STANDARDIZATION GUIDANCE FOR WEATHER DATA, CLIMATE INFORMATION AND CLIMATE CHANGE PROJECTIONS

Overview of Canadian practices, needs and challenges on integrating climate change into infrastructure design

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OURANOS

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EXECUTIVE SUMMARY

This report provides an overview of the collection, management, and use of weather and climate data across Canada; how this information is being used to derive infrastructure design values; and how future climate projections are being factored into design values. It identifies gaps and provides potential standards-related options to address them. It is intended to engage key stakeholders to converge to a common understanding of priorities for standards in the gathering and use of weather and climate data in the infrastructure-design process.

The main findings regarding the current infrastructure-design process and gaps follow.

- Access to weather and climate data is problematic.
  - The spatial density of the weather networks is low and, therefore, often insufficient for engineering projects.
  - High-frequency data is not easily accessible through current web portals.
  - Needed data are not readily available, such as data related to wind, radar, waves, river flow and other variables.
  - The data are scattered among multiple portals, readily accessible only to technically inclined professionals.
  - The type of climate change information currently available does not meet the needs of engineers involved in the design and risk analysis of infrastructure projects.
- Multiple methodologies exist for the development of climate change information. The variety of methodologies and conclusions add uncertainty and create confusion. Interviewees expressed concern about liability. Methodological and liability issues raise the need for an authoritative source of climate change information nationally.
- The amount of uncertainty in climate change projections is significant compared to what engineers previously had to consider. The decision-making process becomes more complex in the context of climate change; historical best practices for infrastructure design are hardly applicable.
- The level of confidence in climate-data projections, and in products derived from them, varies considerably among engineers. Some consider climate models to be “black boxes,” and the inherent uncertainty of simulations based on climate models creates a degree of mistrust. More formal educational guidelines and/or continuing education courses related to climate science would be useful for engineers.
- Climate change science continues to evolve quickly, along with relevant available data and analytical methods. In practice, this means that conclusions are subject to revision and cannot be considered authoritative until they have been confirmed by independent analyses and the test of time.
- The benefits of climate change adaptation are not always readily evident. It is tempting for organizations to prioritize projects and investments that yield short-term benefits.
- The lack of policies in the procurement processes of a project is a challenge for the integration of climate change into infrastructure design. In most cases, the choice to integrate climate change into the design of infrastructure is left to the design engineer.
- Communication between scientists, engineers, planners and stakeholders is difficult, as the same words can carry different meanings in the various disciplines and thereby create misunderstandings and hamper collaboration. A formal, interdisciplinary glossary would help the groups to better understand one another.

The main recommendations are to:

- Develop a national data portal to catalogue relevant weather, climate and earth-observation data, along with user-oriented materials derived from these data. The portal would leverage planned and existing initiatives, such as the Network of Networks (NoN) (section 5.2.2a), the Canadian Centre for Climate Services and the Federal Geospatial Platform.
- Develop guidelines and best practices to help engineers cope with climate uncertainty.
- Develop climate change design parameters for engineers, inspired by ASHRAE's Climatic Data for Building Design Standards (169-2013) in the United States.

Employing a standardization system to reach agreement on these critical factors will establish a common starting point and understanding among relevant parties, and inspire informed decisions about infrastructure projects.

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GLOSSARY

Automated Surface Weather Observation Stations: A meteorological station that records and automatically transmits observations.

Climate: Long-term statistical records of weather conditions, such as patterns of temperature, precipitation, atmospheric pressure, wind, humidity and other meteorological variables in a given region during a given period of time.

Climate Change: Long-term continuous change, an increasing or decreasing trend, in relation to average baseline climate conditions.

Climate Data: Records of the measurement of weather variables, such as minimum and maximum temperature and total precipitation, usually collected once or twice a day. Climate data is more important than weather data for identifying longer-term trends in climate, such as trends in temperature and precipitation.

Climate Information: Generated from examination of archived climate data, this type of information includes climate extremes like record temperatures and record levels of precipitation, climate projections and scenarios, and other derived climate products.

Climate Models: Numerical tools based on mathematical equations that aim to represent processes of the climate system. These equations are based on the physical laws governing fluid mechanics, such as the laws of conservation of mass, energy and momentum. They describe the behaviour of, and interactions between, the atmosphere, lithosphere, hydrosphere, cryosphere and biosphere, under external forces such as solar radiation and aerosols, as well as natural and anthropogenic greenhouse gas (GHG) emissions.

Climate Normals: Average of climate indices used to represent the recent past climate for a given area. The time period used for climate normals often corresponds with the time period used as a baseline or reference period in climate change calculation.

Climate projections: Portions of a climate model simulation that forecast the future.

Climate simulations: End product of climate models; the results produced by solving a climate model's equations for a certain period of time.

Downscaling: A procedure in which information known at large scales is used to make predictions at local scales (GIS Program 2017).

Emissions scenarios: Plausible future releases of greenhouse gases, aerosols and other anthropogenic gases into the atmosphere. These are based on a coherent and internally consistent set of assumptions about driving forces--such as technological change, demographic and socioeconomic development--and their key interactions (IPCC 2007).

Engineering vulnerability: The shortfall in the ability of public infrastructure to absorb the negative effects and benefit from the positive effects, of changes in the climate conditions used to design and operate infrastructure (Engineers Canada 2017b).

Ensemble: A set of simulations encompassing multiple global or regional climate models, and/or simulations from the same model.

Extreme: An event that is rare at a particular place and time of year (IPCC 2007).

Global Climate Model (GCM): Models that cover the entire planet, with calculation grids (domains) at a horizontal resolution typically between 150 and 300 km. There are three main types of GCMs. The first generation of GCMs, known as Atmospheric General Circulation Models (AGCMs), included only the atmosphere and its interaction with continental land masses. The second generation, Atmosphere-Ocean General Circulation Models (AOGCMs), coupled the atmosphere and land with physical ocean models. The latest generation, known as Earth System Models (ESM), include biogeochemical interactions and cycles, as well as changes in land cover (such as vegetation types). Thus far, most ESMs implement the carbon cycle, and research is ongoing to include other cycles (Charron 2016).

Hindcast: Numerical weather simulation initialized at some point in the past with observations and then run to the present time to produce a historical climate record. A specific application of hindcasts, inspired by reanalysis, can be made by creating a synthetic dataset able to produce an ensemble of possibilities for a specific weather event or climate state.

Homogenized data: Adjustments applied to original station data to address shifts due to changes in instruments and observing procedures. At times, observations from several stations are joined to generate a longer time series (Climate Scenarios Canada 2017).

Infrastructure: Includes buildings of all types, communication facilities, energy generation and distribution facilities, industrial facilities, transportation networks, water-resource facilities and urban water systems.

Natural Variability: Naturally occurring variations of the climate state arising from the non-linear interactions between climate components. Natural climate variability refers to the variation in climate variables caused by nonhuman forces. There are two types of natural variability: those external and those internal to the climate system. Variations in the sun, volcanic eruptions, and Earth's orbit alter climate patterns over long time periods, from centuries to millennia. Processes internal to the climate system arise, in part, from interactions between the atmosphere and ocean, such as those occurring in the tropical Pacific Ocean during an El Niño event. These changes occur over shorter time periods, from months to decades. In any given year, natural variability may cause the climate to fluctuate from long-term averages.

Non-Reference Monitoring Station: A station designed to meet the weather and climate monitoring needs of its public or private owner. The data collections do not follow World Meteorological Organization (WMO) requirements and specifications.

Reanalysis: A scientific method for developing a comprehensive record of how weather and climate are changing over time. In it, observations and a numerical model that simulates one or more aspects of the Earth's system are combined objectively to generate a synthesized estimate of the state of the system. A reanalysis typically extends over several decades or longer and covers the entire globe from the Earth's surface to well above the stratosphere. Reanalysis products are used extensively in climate research and services: to monitor and compare current climate conditions with those of the past, identify the causes of climate variations and change, and prepare climate predictions. Information derived from reanalyses is also being used increasingly in commercial and business applications in sectors such as energy, agriculture, water resources, and insurance (Reanalysis.org 2017).

Regional Climate Models (RCM): Models covering only a portion of the planet, RCMs make it possible to solve equations at a relatively fine horizontal resolution (45 km or less) within a reasonable amount of time. To run an RCM, data from GCMs must be integrated at the RCM's boundaries. This can also be done using reanalyses, essentially a technique that uses computer models to combine historical data from various sources to recreate the past climate; this procedure is called driving an RGM (Charron 2016).

