then experimented with the assimilation of radar data using traditional and then novel assimilation techniques. Finally, in parallel, he championed the improved use of radar data for operational and research uses, whether the task was better cleaning radar data, making possible the development of the refractivity measurements by radar, or developing MAPLE (McGill Algorithm for Precipitation Nowcasting by Lagrangian Extrapolation) for radar nowcasts, often using those efforts as leads for new research. His noteworthy work on the scale-dependence of precipitation predictability resulted directly from trying to improve precipitation nowcasts and forecasts. He also led a last upgrade of the McGill radar to make it the first known operational dual-polarization radar in the world. Isztar had a knack for foreseeing interesting research avenues and for how to organize initial efforts to advance research goals. The recent expansion in the infrastructure and the use of radar for operational meteorology in Canada owes much to the work of his group at McGill.

In recognition of his numerous scientific achievements Isztar was awarded the Patterson Medal of the Meteorological Service of Canada (1991) and the CMOS President's Prize (1998); he was made a Fellow of the Canadian Meteorological and Oceanographic Society (2001) and of the American Meteorological Society (2004). In 2007, he was the first recipient of the AMS Remote Sensing Prize, the recipient of the Luis Federico Leloir Award for International Cooperation in Science, Technology, and Innovation and was inducted into the Academy of Science of the Royal Society of Canada.

Isztar had wide-ranging interests beyond science, including music – he personally crafted wooden flutes and played them in a South-American-type band in the 1970s, as well as horticulture – he devotedly attended to his garden and trees at his mini-farm, and sculpture, an art that he enjoyed as he recovered from his first stroke.

Isztar's warm personality will be missed by the love of his life, Dominique Robert, his former students, who remained important to him to the end, and a multitude of colleagues and friends worldwide.

Towards the “Perfect” Weather Warning

WRITTEN BY CMOS BULLETIN SCMO ON APRIL 13, 2023. POSTED IN CLIMATE, NEWS & EVENTS, WEATHER, WHAT'S CURRENT.

– By Brian Golding –

This book is a product of the 10-year High Impact Weather (HIWeather) project of the World Weather Research Programme in World Meteorological Organisation (WMO), drawing on research carried out in its first six years. It contains contributions from fifty eminent experts in the various fields spanned by the warning process, representing fourteen countries around the world. Endorsed by the World Meteorological Organisations and the United Nations Office for Disaster Risk Reduction, it offers an in-depth review of the relevant science, complementing the recently updated WMO guide to impact-based warnings and extending its readership to a wide range of emergency managers in government and industry as well as in the weather services. It is structured around the concept of a value chain connecting the various contributors to warning creation, emphasising communication, between experts and with the user, as the potential weak links that may break the chain. The underlying theme of the book is therefore partnership as a means to bridge the communication gaps. Starting with the user of the warning, i.e. anyone who will take protective action on receipt of a warning, the book looks at the information they need to inform their decision to act and how that information needs to be communicated if the right decision is to be made. From there it proceeds up the chain, at each stage addressing the questions: what information is needed at this stage? what information is the provider able to give? and how can the two work together effectively to optimise the end warning.

To set everything in context, the first chapter after the introduction looks at warnings within the wider canvas of disaster risk management and the need for an appropriate governance framework, including assured funding, to enable the key actors to work in partnership. The next chapter addresses the psychology of response and the tools available to the issuer of the warning to make their warnings more effective. Next the book moves to the content, starting with information on the expected impact of the hazard. This draws in disciplines of engineering, epidemiology and economics amongst others. At this point, the book reaches a mid-point where the social, behavioural and economic sciences give way to the physical sciences in the translation of hazard into impact. Here the book exposes most clearly the differences of approach, language and culture that are a challenge to successful partnership. These challenges are also evident in the next chapter where weather forecasting connects with hazard forecasting across the disciplines of meteorology, oceanography, hydrology and atmospheric chemistry, although earth system modelling for climate prediction has given an impetus to integration of these disciplines. Finally, the book addresses the relationship between observations and weather prediction, citing several examples of effective collaboration. Bringing the whole chain back together, a final summary chapter concludes with some recommendations for consideration when building a new warning system.

Each chapter has a brief synopsis and a summary, containing the key questions covered. The main text is written in discursive style in a form that is accessible to non-experts in any of the fields covered. Nevertheless, reference is made to the major primary research contributions, and the chapter bibliographies run to over 500 references in total. An attractive feature of most chapters is the inclusion of illustrative examples, many of them told in a personal style by those involved.

Thanks to generous contributions to the HIWeather trust fund, the book has been published in Open Access and can be downloaded free from the SpringerLink website at Towards the "Perfect" Weather Warning | SpringerLink.

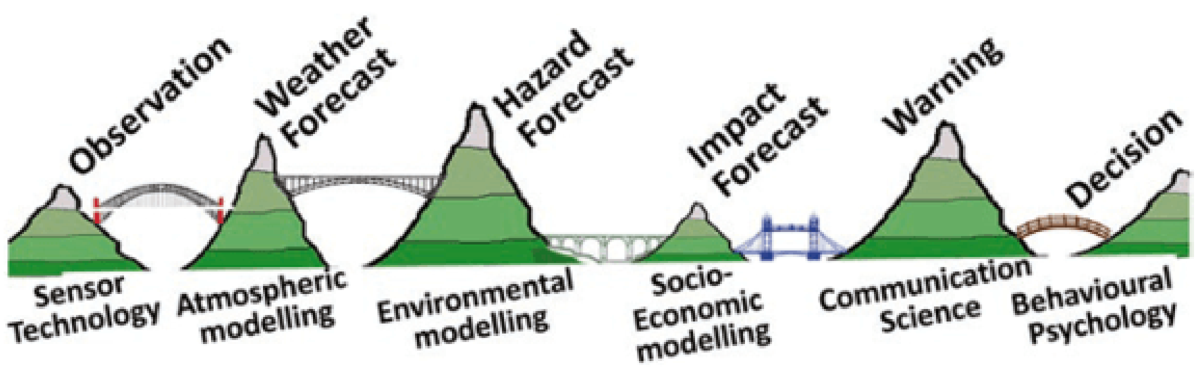


Figure 1: The value chain for weather warnings showing the partnerships and bridges needed to overcome the valleys of death.

