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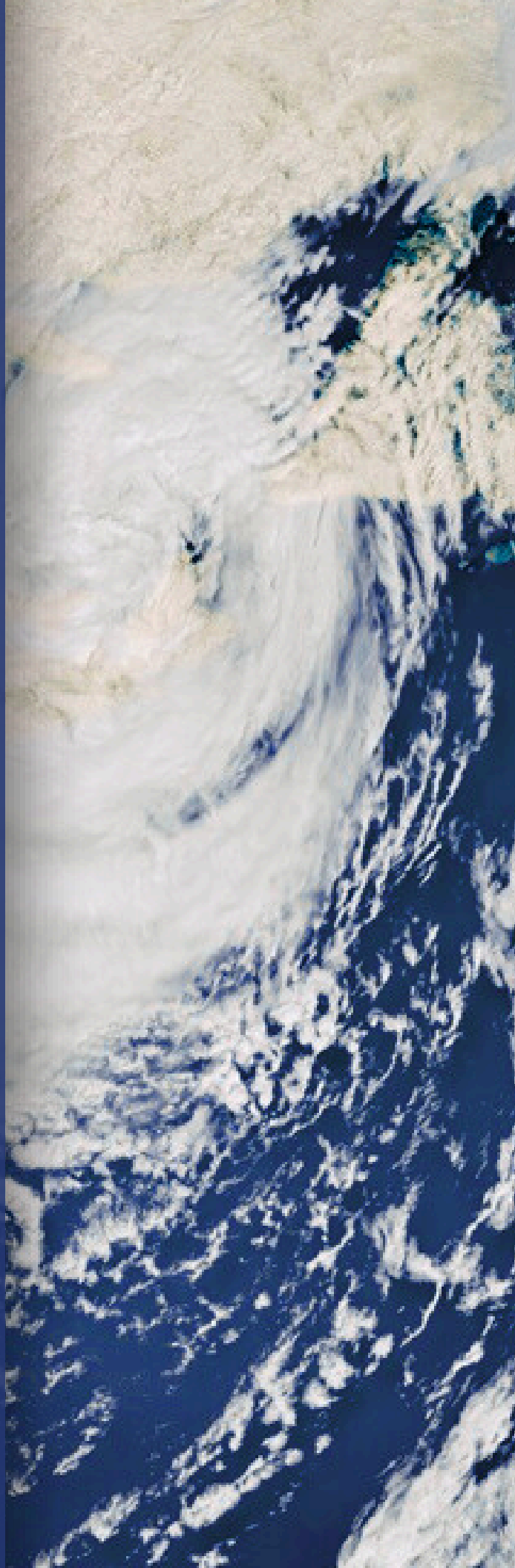
The Future of Hydrological and Meteorological Services in Canada

Expert Panel Report



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The Future of Hydrological and Meteorological Services in Canada

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This project was undertaken with the approval of the Board of Directors of the Council of Canadian Academies and responds to a request from the sponsor, Environment and Climate Change Canada, for an independent assessment. The sponsor was not involved in either panel selection or report development; any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on the Future of Hydrological and Meteorological Services in Canada, and do not necessarily represent the views of their organizations of affiliation or employment.

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The Council of Canadian Academies' (CCA) offices in Ottawa are located on the unceded traditional territory of the Anishinaabe Algonquin People, who have cared for these lands for millennia.

The CCA is committed to reconciliation and honouring Indigenous sovereignty. Through our work in providing evidence for decision-making, we recognize that a wide range of knowledges and experiences contribute to building a more equitable and just society. We encourage all who engage with our work to further learn about and acknowledge the past and present context of the land now known as Canada and of the Indigenous Nations and Peoples who steward it.

Expert Panel on the Future of Hydrological and Meteorological Services in Canada

Expert panel members serve as individuals and do not represent their organizations of affiliation or employment. Each panellist was selected for their expertise, experience, and demonstrated leadership in fields relevant to this project.

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This report was reviewed in draft form by reviewers selected by the CCA for their diverse perspectives and areas of expertise. Their anonymized submissions were considered in full by the expert panel. Reviewers were not asked to endorse the conclusions, nor did they see the final draft before its release. Responsibility for the final content of this report rests with the expert panel and the CCA.

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The peer review process was monitored on behalf of the CCA by **Madison Rilling,** Executive Director, Optonique.

Contents

Report summary

Public hydro-meteorological services are critical to the prosperity, sovereignty, and well-being of people across Canada. These services play a crucial role in public safety, as well as in national defence, transportation, agriculture, and energy—among other sectors—ultimately supporting a strong and resilient economy. Three trends are changing the way these services are built and delivered: (i) technological advances, particularly artificial intelligence and machine learning; (ii) an expanding information environment and global weather enterprise; and (iii) climate change, which is causing more extreme weather events that threaten the lives and prosperity of Canada and its people.

These trends, coupled with changing geopolitics and financial constraints, underscore the need to strategically transform the Government of Canada's hydro-meteorological operations to enhance their value by improving efficiency and adaptability. At the same time, essential and foundational functions of the Meteorological Service of Canada (MSC), some of which have been reduced over time, need to be maintained. These essential functions include backbone infrastructure—such as a country-wide observation system and modelling capabilities—critical to Canada's weather enterprise and climate change adaptation strategy. An effective warning system is also essential for public safety. All people in Canada need to know about local weather and environmental conditions and be warned of dangerous weather and flooding events. It is also essential that the MSC lead by facilitating collaboration with the broader hydro-meteorological ecosystem—including other orders of government, private companies, NGOs, the media, and academia—and continue to maintain strong relationships with international meteorological organizations to support improved services in Canada.

Thoughtful prioritization of the MSC's activities, a strategic increase in partner involvement, and a clear understanding of user needs are critical to ensuring high-quality service while also responding to threats to the integrity of an increasingly complex global hydro-meteorological ecosystem. Updating and diversifying skills within the MSC workforce and strengthening ongoing partnerships (both domestic and international) will help resist fragmentation and improve end-to-end resilience. Leadership, communication, and coordination skills are as relevant to the beneficial delivery of hydro-meteorological services as are modelling and forecasting skills. However, the MSC need not do it all alone—by embracing standards, building partnerships, and taking a stronger leadership role where needed, the MSC can leverage its resources to maximize efficiency and return on investment while protecting Canadian sovereignty, safety, and prosperity.

1 Introduction

Weather and climate impact everyone and influence a wide variety of government, industry, and personal decision-making. *Weather* reflects current and short-term forecasted atmospheric conditions, including temperature and rainfall, whereas *climate* reflects expected conditions based on long-term trends in weather (i.e., over decades) (ECCC, 2020). People in Canada have come to rely on public and private hydro-meteorological services for all kinds of weather, climate, and hydrometric (i.e., water level and flow) information, from basic observations and forecasts (do I need a raincoat today?) to specialized information on air quality, UV radiation, and pollen counts (ECCC, 2025a; Pelmorex Corp, 2025). Knowing what to expect in terms of weather and its impacts (such as wildfires or flooding) is critical to personal and public safety—from timing the deployment of snowplows, to diverting traffic away from flood-prone roadways, to opening cooling stations during heatwaves. The positive outcomes of accurate and timely weather and flood reports are so ubiquitous they can sometimes be overlooked.

Public hydro-meteorological services are operating in a rapidly shifting context—from the way the public accesses and interacts with information, to the impacts of climate change, to the adoption of advanced technologies—and the role of the public sector in weather and hydrometric monitoring and forecasting is evolving. To understand the essential functions of a public hydro-meteorological service in light of these trends, Environment and Climate Change Canada (ECCC), on behalf of the Meteorological Service of Canada (MSC, hereafter "the sponsor") asked the Council of Canadian Academies (CCA) to convene an expert panel tasked with examining the following question and sub-questions:

What are the essential functions of Canada's public meteorological service, and how are these changing in the context of climate change, new technology, a shifting information landscape, and other trends?

- How might emerging and/or rapidly developing technologies (e.g., Space-based Earth Observation; Artificial Intelligence and Machine Learning) affect the way that hydro-meteorological services are provided?
- How can the Meteorological Service of Canada ensure that it can continue to meet the current and future needs of Canadians, particularly in a context of increasingly frequent and intense severe weather events and fast-evolving technological progress, that together, challenge how public hydro-meteorological organizations monitor weather and environmental conditions, predict future conditions, and deliver critical products and services?

To answer the charge, the CCA assembled a multidisciplinary four-member panel[1] (the Expert Panel on the Future of Hydrological and Meteorological Services in Canada, hereafter "the panel") with backgrounds and expertise in atmospheric science, engineering, artificial intelligence (AI)[2] and modelling, and climate change from academia as well as from the public and private sectors. At the beginning of the assessment, the panel met with the sponsor[3] to gain an understanding of the charge and confirm which issues were in and out of scope. The sponsor confirmed that Canada's public meteorological service encompasses actors other than the MSC, both within and outside the federal service, and that hydrological services fall within scope. The panel met virtually five times in three months to review evidence and deliberate on the charge. This includes evidence that was gathered at an in-person workshop with a broader group of experts (Section 1.2).

1.1 Public hydro-meteorological services in Canada

The MSC, responsible for the vast majority of public hydro-meteorological services in Canada, was founded in 1871 and issued its first Canadian-prepared storm warning for shipping activities in 1876; the first weather forecast for Canada in general was produced a year later in 1877 (ECCC, 2022). Weather services were expanded to meet aviation needs in the 1930s and were further broadened to meet military needs in the 1940s. Meteorological services are critical to the operations of numerous federal departments, including transportation, commerce, national defence, and public safety. In 1971, Canada's weather service was transferred to the newly created Canada Department of the Environment, where it remains to this day (now Environment and Climate Change Canada) (ECCC, 2022). The MSC has four dimensions to its mandate:

- "Provide Canadians with authoritative information on weather, water quantity, climate, ice, and air quality 24 hours/day, 365 days/year;
- monitor, predict, and warn Canadians of high-impact weather, air quality, and other environmental conditions to mitigate and reduce disaster-related risks;
- support mission-critical operations of federal, provincial and territorial, municipal, and private organizations that rely on MSC's infrastructure, ECCC science capacity, and deliver on their mandate (e.g., aviation, emergency management, water management, military & marine ops); and
- deliver on international responsibilities related to data exchange, atmospheric modelling (e.g., emergency related to airborne substances, volcanic ash, chemical, biological, nuclear and radioactive (CBNR)), and marine forecasts and warnings for defined areas of the Arctic Ocean."

(ECCC, 2023a)

[1] To ensure the integrity of the assessment process, panel members disclosed to the CCA and fellow panellists any conflicts of interest—actual, foreseeable, or perceived—relevant to the issues being discussed, to manage these transparently. Panellists also abided by a confidentiality agreement and code of conduct designed to support an environment that fostered effective and respectful deliberations, was conducive to the free exchange of knowledge, and supported the assessment of evidence.
[2] Throughout the report, the term AI encompasses both artificial intelligence and machine learning unless otherwise specified.
[3] As part of CCA's process to maintain panel independence, sponsors do not appoint panel members or workshop participants, nor do they engage with the panel during the assessment process, with the exception of the panel's first meeting, when the sponsor is invited to present the charge and answer any panel questions.

The MSC is a part of the global weather enterprise, "a well-established and successful global public-private partnership in which both sectors share common goals" (Thorpe, 2016). Around the world, weather and climate information is essential to the protection of life and property, as well as economic growth and prosperity (Thorpe & Rogers, 2021; Seitter *et al.*, 2025). For example, the National Weather Service of the United States (2017) estimates that 3–6% of variability in that country's GDP is attributable to weather. Moreover, the weather information provided by the National Weather Service generates economic value of upwards of US$13 billion for businesses, while also enabling a private weather industry (valued at US$7 billion in 2017) that offers tailored products and services to companies and other customers (NWS, 2017). Public hydro-meteorological services cooperate with actors in public, private, and academic sectors around the world to enable this global weather enterprise.

As illustrated by Figure 1.1, several responsibilities often considered the purview of a public hydro-meteorological service lie outside the mandate of the MSC. In Canada, some of these relevant functions are carried out by other entities within ECCC (2023b). For example, the Science and Technology Branch, which includes the Meteorological Research Division, leads environmental science and monitoring; conducts research on climate, ecosystems, wildlife, and pollution; and supports evidence-based policies, regulations, and international standards (ECCC (2023b).

Departments and agencies outside of ECCC provide essential support for the public hydro-meteorological service or use their data. For example, the supercomputing capacity required to carry out numerical modelling for weather forecasts and climate projections is operated by Shared Services Canada (SSC, 2025). A wide range of departments use weather data and/or climate model outputs to inform decision-making related to their mandates (e.g., Agriculture and Agri-Food Canada (AAFC, 2020), Public Safety Canada (PS, 2023), Natural Resources Canada (NRCan, 2020)).

Several hydro-meteorological services lie outside of federal mandates. For instance, while the MSC houses the National Hydrological Service, which monitors water level and flow at a national scale, under the *Constitution Act* (GC, 1982), water is considered a provincial resource. The provinces (and Yukon[4]) hold primary responsibility for water management in most cases, although many of these responsibilities are delegated to municipalities or other local authorities (e.g., river basin management) (ECCC, 2016, 2024a). In Ontario, local flood messaging is the responsibility of conservation authorities, which are watershed-based, public sector organizations (Gov. of ON, 2024, 2025).

[4] Water resources in the Northwest Territories and Nunavut are under federal jurisdiction. Management of water and wastewater on First Nation reserves is under shared responsibility between First Nation governments and the federal government (ECCC, 2024a).

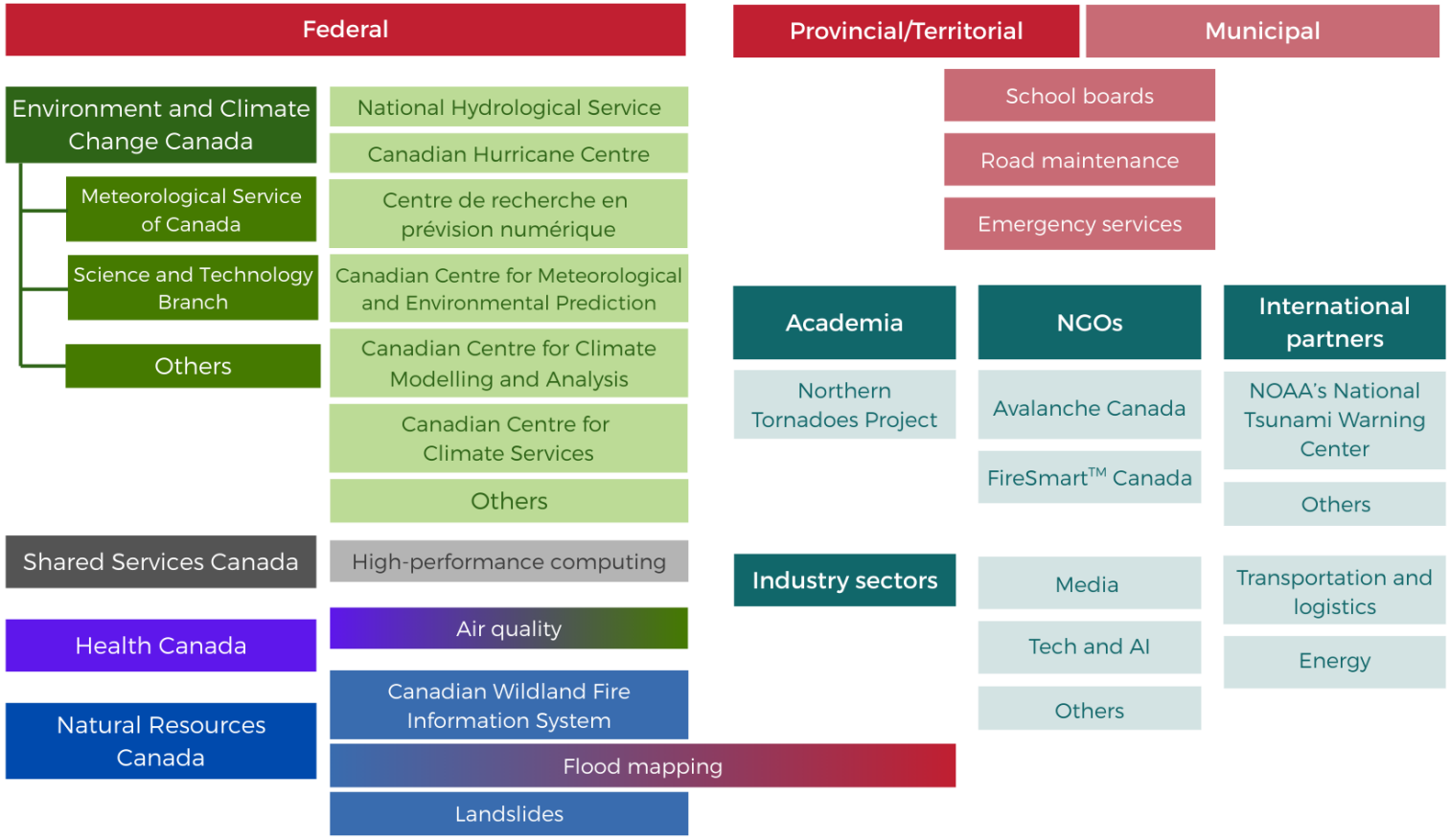

Figure 1.1 "Simplified" diagram of some participants in Canada's hydro-meteorological service ecosystem

This diagram is not comprehensive of all the players in the ecosystem; departments, projects, and sectors are included as illustrative examples. The figure is intended to highlight some of the complexities and interdependencies of the weather enterprise from a Canadian perspective. Colour coding is intended to group differences in type of organizations, jurisdiction, and responsibilities. Canada's hydro-meteorological ecosystem comprises federal, provincial, territorial, and municipal actors whose responsibilities include protecting life and property, as well as supporting economic activities. Government actors work with private organizations in industry, academia, and other NGOs, as well as international partners; these organizations provide specialized services to people, businesses, and governments in Canada. Within the federal government, there are numerous departments, agencies, and organizations that contribute to or utilize weather and climate services, including the MSC. For example, NRCan utilizes weather information for wildfire monitoring and prediction, as well as for flood mapping, which is done in partnership with provincial and territorial governments. Another federal department, Shared Services Canada, supports the high-performance computing used for modelling and other analyses.