Reference Monitoring Station: A station that provides long-term, homogenous data for the purpose of determining climatic trends. It is desirable to have a network of these stations in each country, representing key climate zones and areas of vulnerability. The stations use high-quality instruments to measure weather and climate parameters according to WMO requirements and specifications.

Resilience: The ability of a system, community or society to resist, absorb, accommodate and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (Engineers Canada 2017b).

Standards: A document, established by consensus and approved by a recognized body that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, seeking to achieve the optimum degree of order in a given context. Standards should be based on the consolidated results of science, technology and experience, and promote optimum community benefits.

Standardization: The processes used to formulate, issue and implement standards.

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate, including climate variability and extremes. It is a function of the character, magnitude and rate of climate variation to which a system is exposed, along with the system's sensitivity and adaptive capacity (Engineers Canada 2017b).

Weather: Current state of the climate system at a given time over a specific area with respect to temperature, precipitation, clouds, humidity, and other meteorological variables.

Weather Data: Records, on a continuous basis, of weather variables, such as temperature, wind, and air pressure. Forecasters rely on data from weather stations to forecast the weather, including severe weather.

ACRONYMS

AR5	IPCC Fifth Assessment Report
CA	Conservation authorities
CaPA	Canadian Precipitation Analysis
CC	Climate Change
CCDP	Ontario Climate Change Data Portal
CCDS	Canadian Climate Data and Scenarios
CCHIP	Climate Change Hazards Information Portal
CMIP5	Coupled Model Intercomparison Phase 5
CoCoRaHS	Community Collaborative Rain, Hail and Snow Network
CORDEX	Coordinated Regional Climate Downscaling Experiment
CSA	Canadian Standards Association
CSP	Climate Services Provider
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
ESGF	Earth System Grid Federation
EVT	Extreme Value Theory
GCM	Global Climate Model
GEV	Generalized extreme value
GHCN	Global Historical Climatology Network
GHG	Greenhouse gases
IDF	Intensity-Duration-Frequency
IEESC	Institute for Energy, Environment and Sustainable Communities
IPCC	Intergovernmental Panel on Climate Change
MDDELCC	Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques
MFFP	Ministère des Forêts, de la Faune et des Parcs
NARCCAP	North American Regional Climate Change Assessment Program
NCAR/UCAR	The National Center for Atmospheric Research/University Corporation for Atmospheric Research
NRCan	Natural Resources Canada
NoN	Network of Networks

NWP	Numerical Weather Prediction
OCC	Ontario Climate Consortium
PCDS	Provincial Climate Data Set
PCIC	Pacific Climate and Impacts Consortium
PGMN	Provincial Groundwater Monitoring Network
PIEVC	Public Infrastructure Engineering Vulnerability Committee
PRISM	Parameter-elevation Relationships on Independent Slopes Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RMCQ	Réseau météorologique coopératif du Québec
SCC	The Standards Council of Canada
SOPFEU	Société de protection des forêts contre le feu
SOPFIM	Protection des forêts - Lutte contre les insectes ravageurs
TRCA	Toronto and Region Conservation Authority
WES Renewal	Major modernization project (begun 2011) to upgrade to dual polarization all Canadian Radars in two separate five-year plans.
WMO	World Meteorological Organization

1 INTRODUCTION

Infrastructure is an essential component of modern societies, and the backbone of current and future prosperity. Engineers face an important challenge when assessing the vulnerabilities of infrastructure to a changing climate. Canadian buildings, facilities, networks and systems are regularly exposed to severe weather, with large impacts expected. Extreme weather events are expected to increase in frequency and intensity, and to test the limits of traditional design frameworks.

Engineering practices, codes and standards guide engineers on aspects of functionality, durability and safety over the service life of infrastructure. To date, this guidance has largely been based on the assumption of a stable or constant climate. Going forward, engineering design will need to account for the extreme weather conditions anticipated under a changing climate. If the design of infrastructure fails to accommodate future climate, these structures will not be resilient throughout their lifespan.

Assessing the significance of climate change at temporal and spatial scales relevant to infrastructure and to engineering practice is necessary, yet difficult, as it involves scales that are not well resolved by climate models. Bridging the gap between climate change information scales and the needs of engineers is an ongoing challenge; the tools and methods currently used by climate scientists do not always align with the practical needs of engineers.

The interactions between infrastructure and the natural environment, along with the interdependency of facilities, add additional challenges. Buildings, facilities, networks and systems usually function in conjunction with other infrastructure; each facility and installation has its own vulnerabilities. This means that each important structure of a community is dependent not only on its own designed climatic threshold, but also on that of others, which creates a complex set of vulnerabilities.

The integration of climate change into the design value process is essential to the future resilience of national infrastructure. Proper planning might better predict the future costs of buildings, facilities, networks and systems and improve their resilience; for example, through modular and adaptive designs. Climate change may represent only one of the risks to infrastructure, but it is not accurately and consistently accounted for in current engineering design; effective standardized guidance would help address this.

To inform and guide the integration of climate information into engineering practice, the Standards Council of Canada (SCC) commissioned this report. SCC is a Crown corporation that leads Canada's standardization network. It facilitates the development and use of national and international standards and accreditation services in order to enhance Canada's competitiveness and well-being. SCC is part of the Innovation, Science and Economic Development Canada portfolio.

In 2016, SCC received funding from the Government of Canada to lead the development of standardization solutions that will help adapt infrastructure to our changing climate. This report will guide SCC's Infrastructure program in developing standardization guidance for weather data, climate information and climate change projections. SCC will also continue to invest in updating a broad range of existing critical standards that ensure infrastructure is climate-ready in Canada's North and across the country.

2 OBJECTIVES

The purpose of this report is to:

- provide an overview of the collection, management and use of weather and climate data across Canada
- examine how this information informs infrastructure design values
- identify how future climate projections are being factored into design values
- identify gaps between climate change information scales and the practical needs of engineers, and provide potential standards-related options to address them.

The report will be used by the SCC to understand the needs of stakeholders and, accordingly, determine priorities in honing Canadian standards for weather and climate data collection, management and use.

The report aims to provide an overview of *current* practices, challenges, gaps and solutions, and relevant recommendations for the integration of climate change information into infrastructure design in Canada. The scope of the report is not to give best practices or to pose judgment on current practices and best datasets. Finally, while acknowledging that climate change information is useful at all stages --from planning to maintenance--the report's focus is solely on the design stage of infrastructure.

2.1 SCOPE

1. An overview of the current status of collection and management of weather and climate data from both reference and non-reference weather and climate (surface-based elements) monitoring stations across Canada.
2. An overview of the current status of analysis and incorporation of climate information into design values for infrastructure at the regional, national and international levels.
3. An overview of the incorporation of future climate projections into design values for infrastructure at the regional, national and international levels.
4. Identification of gaps and potential issues associated with the "supply chain" of collection and management of weather and climate data, analysis of climate information, and incorporation of climate change projections into design values for infrastructure planning and operations.
5. Recommendations for standards (or standardized guidance) that would:
    - Increase the usability of data collected at weather and climate monitoring stations for multiple purposes
    - Improve the consistency and comprehensiveness of the climate information used across Canada
    - Ensure climate change is reflected in infrastructure design, and that risks inherent in interpretation, and resulting infrastructure design are understood and articulated
    - Improve the communication of uncertainty in climate-scenario based information used to develop climate-design information.

3 METHODOLOGY

This report is based on a series of 33 telephone interviews conducted with end users and providers of weather and climate data across Canada. As shown in Figure 3-1, the sample was diverse; interviewees represent varied fields of practice, organizations (federal, provincial, municipal, and private sector), regions of Canada, and relevant skills. The end users were mostly engineers, and they tended to be highly skilled in climate change issues. Appendix A and B feature themes discussed in the interviews.

To complement the interviews, a literature review was conducted to confirm or qualify the completeness of the interviews and to identify alternative solutions.