Professor Brian Golding has made major contributions to high resolution Numerical Weather Prediction and its use in a wide variety of applications, particularly flood prediction during his long career with the Met Office. He was instrumental in the early adoption of operational convection-permitting models in the Met Office during his tenure as the Met Office's Director of Weather Science. He currently co-chairs the World Meteorological Organisation's High Impact Weather (HIWeather) project which has brought together physical, social, behavioural and economic scientists to enhance the effectiveness of weather warnings. He is a visiting professor at Bristol University and was awarded the OBE for services to severe weather forecasting.

Obituary notice for Dr. Peter Summers

WRITTEN BY CMOS BULLETIN SCMO ON MAY 6, 2023. POSTED IN CLIMATE, MEMBERS, NEWS & EVENTS.

Husband, father, grandfather, great grandfather, scientist, tennis and badminton player, bridge player, world traveller and dessert lover.

Peter passed away peacefully and surrounded by his children on February 7, 2023, he was 93 years old. He was predeceased by his loving wife Alice, (nee Francis), of 62 years.

A native of Birmingham, England, Peter was a quick learner and excelled at school. During WWII he and his sister Janet moved to the countryside and stayed with cousins in order to escape the bombing. Peter's strong foundation in mathematics and science via the University of Nottingham and later Imperial College London, led him to a lifelong career in meteorology. One of his first full time postings was in 1952, to New Zealand, via an eight day voyage on an unheated, noisy military transport plane. Two years later he was posted to Fiji where he stayed until he immigrated to Canada in 1958.

Peter and Alice met while she was a flight attendant based in Montreal, and they married in 1959. He earned his PhD from McGill University and presented research papers on pollution to much public acclaim, and a little less from the incumbent provincial government. In 1964 they moved to Edmonton, Alberta where son Brian (Anita) and daughter Linda soon joined them.

As a meteorologist, Peter's skills were in demand. He specialized in hail projects; seeding clouds so that the precipitation would fall as rain and not crop-flattening hail. The family also lived in Boulder, CO., and Geneva, Switzerland where Peter worked for the United Nations.

Upon return to Canada, Peter worked with Environment Canada in the Toronto area where he occasionally advised Ministers and Prime Ministers on a variety environmental issues including acid rain.

When Peter and Alice retired in 1991 they sold their house, bought a condominium and a cottage on Lake Chandos in the Kawarthas. There they hosted many friends, bridge tournaments, family reunions, grandchildren and made new friends in the local community. They also took advantage of this time together to travel and the destinations include: an African safari, Japan, Fiji, Turkey, Peru, England, France, Nunavut, Egypt, Australia, New Zealand, Costa Rica and places closer to home.

In addition to his children, Peter leaves behind grandchildren: Sacha, Brittany (Alton), Jaleah, Mauricie, Everett, Laurier and great grandchildren Eva, Maya and Chandos.

Peter stayed interested and curious about science right up to the very end, wanting to know more about the latest announcements in fusion energy. Like Alice before him, Peter chose MAiD.

In these times of heightened climate awareness, it is reassuring to know that Peter’s diligent work contributed to the creation of better government policies regarding the environment.

Lake sediment records of water quality and quantity in the Laurentian Great Lakes region over the last ~900 years

WRITTEN BY CMOS BULLETIN SCMO ON MAY 10, 2023. POSTED IN WHAT'S CURRENT.

– By Rebecca M. Doyle, Katrina A. Moser, Fred J. Longstaffe –

The Laurentian Great Lakes of North America are a critical global water resource comprising approximately 1/5th of the liquid freshwater available on the Earth's surface (Campbell et al., 2015). The area around these lakes, the Great Lakes region (GLR) (37.1 to 56.9 °N, 97.3 to 70 °W), is home to ~40 million residents who depend on this water. In this water-rich region, one might assume that clean freshwater is, and will always be, readily available. Rapid population growth and climate change, however, threaten to reduce water availability through reductions in water *quality* and *quantity* in the GLR (Cotner et al., 2017; Bonsal et al., 2019).

In this context, we define water *quality* as the chemical, physical and biological characteristics of water that determine ecosystem and human health and water *quantity* as the amount of surface water available for ecosystems, human health, industry and recreation. Phosphate-rich runoff from agricultural fields can fertilizes lakes, leading to harmful algae blooms (Sinha et al., 2017). As populations in and around the GLR rise, governments face increasing pressure to divert water resources away from lakes and towards growing communities (Cotner et al., 2017). Climate change can exacerbate these threats as rising temperatures can encourage algal growth and increase summer droughts that reduce water availability (Nazari-Scharabian et al., 2018). Predicting the effects of climate change on water *quantity* in the GLR, however, is difficult because we have yet to fully understand the influences of natural internal variability of climate, including the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation (AMO), on water *quantity* (Rodysill et al., 2018). To better understand the role of internal ocean and atmospheric processes on climate requires records that extend beyond what is available from instrumental records and measurements.