In Quebec, it is a provincial ministry (Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs) that monitors and reports water levels and flow online (Vigilance – Surveillance de la crue des eaux) for municipal and government authorities to issue warnings and emergency interventions (Gov. of QC, 2023). Nova Scotia does not have dedicated resources for flood monitoring or prediction, though the provincial Department of Environment and Climate Change does track long-term hydrometric trends (Gov. of NS, n.d.). The *Canada Water Act*, proclaimed in 1970, is intended to provide for the management of water resources in Canada by enabling cooperation among federal, provincial, and territorial governments regarding the conservation, development, and use of water resources (GC, 1985). This act is under review by the Canada Water Agency, which is part of ECCC (CWA, 2024, 2025).

1.2 Expert workshop

As part of the evidence-gathering process for this project, the panel hosted a workshop in May 2025 that brought together an additional 10 experts with diverse perspectives and backgrounds, including those with experience in atmospheric sciences and hydrology, as well as those from public hydro-meteorological services in other countries and user groups. Analysis, discussion, and debate were aided by a facilitator using a group decision-support platform that enables rapid idea generation and consensus building. Much of the evidence presented in this report is based on insights shared during this event.

1.2.1 Key trends impacting hydro-meteorological services

Workshop participants (including the panel) were asked to identify key trends that are impacting the functions of Canada's public hydro-meteorological service. The top three trends identified were climate change, technological development, and an evolving communication ecosystem (including an increasing number of actors in global and domestic hydro-meteorological services). Funding limitations and geopolitical concerns, particularly related to Canadian sovereignty and competition for the Arctic were also identified as important trends.

Climate change increases the strain on hydro-meteorological resources

Workshop participants noted that extreme weather from a changing climate is impacting hydro-meteorological services and increasing demand for high-quality weather services and products, such as timely, accurate, and actionable weather and flood warnings and alerts. Climate change is also increasing the demand on physical infrastructure and budget resources, for example, through damage caused by extreme weather events and heightened demand for high-quality weather data to inform climate models.

Technological developments are transforming the way weather services work

Technological developments, such as AI and advances in remote sensing, can offer new approaches and improve efficiency in data collection, assimilation, and forecasting, among other applications. These advances have the potential to fundamentally alter the human and physical resources required for hydro-meteorological services. Moreover, the responsible and equitable application of advanced technologies can be resource-intensive and require specialized skill sets.

The way people and organizations communicate and understand information is evolving

The increasing complexity of the service ecosystem—which includes public sector agencies and departments across all orders of government, a growing number of private sector companies and services, and academic and non-profit institutions, as well as an evolving international network of organizations—points to challenges of coordination and competition, but also opportunities for collaboration and strategic partnerships. At the same time, an increasingly complex information ecosystem coupled with more extreme weather events highlights the need for efficient, relevant, and equitable communication in the service of saving lives and protecting property. However, increasing social vulnerability, decreasing public trust in government institutions, and fragmentation of communication channels challenge the design and delivery of science and health information (CCA, 2023). It is increasingly challenging to build credibility as an authoritative source of information in a diffuse media landscape. The panel notes that ongoing weather and climate communication and education across a variety of platforms will help ensure that warnings about extreme events are understood and acted upon.

While advanced technologies and the expansion of the communication ecosystem can lead to more and better data and products for broader and niche audiences, they also require specialized skills and strategic collaborations to ensure equitable, efficient, and accessible use. Taken collectively, these key trends underscore the urgency of thoughtfully and strategically positioning MSC's essential functions within Canada's and the world's collective hydro-meteorological service system.

1.2.2 A changing global context

Workshop participants emphasized that the impacts of these key trends are operating in the context of changing financial and geopolitical systems. Program spending on hydro-meteorological services has remained relatively static over the past five years (Figure 1.2), despite increased damages from extreme events (Section 2.2). Funding limitations constrain the ability of a single agency or organization to deliver adequate services and products to meet a wide variety of user needs. Partnerships among public, private, and academic organizations offer mechanisms to improve efficiency and deliver services under financial constraints; however, these also demand leadership and coordination of resources and skills.

Geopolitical shifts are changing Canada's relationships with international partners

Geopolitical risks and threats to Canadian sovereignty have changed the context in which Canada engages with international partners (PMO, 2025). Evolving geopolitics have increased the focus on Arctic regions critical to Canada's economy, environmental stability, and sovereignty. This focus creates demand for hydro-meteorological data collection, forecasting, and other products and services specific to sparsely populated northern regions. The United States has long been a world-leading source of weather information and a major partner for Canada's hydro-meteorological services, given the shared border that includes the Great Lakes. Significant cuts in funding and personnel in the United States' weather enterprise threaten a wide range of monitoring activities in Canada, from the Arctic to the Great Lakes, to satellite data on flooding, hurricanes, and changing atmospheric conditions, among others (Boasiako, 2025).

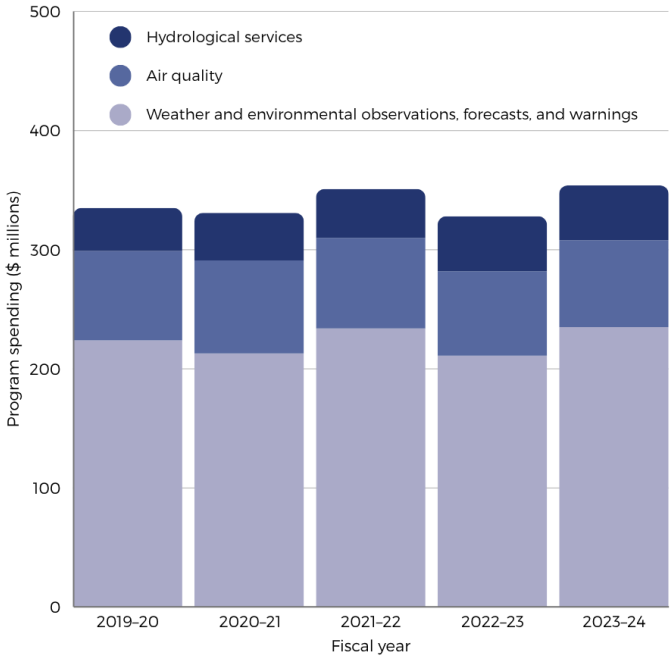

Figure 1.2

Program spending by ECCC on hydro-meteorological services, 2019–2024

Despite increasing pressure on hydro-meteorological services from climate change, program spending has remained stable over the past five years. Little information is provided with these data to contextualize spending, such as information on investments in computing, satellite, or radar infrastructure that may not be captured under program spending.

Data source: GC (2025a)

1.3 Report structure

Based on workshop and panel discussions, as well as supporting published evidence, the report highlights the essential functions of Canada's hydro-meteorological service in the context of the key trends identified above (**Chapter 2**). It reflects on the potential for adaptation in how these essential functions are delivered through the application of advanced technologies (**Chapter 3**). **Chapter 4** considers the task of meeting user needs through the lens of critical communication strategies and products. **Chapter 5** offers a high-level discussion of the potential for Canada's hydro-meteorological services to assume leadership and coordination roles both domestically and internationally, concluding with the panel's reflections and final thoughts.

2 Essential Functions of Canada's Public Hydro-Meteorological Service

The National Hydrological and Meteorological Services, as recognized in the Convention of the World Meteorological Organization, are a fundamental part of national infrastructure and play an important role in supporting vital functions of governments.

(WMO, 2015)

Chapter findings

- The MSC has a duty to provide and maintain Canada's backbone infrastructure for weather and climate monitoring, which remains essential despite advances in AI and modelling. Beyond the technology and resources for data collection, the MSC's backbone infrastructure encompasses the expertise in, and access to, computing resources required for modelling and forecasting, which are evolving rapidly due to AI.
- The MSC holds sole responsibility for issuing weather warnings and alerts in Canada to save lives and protect property from extreme weather events. Warnings and alerts are critical in the face of the growing threats stemming from climate change, which is making extreme weather events more frequent, severe, and complex. While all people in Canada are at risk, these events disproportionately affect marginalized populations.
- The importance of federal leadership through effective coordination and collaboration with other actors in the complex weather enterprise is growing as the number of entities—including private companies, NGOs, and academia—continues to rise. International engagement also remains critical, as Canada benefits substantially from participating in data exchange, diplomacy, and advocacy with the global hydro-meteorological community.

The mandate of the MSC, as outlined in Chapter 1, is extensive and multifaceted, encompassing a wide array of tasks and responsibilities. These responsibilities are evolving in response to major trends—most notably climate change and technological innovation—while fiscal constraints across governments are simultaneously driving a need for greater efficiency. At the same time, ECCC has identified strengthening and enhancing meteorological capabilities as a key direction in its most recent science strategy (ECCC, 2024b). These factors present a timely opportunity to strategically consider the essential functions of the MSC and how they can best serve the needs of people in Canada. For this assessment, workshop participants, including members of the expert panel, were asked to identify the essential functions of Canada's public hydro-meteorological service and reflect on how these functions are changing due to key trends (Section 1.3.1). The participants first considered public hydro-meteorological

services in general before examining the specific role and mandate of the MSC as, in Canada, the responsibility for some services lies elsewhere. The insights gathered during the workshop formed the foundation for the panel's subsequent analysis, which identifies three key essential functions: backbone infrastructure, protecting people, and leadership in the weather enterprise.

2.1 Backbone infrastructure

Providing backbone physical and human infrastructure is a critical role of the MSC

An understanding of weather and climate depends on a reliable foundation of both physical and human infrastructure, and the maintenance of this infrastructure is an essential function for the public hydro-meteorological service in Canada. Regardless of who uses it, the collection, assimilation, and distribution of observational data are indispensable functions of the public sector, as is having the capacity to undertake weather modelling, in terms of both the skills and access to the necessary computing power. There is a role for the private sector and crown corporations (e.g., public utilities) in contributing to the data and modelling that strengthens the weather enterprise; however, this should be viewed as a complement to (as opposed to possible replacement of) a strong public system that provides a minimum level of coverage across the country with long-term continuity and strict compliance with international standards (Freebairn & Zillman, 2002a).

An effective cross-country, real-time observation network requires the collection of diverse measurements using a range of land-, sea-, and space-based sensors. The observation network maintained by the MSC as of July 2023 is outlined in Box 2.1. Although AI is revolutionizing weather forecasting and modelling (Section 3.1), it is unlikely to alleviate dependence on data collection and the need for observation networks that collect the data. Additionally, many of the advances in AI depend on having a rich source of data on present and past weather events. Backbone infrastructure is also essential for providing inputs to the global weather community. Canada benefits significantly from being part of this community, as it relies on data collected by other public hydro-meteorological services from around the world, particularly the United States, to gain a comprehensive understanding of the weather here.

There are known gaps in the existing observation network, however. For instance, inadequate coverage in the North, along with shifts in how weather and environmental conditions are monitored (e.g., increased focus on satellites and automation), have been criticized for not providing the information wanted and needed by people in these regions (Hancock *et al.*, 2022; Sanders, 2023; Voosen, 2023). In parts of the North, there are hundreds of kilometres between weather stations, meaning some small communities do not have access to accurate local weather or climate information (Sanders, 2023). Additionally, less than a third of stations located north of the 55th parallel record at least three of five key weather variables (rainfall, snow depth, snowfall, temperature, and wind) and this percentage has been on the decline over the last 30 years (Way, 2022).

Box 2.1 Physical Observation Networks of the MSC (as of July 2023)

"**Weather radar network**, which includes 32 operational radars.

Marine weather network composed of 45 moored buoys, 49 automatic volunteer observing ships, and 19 drifter buoys.

Surface weather and climate network comprising 575 automatic weather stations, 225 cooperative climate network stations, and 29 lighthouse stations.

Upper-air network composed of more than 30 stations across Canada.

Satellite-borne sensors delivering data to eight ground receiving stations.

82 **lightning detection sensors**.

~2,200 **hydrometric monitoring stations** (operated by the MSC on a cost-shared basis with the provinces and territories)."

(ECCC, 2023a)

Backbone infrastructure extends beyond observation. It also includes having the knowledge needed to carry out analysis and prediction through modelling and data integration. In these areas, technological advancements (e.g., AI, accuracy of numerical weather prediction) are revolutionary, opening the door to new approaches to forecasting (Section 3.1). Access to the calibre of technologies needed for analysis and prediction—such as high-performance computing, data storage, and communications infrastructure—is also critical. However, the maintenance of such infrastructure may be the responsibility of entities outside the public hydro-meteorological service.

There are substantial benefits that come from public maintenance of backbone infrastructure including informed and higher benefit decisions made possible by the range of services stemming from it (Freebairn & Zillman, 2002a,b). This is true for individuals, communities, governments, and the private sector, as "virtually every sector of the economy in virtually every country makes some direct or indirect use of general or user-specific meteorological services" (Freebairn & Zillman, 2002a). Obtaining a comprehensive picture of the total or marginal benefits of backbone infrastructure is challenging, however, because it has public good properties (Freebairn & Zillman, 2002b). At the same time, Freebairn and Zillman (2002a) find that these same properties mean that "direct government funding and free provision to all are favoured" due to economic efficiency and a range of practical considerations (e.g., high costs of exclusion, frequent shifts in user valuation).

High-quality, consistent, and long-term measurements are needed to support the climate adaptation that is necessary for protecting the lives and livelihoods of people in Canada

The data obtained through the backbone observation network provide the basis for a range of subsequent analyses and products related to climate, which are primarily being carried out by entities outside the

MSC. Observational data collected consistently over long time scales and across Canada's vast geography are needed to monitor critical regime shifts, such as an increase in atmospheric rivers in specific areas. This is particularly true in the Arctic, where air temperatures are increasing at rates faster than all other regions of Canada and where there have been recognized gaps in observational capacity (Hansen *et al.*, 2010; Jung *et al.*, 2016; Joe *et al.*, 2020; Melo *et al.*, 2023). While continuity in data banks may be less important for short-term weather monitoring, it is critical for Canada's climate needs and services, including supporting the adaptation efforts of a wide range of departments across all orders of government. Although climate change is largely outside the mandate of the MSC, it is important that the climate monitoring implications of any changes to the observational network be considered.