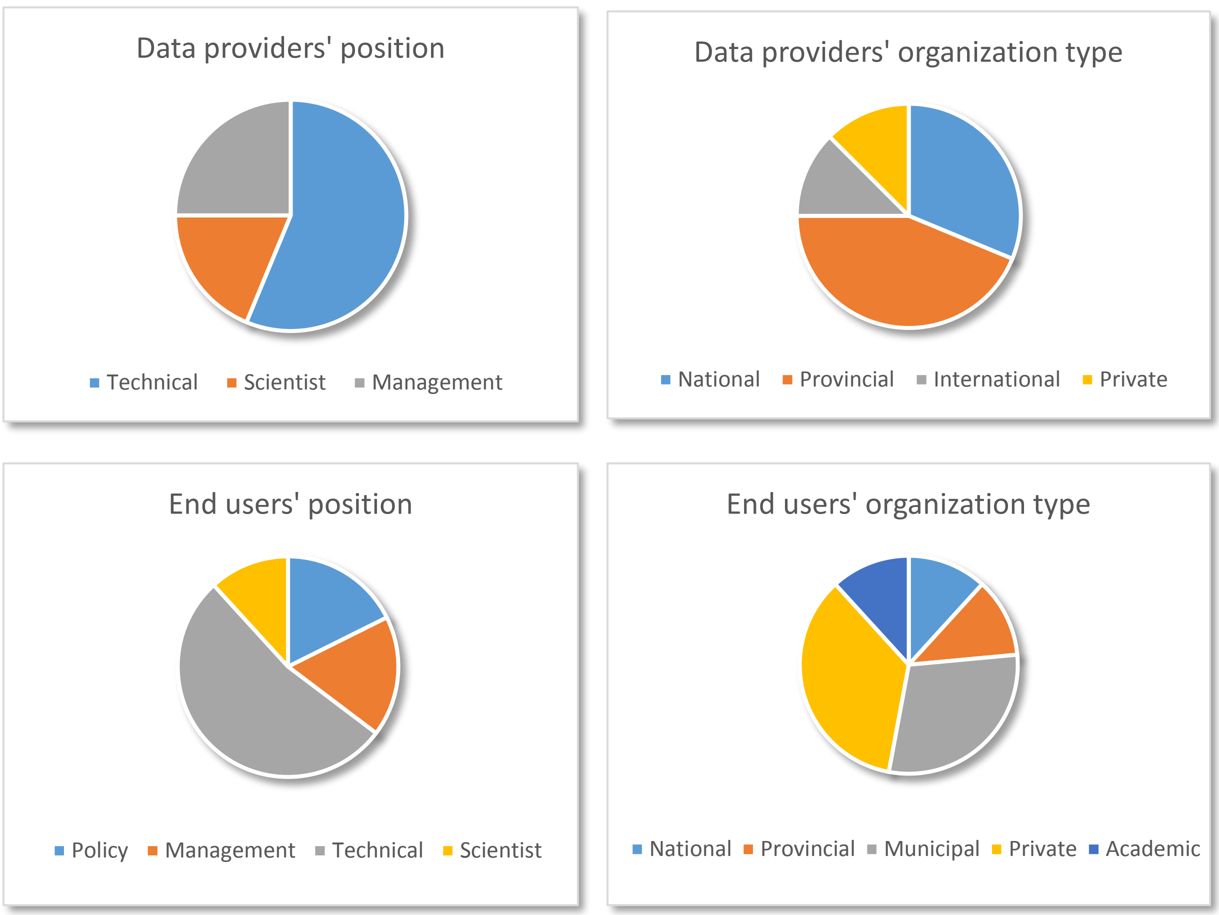

Figure 3-1 *Characteristics of the 33 interviewees contacted for this report: 16 data providers and 17 end users.*

4 WEATHER AND CLIMATE DATA

4.1 OBSERVED DATA

4.1.1 GLOBAL

The Global Historical Climatology Network (GHCN) is the main network providing daily variables of weather stations around the world. GHCN encompasses national networks, such as Environment and Climate Change Canada's (ECCC) network and provincial weather stations. The primary benefit of GHCN is that global climate information is available through one portal. However, data coverage for Canada has been limited in recent decades.

Weather Underground is another source of data mentioned in the interviews.

4.1.2 NATIONAL

At the national level, ECCC collects weather data across the country and is regarded as the authoritative expert and reference for weather and climate data. The department is respected for operating and maintaining a reliable weather network and for having collected data over many decades. In addition to data services, the department also provides weather forecasts, climate-model development and simulations projections.

Ocean Networks Canada was founded in 2007. It uses observatories to collect data about the oceans surrounding Canada. The collected data is "on physical, chemical, biological, and geological aspects of the ocean over long time periods, supporting research on complex Earth processes in ways not previously possible" (Ocean Networks Canada 2017).

4.1.3 PROVINCIAL AND TERRITORIES

Many provincial/territorial governments and government agencies also operate weather networks and sometimes share their data with ECCC; for example, Quebec's Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDELCC). Some of these weather data are not readily available because there are no web portals; the data must be requested via phone, e-mail or web form. Table 4-1 provides a brief, albeit incomplete, overview of the main weather networks across Canada.

4.1.4 MUNICIPAL AND WATERSHED BASIN

Populous cities, such as Montréal, Toronto and Vancouver, operate their own weather networks, mainly to track precipitation. These networks often feature large numbers of weather stations in relatively small areas. For example, the City of Montréal operates a network of about 50 rain gauges covering the Island of Montréal. In Ontario, conservation authorities operate weather networks at the watershed-basin level.

4.1.5 PRIVATE

Numerous private companies operate small weather-station networks, collecting and sometimes sharing data with partner organizations. These private networks represent only a fraction of all weather stations in Canada.

Hydro-Météo is a Québec company specializing in flood support, but it also helps to install and manage weather stations in some parts of the province. In Saskatchewan, Weather Innovations Incorporated (WIN) operates a private weather network for crop insurance purposes. Private weather stations in Canada can be accessed through this web portal: Weatherlink.com, an important independent global network, which posts data from many of these stations.

Finally, airport weather station records are not always available through ECCC. For example, there are several local airports, like Harbour Tower, Pitt Meadows and Boundary Bay in British Columbia that provide aviation-grade weather data by phone, or over aviation radio frequencies, but none of the data is recorded. Lack of quality control is a concern (Port of Vancouver 2017).

Table 4-1 *Weather Networks Across Canada Mentioned in Interviews*

Province / Territory	Weather Networks
British Columbia	Provincial Climate Data Set (PCDS).
Alberta	Alberta's Ministry of Agriculture and Forestry Alberta's Agriculture, Food and Rural Development's two weather station networks: DroughtNet AGDM and Irrigation Management Climate Information Network (IMCIN) Alberta's Ministry of Environment and Sustainable Resource Development Alberta's Ministry of Environment and Parks Alberta's Ministry of Transportation
Saskatchewan	Saskatchewan Research Council
Manitoba	Manitoba Agriculture weather network.
Ontario	Provincial Groundwater Monitoring Network (PGMN) Air Quality Health Monitoring
Québec	Ministère du Développement Durable, de l'Environnement et de la Lutte contre les Changements Climatiques (MDDELCC) Société de protection des forêts contre le feu (SOPFEU) Protection des forêts - Lutte contre les insectes ravageurs (SOPFIM) Hydro-Québec La Financière Agricole
New-Brunswick	New-Brunswick Natural Resources fire weather stations
Prince Edward Island	PEI Department of Agriculture and Forestry
Yukon	Wildland Fire Management Yukon

4.2 CLIMATE MODELS

4.2.1 GLOBAL

Numerical climate simulations generate knowledge about future climate states. During the 1950s and 1960s, researchers began to run computerized climate models (cf. Charney et al. 1950) to simulate atmospheric processes. Although the first models were crude by today's standards, their results roughly align with recent values, which put the warming associated with a doubling of CO2 concentrations at around 3.5°C. Global climate models (GCM, Table 4-2) simulate the entire planet's climate system by examining the system's five components: atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. Given computer limitations, modellers must use relatively low, horizontal resolutions of 150 to 300 km (current models for the last IPCC report (Flato et al. 2013)), depending on the complexity of the model and on available computing power. It is essential for simulations to be run for long periods of times – from centuries to thousands of years. Using higher resolutions is not possible within the GCM framework, as today's computers are not powerful enough. From the engineering perspective, such coarse resolution is problematic; precise information about location and time is needed. Local or regional scales are useful for engineering purposes. This is particularly true for severe weather events, such as wind gusts, snow loads and heavy precipitation, which are all driven by small-scale physical processes.

An additional use of GCMs is "reanalysis" – an objective method that combines a numerical model, usually a Numerical Weather Prediction (NWP) model, with historical observations to create a synthetic dataset covering the entire globe for a historical period. Using assimilation techniques (i.e. merging the reanalysis run with observations through mathematical equations), observations derived from numerous datasets, such as satellite and weather station data, are included in a reanalysis run. During a reanalysis simulation, the model assimilates observations at regular time intervals, forcing it toward an observation state.