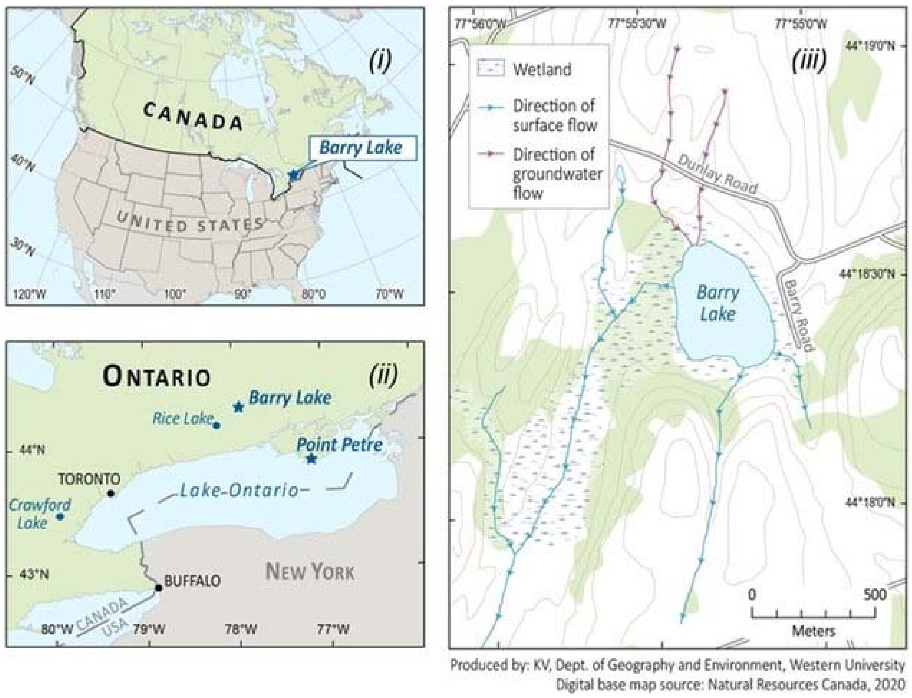


Figure 1. Barry Lake: (i, ii) location, and (iii) local hydrology. From Doyle et al. (2021). Used with permission.

To further understand how water *quality* and *quantity* in the GLR are changing, researchers from The University of Western Ontario studied sediments from Barry Lake (44.30765, -77.92137), a small kettle lake situated in the GLR near Peterborough (Ontario, Canada), on the traditional lands of the Mississauga, Huron-Wendat and Anishinaabeg peoples (Doyle et al., 2021; Fig. 1, 2). Variations in the chemistry of organic matter and certain minerals in these sequentially layered and dated sediments provide a proxy record of changes in water *quality* and *quantity* over the last millennium. The Barry Lake results were compared with other lake sediment records to determine if time-dependent patterns observed at Barry Lake occurred across the entire GLR. This ~900-year record provides a context for differentiating natural environmental variations from more recent perturbations associated with urbanization and rapid climate warming.

The researchers collected three 40- to 50-cm sediment cores from the centre of Barry Lake (Fig. 3). These cores were then subsampled at 0.5-cm intervals. Radiometric dating (210Pb and 14C) was used to assign dates to certain layers of the sediment, and these dates were then interpolated using the statistical package “rbacon” (Blaauw et al., 2021; R Core Development Team, 2023) to establish the down-core sediment chronology. The authors then analyzed specific organic and mineral components from dated layers in the sediment and interpreted those data in terms of water *quality* and *quantity* changes over the last ~900 years.

Figure 2. Barry Lake, southeastern Ontario, July 2017. Photographic credit: Western's Laboratory for Stable Isotope Science (LSIS) / Lake and Reservoir system Facility (LARS) coring team: Rebecca Doyle, Carolyn Hill-Svehla, Amanda Philavong, Maria Sia and Jacob Walker.

Changes in water *quality* were evaluated using sedimentary chlorophyll a, a pigment produced by photosynthetic lifeforms. Sedimentary chlorophyll a content, a sensitive indicator of algal growth, which is closely tied to water *quality*, was measured using visible near-infrared spectroscopy (VNIRS). Changes in water *quantity* were inferred by measuring oxygen- and stable carbon-isotope compositions of marl (calcium carbonate precipitated in the lake water, mostly during the summer). These isotopic proxies technically track the balance of evaporation minus precipitation rather than water quantity; however, in small lakes like Barry Lake these variables are closely related.

These proxy records showed that, at Barry Lake, water *quality* has deteriorated in the modern era (1850 CE to present) but modern water *quantity* remains typical when compared with past conditions. Chlorophyll a concentration was low and unchanging from 0 to 1850 CE, but rose substantially from 1850 CE to present day, indicating a progressive increase in algal growth. The local census revealed that European settlement around Barry Lake occurred around 1850 CE. European settlers typically converted forests into farmland shortly after arriving, a process that commonly introduced nutrients to the lake and promoted algae growth.

Water *quantity* (i.e., lake level) in Barry Lake varied substantially over the last millennium with fluctuating values during the warm and dry Medieval Climate Anomaly (1000 to 1300 CE) and higher values during the cool and wet Little Ice Age (1450-1850 CE). Modern (1850 CE to present) values lie between those of these two periods. This finding suggests that, while air temperatures in the GLR are certainly rising, this rapid climate warming has not yet translated to noticeable changes in water *quantity* at Barry Lake.

Figure 3. Sediment coring at Barry Lake, southeastern Ontario. Clockwise from top left: Carolyn Hill- Svehla and Rebecca Doyle with piston core top; sediment gravity core; Amanda Philavong with core extruder; Maria Sia with gravity core showing sediment-water interface; Rebecca Doyle and Amanda Philavong with sediment core extruder. Photographic credit: Western's Laboratory for Stable Isotope Science (LSIS) / Lake and Reservoir system Facility (LARS) coring team.