Ongoing research and skills development are needed to maintain the quality of backbone infrastructure

The evolving technological landscape illustrates the importance of a culture of continuous learning within the public meteorological service, as well as collaboration with the broader weather ecosystem. Similarly, ensuring ongoing R&D, whether conducted internally or by close collaborators, is critical for harnessing opportunities and maintaining backbone modelling and forecasting infrastructure. For example, workshop participants identified the need for research on the coupling of numerical prediction systems with socioeconomic applications.

2.2 Protecting people

The MSC has a responsibility to issue warnings to ensure the safety of life and the protection of property from weather-related harms

Climate change, combined with factors such as urbanization and a growing population, is increasing the need for accurate and timely warnings in cases of extreme weather-related risks. It is well established that climate change is leading to increases in climate variability and dangerous events, including extreme heat, drought, wildfires, and flooding (IPCC, 2023). Not only are these events occurring more frequently, but they are also becoming more severe. While there are a range of individuals and organizations in the private sector and academia engaged in weather forecasting, the issuing of warnings to ensure the safety of life and protection of property is a responsibility that lies solely with the national hydro-meteorological service (in Canada, the MSC) (WMO, 1999, 2015; Freebairn & Zillman, 2002b).

Extreme weather events are having devastating impacts across the country

Extreme weather is leading to loss of life, with over 40 people[5] dying due to the 10 most extreme weather events in Canada in 2024 (ECCC, 2025b). In British Columbia, 36 deaths were attributed to extreme cold, while flooding led to fatalities in Nova Scotia, British Columbia, and Quebec (ECCC, 2025b). Populations that are at a greater risk of harm from extreme weather include those who are marginalized or disadvantaged in other ways. These populations include: older adults (over 65 years), children, Indigenous people, racialized populations, people with disabilities or pre-existing medical conditions, people who live in northern and/or remote communities, and people who are economically

[5] This number refers to attributed deaths only and is therefore likely an underestimate of total deaths.

disadvantaged (Clark *et al.*, 2021; HC, 2022). For example, extreme heat is known to increase cardiovascular and respiratory mortality, particularly for people over 65 and in urban settings with higher proportions of renters (Quick, 2024).[6] The deadly impact of heat was demonstrated by the more than 600 heat-related deaths reported in British Columbia during the western heat dome of 2021 (GC, 2022). Clear, actionable warnings that reach all affected people, regardless of jurisdiction, are therefore needed to protect the health and security of people in Canada. Beyond supporting individuals, they also enable community-level preparation for these events, for example, establishing cooling centres for upcoming heatwaves or ensuring all snowplows will be working during winter storms.

Extreme weather events are also costly. According to Catastrophe Indices and Quantification Inc. (CatIQ), 2024 was the costliest year on record for weather-related insurance losses, totalling $8.5 billion (IBC, 2025). The high volume of losses was the result of high-cost events across the country throughout the year, including a deep freeze in western Canada, flooding in Ontario, hailstorms in the Prairies, the Jasper wildfire, and the remnants of Hurricane Debby in Quebec (IBC, 2025). Importantly, it is climate adaptation that will have the greatest impact in terms of reducing the cost of extreme events, but clear and actionable communication such as warnings or alerts, can support individuals in making decisions to minimize impacts (e.g., parking indoors in advance of hail) and allow business and governments to make proactive decisions to avoid problems (e.g., on-street parking bans in advance of large snowfalls, modifying schedules or transportation routes).

The MSC has an opportunity to educate people in Canada about climate change and the need for adaptation

In addition to warnings and alerts for acute events, climate adaptation is needed to increase the resilience of communities and infrastructure to extreme weather. Climate adaptation is included within the mandates of several departments, including the MSC's parent department, ECCC. Despite climate change being outside the mandate of the MSC itself, as Canada's authoritative provider of weather information, the service is well-positioned to inform people on climate attribution and the need to adapt to a new climate reality, decrease vulnerability, and increase resilience (Section 4.3).

Communication channels are changing, but building trust remains critical

While weather-related risks and the need for clear advice are increasing, the way people obtain information is undergoing a major shift. The reach and impact of social media are growing as fewer and fewer people get their weather forecasts from traditional media sources and a larger proportion of people report not using forecasts at all, as compared to the mid-2000s (Lazo, 2024a, 2024b). This may be particularly true for younger adults, who have grown up in the internet age and who primarily get weather information from weather apps on their smartphones (Phan *et al.*, 2018). Additionally, in the past, many people would obtain their forecasts and warnings from a trusted media weather forecaster, who built long-term relationships with their audience. This type of relationship is far less common in the digital age and coincides with a proliferation of misinformation made possible through social media. The volume of information available, which includes false or misleading claims, underscores the continued need for a trusted source of meteorological information (Section 4.1). It is therefore essential that the

[6] Quick (2024) suggests this may be due to rental homes being less likely to have air conditioning.

public meteorological service foster relationships and maintain trust with the public, particularly those at greater risk from weather-related events.

2.3 Leadership

The importance of MSC leading through coordination and collaboration in the Canadian weather enterprise is growing

Workshop participants emphasized the importance of the public hydro-meteorological service providing leadership and coordination in the broader ecosystem. The critical nature of soft leadership is growing in an era where the number of players in, and the complexity of, this ecosystem are increasing. This includes the complexity created by the siloing of different elements of public hydro-meteorological services, such as R&D and climate (or flood forecasting), from the primary meteorological service (i.e., the MSC). Beyond other public sector entities and departments, the importance of the private sector, NGOs, and academia in the weather enterprise is growing. This diversity of players can be seen as a strength. In an era of federal funding limitations and a push to reduce operating budgets (GC, 2025b), there are limits on the ability of a public hydro-meteorological agency to single-handedly carry out all necessary functions related to hydro-meteorology. Workshop participants noted that there are some functions that may best be provided by collaboration with the private sector, NGOs, or academia. For example, universities can support the weather enterprise by creating targeted products, conducting cutting-edge research across a range of disciplines, and providing staff training through continuing education programs, in addition to training the next generation of workers.

Facilitating effective collaboration among the growing range of players in Canada is an essential function of the MSC

The private sector has long had a role in weather forecasting and the delivery of targeted products to individuals and organizations in Canada. With technological advances and a growing demand for accurate forecasts to support revenue generation, there has been substantial growth in the number of private companies providing targeted weather forecasts on a range of timescales (Brunet *et al.*, 2023). In some cases, it is the private sector that is driving advancements. For example, private companies, empowered by AI (and largely dependent on government-led observation and data assimilation activities), have accelerated progress in the area of numerical predictions (Bauer, 2024). With a range of players involved in running forecast models and/or designing and deploying observational platforms, there is a heightened need for coordination to ensure benefits are maximized for Canada.

A strong public hydro-meteorological service ensures Canada's sovereignty in terms of meteorological capabilities and understanding climate impacts

It is vital that Canada maintain its domestic capacity to carry out essential hydro-meteorological functions, particularly in light of geopolitical instability and the fact that our borders include several transboundary waters, including the Great Lakes. Supporting sovereignty is also critically relevant in the context of the North, given the increased economic and jurisdictional competition in the Arctic from foreign entities and the disproportionate impact of climate change in northern regions, including substantial warming and resulting permafrost thaw and sea ice melt (Freebairn & Zillman, 2002a; Hansen

et al., 2010; IPCC, 2023; Austen, 2024; ECCC, 2025c). There is an opportunity to build on existing strengths— in the panel's experience, Canada is seen as a world leader in terms of understanding Arctic weather and climate. Despite this leadership, known gaps in observational capacity in the North create substantial challenges for weather and climate modelling (Section 2.1). Addressing these gaps is one of many potential benefits of advancing meaningful collaboration with and support for northern Indigenous Peoples, as well as the application of evidence from Indigenous knowledge systems. Beyond creating a more comprehensive understanding of the weather and climate in these regions, meaningful collaboration is needed to ensure the MSC carries out their work in a good way and meets the needs of the people who live in the northern regions of Canada.

Canada benefits from engaging in data exchange, diplomacy, and advocacy with the global community

While ensuring sovereignty over hydro-meteorological functions is essential, so too is engagement with the global community, including membership and participation in the World Meteorological Organization (WMO). Active collaboration with, and leadership among, international and foreign meteorological organizations supports a robust and cutting-edge service that is more effective for people in Canada while also benefiting the global weather community. Canada benefits substantially from having access to the data and modelling of other national hydro-meteorological services and has a responsibility to share data with others in an equitable manner. As such, Canada has several commitments to engage with the international meteorological community, and it is the role of the public meteorological service to fulfill these obligations. For example, international users of MSC data include the WMO and the United Nations Group on Earth Observations, while the Canadian Centre for Climate Modelling and Analysis is one of four decadal climate prediction-producing centres (ECCC, 2023a). Canada also has memoranda of understanding with the United States, China, France, and the United Kingdom; agreements with Australia, Finland, and Germany; and a co-operation agreement with the EU Copernicus Programme (ECCC, 2023a).

3 Essential Functions and Technology

The advances expected in weather forecasting and climate prediction during this decade will support [ambitious sustainable development goals] by enabling a next generation of weather and climate services that help people, businesses, and governments to better mitigate risks, reduce losses, and materialize opportunities from the new intelligence of highly accurate and reliable forecasts.

(Brunet *et al.*, 2023)

Chapter findings

- Technology is rapidly evolving, and the MSC must keep pace. Many core functions will be impacted by AI and new digital technologies, particularly in data collection, remote sensing, weather modelling and forecasting, and monitoring of conditions across the country.
- Some digital technologies, such as remote sensing, miniaturization of sensors, and Internet of Things (IoT) networking, bring incremental yet impactful developments to the MSC's existing activities. AI appears to be leading to paradigm shifts in the way numerical weather predictions are made.
- New digital technologies are leading to an increase in private sector involvement in the market. These companies have the potential to supplement or support the public hydro-meteorological service, for example, by providing specialized products for niche markets.
- The adoption of new digital technologies will likely lead to a proliferation of data and necessitate the updating of key infrastructure, including high-power computing. It will also demand staff training and skills development, as well as the recruitment of highly sought-after expertise.

Advances in technology over the last 150 years have significantly changed the way weather observation, forecasting, and communication have evolved (ECCC, 2021). In the 1920s, weather forecasting in Canada was revolutionized by wireless radio, enabling rapid communication of weather information to remote areas and ships. This technology evolved to the point that, by the 1930s, a small team in Toronto was able to issue forecasts for nearly all regions of Canada twice daily, based on data from more than 200 stations. Radio broadcasts began including daily forecasts in 1935, making weather a staple of news programs (ECCC, 2021). This evolution continues today, with a variety of innovations, such as remote sensing and AI, revolutionizing the way weather services perform their duties.

3.1 AI and the NWEP production chain

In their Artificial Intelligence Integration Roadmap for Numerical Weather and Environmental Predictions, ECCC presents a value chain that stretches from environmental observations to expert products, such as customer-focused weather forecasts and other products that mobilize and communicate weather-based information to the public (ECCC, 2024c) (Figure 3.1). While that roadmap identifies challenges and opportunities related to the adoption and application of AI specifically, there is a wide range of additional technology-based innovations that show promise for advancements across the value chain. Many of these innovations relate to numerical weather and environmental predictions (NWEPs), and a variety of foundational, backbone competencies along this value chain will be affected by technological innovation.

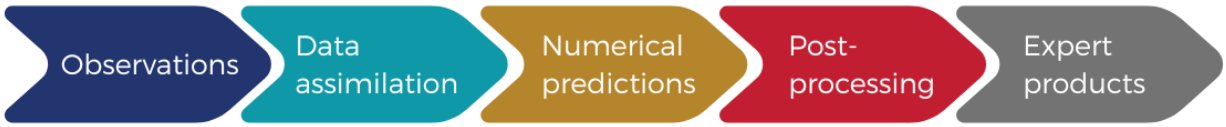

Figure 3.1 ECCC's numerical weather and environmental prediction production chain

Technological innovations promise to affect nearly all stages of the NWEP value chain, from observations to expert products.

NWEPs start from observations of Earth through a wide range of weather and climate monitoring activities using a variety of land-, sea-, and space-based sensors. These observations are merged with previous forecasts during the data assimilation phase to determine current atmospheric and environmental states, laying the groundwork for reliable forecasts via numerical predictions. The post-processing phase is important for adjusting the output of the numerical modelling to account for biases and to generate additional outputs such as the likelihood of acute weather elements (e.g., lightning, hail, tornado, blowing snow, fog). These outputs are used to develop expert products, such as vigilance maps (i.e., geographical maps that denote areas of increased risk of high-impact weather events) (ECCC, 2024c).

Emerging technologies appear poised to affect all MSC activities across the full production chain

AI is the key technology that will most impact hydro-meteorological services moving forward. AI is revolutionizing meteorological workflows, from data assimilation to physics-informed modelling, post-processing, and expert products, enabling faster forecasts, super-resolution modelling, and explainable predictions. Foundation models[7] and AI-driven impact communication are reshaping how forecasts are

[7] Foundation models can refer to AI weather models like Aurora (Bodnar *et al.*, 2025), or large language models like Gemini 2.5 Pro. The panel notes that AI weather models are more likely to be implemented for weather forecasting while large language models appear more appropriate for communication and expert products.

generated and shared (Bodnar *et al.*, 2025). Other notable technological advances are those in remote sensing, miniaturization of sensors, and IoT[8]-enabled sensors and observation systems:

- **Remote sensing**: New technologies in remote sensing have increased both the temporal and spatial resolution of satellite-based imaging, as well as the processing and interpretation of imaging data (Mitra, 2023; Richardson *et al.*, 2025). New hardware and imaging techniques are pushing the limits of resolution in both time and space, allowing for more accurate and fine-grained forecasting, while machine learning systems are showing promise in filling gaps in data due to technical and environmental complications (e.g., imaging scan lines, cloud cover, inaccessibility by ground). While satellite-based remote sensing has typically been used for observing atmospheric phenomena, advances in technology have broadened the accuracy of ground-based data that can be obtained, such as water surface temperature and ground and crop coverage (Mariani *et al.*, 2022; Mitra, 2023; Richardson *et al.*, 2025).
- **IoT**: Various AI systems have been explored to give these networks of devices the ability to adapt to changing environmental conditions and to combine and error-correct data from multiple sensors. Since IoT technologies create links between observation systems, they may be applied across the range of sensors and devices that the MSC uses to measure a variety of atmospheric and hydrological variables.
- **Miniaturization**: Miniaturization of satellite-based devices has also begun to revolutionize weather forecasting (Stephens *et al.*, 2021). Traditional space-based observation tools are costly and large, requiring major investments to build and launch. Over the last several years, the size of these payloads has been decreasing, allowing for the launching of more and different sensors into orbit (Stephens *et al.*, 2021). This has the potential to provide affordable, interconnected, global coverage of most measurements required to make weather and climate projections.

Notably, the combination of remote sensing, IoT, and miniaturization technologies with AI is likely to yield the most significant benefits.

Technological advancements will substantially increase the volume of data available and enable more localized forecasts

Technologies related to remote sensing, miniaturization, and IoT have the potential to enhance the spatial and temporal resolution of observations. Workshop participants noted that advancements will generate copious amounts of data and will rely on cloud computing and optimized data storage strategies. IoT-enabled sensors and real-time data streams enable continuous model updates and, potentially, autonomous sensing devices, such as drones and networked sensors, that can adapt to changing conditions. This supports applications like flood forecasting and personalized services, with AI optimizing data integration from diverse sources.

[8] The IoT refers to networks of physical objects embedded with sensors, actuators, and communications capabilities (e.g., WiFi, Bluetooth, LoRaWAN, 5G) (Albuali *et al.*, 2023). These networks allow for real-time, high-resolution, localized data collection and, in some cases, on-the-ground calculations and data analysis that can supplement data from traditional weather stations (Albuali *et al.*, 2023; Selvam & Al-Humairi, 2023).