The advantage of using reanalysis compared to weather observations is that the model simulates many more variables, such as 3D humidity, 3D pressure fields, and wind, that are available even at ungauged sites, as reanalysis generates information on regularly spaced computational grids. The resolution, however, can be low – typically between those of GCMs and regional climate models (RCMs) – which is not sufficient for proper simulation of extreme precipitation. In the next few years, new generations of reanalysis will consistently provide resolutions around 25 to 35 km.

Climate simulations and reanalyses are produced in several climate research institutions around the world, for example: Canadian Center for Climate Modelling and Analysis, Institut Pierre-Simon-Laplace, Commonwealth Scientific and Industrial Research Organisation, Danish Meteorological Institute, European Centre for Medium-Range Weather Forecasts (ECMWF) and The National Center for Atmospheric Research/University Corporation for Atmospheric Research (NCAR/UCAR). Most of the data are open source, free and distributed through portals (section 5.2.1).

Table 4-2 *Types of Numerical Models Used in Climate Change Studies*

Type	Resolution (km) (current generation)	Spatial Coverage	Use
Global Climate Models	150 - 300	World	Climate projections at low resolution

Regional Climate Models	20 - 50	Limited area	Climate projections at high resolution
Reanalysis	50 - 250	World	Historical climate reconstruction
Hindcast	1 - 300	World or Limited area, depending on the objective	Knowledge about specific event

4.2.2 REGIONAL

Since GCM climate information is usually low resolution, downscaling techniques need to be applied. Techniques for the production of finer-scale information can be divided into two main categories of downscaling: dynamical and statistical.

Dynamical downscaling is performed with an RCM (Table 4-2) that uses information from a GCM or reanalysis. By concentrating the entire computing power on a limited area of the globe, the RCMs can accommodate a higher spatial resolution. However, since their computational domain cover only a limited area of the globe, RCMs need climate information at their boundary to describe the evolution of atmospheric systems that flow into the regional domain. These conditions that drive the RCM are usually obtained from GCM simulations or model reanalysis. RCM resolutions are finer than GCMs and are usually between 20 and 50 km, when the domain covers the whole North American continent; higher resolution can be achieved by using a smaller domain. The highest resolutions, ~20 km, are achieved by only the latest generation of RCMs, available since 2012. As a result, there are only a handful of simulations available, and the uncertainty is not adequately sampled due to the lower number of simulations available. The main advantage of higher resolution is a better representation of small-scale features, such as local topography, lakes, varying types of vegetation and land-sea temperature contrasts. All of these factors can influence local precipitation patterns and can be important for engineering considerations.

Statistical downscaling approaches are based on the assumption that local and regional characteristics of observed climate can be extracted from large-scale climate variables. Various techniques can be used, such as multiple regressions, stochastic generators and neural networks, to establish statistical relationships between observed local conditions and predictors obtained from a GCM or RCM. Statistical downscaling relies on the hypothesis that statistical relationships established for the recent past will remain constant in the future. Statistical downscaling is a relatively inexpensive and quick approach compared to dynamical downscaling, but it is not as physically-based. It is important to highlight that even though statistical downscaling produces information at a finer resolution, it does not provide more information or higher precision and accuracy.

Similar to GCMs, RCMs are developed at numerous institutions around the world, and most institutions participate in the Coordinated Regional Climate Downscaling Experiment (CORDEX). Sponsored by the World Climate Research Programme (WCRP), CORDEX provides global coordination of Regional Climate Downscaling for improved regional climate change adaptation and impact assessment.

4.2.3 HINDCASTS

A hindcast is a specific application, inspired by reanalysis, used in: climate research and services; commercial and business applications, mainly in the oil and gas sector for offshore and coastal design and operational decisions; and for high resolution climate assessments (York University & Novus Environment Inc. 2017). Scientific and private companies use this technique to produce synthetic datasets of a specific event by creating an ensemble of possibilities. The hindcast simulations are usually initialized with a specific weather event or climate state for a short duration (e.g. weeks to a small number of years). Their objective is to gain hindsight about past extreme events and the probability of recurrence for the estimation of design values. These types of simulations are usually done by private companies, such as Novus Environmental Inc. (York University & Novus Environment Inc. 2017), Ocean Weather Inc. and by reinsurers such as Swiss Re.

Climate change is not included in hindcast applications, but will generally be taken into account in reanalyses produced over a historical period; for example, from 1979 to 2015.

4.2.4 CLIMATE SCENARIOS

Climate scenarios are defined as plausible future climate trajectories. They are constructed from climate simulations and are generally obtained by a post-processing method. The climate scenarios are available for variables with reliable observation records. The method involves merging observed historical climate information with future trends simulated by a climate model (Themeßl et al. 2012; Gennaretti et al. 2015). The scenarios provide a more tailored product than direct climate model outputs by leveraging the observed climate information into climate simulations. For example, the bias-corrected simulations (i.e. climate scenarios) can be used directly with impact models, which are calibrated against observed critical thresholds, as opposed to direct output from climate models that can present important biases.

a) Downscaling and Bias Correction

As mentioned, downscaling information to a local scale so that it may be relevant for engineers generally involves either dynamical or statistical downscaling. Once downscaled, the climate information contained in a GCM or RCM will have some bias arising from imperfect mathematical representations of the climate system; for example, the physical equations in a GCM and RCM are discretized on specific resolution grids, as opposed to reality, which occurs in a continuous fashion. Since not all physical processes are explicitly resolved at the GCM and RCM resolution, their outputs should never be compared directly with observations; instead, outputs must be corrected using a reference-observed dataset. This is known as bias correction. Numerous bias-correction techniques exist, and listing them is beyond the scope of this report. An excellent starting point for an exhaustive and critical overview of bias-correction techniques is Maraun (2016) and references therein. For reference purposes, Pacific Climate and Impacts Consortium (PCIC) has produced a large set of statistically downscaled data.

4.2.5 UNCERTAINTY AND VARIABILITY

Uncertainty in climate projections is typically associated with three factors:

- future anthropogenic emissions
- variety in model formulation
- natural climate variability (Hawkins & Sutton 2011).

Each source acts on different timescales and planning horizons, as shown in Table 4-3. For short-term planning horizons of less than 30 years, decision-makers must take natural climate variability into account. At this timescale, the climate signal is smaller than the natural climate oscillations envelope, while uncertainty from the climate model is moderate. For medium-term planning horizons of between 30 to 50 years, emissions scenarios and the climate model are the two main sources of uncertainty. For long-term planning horizons of greater than 50 years, the greatest source of uncertainty is the emissions scenario, followed by the climate model scenarios and natural climate variability. In this planning horizon, the climate change signal is stronger than the natural climate variability, but uncertainty is high because future greenhouse gases (GHG) emissions based on human activity are unknown.

Table 4-3 *Planning Horizons and Uncertainty Sources (adapted from Charron 2016).*

Planning Horizon	**Relative Importance of Sources of Uncertainty**			**Main Sources to Consider for Decision-Making**
	Natural Variability	**Emissions Scenario**	**Climate Model**	
Short Term (< 30 years)	***	*	**	Natural variability
Medium Term (30–50 years)	*	**	**	Emissions scenarios and climate model
Long Term (> 50 years)	*	***	**	Emissions scenarios

5 WEATHER AND CLIMATE DATA PROVIDERS

This chapter describes the current situation regarding weather data providers and climate services, and is based on a series of semi-directed interviews with observational-data providers. It looks at climate simulations, the entire data supply-chain, instrument deployment, weather-station network management, data dissemination, and value-added services that rely on weather and climate data.

The collection, distribution and quality control of data are mostly uniform across Canada, although variables differ somewhat. In coastal regions, for example, data are gathered about tides and waves, in addition to those related to temperature, precipitation, wind and snow load.

5.1 DATA COLLECTION AND OPERATION

5.1.1 MAIN PURPOSE OF CURRENT DATA COLLECTION AND INSTRUMENT DEPLOYMENT

The purpose of data collection varies widely across organizations and agencies, although it generally falls into two main categories:

1. **Climate characterization:** for the calculation of climate normals (ECCC), climate scenarios for users {Ouranos, Toronto and Region Conservation Authority (TRCA), OCC, PCIC}, Intensity-Duration-Frequency (IDF) curves and modelling needs (ECCC).

2. **Operational optimization:** for data to inform the management of watersheds and municipal infrastructure, such as for infrastructure placement and design of water and sewer systems. Other examples of real-time use of weather data include construction operations (helicopters, marine terminals), providing context for environmental surveys (e.g., a recent drought will affect plant phenology surveyed), and management of existing infrastructure, like dams.

Deployment strategies vary and are influenced by the purpose of data collection, as well as the specific goals of each organization.