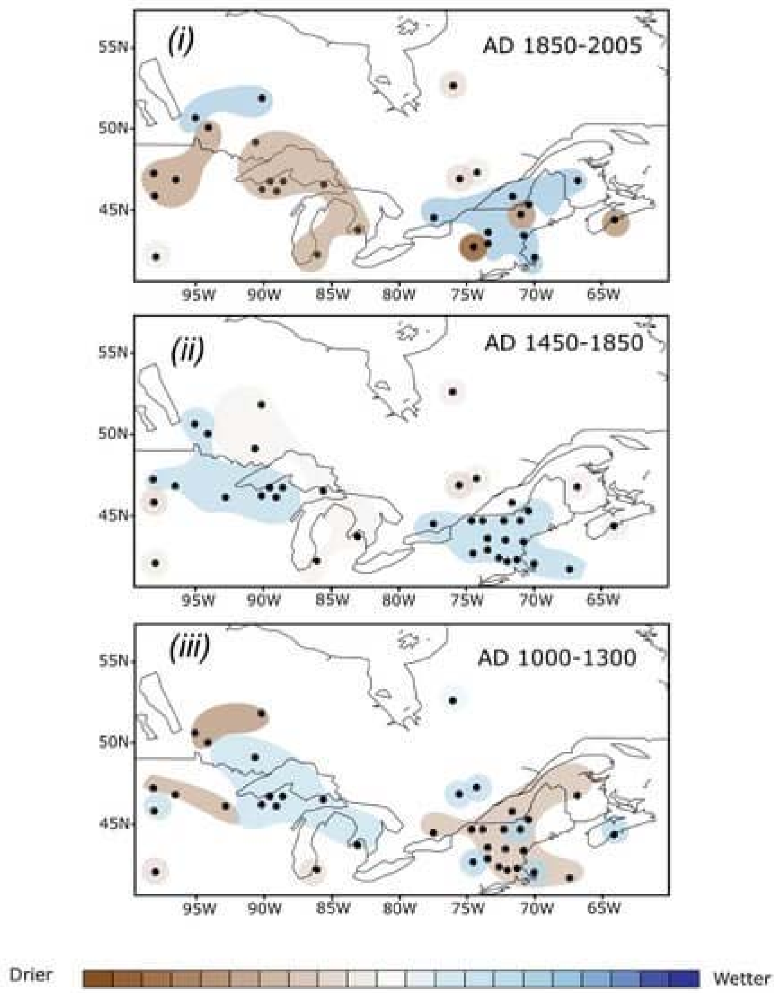


Figure 4. Variations in wet versus dry conditions during the (i) modern period (1850 CE to present), (ii) Little Ice Age (1450 to 1850 CE), and (iii) Medieval Climate Anomaly (1000 to 1300 CE). The sites shown here lie between 40 and 55 °N and 60–100 °W; their data are available from the National Oceanic and Atmospheric Administration (NOAA) paleoclimate database (https://www.ncdc.noaa.gov/paleo-search/). Shades of blue represent wet conditions while shades of brown represent dry conditions. See Doyle et al. (2021) for exact locations and citations associated with each site. Modified from Doyle et al. (2021). Used with permission.

Doyle and coworkers also compared records of water *quantity* and/or atmospheric moisture across the GLR to assess whether trends observed at Barry Lake were also observed at nearby sites (Fig. 4). The 38 records of interest were divided into three time periods representing the Medieval Warm Period, the Little Ice Age, and the modern period, respectively, and only long-term (e.g., centennial) trends were extracted from the data. We note that most of the proxies used are more sensitive to summer than winter conditions, which may have resulted in a warm-season bias in the interpretation.

This analysis revealed differences between the western-half of the GLR (i.e., west of Lake Ontario) and the eastern-half of the GLR (i.e., east of Lake Ontario) and Northeastern United States (NE US). During the Medieval Climate Anomaly, the eastern half of the GLR/NE US was generally dry, indicating lower water table depths, precipitation amounts, and lake levels. By comparison, many sites in the western half of the GLR were wet. During the Little Ice Age, the entire region was generally wet. In the modern period, much of the western GLR has been dry while the eastern GLR/NE US has been wet.

In general, Doyle and coworkers' findings correspond with previous studies, particularly for widespread wetness during the Little Ice Age. The west-east dipole in conditions observed during the Medieval Climate Anomaly and the modern period likely result from regional climate patterns related to the Atlantic Multidecadal Oscillation (AMO) and/or the Pacific Decadal Oscillation (PDO). This result suggests that the AMO and PDO are critical regulators of hydroclimate across the GLR.

To summarize, the contributions of Doyle and coworkers are threefold:

(1) Modern water *quality*/algal growth in Barry Lake is higher today than at any time in the last ~900 years. An appropriate restoration target would be to reduce chlorophyll a concentrations to pre- 1850 CE levels.

(2) Small lakes, which are commonly thought to record only local climate signals, may also record regional climate patterns linked to internal oceanic and atmospheric processes (e.g., AMO and PDO), as demonstrated across the eastern GLR and NE US.

(3) Doyle and coworkers' study underscores the importance of regional climate patterns in controlling moisture across the GLR. Improving our understanding of these climate patterns will improve our capabilities to predict future wet/dry periods in this economically and ecologically important region.

Rebecca Doyle is presently a Postdoctoral Fellow at the Analytical, Environmental and Geo-Chemistry (AMGC) Research Group at the Vrije Universiteit Brussel (VUB) in Belgium. Her research focuses on using the chemical, physical and biological properties of lake sediments to reconstruct paleoenvironmental conditions over the last 2.6 million years.

Katrina Moser is a professor and Chair of Geography and Environment at The University of Western Ontario, in London, Ontario, Canada. Katrina is a paleolimnologist who uses fossils and biogeochemical signals preserved in lake sediments to study climate change and its impact on lake ecosystems.

Fred J Longstaffe is Distinguished University Professor and Canada Research Chair (Tier 1) in Stable Isotope Science at The University of Western Ontario, in London, Ontario, Canada. Fred uses light stable isotopes to understand interactions across the lithosphere-hydrosphere-biosphere- atmosphere continuum, and to decipher the paleoclimatic, paleoenvironmental and paleoecological information recorded in these isotopic
signals.