Workshop participants noted that hyper-resolution forecasts and increased computing power appear to be leading toward household-scale predictions, which could become something offered by the private sector. Improved temporal and spatial resolution, along with data-driven models, refine accuracy. Alternative forms of weather forecasting that move away from physics-based modelling are also being explored using AI. For example, hydro-meteorological systems now emphasize socioeconomic impacts, integrating environmental, economic, and social factors. Real-time impact data and digital twinning (i.e., highly detailed, lifelike simulations of weather evolution and impacts) enable dynamic risk assessments with the potential to improve early warnings (Bauer *et al.*, 2021; ECMWF, n.d.). The trend toward decentralization—including cloud computing, international collaboration, and public-private partnerships—can democratize access to forecasting tools and increase the volume of data from which forecasts can be derived. However, this also implies the need for additional caution regarding data privacy and security.

Canada depends on international data flow to ensure the quality of Canadian forecasts

No single source of observational data is used in isolation; multiple observation sources are required to ensure the accuracy of forecasts and models. For example, remote sensing techniques (e.g., satellite-based imaging) have been used for decades to inform weather and climate models by expanding and complementing the range of what is measurable by ground-based systems (NRCan, 2025a; NOAA, n.d.). Remote sensing results are routinely used as inputs to physics-based models, which enable forecasting and future modelling. Satellites can be geosynchronous (remaining stationary relative to the east-west rotation of the Earth) or polar-orbiting (north-south orbiting), with each type providing different measurements (NOAA, n.d.). Canada relies heavily on the remote sensing data obtained by the U.S. National Oceanic and Atmospheric Administration's (NOAA) GOES satellites (geosynchronous, observing North and South America as well as the Pacific and Atlantic Oceans), Advanced TIROS satellites (near-polar orbit, global coverage), Defense Meteorological Satellite Program (DMSP, for large-scale, near-polar coverage), and oceanic coverage (IOOS News/Ocean Enterprise, 2024; NRCan, 2025a). Amid the recent funding cuts to NOAA and restrictions on their scientists' international collaborations, Canada's access to rich remote sensing data may be in jeopardy. Disruptions to the flow of data between the United States and Canada, and restrictions on the sharing of satellite data in particular, could be detrimental to Canada's ability to generate accurate and precise weather and climate analysis. However, advances in remote sensing, AI, and miniaturization could all reduce Canada's dependence on U.S. satellites, as could engaging with other international collaborators (Section 3.2).

3.1.1 Observations, data assimilation, and numerical predictions

Technological advancements have the potential to improve data quality and fill measurement gaps

Data collection helps create a more accurate representation of the atmospheric and/or environmental state, enabling reliable weather forecasts. The importance of high-quality observations cannot be overstated. AI is unlikely to alleviate the dependence on data collection; however, it could potentially improve observation quality control, error estimation, and the estimation of various parameters not immediately measurable, such as local conditions in hard-to-access areas (ECCC, 2024c; Camps-Valls *et al.*, 2025). Observation data is vital to the MSC—innovations in remote sensing, IoT, and the miniaturization of sensors are making it possible to collect more detailed, high-resolution data than was previously possible. However, these advancements will increase the need to carefully manage data collection and usage.

With greater observational power comes the ability to collect more and different types of data. Local data, especially from underserved communities and the North, is becoming more accessible to observation. The expansion of core observations could meet the diverse needs of people in Canada, including through metrics that describe air quality, water (including oceanic features, rainfall, and data related to flooding), land surface (e.g., crop cover, heat islands), and changes in northern ice coverage. This is particularly relevant in the context of climate change, as collecting and managing comprehensive data over a wide range of variables and timescales allows for greater understanding of the phenomenon. AI has been identified as a technology that could help fill gaps where direct observation is not possible (Lewis *et al.*, 2024). Likewise, networked observation devices (i.e., IoT) can be developed to increase the spatial and temporal resolution of observations across a range of variables, as well as perform real-time adjustment and analysis of data to adapt to changing conditions (Selvam & Al-Humairi, 2023 & Camps-Valls *et al.*, 2025). Workshop participants also noted the potential for incorporating Indigenous-led approaches to observation and ways of knowing. Considerations regarding ethical, non-extractive, and equitable access to this knowledge, as well as privacy and security, will be important to ensure that such work is conducted in a responsible manner.

Data sovereignty, interoperability, and access will influence collaboration opportunities

Another aspect of the MSC's observational requirements includes the quality, control (including sovereignty), storage, and sharing of data in accordance with the WMO's Unified Data Policy (WMO, 2025a). Data quality is of the utmost importance. However, this is not only a matter of more accurate, precise, and comprehensive observations; workshop participants emphasized the importance of well-structured, shareable, and interoperable data that are accessible to public, private, and foreign partners and collaborators. High-quality data collected and owned by the MSC was identified as both a strategic and financial asset that could be leveraged to further develop partnerships, especially abroad. In particular, participants noted that reduced funding for NOAA and its uncertain position as an active data-sharing partner further emphasize the need to support Canada's data sovereignty and points to the potential for greater collaboration with service providers in Europe. Relatedly, data storage concerns, including challenges related to the massive amount of data collected, as well as the ability for

observational data to be utilized by other service providers' models, were noted as high-priority considerations. Cloud computing was identified as a technology that would impact data storage needs; coupled with data sharing, workshop participants emphasized the need for well-planned data privacy and security policies to both protect communities and maintain Canada's data sovereignty.

AI has the potential to revolutionize data assimilation and numerical prediction

NWEPs have traditionally relied on physics-based models, using observational data and initial conditions obtained from the data assimilation stage. These models have long provided reliable forecasts; however, AI is beginning to change this approach by generating forecasts directly from data by leveraging machine learning algorithms, neural networks, and big data analytics to enhance predictive capabilities (Gruber & Prein, 2025). AI models use only a small subset of mathematical computations, enabling efficient, massively parallel processing on modern GPUs.[9] This speed advantage is beneficial, allowing for more scenarios to be explored quickly, leading to better confidence limits and more reliable decision-making, especially in severe weather events. ECCC, including the MSC, and other major forecasting centres are exploring and evaluating AI-based models such as GraphCast (Google DeepMind), FourCastNet (NVIDIA), and Aardvark Weather (Pathak *et al.*, 2022; Mulligan, 2024; Soliman, 2024; Hua *et al.*, 2025). Models such as Pangu-Weather have shown that AI can outperform traditional models in medium-range forecasting, demonstrating the value of AI alternatives. Still, AI models currently fall short in critical areas such as ocean dynamics, wave modelling, atmospheric chemistry, and extreme weather prediction (Bodnar *et al.*, 2025).

New foundation models such as Aurora aim to address these limitations by forecasting a wide range of Earth system variables at various scales, while Aardvark attempts to replace the entire weather prediction pipeline (Allen *et al.*, 2025; Bodnar *et al.*, 2025). The panel notes that AI-enabled increases in accuracy and precision will depend on increasing accuracy and precision in traditional observations and will need to be benchmarked and evaluated against physics-based models.

Alongside these developments, interest from the private sector in AI-driven forecasting has grown (Bi *et al.*, 2023; Han *et al.*, 2024; Wong, 2024). Historically, the complexity and cost of traditional numerical modelling have limited private participation. With AI reducing both computation time and costs, more private actors are entering the space. However, workshop participants suggested that the private sector may have the most impact at the end of the forecasting chain—developing specialized, user-focused forecast products rather than core model development. It is also crucial to ensure privatization does not lead to inequitable access to forecasts and weather warnings (Wiedinmyer & Bowen, 2025).

AI will complement, but should not replace, physics-based models

Despite AI's promise—especially for increasing forecast accuracy and enabling super-resolution forecasting—the panel notes that it should not fully replace physics-based systems. AI models struggle with explainability and trust, as their decision-making processes are not transparent and often not easily understood (Gruber & Prein, 2025). Furthermore, AI models may fail in unprecedented scenarios, such as those caused by climate change, where past data may no longer be relevant. Therefore, future forecasting

[9] The Graphics Processing Unit (GPU) is a computer component that renders images and videos; it excels at running many smaller tasks simultaneously. The Central Processing Unit (CPU) handles the main functions of a computer (CDW Expert, 2025).

systems that integrate AI and traditional physics-based modelling will help ensure accurate, reliable, and more frequent predictions.

3.1.2 Post-processing and expert products

The final stages of ECCC's production chain include post-processing and the production of expert products. Post-processing involves a range of activities, including correcting systematic biases introduced in previous steps and downscaling regional or global forecasts. Similar to the gains achieved with AI in the numerical predictions stage, a variety of techniques are becoming available that leverage the ability of AI to perform iterative and probabilistic tasks quickly, enabling higher resolution and accuracy, faster outputs, and more refined statistical calibration of weather models.

AI has the potential to improve short-term weather forecasting and public risk communication

Nowcasting extrapolates from multiple sources of data, including the results of numerical predictions and real-time observations (e.g., radar data), to produce high-resolution and highly accurate short-term forecasts (Schmid *et al.*, 2019). The prediction of other weather elements, such as lightning, fog, and hail, is generally not a part of the numerical prediction stage (ECCC, 2024c). They are typically calculated using physics-based or semi-empirical models using rudimentary machine learning algorithms that depend on far less data. Similar to the observation and data assimilation stage, AI has the potential to enhance predictions with less robust datasets, or to help improve datasets by aiding in the detection of rare weather events using remote sensing. Workshop participants noted that the translation of these forecasts and predictions into vigilance maps and other public-facing products may also benefit from AI-based design and dissemination tools.

The private sector has an important role to play in delivering customer-facing products to consumers

While workshop participants do not believe that post-processing activities should be delegated exclusively to private companies, they did identify some benefits from the participation of the private sector. In particular, more powerful data processing using AI will allow for more customized and niche forecasting products, a market that the private sector could potentially fill (Thorpe, 2016; Wiedinmyer & Bowen, 2025). More tailored and targeted forecasting activities, such as those related to agriculture or infrastructure, will likely be more efficient for the private sector to produce. Further consideration of expert products related to communication is discussed in Chapter 4.

3.2 AI in foreign and international meteorological services

Meteorological services worldwide are beginning to incorporate AI into their forecasting and weather prediction services. The following sections present two examples of recent AI adoption initiatives in other jurisdictions.

3.2.1 European Centre for Medium-Range Weather Forecasts (ECMWF)

The ECMWF released its 2025–2034 Strategy in December 2024 (ECMWF, 2025a; Gruber & Prein, 2025). The strategy outlines the ECMWF's plans for advancing weather prediction, focusing heavily on collaboration, AI, and technological innovation. Close partnerships with national meteorological services and global organizations remain central, with emphasis on shared progress within the European Meteorological Infrastructure to improve public services and societal resilience (ECMWF, 2025a).

In 2025, the ECMWF launched its Artificial Intelligence Forecasting System (AIFS) (Lang *et al.*, 2024; ECMWF, 2025b). AIFS runs alongside the traditional physics-based Integrated Forecasting System (IFS) to enhance weather prediction. According to the ECMWF (2025b), AIFS can generate high-accuracy forecasting, outperforming traditional models by up to 20% in areas such as tropical cyclone tracking. It also offers faster predictions and a substantial reduction in energy use. ECMWF emphasizes that AIFS and IFS are complementary, aiming to provide diverse tools to support national weather services and industries.

Building on the ECMWF's AIFS, Anemoi was released as a collaborative, open-source framework for developing bespoke machine learning weather forecasting systems (ECMWF, 2024). It was launched in collaboration with the ECMWF and several national meteorological services across Europe. The purpose of Anemoi is to provide open-source tools to train and run data-driven weather models based on meteorological institutions' own data. It downscales from a global model to support regional systems (e.g., MET Norway's high-res Scandinavian model, Germany's AICON). Anemoi is open-source under a permissive license, allowing for contributions from meteorologists, machine learning experts, and students (ECMWF, 2024).

3.2.2 Aotearoa New Zealand (National Institute of Weather and Atmospheric Research, NIWA)

NIWA was formed in 1992 and is Aotearoa New Zealand's primary climate and weather research body. In July 2025, it merged with another New Zealand Crown Research Institute, GNS Science, to form Earth Services New Zealand (ESNZ, 2025). MetService, Aotearoa New Zealand's national weather authority and official source of forecasts and weather warnings, is expected to become part of ESNZ in 2025 (Collins, 2024; RNZ News, 2024), combining expertise in water, atmospheric, geological, and environmental sciences into a single organization.

NIWA does not appear to have an explicit and public roadmap for implementing AI technologies; however, AI has begun to permeate into their operations. In particular, NIWA has started exploring the use of AI in high-resolution climate projections, drought forecasting, floodplain mapping, and forecasting extreme weather events (Cleland, 2024; NIWA, n.d.-a,-b,-c).

NIWA is developing a physics-informed AI-driven method for climate projections (NIWA, n.d.-b). Existing climate models require considerable computing power; however, NIWA has identified that AI-based methods can leverage rapid calculations and low operational costs once a model is initially trained. This model is designed to enhance existing regional climate models and aid in predicting extreme weather events. The project includes engagement with iwi/hapū, regional councils, central government,

and industry leaders to meet the needs of all users (NIWA, n.d.-b). NIWA, in collaboration with the Ministry for Primary Industries, also launched a machine learning-driven tool for drought forecasting in 2023 (NIWA, n.d.-c). The tool is designed to assist farmers and growers in preparing for droughts, building on its existing rainfall prediction services. Notably, the platform on which this tool is built uses data generated daily by one of the U.S. NOAA models (NIWA, n.d.-c).

Flooding is Aotearoa New Zealand's most common and costly natural disaster—as such, NIWA has begun implementing machine learning into their flood map forecasting to enable more effective flood preparation and response (Cleland, 2024). Traditional flood forecasting combines weather forecasting, ocean models to predict sea levels, and hydrological simulations to predict river flow. It can take on the order of 24 hours to generate a flood forecast. A pre-trained machine learning model (pre-training, like other AI techniques, can be expensive and time-consuming) was shown to produce similar results in minutes, allowing for rapidly updated flood maps. NIWA is working to operationalize this project for real-world use (Cleland, 2024).

3.3 Enabling factors

Computing infrastructure will need to be updated to support innovation

Current high-performance computing infrastructure is designed for standard physics-based modelling and requires massive parallel CPU computing power. While this requirement will not change, the reliance on high-performance computing may be reduced with the adoption of AI. Conversely, AI requires expensive, up-front GPU-based computing to generate training datasets and train initial models but will likely result in significantly lower usage of regular computing power (ECCC, 2024c).

In 2022, ECCC updated their supercomputers with several AI-ready GPU nodes sufficient for: adapting existing models developed elsewhere (GraphCast or FourCastNet); applying GPU computing techniques to the existing prediction system; and training small, experimental machine learning models for research purposes and early testing (Lam *et al.*, 2023; ECCC, 2024c). However, the GPU nodes acquired are insufficient for the development and training of ECCC's own models, limiting its ability to engage in advanced R&D activities (ECCC, 2024c). One option for increasing GPU availability is to rely on shared cloud computing infrastructure to offload some of the initial development, benchmarking, and debugging of new systems, freeing up ECCC's existing computing resources. As discussed above, large databases of potentially new types of data will require well-designed data storage infrastructure that, depending on collaboration and data sharing, will also require consideration of privacy and data sharing standards. Workshop participants noted that cloud computing, while expensive, has the potential to benefit the MSC in terms of data accessibility to collaborators. Coupled with IoT and other remote technologies, meteorologists would likely be capable of running simulations and models in the field.

To enhance software infrastructure, ECCC has begun using containerized virtual systems that allow for the development of AI tools and techniques that can later be integrated into the main AI systems (ECCC, 2024c). Data infrastructure needs will require adapting ECCC's large volume of data into AI-ready formats with open access to enable external collaborations. One proposed model for data formatting and handling protocols is to follow the lead of the ECMWF Meteorological Archival and Retrieval System, which would ideally enable close international collaboration (ECCC, 2024c).