Climate Characterization

Regional, provincial, territorial and national data-collection networks typically respect World Meteorological Organization (WMO) standards, and follow a long-term deployment strategy that involves maintaining stations equipped with the same types of sensors at the same locations for as long as possible. Operating out of the same location prevents new weather records from disrupting the homogeneity of an observational time series and causing an incorrect estimation of the trend for a given variable. In this way, climate characterization provides the context needed to understand rare extreme events and aligns more with the infrastructure-design domain.

Examples of data collection networks are: ECCC; Quebec’s Ministère du Développement Durable, de l’Environnement et de la Lutte contre les Changements Climatiques (MDDELCC); British Columbia’s Provincial Climate Data Set (PCDS); public organizations like Hydro-Québec, TRCA, cities, Financière Agricole du Québec ; and private organizations like Mesonet-Solutions.

Operational Optimization

Urban weather networks are an important source of weather data. These networks are usually spatially dense, as the heterogeneous nature of the urban landscape significantly modifies weather fields (Muller et al. 2013). However, most such networks have operational objectives. Populous cities, such as

Montréal, Toronto and Vancouver, maintain weather stations for operational purposes. The rain gauges at some of these stations have operated for more than 20 years, and their data could be used for an assessment of spatial and temporal variability (City of Montréal 2017). It is dubious whether or not such strategic deployment can be incorporated into climate characterization, as the operational optimization is geared towards answering operational questions; for example, to evaluate flow in a given urban canal (Direction de l'Expertise Hydrique du Québec 2017; City of Montréal 2017). Once these questions have been answered, the rain gauges might be deployed elsewhere to address another operational challenge, thus breaking the continuous record generally needed for scientific purposes.

The installation of urban weather networks follows international norms as closely as possible to reduce measurement uncertainty. However, some stations do not respect WMO standards because of the urban-space constraint—for example, they are located on the roofs of buildings-- which means that not all municipal weather stations can be used for the calculation of IDF curves (City of Montréal 2017).

5.1.2 MANAGEMENT, MAINTENANCE AND OPERATIONAL CHALLENGES

The high cost of maintaining weather stations jeopardizes data quality over the long term. The cost of a new weather station is often not prohibitive, but long-term operation and maintenance can require considerable investments (ECCC 2017a; Hydro-Québec 2017; Solutions Mesonet 2017). According to the operators interviewed for this study, a common maintenance schedule involves station inspections each year in spring and fall. The failure rate of weather sensors is low, but problems arise when snow blocks sensors. Other problems can be attributed to wildlife, vandalism and battery failure. Stations in remote locations that cease to function during winter often remain that way until spring, due to access difficulties. As a result, data are not captured for a period of time, potentially disrupting the establishment of long-term trends.

5.1.3 QUALITY CONTROL

Quality control (QC) in the weather and climate data supply-chain is of utmost importance to ensure measured variables remain reliable throughout time. The first step in the QC process involves checking that weather station sensors are of good quality, that the site and installation follow WMO standards, that site maintenance is adequate, and that data are properly transmitted to the central database. The QC protocols of most organizations involve both automatic algorithms and human interventions. Staff typically develop and apply algorithms that align closely with best practices from international organizations; for example, WMO, Météo-France and Oklahoma University. These methods assure that the entire supply-chain is reliable.

Since QC protocols can be competitive differentiators for organizations, details about protocols are usually shared only with partners and clients. However, the protocols feature the same general approach and best practices, such as the one developed by the Oklahoma Mesoscale weather network (Fiebrich et al. 2010). The reader is invited to consult Fiebrich et al. (2010) for a complete overview of the steps listed in Table 5-1, which represent the best practices of weather networks around the world. The reader can replicate best practices and develop appropriate protocols. Muller et al. (2013) describes other mesoscale networks in the United States.

Organizations apply the QC data to the entire data-time series using sub-hourly and daily values or daily values only (Hydro-Québec 2017). Some organizations collect data hourly, but need only daily values, and complete QC using aggregated values. This means that the non-QC data might be unusable for the calculation of IDF curves.

For organizations that reference stations for real-time or short-term operations, the QC is usually done only through automated tests. Data flagged as erroneous are not further investigated, and when they are, the objective of the verification is usually to understand and validate the proper operation of the automated tests. Verification also validates the importance of the data, in case of flood events, for engineering purposes and potential legal proceedings (City of Montréal 2017).

Table 5-1 *Overview of the Main Steps Involved in a Quality Control Protocol of Weather Data (based on* Fiebrich et al. 2010*).*

Category	Modules	Existing Standards	Considerations
General QC Considerations	Proper station siting Proper site maintenance Proper calibration of sensors Archival of the original data Use of standard time and observation units Use of similar instruments and configurations for sites Use of redundant sensors	WMO	Strategic and tactical choices
General Automated QC Tests	Range tests Temporal checks Spatial checks Like-instrument and internal consistency tests Adjustment tests Decision-maker for final automated QC flag	None	Location specific
Variable-Specific Tests and Considerations	Air temperature Air pressure Relative humidity and dew point temperature Soil moisture Soil temperature Rainfall Snowfall and snow depth Radiation Winds	None	Each variable has different constraints that need to be checked and are location-specific
Manual QC	After completion of automated-QC variable-specific tests, technician will check erroneous data	None Expert judgment	Counter-verification of flagged data through comparison with nearby stations or through human observation

General QC considerations, such as location and maintenance of weather stations, and calibration of sensors, can be found in the WMO-No. 8 publication, "*Guide to Meteorological Instruments and Methods of Observation.*" The guide is a "comprehensive and up-to-date [document] on the most effective practices for making meteorological observations and measurements." All significant weather networks in Canada with climate characterization ability follow this guide. During automated QC, data can be flagged as erroneous, but the raw (original) data are never deleted.

The general automated QC test is a suite of tests that detect potentially erroneous data by ensuring that recorded values are coherent. The range test looks at consecutive data and identifies any overly large ranges between them. For example, an hourly observation of 32 °C will be flagged as potentially erroneous when the previous observation was 5 °C. The spatial check ensures that weather stations located close to one other record similar values, consistent with the spatial fields of the variable; for example, the precipitation field is more heterogeneous than the temperature field. As a consequence, spatial checks are different for different variables.

The variable specific tests and considerations look at the physical coherence of recorded values and flag negative precipitation, overly high and overly low temperatures, and more.

The manual QC is essential to QC protocol because it is impossible to develop an automated algorithm that will always flag erroneous data with 100 per cent accuracy. Manual verification of erroneous data is necessary, both for a robust dataset and to validate automated tests.

Mesonet-Solutions is an important and relatively new player in second-party QC. Mesonet-Solutions, a non-profit organization, performs QC for numerous partners and clients. It follows the procedures described above through a partnership with the Oklahoma Mesoscale weather network (www.mesonet.org) and works with multiple clients and partners, including: Hydro-Québec, Rio Tinto, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ), la Financière Agricole and the Réseau météorologique coopératif du Québec (RMCQ). Most partners upload their data to Mesonet-Solutions; the QC procedure is done either by Mesonet-Solutions or its partner by remote connection; and then the data are sent back. Other organizations use the Mesonet-Solutions algorithm internally. By sharing a common QC process, these organizations can more easily share their data, confident that the same QC protocols were used.

5.2 DATA DISTRIBUTION

5.2.1 DATA PORTALS

Most organizations that collect climate data also distribute their data via one of several web portals that post raw and/or quality-controlled data. Timely access to reliable data and climate information is essential for reliable scientific knowledge and the ability to make informed decisions (Giuliani et al. 2017). Most of these portals suffer from limitations in that they are missing the information users need to utilize the data properly. Others post only partial lists of all hosted variables. The stand-alone nature of some websites means that many end users are not aware of their existence. Climate-data providers and engineers would benefit from a more efficient communication channel.

Additional data portals continually become available online, and practitioners become unsure about which portals provide credible information. This suggests a lack of available expertise about which datasets to use or avoid.

Other types of data include reanalysis and climate model simulations. These data are used by engineering firms and are sometimes needed for a more exhaustive climate change assessment. They are available through portals, such as a modelling centre portal like CCCMA or a project portal like Coupled Model Intercomparison Phase 5 (CMIP5) and CORDEX that host multiple model outputs.

a) Environment and Climate Change Canada (ECCC)

ECCC is the only organization to cover all of Canada and as such, is a leader in data provision. ECCC provides numerous types of data, such as hourly and daily weather observations, climate normals, weather-forecast model data and radar data. The dissemination of such diverse datasets is a challenge in itself, as each type of data has a unique set of constraints. To help meet this challenge, ECCC provides multiple ways to access its data, such as Datamart and the Environment and Natural Resources website.