References

Blaauw, M., Christen, J.A., Lopez, M.A.A., Vazquez, J.E., Gonzales, O.M.V., Belding, T., Theiler, J., Gough, B., Karney, C., 2021. Package “rbacon”. http://cran.rproject.org/web/packages/rbacon/rbacon.pdf

Bonsal, B.R., Peters, D.L., Seglenieks, F., Rivera, A. and Berg, A., 2019. Changes in freshwater availability across Canada. Canada’s Changing Climate Report, pp.261-342.

Campbell, M., Cooper, M.J., Friedman, K. and Anderson, W.P., 2015. The economy as a driver of change in the Great Lakes–St. Lawrence River basin. Journal of Great Lakes Research, 41, pp.69-83.

https://doi.org/10.1016/j.jglr.2014.11.016

Cotner, J.B., Weinke, A.D. and Biddanda, B.A., 2017. Great Lakes: Science can keep them great. Journal of Great Lakes Research, 43(5), pp.916-919. https://doi.org/10.1016/j.jglr.2017.07.002

Doyle, R.M., Liu, Z., Walker, J.T., Hladyniuk, R., Moser, K.A. and Longstaffe, F.J., 2021. A 900-year record of effective moisture in the Laurentian Great Lakes region. Quaternary Science Reviews, 270, p.107174. https://doi.org/10.1016/j.quascirev.2021.107174

Nazari-Sharabian, M., Ahmad, S. and Karakouzian, M., 2018. Climate change and eutrophication: a short review. Engineering, Technology and Applied Science Research, 8(6), p.3668. https://digitalscholarship.unlv.edu/fac_articles/562

R Core Development Team, 2023. R: A Language and Environment for Statistical Computing.

https://www.r-project.org/

Rodysill, J.R., Anderson, L., Cronin, T.M., Jones, M.C., Thompson, R.S., Wahl, D.B., Willard, D.A., Addison, J.A., Alder, J.A., Anderson, K.H., Anderson, L., Barron, J.A., Bernhardt, C.E., Hostetler, S.W., Kehrwald, N.M., Khan, N.S., Richey, J.N., Starratt, S.W., Strickland, L.E., Toomey, M.R., Treat, C. C. and Wingard, G.L., 2018. A North American Hydroclimate Synthesis (NAHS) of the Common Era. Global and Planetary Change, 162, 175-198. https://doi.org/10.1016/j.gloplacha.2017.12.025

The unprecedented Pacific Northwest heatwave of June 2021

WRITTEN BY CMOS BULLETIN SCMO ON MAY 25, 2023. POSTED IN CLIMATE, NEWS & EVENTS, WHAT'S CURRENT.
– By Cuiyi Fei, Rachel H. White, Chris Rodell –

The extreme heatwave that occurred at the end of June 2021 across the Pacific Northwest region of North America was so unprecedented and impactful that it will likely continue to be studied for many years. In our cross-disciplinary study, led by researchers at the University of British Columbia (White et al. 2023), we summarize the conditions leading up to this record-shattering event, and provide insights into the impacts of such unprecedented heat. Understanding such events is particularly relevant in the context of our warming world.

The degree by which local records were broken during this heatwave is shown in Figure 1, with a comparison to two other notorious heatwaves: in Europe in 2003 and Russia in 2010. The Pacific Northwest heatwave broke 70-year temperature records by more than 6 degrees, making it far more unprecedented than most heatwaves (see also Thompson, et al., 2022). In fact, it became one of the most severe extreme weather events in the past decades around the world and broke the national temperature record of Canada by 4.6 degrees. Although the heatwave lasted only around five to six days, shorter than the other two events included in Figure 1, it was still devastating. The maximum heatwave temperature of 49.6C was reached in Lytton, a small town in an arid valley of BC, and much of the town of Lytton was tragically destroyed in a wildfire during the heatwave.

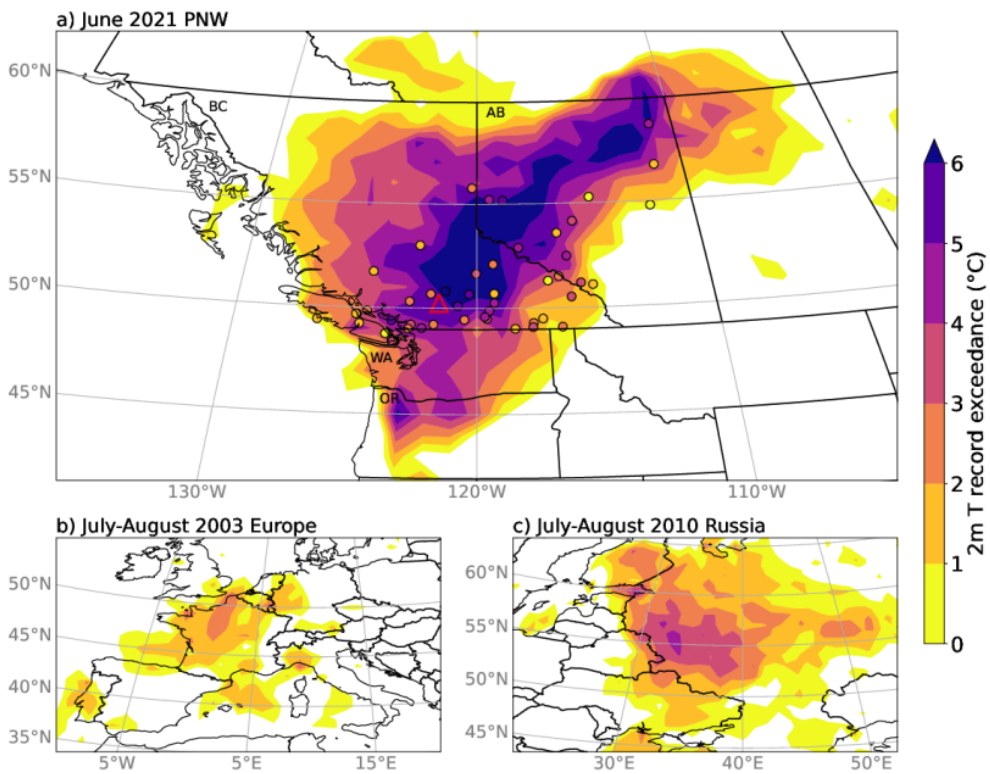


Figure 1. Exceedance of previous record high temperatures by the June 2021 Pacific Northwest heatwave (a), the July–August European heatwave of 2003 (b), and the July–August Russian heatwave of 2010 (c), Shading is re-analysis data (ERA5) from 1950; markers show individual stations with observational lengths of at least 71 years. Figure from White et al. 2023, Nature Communications.