Technological advancements will change the skills and diversity needed in the workforce

While remote sensing, IoT, and miniaturization are largely iterations on existing technologies, requiring minimal reskilling, AI adoption was identified as a source of significant change. The market for highly qualified, AI-trained expertise is becoming increasingly competitive, particularly in the private sector; the recruitment and retention of this skilled workforce has been identified as a challenge (ECCC, 2024c). Training and mentorship programs are one way to increase the in-house AI expertise of current scientists and IT personnel. Strengthening partnerships with academia and the private sector can potentially lead to more opportunities for staff development and skills acquisition and is consistent with the workshop participants' view that a diverse workforce built on continual learning will be key to the MSC's success. Many critical activities, especially in data assimilation, numerical predictions, and post-processing, remain uninitiated or underdeveloped due to a lack of human resources (ECCC, 2024c). AI integration, hybrid modelling, and forecast calibration are particularly resource-intensive gaps, whereas some progress has been made in the development of data-driven models and open-source tools for atmospheric and oceanic studies.

A strategy or roadmap could clarify an implementation plan for technological advances

While ECCC has examined the integration of AI into their activities in general (ECCC, 2024c), workshop participants identified the need for a comprehensive roadmap for the MSC that would incorporate other sources of technological innovation, while also recognizing budgetary constraints and the potential for an evolving role of the MSC in Canada's hydro-meteorological services. Technological adoption and evolution of the MSC's core responsibilities will require deliberate planning and prioritization.

4 Meeting the Needs of People in Canada

It is important to remember that further development of public weather services should only be undertaken in response to actual and real needs and requirements expressed by the user community and not as an end in itself.

(WMO, 1999)

Chapter Findings

- Understanding user needs and requirements is key to maintaining and improving public hydro-meteorological services. Everyone in Canada is impacted by local weather and environmental conditions, and they need to be forewarned of potentially dangerous weather and flooding events.
- People and organizations will act on forecasts and warnings if they trust the source of those warnings. Trust is built through authentic and transparent relationships; it is important to include measurements of uncertainty in risk communication and provide the most accurate, up-to-date information.
- Public hydro-meteorological services are strengthened through partnership, critical evaluation, and co-production with user communities, academia, and other public and private sector actors. Leadership, communication, and coordination skills are as relevant to the beneficial delivery of hydro-meteorological services as are modelling and forecasting skills.

ECCC's production chain for weather and climate predictions begins with observations and ends with expert products, among which are alerts and warnings of high-impact weather. Golding (2022) presents a similar weather warnings value chain, which distinguishes between a *forecast*, which "produces information about the future state of the weather or some other aspect of the environment," and a *warning*, which "provides information about a threat so as to enable a response." This value chain encompasses the products and underlying data, information, and expertise required to produce a warning that enables a response by the end user. Workshop participants emphasized the importance of activity beyond the end of ECCC's production chain in meeting the current and future needs of people in Canada. That is, they stressed the importance of examining decision-making in response to warnings and ensuring that critical communications are clear, accurate, accessible, valuable, and used by the intended audiences (Figure 4.1).

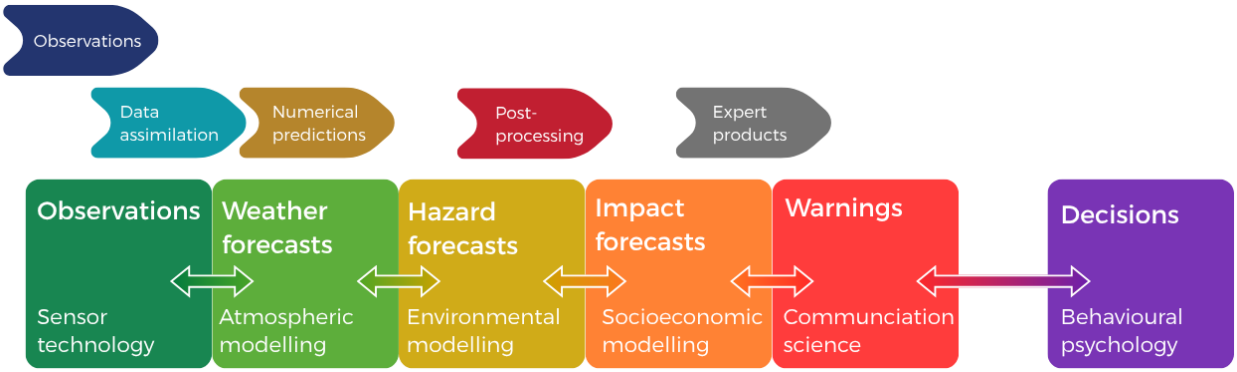

Figure 4.1 ECCC's NWEP production chain overlaid on the warnings value chain

ECCC's NWEP production chain flows from observations and data assimilation to the creation of expert products. The warnings value chain follows a similar path, bridging steps from observations through to warnings, but moves beyond the expert products to consider how warnings influence decision-making. The panel emphasized that critical user needs will be met by considering this part of the value chain, while recognizing that organizations outside of ECCC may take a leadership role. The first five elements of the warnings value chain (observations, weather forecasts, hazard forecasts, impact forecasts, and warnings) feed directly into each other. The gap between warnings and decisions illustrates the role of individuals in making decisions based on the information they are provided.

A key step in understanding the essential functions of Canada's public hydro-meteorological service is to gain a more comprehensive understanding of its users and their responses to existing products and services. Workshop participants identified the following as priority needs for current and future users of Canada's hydro-meteorological services:

- Ubiquitous coverage of current and forecasted environmental conditions, including temperature, wind, precipitation, air quality, UV radiation, water conditions, and ocean and land surface information, across the entirety of the country.
- Highly accurate, impact-based, actionable, and effectively communicated warnings with associated uncertainties (e.g., severe weather, flooding) that maximize lead time.
- A centralized and authoritative source for data, information, and education for people in Canada as well as for key sectors (e.g., energy, water, emergency management) and long-term planning (e.g., climate, recovery, resilience).

4.1 Current and forecasted environmental conditions

Workshop participants recognized that reliable, well-maintained equipment and high-quality forecasts are the mainstay of trustworthy and authoritative hydro-meteorological services. The backbone infrastructure and components of the production chain must be maintained and upgraded to provide the best available information.

Public hydro-meteorological services are needed to ensure coverage across Canada

Workshop participants emphasized the importance of maintaining baseline coverage for weather and hydrometric observations across the country. Multiple communication channels are also important—for example, through radio, television, and landline and cellular phone numbers—to ensure the broadest most accessible coverage. This baseline of weather and water information, including warnings, needs to be accessible and consistent throughout the country to ensure there are no gaps.

Workshop participants also noted that people in Canada expect their hydro-meteorological services to provide a wide variety of current and forecasted environmental conditions. Visitors to the Government of Canada weather website will find information on present weather, temperature, pressure, dew point, and humidity, as well as a seven-day forecast and links to satellite, lightning, and radar maps, an hourly forecast, alerts, air quality information, and historical data, among other information (GC, 2025c). In addition to such detailed weather observations, visitors to the Weather Network website, for example, can find information on bugs and pollen, among other specialized products (Pelmorex Corp, 2025). There is substantial value added by public-private partnerships, as well as by the private sector more broadly, in delivering specialized and targeted products, and workshop participants emphasized the essential function of the MSC in maintaining a baseline standard of quality and coverage country-wide.

Forecasts and warnings are only valuable if they influence decision-making

As Gruntfest (2018) points out, the biggest challenge to reducing losses from severe weather is not improved forecasting, but "predicting human behavior in response to these weather events or forecasts." Social and behavioural factors influence whether a potential hazard, such as an extreme weather event, becomes an actual disaster (NASEM, 2018). Shrader *et al.* (2023) assert that forecasts can save lives only if people take action based on those forecasts. It can be challenging to measure the value of accurate and timely forecasts, as it requires data on avoided impacts (i.e., things that did not happen) (Göber *et al.*, 2023). That said, researchers have found that people do respond to forecasts by changing their behaviours. For example, Shrader *et al.* (2023) find that people change their electricity use and time use[10] in response to forecasts, and in a survey of college students, respondents reported modifying their behaviour in reaction to forecasts. Moreover, forecasted extreme heatwaves have been shown to be less deadly than unexpected ones, suggesting that people adjust their behaviour in response to heatwave forewarnings (Shrader *et al.*, 2023). Weather warnings also elicit behavioural changes, such as purchasing supplies, securing outdoor furniture, and charging electronics, in response to a significant coastal storm warning (Silver *et al.*, 2025).

A diversified and deliberate media strategy is valuable in maintaining public trust

It is the media who are the face of meteorology—public understanding of context, risk, and uncertainty will be enhanced by close consultation between the MSC, as the source of warnings and forecasts, and the media, including social media creators, who share and contextualize them. People who say they trust their source of weather forecasts and warnings are also more likely to state that they will take protective actions in response to those warnings (Morss *et al.*, 2016).

[10] The U.S. Bureau of Labor Statistics (n.d.) defines *time use* as "the amount of time people spend doing various activities, such as paid work, childcare, volunteering, and socializing."

Trust in government and the media has, in general, been found to be in decline over the past decade in Canada (CCA, 2023). However, Silver *et al.* (2022) found that 76% of survey respondents in Atlantic Canada felt that information on Hurricane Dorian shared by government sources on Twitter was more trustworthy than information shared by non-government sources. Trust is established through transparency and authenticity, and perceived benevolence is more important than a communicator's personal credibility or competence (Lemyre *et al.*, 2017). The survey respondents from Atlantic Canada were "overwhelmingly satisfied" with the "consistently inconsistent" information they received on Hurricane Dorian; that is, they appreciated having more frequent information updates that improved accuracy, even if those updates were not consistent with previous forecasts, understanding the storm to be both dangerous and uncertain in terms of location (Silver *et al.*, 2022).

By providing ongoing public education with weather and climate information delivered through the media, the MSC can help ensure that credibility and understanding are present when warnings are issued. The panel emphasizes that enhancing and maintaining public trust will be even more critical in the context of a diffuse media ecosystem and a changing climate with increasingly severe and never-before-experienced weather events.

Information sharing and co-production with users help ensure their needs are met

Technological advancements, such as hyper-local forecasting and nowcasting, and integration with other services such as snow removal, traffic information, and sport and entertainment event management, could increase the variety of specialized services available and expected by users. As options for specialized weather and water forecasting services proliferate, connecting directly with users will be important to ensure that basic observational needs are met. While it might be more appropriate for these specialized services to be provided by the private sector, MSC would be best suited to improve relationships and deliver specialized services to specific weather-sensitive communities. For example, Pennesi *et al.* (2012) found that experienced Inuit hunters were considered a more reliable source of weather-related information than the MSC for many people living in Iqaluit. This experience holds for other northern communities. Voosen (2023) recounts:

> *Brent Nakashook, an Inuk who lives in Cambridge Bay in the Canadian Arctic, doesn't particularly trust the local weather reports. Several times, he has called off weekend trips to fish for char or hunt musk ox after seeing storms predicted—only to find the Sun shining. "You've just shot your whole weekend based on the forecast," he says.*

Pennesi *et al.* (2012) call for increased interaction and co-production between local communities in Nunavut and the MSC to enhance the value of the weather information. A 2022 online workshop hosted by a multidisciplinary research team brought together "community members, northern/Inuit organizations, researchers, and service providers living and working across Inuit Nunangat" to discuss how environmental services, including hydro-meteorological services, could better address the needs of Inuit communities (Carter & Ljubicic, 2022). As Gruntfest (2018) notes, this kind of work requires a diversification in the type of person employed by hydro-meteorological services, from those who are passionate about advancing the next technological innovation to those who are passionate about doing work that meets expressed user needs.

4.2 Impact-based, actionable warnings

In addition to a baseline of environmental observations and forecasts, people and organizations in Canada must be apprised of anticipated severe weather, flooding, and other potentially catastrophic events—such as avalanches, wildfires, and tsunamis—in order to save lives and property. However, the communication of predicted events is complicated by several factors noted by workshop participants, including the challenge of communicating uncertainty, the proliferation of communication channels, and the complexity of jurisdictional authorities.

Clear and precise messaging about uncertainty aids decision-making

All forecasts and predictions about severe weather and hydrological events come with some uncertainty in their magnitude, timing, and location of impact. Effectively communicating this uncertainty to users is valuable for ensuring that appropriate actions are taken to mitigate risk and to build and maintain confidence in hydro-meteorological service agencies. There is a tendency among experts to assume that the public is incapable of processing probabilistic information. Ripberger *et al.* (2022) review the literature on communicating probability information in weather forecasts and find that people "make better decisions, have more trust in information, and/or display more understanding of forecast information when forecasters use probability information in place of deterministic statements."

There are some recommendations from the literature to ensure that probabilistic information conveys the appropriate message. For example, it is helpful to provide information on the forecasted event itself (i.e., the characteristics of a weather event such as a tornado or hurricane), in addition to the probability of its occurrence (Ripberger *et al.*, 2022). Presenting information in a variety of ways, including orally, numerically and visually, maximizes the proportion of the population that will understand the information (Ripberger *et al.*, 2022). Additionally, workshop participants noted the terminology used by the MSC (Box 4.1) related to alerts lacks clarity and is not widely understood.

Warnings need to reach the people who will be impacted in order to be effective

Over the past two decades, there has been a rapid expansion of the information environment. Communication and entertainment channels have diversified and fragmented with the advent of smartphones, social media, private messaging apps, and streaming services, among other technologies. While 86% of households in Canada have at least one smartphone (Blair, 2025), this means that any emergency alert broadcast exclusively over mobile networks could potentially miss 14% of homes, emphasizing the importance of maintaining alternative communication channels, such as radio and television.

For example, in 2022, a derecho swept across Ontario and Quebec with wind gusts of up to 147 km/h, ultimately claiming the lives of 16 people and resulting in more than $1.2 billion in insured losses (NTP, 2024). Some individuals reported receiving no warning about the storm, as a resident quoted in Bernstien (2022a) described:

> *The sky went dark, then it went green. And then there was a loud roaring sound, and then there was actually a white wall of rain coming at us. I can't believe that with today's technology, [there was] absolutely no alert on my phone, my wife's phone, [or] our daughter's phone.*

Technological advancements could help with maximizing lead time for warnings while minimizing false alarms that can lead the public to ignore future warnings (Gruntfest, 2018).

Box 4.1 The MSC's weather and meteorology glossary

Alert: "A transmitted signal used to heighten awareness and/or initiate preparation for action. Alerts are issued by [MSC] for weather or environmental hazard events that are either occurring, imminent, or forecast to develop. Alerts are currently issued as special weather statements, advisories, watches, and warnings."

> **Advisory**: "A type of alert from [MSC] where a certain weather or environmental hazard (e.g., air quality, tsunami) is either occurring, imminent, or is expected to occur."
>
> **Special weather statement**: "A type of alert from [MSC] where: A warning or watch is not warranted because the expected conditions are less menacing than those of a warning or; a warning or watch is not yet practical to issue because of the high degree of uncertainty of occurrence, location and/or timing of the possible hazardous condition(s). A special weather statement can be used to describe any hazard (unlike an advisory). The statements do not have a formal "in effect" status, since there is no requirement to update or end them."
>
> **Watch**: "A type of alert issued by [MSC] where conditions are favourable for the development of weather or an environmental hazard that poses a significant threat to public safety and property, but the occurrence, location, and/or timing of the expected hazardous condition(s) is still too uncertain to issue a warning. It is intended to heighten public awareness of the potential impact of the event and serves as a lead-up to a warning."
>
> **Warning**: "A type of alert issued by [MSC] where a hazardous weather or environmental event that poses a significant threat to public safety and property is certain or imminent."

(ECCC, 2019)

Communication strategies can help maximize behavioural responses to warnings

Communication literature can help structure warning messages to maximize their effectiveness. For example, Ripberger *et al.* (2022) find that positive statements (e.g., there is a 10% chance of severe weather for this location) are more likely to prompt protective action than negative statements (e.g., there is a 90% chance that severe weather will not affect this location). Additionally, focusing on the benefits of protective actions appears to be more effective in risk communication than emphasizing the potential consequences of inaction (Ripberger *et al.*, 2022).

It is also essential to understand that a wide range of factors can prompt behavioural changes (or not) in the face of extreme weather or flood warnings, and recognizing these factors can help maximize the value of communications (Figure 4.2). Moreover, maximizing the value is not just about ensuring public understanding; it will also require working effectively with public safety, emergency management, local governments, the media, and other relevant actors. For example, local employers may play a larger role than any communication from weather services in the decision to travel under a weather warning (Gruntfest, 2018).