From an end user perspective, this diversity can be overwhelming, and as such, a full list of all ECCC climate-data services would significantly benefit users. Technically inclined users find it easier to access ECCC databases by using coded scripts to efficiently submit queries (ECCC 2017a). A more user-friendly approach could increase levels of usage and dissemination (CBCL 2017).

b) Climate Simulations

There are multiple data portals for climate simulations, from specific modelling-centre portals to unified-project portals such as CMIP5, North American Regional Climate Change Assessment Program (NARCCAP) and CORDEX; the experiment protocol is shared between modelling centers. The unified scientific projects and their portals follow file-naming and data-storage conventions, making it easier for end users to handle large volume of data. As an example, ESGF is a:

> "…collaboration that develops, deploys and maintains software infrastructure for the management, dissemination, and analysis of model output and observational data. ESGF's primary goal is to facilitate advancements in Earth System Science. It is an interagency and international effort led by the US Department of Energy (DOE), and co-funded by National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), and international laboratories such as the Max Planck Institute for Meteorology (MPI-M) German Climate Computing Centre (DKRZ), the Australian National University (ANU) National Computational Infrastructure (NCI), Institut Pierre-Simon Laplace (IPSL), and the British Atmospheric Data Center (BADC)" (ESGF 2017).

c) Other Data Portals

Pacific Climate Impacts Consortium (PCIC)

"The PCIC data portal makes the data that PCIC collects and produces publicly available with an open license (PCIC 2017a). The portal provides access to BC Station Data, High-Resolution Climatology and Downscaled Climate Scenarios" (PCIC 2017a).

Ontario Climate Change Data Portal (CCDP)

"Ontario Climate Change Data Portal is launched to ensure technical or non-technical end users, such as municipalities and the private sector, have easy and intuitive access to the latest climate data over the Province of Ontario, Canada." (CCDP 2017).

Climate Change Hazards Information Portal (CCHIP)

The Climate Change Hazards Information Portal is a web-based tool developed by Risk Sciences International that aims to integrate climate change impacts into the planning and decision phase of organizations. Using tailored algorithms, its objective is to provide information to a wide range of end users looking for specific climate indicators with a user-friendly interface (CCHIP 2017).

5.2.2 COORDINATION WITH OTHER WEATHER AND CLIMATE DATA PROVIDERS

a) Network of Networks

ECCC is currently driving a project to establish a Network of Networks (NoN). While the project is in its early stages of development, some key features are worth highlighting. The project aims to gather all available data from all Canadian partners and entities--from civilian to municipal, regional, provincial/territorial and national levels, without restrictions. Most data are controlled for outliers or unrealistic steps between measurements using the automated QC protocols (section 5.1.3). A problem with this approach is the variety of data reliability in a single database. The mixing of both levels of data standardization might skew results. For example, one interviewee argued that the homogenization process done at ECCC on precipitation records substantially influences some indicators, such as the annual water budget for watersheds. In other words, reducing sampling uncertainty, by adding as much data as possible, increases measurement uncertainty because it results in a mix of QC and non-QC data. However, it can be easily argued that this trade-off is beneficial, as previously ungauged sites stand to benefit much more from new data than a gauged site would suffer from additional measurement uncertainty. This is particularly true for precipitation.

NoN would be a tremendous achievement for data dissemination (ECCC 2017a) and would include multiple weather data sources:

- Airport data (NAV Canada)
- National Defence (mostly northern stations)
- Alberta’s agricultural network
- Federal and provincial forestry ministries
- Pan-Am Games weather stations
- Réseau météorologique coopératif du Québec (RMCQ)
- Community Collaborative Rain, Hail and Snow Network (CoCoRaHS)

b) Réseau météorologique coopératif du Québec (RMCQ)

The main meteorological network managers in Québec – MDDELCC, ECCC, Ministère des Forêts, de la Faune et des Parcs (MFFP), Hydro-Québec, Rio Tinto and la Société de protection des forêts contre le feu (SOPFEU) – cooperate through RMCQ. The choice for sensors, and the transmission and manipulation of data, are based on pre-existing best practices used by ECCC.

The network of nearly 325 stations across Quebec enables members to exchange real-time meteorological data that meets pre-established quality standards. The data are posted in a simple and consistent format on each partner’s website; access is restricted to RMCQ members through password-protected file-transfer protocol (FTP). This enables partners to use the information according to their specific needs. Only uncorrected data – never QC data – are shared at 20 minutes past the hour. Each partner does their own QC, and most use the Mesonet-Solutions QC procedure.

5.3 CLIMATE SERVICES PROVISION

Climate services tailor climate-data provider information to meet the needs of end-users (Huard et al. 2014). These services cover a wide range of expertise and products: from quality-controlled weather data (acting as a hub for climate data providers, as well as adding their expert judgement on the general adequacy between datasets and end user needs); data summaries and statistical analyses; bias-corrected future climate simulations; future hydrological streamflows for different watersheds; spatial analogs; and expert advice delivered with ongoing support (Huard et al. 2014). ECCC plays an important role in providing climate data to end users by generating climate products such as IDF curves; climate normals; and data for building codes, like wind pressure, snow load, and other variables. Recent multidisciplinary projects led by organizations such as PCIC, OCC and Ouranos have brought together scientists and end users. These organizations bridge gaps between climate simulations and end users, and provide other types of climate services.

Numerous climate services providers deliver raw data, as well as tailored products to end users. The providers named in the interviews include:

- ECCC
- University of Western Ontario
- University of Waterloo
- University of Regina
- Ouranos
- PCIC
- OCC
- Private organizations (RSI, Novus Environment Inc., Amec Foster Wheeler, etc.)

Most Climate Services Providers (CSPs) use data collected by ECCC and other suppliers, and rely on the suppliers for QC. CSPs can also analyze datasets to identify their strengths and weaknesses – of great importance for end users (Huard et al. 2014).

Another valuable CSP offering is climate simulations (e.g. CMIP3/5, CORDEX), an essential component of climate change assessments. Modelled data can be confusing for most end users who view climate models as black boxes (i.e. limited descriptions of the choices made by the modelling group, of the strengths and weaknesses of a given model, of the types of model best suited to particular projects, etc.). Engineers interviewed for this study felt that there is a general lack of tailored documentation about climate models and, more specifically, on how to use their outputs.

5.3.1 CLIMATE SCENARIOS

Climate scenarios are a “plausible representation of future climate that has been constructed for explicit use in investigating the potential impacts of anthropogenic climate change” (Mearns et al. 2001). Methods for the construction of climate scenarios vary widely, from direct use of GCM outputs, downscaling of large-scale fields from GCMs and RCMs to a higher resolution, and spatial analogs.

Downscaling to finer resolution is often necessary to provide more regional and local information. This is particularly important for precipitation information generated by climate models. There is no standard for downscaling, in part because techniques are chosen on a case-by-case basis. Research on downscaling techniques is a vast and important topic for climate scientists. Some methods, however, are more common than others. For example, aligning climate simulations with an observed time-series is often done using a Quantile-Quantile probability mapping method – a method that encompasses numerous different implementations. In the absence of consensus about which method to apply, practitioners and scientists use any technique available in the scientific literature. Different techniques produce slightly different results, contributing to uncertainty.

Building a climate scenario at the regional or local scale involves many steps:

- Downscaling large-scale information from GCMs through a dynamical or statistical approach

- If needed, interpolation of global or previously downscaled information from the dynamical or statistical method onto a regular high-resolution grid (or single point) when a reference dataset is available
- Statistical-bias correction of the climate simulation (e.g. Quantile-Quantile mapping) against the reference dataset.

Statistical-bias correction is a necessary step for integration of climate change information into impact models, vulnerability assessments or infrastructure design. It involves comparing climate simulations against a reference dataset; the quality of the subsequent bias correction directly relates to the quality of the reference dataset. The choice of reference dataset is, to a certain degree, subjective, and a variety of available reference datasets can be used to produce results with generally small differences. Differences may be large in some cases, depending on the climate variable/indicator and the area considered; for example, when extreme daily precipitation in areas without observational stations available to generate a gridded dataset is used as a reference. Moreover, natural variability might lead to inaccurate estimates of climate conditions over a given sampling window (e.g. 1980-2010). In other words, if the climate simulations are fitted with an imperfect climatological record, there is a risk of under or overestimating extreme weather and climate conditions. Bias-correction techniques make it possible to use climate-model outputs in impact models that are calibrated with observed data, which is often the previously referenced dataset.