Despite the unprecedented nature of the heatwave, our results show that record-breaking temperatures were successfully forecast at least three days before heatwave onset, consistent with previous work (Emerton et al., 2022). If we pull the perspective back to seven days before the heatwave, weather forecasts were able to predict a heatwave, although how extreme it would be was not clear. Even sub-seasonal forecasts initialized on June 7th showed an enhanced probability of atmospheric blocking, and associated high temperatures, although the forecast uncertainty at these timescales is significant.

Whilst no single comprehensive and quantitative theory can be universally applied to all extreme temperature events, heatwaves in summer can often be attributed to blocking highs — a high-pressure system that is stationary or propagating slowly. These blockings highs are often associated with subsidence, clear sky radiative warming and land-atmosphere feedbacks (Pfahl and Wernli, 2012), all contributing to high surface temperatures. The contribution of different factors varies from one event to another (Röthlisberger and Papritz, 2023). In the case of this heatwave, the preceding atmospheric conditions are shown in Figure 2, with a ridge and high mean sea level pressure just off the west coast of North America, which developed into a blocking pattern in the next few days. High upstream relative humidity (shown in the blue shading) provided latent heating from water vapor condensation, contributing to the anomalously high temperature and likely sustaining the high-pressure ridge (Oertel et al., 2023). Our findings demonstrate that approximately 78% (equivalent to around 14 degrees) of the near-surface temperature anomaly was due to the diabatic heating upstream of the blocking.

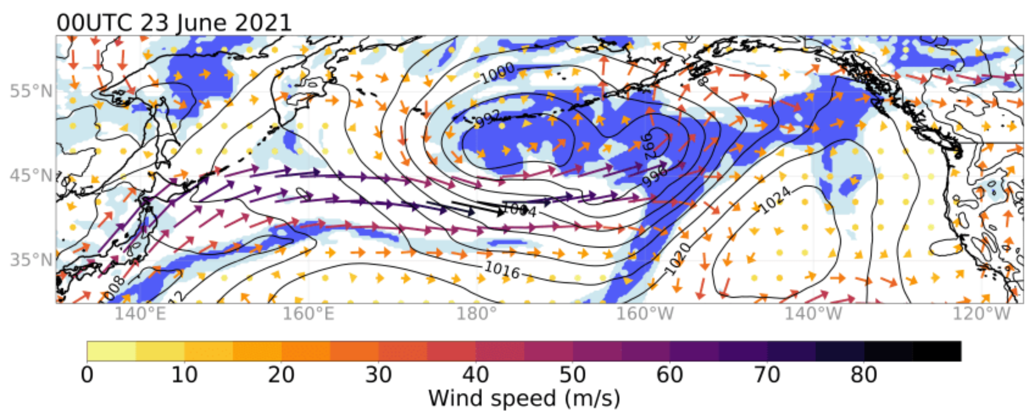


Figure 2. Meteorological conditions over the North Pacific for 00UTC 23 June. Data from ERA5 reanalysis showing: mean sea-level pressure (MSLP; contoured, hPa), 700 hPa relative humidity (RH; shaded, light blue >70%, dark blue >90%), and 250 hPa wind vectors (m/s, colored by wind speed). Coastlines and country borders are shown in black. Figure from White et al. 2023, Nature Communications.

The high temperatures of this heatwave, as illustrated in Figure 1, had a catastrophic impact on human health. A total of 868 deaths have, so far, been attributed to the heatwave, and emergency visits for heat-related illnesses in some impacted regions were 69 times higher compared to the same period in 2019.

Turning to the meteorological and oceanographic impacts, one direct consequence of the heatwave was a significant increase in wildfires. The number of wildfires in BC increased from six on June 20th before the heatwave to 175 on July 3rd, just after the heatwave, with the area affected by wildfires increasing by a factor of about 640 during this period. In addition to extremely high temperatures, the wildfires provided heat, smoke particles and water vapor for convective cloud formation. Upstream midtroposphere moisture also had an indispensable contribution to the convective clouds. These convective clouds, in turn, produced a large amount of lightning, igniting and strengthening wildfires. According to the Canadian Interagency Forest Fire Centre (CIFFC), lightning triggered at least 127 wildfires from June 30th to July 2nd.

This event also had significant impacts on marine life, particularly intertidal species. Figure 3 shows thermal images of mussels and the rocky intertidal shoreline they were on. During the heatwave, the temperature of the rocks, as well as some of the mussels, exceeded 50°C, leading to significant deaths (as evidenced by the mussels gaping open). Such large-scale mortality occurred across various species from the southern end of Puget Sound, Washington State, to the BC Central Coast, with the total number of killed marine invertebrates almost certainly in the billions (Raymond et al., 2022).