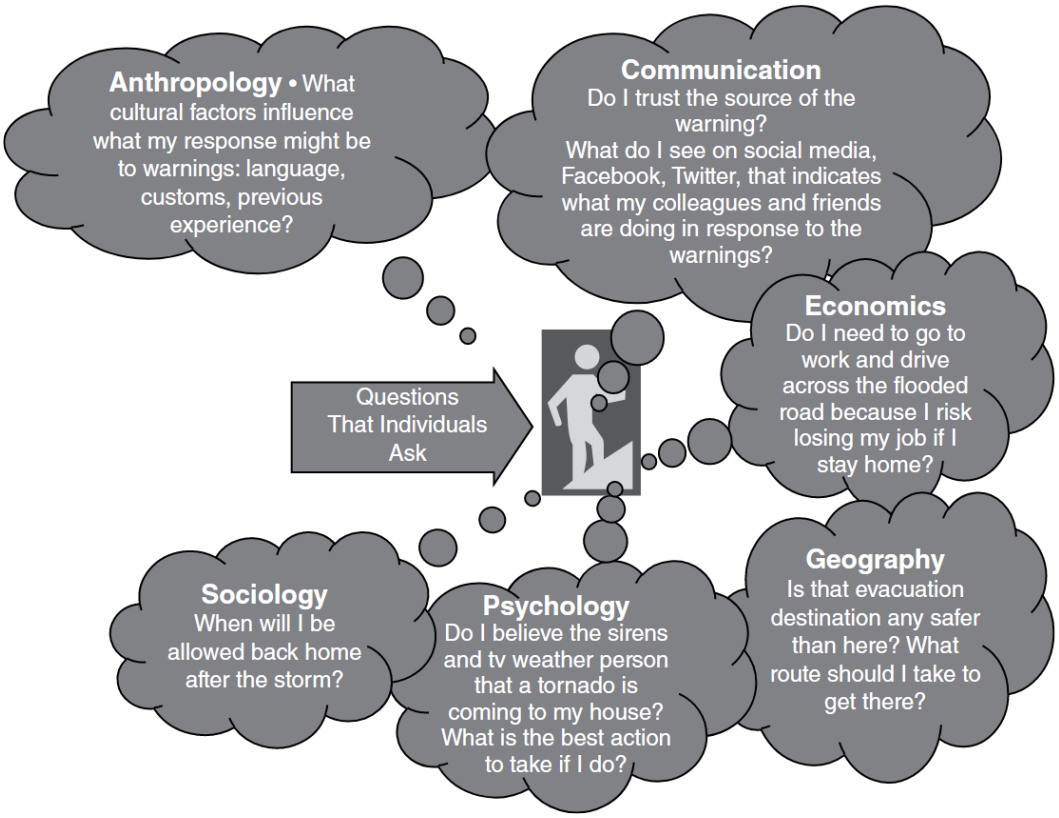

Figure 4.2 A diversity of social science questions are relevant to effective impact-based, actionable hydro-meteorological warnings

A wide range of social science questions is relevant to evaluations of the effectiveness of weather and water warnings. Answering these questions will require expertise from diverse fields, including sociology, psychology, geography, economics, communication, and anthropology.

4.3 Decision-making support

In addition to the challenge of a fragmented information environment, communication about weather and water events is complicated by the existence of multiple jurisdictional authorities and credible weather information providers. The responsibility for issuing warnings and providing information about other severe environmental events is distributed across various organizations and government agencies. For instance, avalanche information and the Mountain Weather Forecast are available through Avalanche

Canada (a non-government, not-for-profit organization) supported by products and services from the MSC (Avalanche Canada, 2024, 2025). NRCan produces the Canadian Wildland Fire Information System, though provinces and territories are responsible for local and emergency wildfire information (GC, 2025d; NRCan, n.d.). Tsunami messages for Canadian coastlines are issued, in collaboration with NRCan, by the National Tsunami Warning Center at NOAA (NRCan, 2021). Responsibility for emergency management is shared among federal, provincial, and territorial governments, as well as their partners, including Indigenous Peoples, municipalities, communities (PS, 2017).

There is a need for a coordinated flood forecast system that includes flash flood warnings

Flooding is the most frequent and costly natural disaster nationally, affecting both urban and remote communities year-round (PS, 2024). Causes include river overflows, heavy rain, snowmelt, ice jams, dam failures, and coastal storms. Parts of major cities, such as Toronto, the Greater Montréal region, Calgary, and Vancouver, are located in high-risk flood zones. Coastal communities are especially vulnerable to storm surges, which can damage infrastructure and disrupt supply chains. Annual costs of flooding events are projected to rise significantly due to climate change (PS, 2024).

The MSC is responsible for weather forecasts, rainfall warnings, and coastal flood monitoring (e.g., storm surges). However, most freshwater flood hazard warnings and related mitigation are under provincial jurisdiction (ECCC, 2025d; NRCan, 2025b). Some provinces, such as Ontario and Quebec, have their own flood forecasting programs, but others do not (NRCan, 2025b). At the same time, no province issues *flash* flood warnings, which are a specific classification of flood that results from short, heavy bursts of rainfall (CBC News, 2023). Moreover, flood mapping in Canada is a collaborative effort among federal, provincial/territorial, municipal, and Indigenous partners, and federal roles are further divided among NRCan, Public Safety Canada, ECCC, and Crown-Indigenous Relations and Northern Affairs Canada and Indigenous Services Canada (NRCan, 2025b). The WMO Flash Flood Guidance System is an example of a project designed to provide operational forecasters and disaster management agencies worldwide with the products needed to issue flood warnings from rainfall events using remote sensing technology and hydrological models (WMO, 2025b). It has been noted[11] the distributed nature of flood warning and response initiatives is a weakness in the Canadian weather forecasting system. Workshop participants identified a need for greater federal leadership in ensuring public safety from flooding through a collaborative approach.

The need for decision-making support will increase under a changing climate

Technological advancements will create demand for leadership in the responsible management of data and information. Workshop participants emphasized the value of a centralized and authoritative source for hydro-meteorological information; however, they also recognized that no single organization would be able to do the work alone. The MSC operates real-time monitoring that includes global data gathering, as well as modelling, data integration, and interpretation services (ECCC, 2023b). These operations form part of the backbone infrastructure that informs products and services for a wide variety of clients; however, as noted for environmental forecasts and warnings, multiple federal departments and agencies,

[11] By workshop participants, as well as others, for example, CMOS (2022).

as well as NGOs and private companies, are also part of the ecosystem. Historical and current weather and water data and information are a critical input to long-term planning and climate projection models (Voosen, 2023). The MSC therefore plays a significant role in facilitating climate projection and planning activities, as there is a need for consolidated, well-documented, and findable data repositories, as well as collaboration with public, private, and academic partners. The MSC could be well-positioned as a liaison among these diverse actors. However, facilitation, leadership, and coordination require a more diversified skill set than that typically captured under hydro-meteorological services.

Technological advancements will also create demand for leadership in the responsible management of data and information. Workshop participants noted a role for the MSC in educating the public about *event attribution*, a method to "quantify how human-influenced climate change affects the occurrence of a particular type (or class) of extreme event" (Zhang *et al.*, 2019). For example, event attribution provides an opportunity to link extreme weather events with climate change, thus contributing to informed personal and political decision-making that can impact vulnerability and climate resilience. Ensuring public understanding of hazardous events—such as the derecho that caused widespread damage across Ontario and Quebec in 2022—will become increasingly crucial for preparedness responses at both societal and individual levels (Bernstien, 2022b).

4.4 Ongoing evaluation of products and services

There are meteorological service standards related to accessibility, timeliness, and accuracy for the MSC enterprise (which also includes MSC partners: ECCC's Science and Technology Branch, ECCC's Corporate Services and Finance Branch, and Shared Services Canada) (ECCC, 2025e). The MSC also verifies its Numerical Weather Prediction model against WMO standards (GC, 2025e). Performance assessments by actors outside of government, such as academia, are also valuable for identifying areas for improvement (e.g., Sills, 2022).

There is little information available on customer satisfaction with the MSC

To be successful, any development of hydro-meteorological services should respond to the needs articulated by the users themselves (WMO, 1999). As Rogers *et al.* (2021) point out, "user engagement is critical in any modernization project. However, it is a skill set that is often missing from the [National Meteorological and Hydrological Services] engagement strategy." The MSC opened an online public consultation platform (*Let's Talk Weather*) in 2022; the platform is now closed, and information on the outcome of this consultation has not been published (GC, 2024).

Available data on user satisfaction for public meteorological services in Canada are relatively sparse and are reported alongside other indicators and metrics in ECCC's departmental results. The Environment and Climate Change Canada 2023–24 Departmental Results Report presents two indicators related to predicting weather and environmental conditions (ECCC, 2024d; GC, 2025a). The first is an index of the timeliness and accuracy of severe weather warnings (on a scale of 0–10), and the second is the percentage of program partners[12] rating their satisfaction with ECCC's hydrological services as at or greater than 80%. ECCC uses these two indicators collectively to evaluate whether "Canadians use authoritative

[12] Note that program partners here refer to organizations and not individual users.

weather and related information to make decisions about their health and safety" (ECCC, 2024d). A single indicator measures hydrological services—the percentage of real-time data points uploaded to an online resource within two hours, relative to expectations (GC, 2025a). Meteorological services are measured through an annual client satisfaction survey from MSC's three main paying clients—the Department of National Defence, NAV CANADA,[13] and the Canadian Coast Guard, by the number of active monthly users of the WeatherCAN app, and by the number of visits to the weather.gc.ca webpage (GC, 2025a).

None of these indicators measures satisfaction or user needs beyond key program partners, nor do they measure outcomes related to health and well-being. Regular and meaningful engagement with the breadth of the MSC's clientele is necessary to understand expectations and perceptions and ensure needs are being met. Panel members note that there are existing options for measuring customer satisfaction with national hydro-meteorological services that include the general public, such as the American Customer Satisfaction Index used by NOAA (U.S. Department of Commerce, n.d.) or the Net Promoter Score (Bunker, 2025).

Relationship-building and engagement are essential to understanding needs

Workshop participants noted their own biases and limitations in identifying the current and future needs of people in Canada. They remarked that, to meet those needs, Canada's public hydro-meteorological services need to consult with people in Canada. In addition to members of the public, the workshop also identified that consultation with three main types of customers would improve the delivery of products and services. These include industry and government organizations that rely on raw data and forecasts from the MSC (e.g., agriculture, energy, defence); public sector actors responsible for daily decision-making and warnings (e.g., emergency management, snow removal, or school closures); and organizations that need to understand long-term trends (e.g., insurance, infrastructure, planning). As with leadership and coordination, engagement and relationship-building will require different skill sets and resources than those typically found in hydro-meteorological services; the integration of social science expertise and methodologies will be key to ensuring such activities are productive and beneficial (Gruntfest, 2018).

[13] NAV CANADA is the private, non-profit organization that acts as Canada's air navigation service provider (NAV CANADA, n.d.).

5 Panel Reflections: The Need for Shared Leadership

Weather, water, and climate monitoring and forecasting are among the most consequential government services in Canada, supporting informed decision-making across sectors, communities, and industries. At the government level, these services support stronger infrastructure planning and emergency preparedness and inform policies on climate adaptation, among other critical functions. Furthermore, hydro-meteorological services play a foundational role in national defence, particularly related to the North and border security. Beyond saving lives and protecting property across Canada, these services have considerable economic benefits for the private sector, enabling higher payoff decision-making across a range of industries, including agriculture, forestry, transportation, and energy.

Now is a critical moment for hydro-meteorological services in Canada and globally. Climate change is leading to drastically altered weather, with the most substantial warming occurring in the North, a region of growing importance for Canadian sovereignty, where existing observational gaps hinder understanding and contribute to community needs not being met. But climate change is also leading to more extreme weather events across the country. More heatwaves, severe storms, wildfires, floods, and poor air quality days demand that the public hydro-meteorological service evolve to ensure effective and equitable services to everyone, regardless of jurisdiction. This is particularly true for those most likely to face inequities—including racialized people, Indigenous people, older adults in an aging society, people living in the North, and those who are economically disadvantaged—as they are at greatest risk of weather-related harm. In some cases, protecting people means filling shortfalls where they exist, for example by ensuring hydrology forecasts and flash flood alerts are provided in all regions–something that can be supported by efficient data-driven models. Across Canada, effective service demands the breaking down of silos across all elements of the public hydro-meteorological service, whether they be between different orders of government or among different groups within the federal government. This is the case for functions related to both weather and climate, as well as the R&D and technology that support these functions.

While people are at greater risk from extreme weather, hydro-meteorological services are in an era of AI revolution and digital transformation, with a growing reliance on data and information technology that offers considerable opportunities to improve the quality of forecasts and services (Brunet *et al.*, 2023). Advances in AI are creating opportunities across the value chain that have the potential to improve efficiency, forecast accuracy, and the quality of public services. The AI revolution and digital transformation are also leading to greater involvement by private companies, which are increasingly in competition with the public sector in providing targeted forecasts (Brunet *et al.*, 2023). This has the potential to increase the diversity of services and capabilities available to people across Canada. Academia and NGOs are also playing a greater role in technological advances, while contributing to the development of more meaningful and targeted weather and climate products that serve the needs of diverse users. Despite these developments, however, it is essential that certain functions remain the

responsibility of the public hydro-meteorological service, namely the provision of strong backbone infrastructure; an effective cross-country forecasting and warning system to protect against weather-related harms; and leadership within the domestic and global weather enterprise.

Coordination is critical in this period of change for public hydro-meteorological services, particularly considering federal resource constraints and the need to work more efficiently. At a government-wide level, this is an opportunity. A strong public hydro-meteorological service provides accurate and timely forecasts and monitoring, which enables more effective and efficient decision-making across departments while supporting profit in the private sector. At the operational level, budget limitations for hydro-meteorological services necessitate leadership through careful planning and effective collaboration with partners across the ecosystem and the international weather community. The World Bank (2019) found that the best way to ensure national meteorological and hydrological services meet the growing need for accurate forecasts and modelling is through cooperation among the public, private, and academic sectors; workshop participants agreed with this analysis. They also emphasized the importance and benefits of Canada's participation in the global weather community as a collaborator and both a provider and receiver of data and knowledge.

Effective cooperation across the weather enterprise requires leadership and clear direction to ensure the hydro-meteorological ecosystem meets the needs of all users in Canada. However, leadership also entails ongoing collaboration with other orders of government, the international weather community, and the private, NGO, and academic sectors, as well as active and ongoing consultation with people in Canada to better understand their needs and how they are changing over time. By demonstrating such leadership, the MSC can help ensure that Canada's hydro-meteorological ecosystem keeps pace with growing demands and becomes a model of inclusivity, strategic innovation, and resilience in the face of a changing climate. Panel members noted that the MSC is well positioned to support current Canadian government priorities related to defence, border security, and Arctic sovereignty, as well as those related to advancing AI to support productivity with a focus on results. This will make people in Canada safer and enable substantial investments in infrastructure to ensure resiliency to extreme events.

References

AAFC (Agriculture and Agri-Food Canada). (2020). Climate change impacts on agriculture. Retrieved May 2025, from https://agriculture.canada.ca/en/environment/climate-change/climate-change-impacts-agriculture.

Albuali, A., Srinivasagan, R., Aljughaiman, A., & Alderazi, F. (2023). Scalable lightweight IoT-based smart weather measurement system. *Sensors*, *23*(12), 5569. https://doi.org/10.3390/s23125569.

Allen, A., Markou, S., Tebbutt, W., Requeima, J., Bruinsma, W. P., Andersson, T. R., … Turner, R. E. (2025). End-to-end data-driven weather prediction. *Nature*, *641*, 1172-1179. https://doi.org/10.1038/s41586-025-08897-0.

Austen, I. (2024, December 6). Canada moves to protect Arctic from threats by Russia and China. *The New York Times*. Retrieved July 2025, from https://www.nytimes.com/2024/12/06/world/canada/canada-arctic-russia-china.html.