5.3.2 DERIVED CLIMATE DATA

Derived climate data involve the scientific process of transforming data, such as weather observations, climate simulation outputs, climate scenarios, and others, into practical products. The main players are ECCC, and universities – especially universities with engineering departments, like the University of Waterloo and University of Western Ontario – and CSP organizations, like PCIC, Ouranos, RSI, Novus Environment Inc. Each climate indicator, like an IDF curve, has its own unique set of challenges.

a) Rainfall Intensity-Duration-Frequency curves

An IDF curve is a representation of the probability that a rainfall event of a given intensity will occur for a specific duration at a given location. IDF curves are an essential tool for taking rainfall into account during design planning and management (section 6.2.1). However, current methodologies for IDF computation use existing records and implicitly assume that climate is stationary (i.e. there is no climate change signal). Climate change make this a strong assumption, especially as we look further into the future. Some research-level methodologies under development include the climate change signal; for example, Simonovic et al. 2016. Access to accurate information about high-frequency rainfall amounts can be problematic (City of Montréal 2017). For example, ECCC collects precipitation measurements sub-hourly with tipping-bucket rain gauges, but the resulting data are not easily accessible.

A common sentiment expressed in the interviews was that ECCC updates of IDF curves are not quick enough for engineering needs. As a result, engineering firms, municipalities, utilities and researchers find they need to do their own calculations, based on the latest available data and methodologies. This opens the door to non-standardized IDF curves. As the number of groups producing IDF curves has increased in recent years, so too has the confusion among users, who often lack the expertise needed to know which IDF curve to use.

Other reasons for the increase in IDF suppliers are listed in Simonovic et al. (2016).

- As the spatial heterogeneity of extreme rainfall-patterns becomes better understood and documented, a stronger case is made for the value of "locally relevant" IDF information.

- As urban areas expand, watersheds generally become less permeable to rainfall and runoff because of land use modifications throughout the lifecycle, and many older water systems fall increasingly into deficit and fail to meet their performance targets. Fully understanding the magnitude of these deficits requires information on the maximum inputs (extreme rainfall events) that drainage systems must contend with.
- Climate change will likely result in an increase in the intensity and frequency of extreme precipitation events in most regions (IPCC 2012).

In addition to the lack of timely, updated IDF curves, there is limited information about methods to integrate climate change into IDF curves, highlighting the need for a framework of documented and reproducible results.

5.3.3 SPATIAL MODELS

Spatial models are derived from observations at weather stations and provide information on a grid. An advantage of this method is its capacity to create information about specific locations where no observations are available, which could be useful for engineers (SCC-Ouranos Workshop 2017). The accuracy of the gridded end-product relies on the proximity of weather stations to the specific location; for example, if there are no weather stations near the location, spatial models will have important errors, although the errors can be both documented and estimated. Spatial models can also create information for a specific region, such as a watershed or city. In other words, spatial models can be used to fill in missing data and estimate levels of uncertainty about weather observations. The main limitation of spatial models is the lack of density of stations. To capture the spatiotemporal variability of precipitation processes, an additional order of magnitude in spatial density is likely needed {Natural Resources Canada (NRCan) 2017)}.

Multiple methods exist to create spatial information, such as Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly et al. 2008), Canadian Precipitation Analysis (CaPA), Optimal Interpolation and ANUSPLIN software. The latter was frequently referenced in the interviews and is currently used by Canadian Forest Service and National Resources Canada for interpolation of noisy multivariate data. The engine behind this software is based on mathematical surfaces (i.e. thin plate smoothing splines) that represent an approximation of the unknown surface related to the weather observations. From these mathematical surfaces, grids are extracted of 10 km resolution, with comprehensive statistical analyses, data diagnostics and spatially distributed standard errors.

Spatial models can also be used to provide data at a higher resolution, such as grids of resolution greater than 10 km, which are often useful for engineering projects. However, at such fine resolutions, there are data-management issues, mainly in terms of the large volumes of data, but also in terms of transfer and processing. Hence, these high-resolution models can be hosted only on the user's server and cannot be archived at National Resources Canada due to storage limitations (NRCan 2017).

5.3.4 DESIGN LOADS

Inherent difficulties exist in the conversion of weather and climate data into loads in building codes. The granularity needed by the engineers for an adequate design is somewhat incompatible with the granularity offered by weather and climate data; for example, if wind pressure is needed for an infrastructure inside a valley, and the closest weather station is outside the valley, conversion of the weather station wind records into relevant wind pressure for the infrastructure will have to be done using judgment calls based on existing expertise (ECCC 2017b). Such judgment calls are checked against findings of other experts to avoid wrong estimation of loads (Morris 2017; ECCC 2017b).

5.4 OPPORTUNITIES FOR DATASET IMPROVEMENTS

5.4.1 AVAILABILITY OF WEATHER VARIABLES

Frequently mentioned by interviewees was the topic of sub-hourly precipitation data. In the past, users could access records of rainfall in five-minute increments from ECCC, one month following the recording. Currently, it is much harder to access this type of data; only daily values are available in a timely manner (City of Montréal 2017). As such, a number of interviewees expressed concerns about the standardization of sub-hourly precipitation data (City of Montréal 2017) and raised issues of accessibility.

Identifying the type of precipitation is a concern among engineers; for example, snow load needs to be estimated for infrastructure design. Beginning in the 1980s, many weather networks became automated; automated weather stations are known to estimate precipitation type (liquid, solid, freezing rain, sleet) less reliably because they report total precipitation and not snowfall data. While there are methods to convert precipitation to snowfall based on temperature, these methods are less reliable at temperatures near 0 °C. Many interviewees mentioned that one of the biggest challenges for snow load estimation is that measures of snow water equivalents are not recorded (Morris 2017). New sensors used by Hydro-Québec (GMON instrument – Gamma MONitoring) could help improve the accuracy of snow-load estimation. The GMON sensor estimates snow-water equivalents directly. When combined with a measurement of snow depth by a SR50 sensor, a more robust estimation of snow density can be achieved (Hydro-Québec 2017). Finally, ECCC does not have timely access to relevant snow-load data from the provinces, territories and other organizations, making estimation work difficult (ECCC 2017b; Morris 2017).

5.4.2 CONFIDENCE IN CLIMATE VARIABLES AND PROJECTIONS

Engineers work on specific projects, such as bridges, dams, and sewers, for which they need regional and local data. With a low density of stations, historical records of extreme events might be substantially influenced by spatial-sampling errors, creating uncertainties about actual rainfall extremes for a given region. Since the physical processes of precipitation, snow and wind are mostly linked to localized processes, the current density of weather-stations network does not accurately capture data about these key variables. Furthermore, the low density of stations means that large portions of Canada are not well covered. This can lead to sampling errors; for example, an extreme event occurs, but no station records it.

In addition to spatial sampling, another source of error is temporal. What time period must a record cover for an engineer to be able to accurately calculate return periods? For the calculation of a climate normal, the WMO and ECCC recommend 30 years. In some cases, however, periods of 10 years are used (Morris 2017; ECCC 2017b). Basing the likelihood of a 1-in-50 years event on a 10-year sample introduces a great deal of uncertainty. Currently, there is uncertainty associated with historical data, as confidence intervals are calculated but not transferred to various building codes (Morris 2017; ECCC 2017b). It is worth adding that WMO climate-normal standards are designed for average conditions, but not for extreme values. Establishing minimum periods for the calculation of return periods might be an important consideration.

In addition to intrinsic uncertainty associated with climate projections, bias-correction methods can be prone to what is called inflation issues (Maraun 2013; PCIC 2017b); for example, when the future corrected value of precipitation in climate projections reaches amounts well outside of historical observations. This is mostly caused by a mismatch between climate-model outputs and the observed-reference dataset for a common historical period.

Finally, assessment of the scientific confidence of the different variables is documented in numerous reports (IPCC 2013; Ouranos 2015; IPCC 2012).

5.4.3 DATA SHARING

Data from small networks, like those belonging to municipalities and conservation authorities, are shared with provincial/territorial and national networks on an *ad hoc* basis. Sharing datasets poses important technical and scientific challenges. For example, formats for raw data may differ. To mix formats effectively requires a common technical framework and the cooperation of the network owner. Differing QC protocols might also cause problems; QC standardization would be helpful.

In terms of dissemination, many interviewees mentioned confusion caused by multiple data portals and the lack of appropriate documentation.