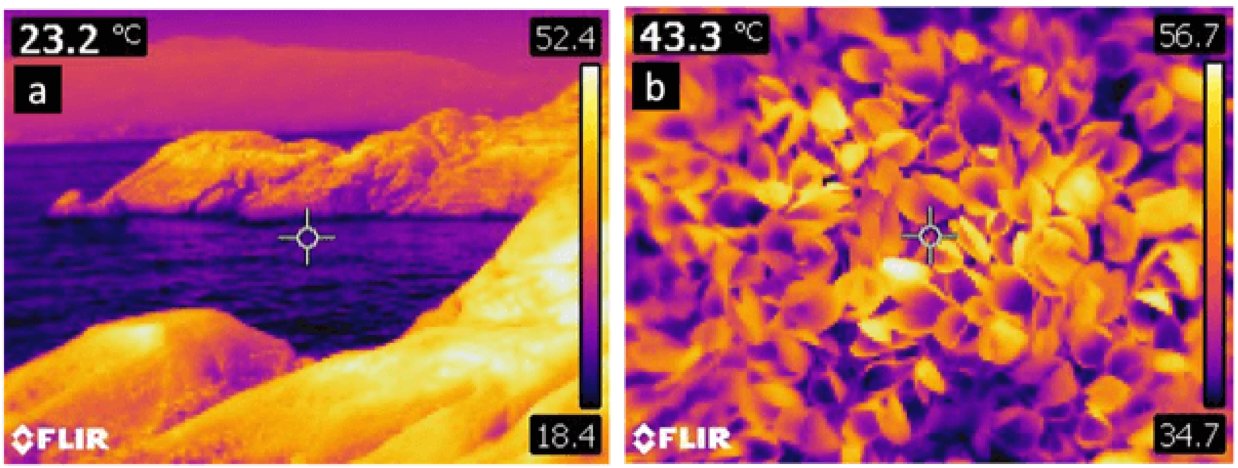


Figure 3. Thermal images showing surface temperatures exceeding 50°C during low tide on 28 June, 2021, on a rocky intertidal shoreline (left) and within a mussel bed (right) in the vicinity of Vancouver, BC; the mussels in this picture have died and are gaping open. Scale bars indicate the range in temperature from the coolest to warmest parts of the image, while the value at the upper left indicates the temperature in the cross-hairs at the center. Figure from White et al. 2023, Nature Communications.

In addition to the direct temperature impacts, the extreme heatwave also increased streamflow in British Columbia by melting ice and snow. Figure 4 shows substantial peaks in streamflow coinciding with the heatwave in heavily or moderately glaciated basins (top and middle rows respectively), while areas with little glacier coverage (and therefore likely little snow cover) experienced minimal change during the heatwave (bottom row). After the heatwave, streamflow in areas with moderate or little glacier coverage was typically lower than climatological values (middle and bottom row). In contrast, the streamflow from glaciated basins remained close to the climatological average (top row); this was almost certainly achieved at the cost of potentially irreversible glacier mass loss. Managing water resources may be critical during and after extreme heatwaves in the future, as the ability of glaciers to sustain streamflow may diminish as glaciers continue to melt in response to climate change (Clarke et al., 2015).

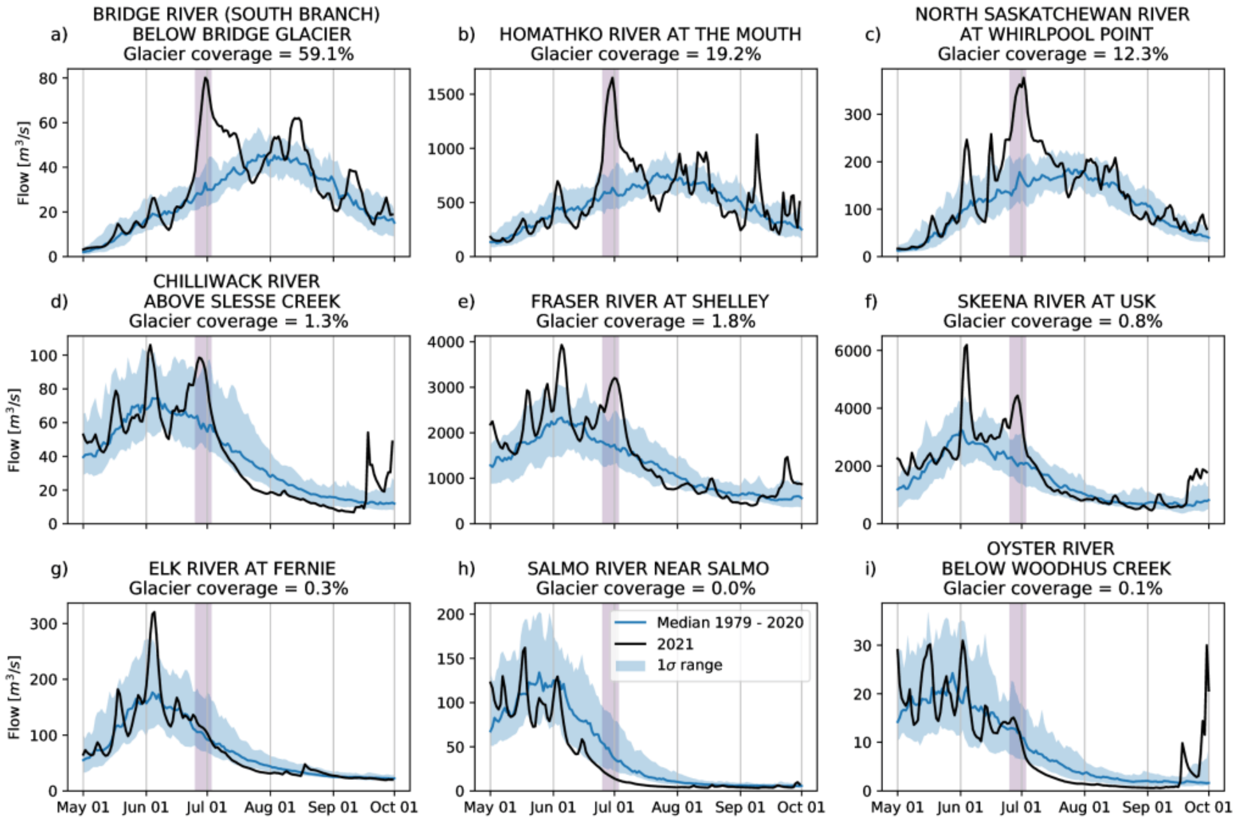


Figure 4. Streamflow observations at nine stream gauge stations in 2021 (black line) relative to the 1979–2020 median (blue line) and one standard deviation range (shaded). Gauges are organized from top to bottom by basin glacier coverage: highly glaciated basins (a–c), lightly glaciated basins (d–f), and minimally or non-glaciated basins (g–i). See Supplementary Fig. S6 for the locations of these gauges. Figure from White et al. 2023, Nature Communications.