Avalanche Canada. (2024). *Avalanche Canada 2023-24 Annual Report*. Revelstoke, BC: Avalanche Canada. https://issuu.com/avalancheca/docs/ac_2023_annual_report.

Avalanche Canada. (2025). About. Retrieved May 2025, from https://avalanche.ca/about.

Bauer, P. (2024). What if? Numerical weather prediction at the crossroads. *Journal of the European Meteorological Society*, *1*, 100002. https://doi.org/10.1016/j.jemets.2024.100002.

Bauer, P., Stevens, B., & Hazeleger, W. (2021). A digital twin of Earth for the green transition. *Nature Climate Change*, *11*, 80-83. https://doi.org/10.1038/s41558-021-00986-y.

Bernstien, J. (2022a, May 26). These Ontario residents didn't receive a storm alert — and want to know why. *CBC News*. Retrieved May 2025, from https://www.cbc.ca/news/canada/canada-storm-alert-failed-peterborough-1.6467263.

Bernstien, J. (2022b, May 25). What's a derecho and why is it so destructive? The science behind this powerful storm. *CBC News*. Retrieved May 2025, from https://www.cbc.ca/news/science/derecho-causes-havoc-in-canada-1.6464409.

Bi, K., Xie, L., Zhang, H., Chen, X., Gu, X., & Tian, Q. (2023). Accurate medium-range global weather forecasting with 3D neural networks. *Nature*, *619*, 533-538. https://doi.org/10.1038/s41586-023-06185-3.

Blair, N. (2025). Internet and cell phone plans and usage statistics in Canada. Retrieved May 2025, from https://madeinca.ca/internet-and-cell-phone-plans-and-usage-canada-statistics/.

Boasiako, B. A. (2025). The NOAA freeze: How U.S. restrictions are chilling Canadian research. Retrieved May 2025, from https://gogeomatics.ca/the-noaa-freeze-how-u-s-restrictions-are-chilling-canadian-research/.

Bodnar, C., Bruinsma, W. P., Lucic, A., Stanley, M., Allen, A., Brandstetter, J., … Perdikaris, P. (2025). A foundation model for the Earth system. *Nature*, *641*, 1180-1187. https://doi.org/10.1038/s41586-025-09005-y.

Brunet, G., Parsons, D. B., Ivanov, D., Lee, B., Bauer, P., Bernier, N. B., … Yu, R. (2023). Advancing weather and climate forecasting for our changing world. *Bulletin of the American Meteorological Society*, *104*(4), E909-E927. https://doi.org/10.1175/BAMS-D-21-0262.1.

Bunker, A. (2025). What is NPS? The ultimate guide to boosting your Net Promoter Score. Retrieved July 2025, from https://www.qualtrics.com/experience-management/customer/net-promoter-score/.

Camps-Valls, G., Fernández-Torres, M.-Á., Cohrs, K.-H., Höhl, A., Castelletti, A., Pacal, A., … Williams, T. (2025). Artificial intelligence for modeling and understanding extreme weather and climate events. *Nature Communications*, *16*, 1919. https://doi.org/10.1038/s41467-025-56573-8.

Carter, N. & Ljubicic, G. (2022). *Weather and Society in Inuit Nunangat: User Needs, Service Provider Efforts, and Opportunities for the Future*. Hamilton, ON: StraightUpNorth. https://straightupnorth.ca/wp-content/uploads/2022/10/weather-society_oct2022-report.pdf.

CBC News. (2023, July 29). Meteorologist says national flash flood warning system would save lives. *CBC News*. Retrieved May 2025, from https://www.cbc.ca/news/canada/nova-scotia/flash-flood-warning-system-1.6922181.

CCA (Council of Canadian Academies). (2023). *Fault Lines*. Ottawa, ON: Expert Panel on the Socioeconomic Impacts of Science and Health Misinformation, CCA. https://doi.org/10.60870/rvw4-an82.

CDW Expert. (2025). CPU vs. GPU: What's the difference? Retrieved May 2025, from https://www.cdw.com/content/cdw/en/articles/hardware/cpu-vs-gpu.html.

Clark, D. G., Ness, R., Coffman, D., & Beugin, D. (2021). *The Health Costs of Climate Change*. Ottawa, ON: Canadian Institute for Climate Choices. https://climatechoices.ca/wp-content/uploads/2021/06/ClimateChoices_Health-report_Final_June2021.pdf.

Cleland, D. (2024, October 17). AI flood maps: Forecasting where and when, in real-time. *NIWA*. Retrieved April 2025, from https://storymaps.arcgis.com/stories/74b76789244249158b03c9c6e3c865b5.

CMOS (Canadian Meteorological and Oceanographic Society). (2022). How can Canadians be protected from extreme weather they have never experienced before? Retrieved May 2025, from https://www.cmos.ca/site/publications/pos_statements/extreme_weather?nav=sidebar.

Collins, J. (2024). Building a stronger weather forecasting system. Retrieved April 2025, from https://www.beehive.govt.nz/release/building-stronger-weather-forecasting-system.

CWA (Canada Water Agency). (2024). About the Canada Water Act review. Retrieved May 2025, from https://www.canada.ca/en/canada-water-agency/canada-water-act-review/about-canada-water-act-review.html.

CWA (Canada Water Agency). (2025). Organizational structure. Retrieved July 2025, from https://www.canada.ca/en/canada-water-agency/corporate/organizational-structure.html.

ECCC (Environment and Climate Change Canada). (2016). Water governance and legislation: Shared responsibility. Retrieved May 2025, from https://www.canada.ca/en/environment-climate-change/services/water-overview/governance-legislation/shared-responsibility.html.

ECCC (Environment and Climate Change Canada). (2019). Weather and meteorology glossary. Retrieved May 2025, from https://www.canada.ca/en/environment-climate-change/services/weather-general-tools-resources/glossary.html.

ECCC (Environment and Climate Change Canada). (2020). Climate change concepts. Retrieved June 2025, from https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/basics/concepts.html.

ECCC (Environment and Climate Change Canada). (2021). From telegraph to mobile apps - 150 years of Canadian weather service history. Retrieved May 2025, from https://www.canada.ca/en/environment-climate-change/services/weather-resource-centre/history-services.html.

ECCC (Environment and Climate Change Canada). (2022). Timeline: Major milestones of the Meteorological Service of Canada. Retrieved April 2025, from https://www.canada.ca/en/environment-climate-change/campaigns/150-msc/timeline.html.

ECCC (Environment and Climate Change Canada). (2023a). *Meteorological Service of Canada*. Gatineau, QC: Government of Canada. https://www.canada.ca/content/dam/eccc/documents/pdf/corporate-info/transitional-material/dm-transition-2023/ECCC-5-meteorogical-service-canada.pdf.

ECCC (Environment and Climate Change Canada). (2023b). *2023 DM Transition Booklet - Overview of the Department*. Gatineau, QC: Government of Canada. https://www.canada.ca/content/dam/eccc/documents/pdf/corporate-info/transitional-material/dm-transition-sept-2023/ECCC-1-transition-booklet-sept-2023.pdf.

ECCC (Environment and Climate Change Canada). (2024a). Water governance: Federal policy and legislation. Retrieved May 2025, from https://www.canada.ca/en/environment-climate-change/services/water-overview/governance-legislation/federal-policy.html.

ECCC (Environment and Climate Change Canada). (2024b). *Science Strategy 2024 to 2029*. Gatineau, QC: Government of Canada. https://www.canada.ca/content/dam/eccc/documents/pdf/science-technology/strategy/En4-76-2024-eng.pdf.

ECCC (Environment and Climate Change Canada). (2024c). *Environment and Climate Change Canada's Artificial Intelligence Integration Roadmap for Numerical Weather and Environmental Predictions*. Gatineau, QC: Government of Canada. https://publications.gc.ca/collections/collection_2024/eccc/en4/En4-745-2024-eng.pdf.

ECCC (Environment and Climate Change Canada). (2024d). *Environment and Climate Change Canada 2023–24 Departmental Results Report*. Gatineau, QC: Government of Canada. https://www.canada.ca/en/environment-climate-change/corporate/transparency/priorities-management/departmental-results-report/2023-2024.html.

ECCC (Environment and Climate Change Canada). (2025a). Weather information. Retrieved May 2025, from https://weather.gc.ca/.

ECCC (Environment and Climate Change Canada). (2025b). Canada's 10 most impactful weather stories of 2024. Retrieved May 2025, from https://www.canada.ca/en/environment-climate-change/services/ten-most-impactful-weather-stories/2024.html.

ECCC (Environment and Climate Change Canada). (2025c). *Sea Ice in Canada: Canadian Environmental Sustainability Indicators*. Gatineau, QC: Government of Canada. https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/sea-ice/2025/sea-ice-en.pdf.

ECCC (Environment and Climate Change Canada). (2025d). Criteria for public weather alerts. Retrieved June 2025, from https://www.canada.ca/en/environment-climate-change/services/types-weather-forecasts-use/public/criteria-alerts.html.

ECCC (Environment and Climate Change Canada). (2025e). Meteorological service standards. Retrieved July 2025, from https://www.canada.ca/en/environment-climate-change/services/meteorological-service-standards.html.

ECMWF (European Centre for Medium-Range Weather Forecasts). (2024). Anemoi: A new framework for weather forecasting based on machine learning. Retrieved March 2025, from https://www.ecmwf.int/en/about/media-centre/news/2024/anemoi-new-framework-weather-forecasting-based-machine-learning.

ECMWF (European Centre for Medium-Range Weather Forecasts). (2025a). *ECMWF Strategy 2025-2034*. Reading, United Kingdom: ECMWF. https://www.ecmwf.int/sites/default/files/elibrary/2025/81641-ecmwf-strategy-2025-2034.pdf.

ECMWF (European Centre for Medium-Range Weather Forecasts). (2025b). ECMWF's AI forecasts become operational. Retrieved April 2025, from https://www.ecmwf.int/en/about/media-centre/news/2025/ecmwfs-ai-forecasts-become-operational.

ECMWF (European Centre for Medium-Range Weather Forecasts). (n.d.). The Digital Twins. Retrieved June 2025, from https://destine.ecmwf.int/digital-twins/.

ESNZ (Earth Sciences New Zealand). (2025). About us. Retrieved August 2025, from https://www.earthsciences.nz/about-us.

Freebairn, J. W. & Zillman, J. W. (2002a). Funding meteorological services. *Meteorological Applications*, *9*, 45-54. https://doi.org/10.1017/S1350482702001056.

Freebairn, J. W. & Zillman, J. W. (2002b). Economic benefits of meteorological services. *Meteorological Applications*, *9*, 33-44. https://doi.org/10.1017/S1350482702001044.

GC (Government of Canada). (1982). *Constitution Act, 1982, being Schedule B to the Canada Act 1982 (UK)*, 1982, c 11. https://laws-lois.justice.gc.ca/PDF/Const_TRD.pdf.

GC (Government of Canada). (1985). *Canada Water Act*, R.S.C., 1985, c. C-11. https://laws-lois.justice.gc.ca/PDF/C-11.pdf.

GC (Government of Canada). (2022). Surviving the heat: The impacts of the 2021 western heat dome in Canada. Retrieved July 2025, from https://science.gc.ca/site/science/en/blogs/science-health/surviving-heat-impacts-2021-western-heat-dome-canada.

GC (Government of Canada). (2024). Join the discussion: Let's Talk Weather. Retrieved July 2025, from https://www.canada.ca/en/services/environment/weather/lets-talk-weather-consultation.html.

GC (Government of Canada). (2025a). Infographic for Environment and Climate Change Canada [GC InfoBase]. Retrieved April 2025, from https://www.tbs-sct.canada.ca/ems-sgd/edb-bdd/index-eng.html#infographic/dept/137/results.

GC (Government of Canada). (2025b). *Building Canada Strong: A Bold, Ambitious Plan for Our Future Speech from the Throne to Open the First Session of the 45th Parliament of Canada, May 27, 2025*. Ottawa, ON: GC. https://www.canada.ca/content/dam/pco-bcp/documents/pm/STF2025_EN_Web.pdf.

GC (Government of Canada). (2025c). Canadian weather. Retrieved May 2025, from https://weather.gc.ca/canada_e.html.

GC (Government of Canada). (2025d). Wildfires. Retrieved May 2025, from https://www.canada.ca/en/public-safety-canada/campaigns/wildfires.html.

GC (Government of Canada). (2025e). Numerical Weather Prediction (NWP) Model Verification. Retrieved July 2025, from https://weather.gc.ca/verification/index_e.html.

GFDRR (Global Facility for Disaster Reduction and Recovery). (2019). *The Power of Partnership*. Washington, D.C.: The World Bank. https://www.gfdrr.org/sites/default/files/publication/The%20Power%20of%20Partnership_WEB.pdf.

Göber, M., Christel, I., Hoffmann, D., Mooney, C. J., Rodriguez, L., Becker, N., … Williams, H. (2023). *Enhancing the value of weather and climate services in society: Identified gaps and needs as outcomes of the first WMO WWRP/SERA Weather and Society Conference*. Boston, MA: American Meteorological Society. https://journals.ametsoc.org/view/journals/bams/104/3/BAMS-D-22-0199.1.xml.

Golding, B. (Ed.). (2022). *Towards the "Perfect" Weather Warning*. Cham, Switzerland: Springer Nature Switzerland AG.

Gov. of NS (Government of Nova Scotia). (n.d.). Surface water: Monitoring and reporting. Retrieved July 2025, from https://novascotia.ca/nse/surface.water/surfacewater.monitoring.reporting.asp.

Gov. of ON (Government of Ontario). (2024). Flood Forecasting and Warning Program. Retrieved May 2025, from https://www.lioapplications.lrc.gov.on.ca/webapps/swmc/flood-forecasting-and-warning-program/.

Gov. of ON (Government of Ontario). (2025). Conservation Authorities. Retrieved July 2025, from http://www.ontario.ca/page/conservation-authorities.

Gov. of QC (Government of Quebec). (2023). Vigilance — Surveillance de la crue des eaux. Retrieved July 2025, from https://vigilance.geo.msp.gouv.qc.ca/.

Gruber, N. & Prein, A. (2025, May 27). Is AI the future of weather and climate modelling? *ETH Zurich*. Retrieved June 2025, from https://ethz.ch/en/news-and-events/eth-news/news/2025/05/is-ai-the-future-of-weather-and-climate-modelling.html.

Gruntfest, E. (2018). *Weather and Society: Toward Integrated Approaches*. Hoboken, NJ: John Wiley & Sons.

Han, T., Guo, S., Ling, F., Chen, K., Gong, J., Luo, J., … Bai, L. (2024). FengWu-GHR: Learning the kilometer-scale medium-range global weather forecasting. *arXiv*. *Preprint*. http://arxiv.org/abs/2402.00059.

Hancock, B., Andersen, W. B., Calmels, F., Collier, J., Cunsolo, A., Dawson, J., … Wong, C. (2022). Northern Canada. In F.J. Warren, N. Lulham, D.L. Dupuis, & D.S. Lemmen (Eds.), *Canada in a Changing Climate: Regional Perspectives Report*. Ottawa, ON: Government of Canada.

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, *48*, RG4004. https://doi.org/10.1029/2010RG000345.

HC (Health Canada). (2022). Who is most impacted by climate change. Retrieved May 2025, from https://www.canada.ca/en/health-canada/services/climate-change-health/populations-risk.html.

Hua, Z., Hakim, G., & Anderson-Frey, A. (2025). Performance of the Pangu-Weather deep learning model in forecasting tornadic environments. *Geophysical Research Letters*, *52*, e2024GL109611. https://doi.org/10.1029/2024GL109611.

IBC (Insurance Bureau of Canada). (2025). 2024 shatters record for costliest year for severe weather-related losses in Canadian history at $8.5 billion. Retrieved May 2025, from https://www.ibc.ca/news-insights/news/2024-shatters-record-for-costliest-year-for-severe-weather-related-losses-in-canadian-history-at-8-5-billion.

IOOS News/Ocean Enterprise. (2024). NOS, Canada's Ocean Supercluster enter into Ocean Enterprise MOU. Retrieved June 2025, from https://ioos.noaa.gov/news/nos-canadas-ocean-supercluster-enter-into-ocean-enterprise-mou/.