This unprecedented heatwave is a vivid example of a record-shattering mid-latitude heatwave, illustrating some potential effects of extreme heat. There is no doubt that increasing background temperatures due to anthropogenic climate change made this heatwave hotter and, therefore, more extreme; however, the recording-breaking temperatures of recent extreme weather events such as this heatwave are a combination of anthropogenic climate trends and internal variability that has always been able to cause large anomalies in temperature. Understanding of our complex interacting climate system remains incomplete and quantitative estimates of the contribution of anthropogenic factors to this heatwave have relatively large uncertainties due to the many interacting factors that may have played a role, including moisture and land-atmosphere feedbacks and possible anthropogenically-forced changes to atmospheric circulation patterns. Long-term adaptation in response to long-term climate change and the short-term response to extreme events have both overlapping and separate components (Dolan, 2021). To reduce the impacts of future heatwaves, it is imperative that we understand, mitigate, and adapt on both timescales.

While anthropogenic climate change was not the sole cause of this event, this heatwave presents an opportunity to enhance people's awareness and preparedness. Even though many future extreme weather events may not be as unprecedented as this heatwave, it is undeniable that global warming will result in more record-shattering heatwaves in the future (Fischer et al. 2021). Hence, it is vital to take proactive measures toward climate adaptation, including building infrastructure, improving emergency response, and promoting sustainable strategies such as the use of clean energy in the industry, agriculture, and people's daily lives. We must build resilience against extreme events and climate change for a safer and more sustainable future.

Cuiyi Fei is a PhD Candidate in the Department of Earth, Ocean and Atmospheric Sciences at University of British Columbia. She is working on understanding the mechanism of quasi-stationary waves, but she has a broad interest in general circulation in the atmosphere and ocean.

Rachel White is an Assistant Professor in Atmospheric Science in the Department of Earth, Ocean and Atmospheric Sciences at University of British Columbia. Her research interests include large-scale climate dynamics, connections between atmospheric circulation patterns and extreme weather events, and the subseasonal to seasonal predictability of extremes.

Chris Rodell is a PhD Candidate in Atmospheric Science at the University of British Colombia. His focus is on Fire Weather, Behaviour and Smoke forecasting.

References

Clarke, G.K., Jarosch, A.H., Anslow, F.S., Radić, V. and Menounos, B., 2015. Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8(5), pp.372-377. https://www.nature.com/articles/ngeo2407

Emerton, R., Brimicombe, C., Magnusson, L., Roberts, C., Di Napoli, C., Cloke, H.L. and Pappenberger, F., 2022. Predicting the unprecedented: forecasting the June 2021 Pacific Northwest heatwave. Weather, 77(8), pp.272-279. https://rmets.onlinelibrary.wiley.com/doi/10.1002/wea.4257

Fischer, E.M., Sippel, S. and Knutti, R., 2021. Increasing probability of record-shattering climate extremes. Nature Climate Change, 11(8), pp.689-695. https://www.nature.com/articles/s41558-021-01092-9

Oertel, A., Pickl, M., Quinting, J.F., Hauser, S., Wandel, J., Magnusson, L., Balmaseda, M., Vitart, F. and Grams, C.M., 2023. Everything hits at once: How remote rainfall matters for the prediction of the 2021 North American heat wave. Geophysical Research Letters, 50(3), p.e2022GL100958. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL100958

Pfahl, S. and Wernli, H., 2012. Quantifying the relevance of atmospheric blocking for co - located temperature extremes in the Northern Hemisphere on (sub -) daily time scales. Geophysical Research Letters, 39(12). https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012GL052261

Raymond, W.W., Barber, J.S., Dethier, M.N., Hayford, H.A., Harley, C.D., King, T.L., Paul, B., Speck, C.A., Tobin, E.D., Raymond, A.E. and McDonald, P.S., 2022. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. Ecology, 103(10). https://esajournals.onlinelibrary.wiley.com/doi/10.1002/ecy.3798

Röthlisberger, M. and Papritz, L., 2023. Quantifying the physical processes leading to atmospheric hot extremes at a global scale. Nature Geoscience, pp.1-7. https://www.nature.com/articles/s41561-023-01126-1

Thompson, V., Kennedy-Asser, A.T., Vosper, E., Lo, Y.E., Huntingford, C., Andrews, O., Collins, M., Hegerl, G.C. and Mitchell, D., 2022. The 2021 western North America heat wave among the most extreme events ever recorded globally. Science Advances, 8(18), p.eabm6860. https://www.science.org/doi/full/10.1126/sciadv.abm6860

White, R.H., Anderson, S., Booth, J.F., Braich, G., Draeger, C., Fei, C., Harley, C.D., Henderson, S.B., Jakob, M., Lau, C.A., Mareshet Admasu, L., Narinesingh, V., Rodell, C., Roocroft, E., Weinberger, K.R., and West, G. 2023. The unprecedented Pacific Northwest heatwave of June 2021. Nature Communications, 14(1), p.727. https://doi.org/10.1038/s41467-023-36289-3