IPCC (Intergovernmental Panel on Climate Change). (2023). Summary for Policymakers. In Core Writing Team, H. Lee, & J. Romero (Eds.), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Joe, P., Melo, S., Burrows, W. R., Casati, B., Crawford, R. W., Deghan, A., … Strawbridge, K. (2020). The Canadian Arctic Weather Science Project: Introduction to the Iqaluit site. *Bulletin of the American Meteorological Society*, *101*(2), E109-E128. https://doi.org/10.1175/BAMS-D-18-0291.1.

Jung, T., Gordon, N. D., Bauer, P., Bromwich, D. H., Chevallier, M., Day, J. J., … Yang, Q. (2016). Advancing polar prediction capabilities on daily to seasonal time scales. *Bulletin of the American Meteorological Society*, *97*(9), 1631-1647. https://doi.org/10.1175/BAMS-D-14-00246.1.

Lam, R., Sanchez-Gonzalez, A., Willson, M., Wirnsberger, P., Fortunato, M., Alet, F., … Battaglia, P. (2023). GraphCast: Learning skillful medium-range global weather forecasting. *arXiv*. *Preprint*. http://arxiv.org/abs/2212.12794.

Lang, S., Alexe, M., Chantry, M., Dramsch, J., Pinault, F., Raoult, B., … Rabier, F. (2024). AIFS - ECMWF's data-driven forecasting system. *arXiv*. *Preprint*. http://arxiv.org/abs/2406.01465.

Lazo, J. K. (2024a, December 16). How does the U.S. public get its weather forecasts? *The Front Page | The American Meteorological Society*. Retrieved June 2025, from https://blog.ametsoc.org/2024/12/16/how-does-the-u-s-public-get-its-weather-forecasts/.

Lazo, J. K. (2024b). *Communicating Forecast Uncertainty (CoFU) 2: Replication and Extension of a Survey of the US Public's Sources, Perceptions, Uses, and Values for Weather Information*. Washington, D.C.: American Meteorological Society. https://www.ametsoc.org/index.cfm/ams/policy/studies-analysis/communicating-forecast-uncertainty-cofu-2/.

Lemyre, L., Beaudry, M., & Yong, A. G. (2017). Psychosocial aspects of risk perception and communication. In B. Motulsky, J.B. Guindon, & F. Tanguay-Hébert (Eds.), *Weather and Climate Risk Communication*. Québec, QC: Presses de l'Université du Québec.

Lewis, J. I., Toney, A., & Shi, X. (2024). Climate change and artificial intelligence: Assessing the global research landscape. *Discover Artificial Intelligence*, *4*, 64. https://doi.org/10.1007/s44163-024-00170-z.

Mariani, Z., Huang, L., Crawford, R., Blanchet, J.-P., Hicks-Jalali, S., Mekis, E., … Strawbridge, K. (2022). Enhanced automated meteorological observations at the Canadian Arctic Weather Science (CAWS) supersites. *Earth System Science Data*, *14*(11), 4995-5017. https://doi.org/10.5194/essd-14-4995-2022.

Melo, S., Chaput-Dyer, M., & Joe, P. (2023, August 3). The evolution of Canada's weather enterprise: 150 years anniversary symposium. *CMOS BULLETIN SCMO*. Retrieved February 2025, from https://bulletin.cmos.ca/the-evolution-of-canadas-weather-enterprise-150-years-anniversary-symposium/.

Mitra, A. K. (2023). Use of remote sensing in weather and climate forecasts. In V.K. Gahalaut & M. Rajeevan (Eds.), *Social and Economic Impact of Earth Sciences*. Singapore: Springer Singapore.

Morss, R. E., Mulder, K. J., Lazo, J. K., & Demuth, J. L. (2016). How do people perceive, understand, and anticipate responding to flash flood risks and warnings? Results from a public survey in Boulder, Colorado, USA. *Journal of Hydrology*, *541*, 649-664. https://doi.org/10.1016/j.jhydrol.2015.11.047.

Mulligan, S. J. (2024). Google DeepMind's new AI model is the best yet at weather forecasting. *MIT Technology Review*. Retrieved February 2025, from https://www.technologyreview.com/2024/12/04/1107892/google-deepminds-new-ai-model-is-the-best-yet-at-weather-forecasting/.

NASEM (National Academies of Sciences, Engineering, and Medicine). (2018). *Integrating Social and Behavioral Sciences Within the Weather Enterprise*. Washington, D.C.: The National Academies Press. https://nap.nationalacademies.org/catalog/24865/integrating-social-and-behavioral-sciences-within-the-weather-enterprise.

NAV CANADA. (n.d.). What we do. Retrieved July 2025, from https://www.navcanada.ca/en/corporate/about-us/what-we-do.aspx.

NIWA (National Institute of Water and Atmospheric Research). (n.d.-a). Forecasting impacts from extreme weather. Retrieved April 2025, from https://niwa.co.nz/climate-and-weather/forecasting-impacts-extreme-weather.

NIWA (National Institute of Water and Atmospheric Research). (n.d.-b). High-resolution climate projections using physics and AI. Retrieved April 2025, from https://niwa.co.nz/climate-and-weather/high-resolution-climate-projections-using-physics-and-ai.

NIWA (National Institute of Water and Atmospheric Research). (n.d.-c). High resolution drought forecasting. Retrieved April 2025, from https://niwa.co.nz/climate-and-weather/high-resolution-drought-forecasting.

NOAA (National Oceanic and Atmospheric Administration). (n.d.). Satellites. Retrieved May 2025, from https://www.weather.gov/about/satellites.

NRCan (Natural Resources Canada). (2020). Regional, national and international climate modeling. Retrieved May 2025, from https://cfs.nrcan.gc.ca/projects/3.

NRCan (Natural Resources Canada). (2021). Information on tsunamis. Retrieved May 2025, from https://www.earthquakescanada.nrcan.gc.ca/info-gen/tsunami-en.php.

NRCan (Natural Resources Canada). (2025a). Weather satellites/sensors. Retrieved May 2025, from https://natural-resources.canada.ca/maps-tools-publications/satellite-elevation-air-photos/weather-satellitessensors.

NRCan (Natural Resources Canada). (2025b). Flood mapping roles and resources. Retrieved May 2025, from https://natural-resources.canada.ca/science-data/science-research/flood-mapping/flood-mapping-roles-resources.

NRCan (Natural Resources Canada). (n.d.). Canadian Wildland Fire Information System. Retrieved May 2025, from https://cwfis.cfs.nrcan.gc.ca/home.

NTP (Northern Tornadoes Project). (2024). Some updates on the 2022 ON-QC derecho. Retrieved June 2025, from https://www.uwo.ca/ntp/blog/2024/some_updates_on_the_2022_onqc_derecho.html.

NWS (National Weather Service). (2017). *National Weather Service Enterprise Analysis Report*. Sterling, VA: NWS. https://www.weather.gov/media/about/Final_NWS%20Enterprise%20Analysis%20Report_June%202017.pdf.

Pathak, J., Subramanian, S., Harrington, P., Raja, S., Chattopadhyay, A., Mardani, M., … Anandkumar, A. (2022). FourCastNet: A global data-driven high-resolution weather model using Adaptive Fourier Neural Operators. *arXiv*. *Preprint*. http://arxiv.org/abs/2202.11214.

Pelmorex Corp. (2025). The Weather Network: Weather forecasts, maps, news and videos. Retrieved May 2025, from https://www.theweathernetwork.com/en.

Pennesi, K., Arokium, J., & McBean, G. (2012). Integrating local and scientific weather knowledge as a strategy for adaptation to climate change in the Arctic. *Mitigation and Adaptation Strategies for Global Change*, *17*, 897-922. https://doi.org/10.1007/s11027-011-9351-5.

Phan, M. D., Montz, B. E., Curtis, S., & Rickenbach, T. M. (2018). Weather on the go: An assessment of smartphone mobile weather application use among college students. *Bulletin of the American Meteorological Society*, *99*(11), 2245-2257. https://doi.org/10.1175/BAMS-D-18-0020.1.

PMO (Office of the Prime Minister of Canada). (2025). Mandate Letter. Retrieved July 2025, from https://www.pm.gc.ca/en/mandate-letters/2025/05/21/mandate-letter.

PS (Public Safety Canada). (2017). *An Emergency Management Framework for Canada: Third Edition*. Ottawa, ON: Government of Canada. https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/2017-mrgnc-mngmnt-frmwrk/index-en.aspx.

PS (Public Safety Canada). (2023). Emergency management. Retrieved May 2025, from https://www.publicsafety.gc.ca/cnt/trnsprnc/brfng-mtrls/trnstn-bndrs/20231123/02-en.aspx.

PS (Public Safety Canada). (2024). Backgrounder: Floods. Retrieved May 2025, from https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/ntnl-rsk-prfl/bckgrndr-flds-en.aspx.

Quick, M. (2024). *The Impacts of Extreme Heat Events on Non-Accidental, Cardiovascular, and Respiratory Mortality: An Analysis of 12 Canadian Cities from 2000 to 2020*. Ottawa, ON: Statistics Canada. https://www150.statcan.gc.ca/n1/pub/82-003-x/2024006/article/00001-eng.htm.

Richardson, G., Knudby, A., Crowley, M. A., Sawada, M., & Chen, W. (2025). Machine learning approaches to Landsat change detection analysis. *Canadian Journal of Remote Sensing*, *51*(1), 2448169. https://doi.org/10.1080/07038992.2024.2448169.

Ripberger, J., Bell, A., Fox, A., Forney, A., Livingston, W., Gaddie, C., … Jenkins-Smith, H. (2022). Communicating probability information in weather forecasts: Findings and recommendations from a living systematic review of the research literature. *Weather, Climate, and Society*, *14*(2), 481-498. https://doi.org/10.1175/WCAS-D-21-0034.1.

RNZ News. (2024). NIWA to take over MetService in forecaster merger. Retrieved April 2025, from https://web.archive.org/web/20241009214030/https://www.rnz.co.nz/news/political/529112/niwa-to-take-over-metservice-in-forecaster-merger.

Rogers, D. P., Tsirkunov, V., Bogdanova, A.-M., Kootval, H., & Suwa, M. (2021). *Innovation in Public and Private Weather Services*. Washington, D.C.: Global Facility for Disaster Reduction and Recovery, The World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/756191614351406589/innovation-in-public-and-private-weather-services.

Sanders, R. (2023, February 19). Weather stations are sparse in Labrador. The gaps can be a matter of "life or death." *CBC Radio*. Retrieved July 2025, from https://www.cbc.ca/radio/whatonearth/weather-data-gaps-life-or-death-1.6751883.

Schmid, F., Wang, Y., & Harou, A. (2019, November 27). Nowcasting guidelines – a summary. *World Meteorological Organization*. Retrieved July 2025, from https://wmo.int/media/magazine-article/nowcasting-guidelines-summary.

Seitter, K. L., Tipton, E., & Higgins, P. A. T. (2025). *Without a Strong Weather Enterprise, America's Economic Leadership Is at Risk*. Washington, D.C.: The American Meteorological Society. https://www.ametsoc.org/sites/ams/assets/File/policy/Wx_Special_Report_2025.pdf.

Selvam, A. P. & Al-Humairi, S. N. S. (2023). The impact of IoT and sensor integration on real-time weather monitoring systems: A systematic review. *Research Square*. *Preprint*. https://www.researchsquare.com/article/rs-3579172/v1.

Shrader, J. G., Bakkensen, L., & Lemoine, D. (2023). *Fatal Errors: The Mortality Value of Accurate Weather Forecasts*. Cambridge, MA: National Bureau of Economic Research. http://www.nber.org/papers/w31361.

Sills, D. (2022). NTP Tornado Warning Performance Assessment. Retrieved July 2025, from https://www.uwo.ca/projects/ntp//blog/2022/ntp_national_tornado_warning_performance_assessment.html.

Silver, A., Cohen, N., Wilson, T., & Behlendorf, B. (2025). *Exploring the interplay between threat appraisal, efficacy appraisal, and behavior change during a "once-in-a-lifetime" storm*. Paper presented at the 22nd International ISCRAM Conference, Halifax, NS.

Silver, A., Finnis, J., Behlendorf, B., & Reid-Musson, E. (2022). End-user satisfaction with Hurricane Dorian information in Atlantic Canada. *Meteorological Applications*, *29*(3), e2078. https://doi.org/10.1002/met.2078.

Soliman, A. (2024). DeepMind AI weather forecaster beats world-class system. *Nature*, *636*, 282-283. https://doi.org/10.1038/d41586-024-03957-3.

SSC (Shared Services Canada). (2025). High Performance Computing supercomputers. Retrieved May 2025, from https://www.canada.ca/en/shared-services/corporate/hosting-services/high-performance-computing.html.

Stephens, G., Freeman, A., Richard, E., Pilewskie, P., Larkin, P., Chew, C., … Peral, E. (2021). The miniaturization revolution in Earth observing. *Bulletin of the American Meteorological Society*, *101*(5), 373-378. https://doi.org/10.1175/BAMS-D-19-0146.A.

Thorpe, A. (2016). The weather enterprise: A global public-private partnership. *World Meteorological Organization Bulletin*, *65*(2), https://wmo.int/media/magazine-article/weather-enterprise-global-public-private-partnership.

Thorpe, A. & Rogers, D. P. (2021). *Creating Value in the Global Weather Enterprise*. Washington, D.C.: Global Facility for Disaster Reduction and Recovery, The World Bank. https://zerogeoengineering.com/wp-content/uploads/2025/05/Creating-Value-in-the-Global-Weather-Enterprise.pdf.

U.S. Bureau of Labor Statistics. (n.d.). American Time Use Survey. Retrieved April 2025, from https://www.bls.gov/tus/.

U.S. Department of Commerce. (n.d.). NOAA - Customer satisfaction with NWS services, as measured by the American Customer Satisfaction Index. Retrieved July 2025, from https://performance.commerce.gov/KPI-NOAA/NOAA-Customer-satisfaction-with-NWS-services-as-me/rkvb-9sbv.

Voosen, P. (2023). Canadians left in the cold by dwindling weather data. *Science*, *379*(6636), 968-969. https://doi.org/10.1126/science.adh4962.

Way, R. (2022). Climate services in Canada's North: Are we doing enough? *YouTube*. Retrieved July 2025, from https://www.youtube.com/watch?v=AsLV6he6gMs.

Wiedinmyer, C. & Bowen, K. (2025, February 11). NOAA's vast public weather data powers the local forecasts on your phone and TV – a private company alone couldn't match it. *The Conversation*. Retrieved May 2025, from http://theconversation.com/noaas-vast-public-weather-data-powers-the-local-forecasts-on-your-phone-and-tv-a-private-company-alone-couldnt-match-it-249451.

WMO (World Meteorological Organization). (1999). *Guide to Public Weather Services Practices*. Geneva, Switzerland: WMO. https://library.wmo.int/viewer/31935/download?file=wmo_834_en.pdf&type=pdf&navigator=1.

WMO (World Meteorological Organization). (2015). *Role and Operation of National Meteorological and Hydrological Services*. Geneva, Switzerland: WMO. https://library.wmo.int/viewer/49013/download?file=2015_role-operation-nmhs_en.pdf&type=pdf&navigator=1.

WMO (World Meteorological Organization). (2025a). WMO Unified Data Policy Resolution (Res.1). Retrieved June 2025, from https://wmo.int/wmo-unified-data-policy-resolution-res1.

WMO (World Meteorological Organization). (2025b). Flash Flood Guidance System with Global Coverage (FFGS). Retrieved July 2025, from https://wmo.int/projects/ffgs.

Wong, W. (2024, November 15). A meteorological arms race is shaping up about privatizing the weather. *NPR*. Retrieved May 2025, from https://www.npr.org/2024/11/15/nx-s1-5188571/a-meteorological-arms-race-is-shaping-up-about-privatizing-the-weather.

Zhang, X., Flato, G., Kirchmeier-Young, M., Vincent, L., Wan, H., Wang, X., … Kharin, V. (2019). Temperature and precipitation across Canada. In E. Bush & D.S. Lemmen (Eds.), *Canada's Changing Climate Report*. Ottawa, ON: Government of Canada.

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