5.4.4 REMOTE SENSING DATA

Some potentially valuable sources, such as radar and satellite datasets, are not incorporated into most climate products and represent an expressed need (SCC-Ouranos Workshop 2017). While there are some inherent difficulties associated with the use of these data, adequate expertise exists to overcome these difficulties and correctly interpret them. ECCC currently deploys new radars through the WES Renewal program to upgrade all Canadian radars to dual polarization. The advantages of the new radars include a theoretical improvement in the accuracy of precipitation estimates and the ability to discern between heavy rain, hail, snow and sleet. However, some interviewees expressed doubt that radar data can be reliably incorporated into climate research without more QC.

5.4.5 DEALING WITH UNCERTAINTY

A common concern among data users is the ability of climate models to adequately simulate physical variables. Some users have little confidence in climate projections; others trust the projections but consider their effective integration to be the main problem. Procedures should be standardized. This is particularly important, as end users do not always acknowledge the uncertainty, and CSPs do not always know the specific requirements of engineers (TRCA 2017).

5.4.6 ENSEMBLE SELECTION

A common question raised by interviewees was: "What is the best simulation ensemble for a given variable, region, climate phenomena and timescale for impact analysis?" Climate-model simulation selection is generally done prior to an infrastructure planning phase. The selection of an appropriate ensemble is often difficult for engineers, due to the great variety of available models and resolutions available. Many choose shared portals, such as ESGF, CORDEX and NARCCAP. However, these portals do not host climate-scenario data. Climate scientists recognize the potential dangers of comparing the direct outputs of climate simulations to historical observations without proper downscaling and bias correction. This potential danger is less familiar to many engineers.

5.4.7 DOWNSCALING METHODS AND BIAS CORRECTION

The lack of consensus for effective strategies to convert and downscale climate projections for short-duration, localized precipitation events is challenging. Universities and research groups use different techniques for downscaling information; there is no coordinated discussion at the national or provincial/territorial levels about acceptable standards or practices. Common approaches are needed to decide which downscaling techniques to use for precipitation, wind, snow and temperature so that users do not rely on inadequate techniques or undertake this time-consuming task themselves. The downscaling method may need to be tailored to a particular purpose.

6 ENGINEERING PERSPECTIVES

This section examines the main challenges facing engineers seeking to incorporate climate change information into the design of infrastructure. Section 6.1 describes the climate data available and its application by engineers; section 6.2 examines the use of information during infrastructure design; and section 6.3 reviews the specific challenges faced by engineers.

6.1 WEATHER AND CLIMATE DATA APPLICATION FOR INFRASTRUCTURE DESIGN

6.1.1 TYPES AND SOURCES OF DATA

Several types of hydroclimatic data are used in the design process of Canadian infrastructure. Table 6-1 shows the type of data, variables, indicators and sources. Table 6-1 is a non-exhaustive list of the data currently used by engineers.

Most engineers use observed data and climate indicators derived from observed data, for the design of infrastructure (SCC-Ouranos Workshop 2017). The use of more specialized products, like homogenized data, radar data, hindcast data, reanalyses data, and climate projections and its derivatives, remain marginal (SCC-Ouranos Workshop 2017).

Observed data and climate products used for infrastructure design in Canada are mostly drawn from ECCC. It is clear from conducted interviews that provincial/territorial and private weather data and products are not used as commonly as national data. Climate Services Providers (CSPs) vary considerably and include private firms, universities and research centres.

The types of data vary across sectors of engineering practice. Data used at the operational level are quite different from those used at the design level; for example, use of radar data is more common at the operational level. Note that data used at the operational level are not listed in Table 6-1, as the report focuses on data used for infrastructure design.

6.1.2 CONFIDENCE IN DATA PROVIDED

This section addresses the confidence of engineers in the data provided to them. The confidence of climate scientists in different types of data is addressed in section 5.4.2.

a) Observed Data

Engineers generally have confidence in data provided at the national level, such as from ECCC, and Fisheries and Oceans Canada. ECCC is an authoritative CSP and most engineers trust ECCC's observed data and climate products derived from these data (Government of New Brunswick 2017; AME Group 2017; Golder Associates 2017; City of Montréal 2017). The exception is IDF curves, as explained in section 6.3.1a. Engineers will still carry out QC tests when they start using new data to make sure there are no biases or incoherencies (CBCL 2017; Golder Associates 2017).

The confidence level drops when incorporating data from municipalities and private organizations, due to a lack of knowledge of the data-collection and QC processes that these entities apply (Amec Foster Wheeler 2017; CBCL 2017).

Table 6-1 *List of Weather and Climate Data Currently Used by Engineers for the Design of Infrastructure.*

Types of Data	Variables / Indicators	Climate Service Providers and/or Specific Products
Observations	Precipitation	ECCC In-house
	Wind	ECCC
	Evapotranspiration	In-house: Generated with other variables
	Snow cover/Snow water equivalent	Public database In-house
	River flow	ECCC Provincial/territorial entities In-house
	Ocean level	Fisheries and Oceans Canada
Homogenized Data	Temperature	ECCC
	Precipitation	ECCC
Observation Derivatives	IDF curves	ECCC University of Western Ontario University of Waterloo In-house
	Snow loads	United States: US Army Corps of Engineers United States: State entities Canada : ECCC/Building code
	Wind loads	ECCC/Building code/CSA Standards
	Precipitation loads	ECCC/Building code/CSA Standards
	Ice loads on structures (towers, transmission lines, overhead systems)	ECCC/CSA Standards
	Ice loads in river (thickness and density)	Building code
	Solar radiation intensity, diffuse and direct, level of cloud cover, wind speeds, wind direction, outdoor dry-bulb temperature and relative humidity.	Canadian Weather Energy and Engineering Data Sets (CWEEDS files) Typical Meteorological Year (TMY files)
	Waves	Numerical models run in-house such as Mike21
	Peak discharge	Numerical models run in-house such as PCSWMM In-house statistical analysis
Radar Data	Precipitation data	ECCC Private firm
Hindcast Data	Multiple variables coming from climate models	United Kingdom: Private firm (OceanWeather) & Met Office
	Winds and waves for the Atlantic Basin	ECCC (MSC50)
Climate Projections	Precipitation Wind Temperature Sea ice Water levels	CMIP5 project CMIP3 project NARCCAP project Regional Climate Models Large ensemble
Climate Projection Derivatives	IDF curves	University of Western Ontario
	Sea-Level Rise	Fisheries and Oceans Canada Global Sea Level Observing System (GLOSS) Intergovernmental Oceanographic Commission (IOC)
	Precipitation	In-house: Clausius-Clapeyron equation
	Temperature and precipitation indices	PCIC Ouranos Private firms: RSI, Amec Foster Wheeler
	Solar radiation intensity, diffuse and direct, level of cloud cover, wind speeds, wind direction, outdoor dry bulb temperature and relative humidity.	University of Southhampton: Climate Change World Weather File Generator for World-Wide Weather Data

b) Climate Change Data

The level of confidence in climate-data projections, and in products derived from them, varies considerably among the engineers interviewed. Some consider climate models to be "black boxes," and the inherent uncertainty of simulations based on climate models creates a degree of mistrust. The lack of appropriate resources, such as documentation, reinforces the black box analogy. The guide created by Charron (2016) can be a good resource to inspire greater confidence in climate-model projections. Some engineers have, however, demystified climate models and are now comfortable with climate change projections. They understand that climate models are sophisticated, yet imperfect, and manage to find practical applications for them (section 6.2.2).

The level of confidence also varies depending on the climate-data source. Some engineers say they are overwhelmed by the amount of data and publications available on climate change. In this context, engineers would benefit from practical guidelines. Engineers would also benefit from a working relationship with a climate services provider. Two good examples of such collaborations exist between Metro Vancouver and PCIC (Metro Vancouver 2017), and the internal collaboration among staff at Amec Foster Wheeler (2017).

The level of confidence also relates to the state of knowledge of climate scientists concerning different variables, as explained in section 5.4.2. Confidence in temperature data is highest, while confidence in data about precipitation, wind, freezing rain and sea-level rise is lower (Engineers Canada 2017a).

The level of confidence required by engineers to include particular data in an analysis depends on the use case. Lower levels of confidence are tolerated in risk-assessment reports (section 6.2.2e (Amec Foster Wheeler 2017) or when data are used to compare two options (section 6.2.1b) (AME Group 2017). In those cases, the data will be used, even if climate scientists have little confidence in them. Higher confidence levels are needed when data are used for design purposes, especially when security and cost matter (Amec Foster Wheeler 2017).

6.1.3 METHODOLOGIES FOR QUALITY CONTROL

Engineers usually perform basic quality control (QC) tests when using new data. As confidence in the data grows with usage and time, QC tests are not carried out systematically. The nature of QC testing varies with data type. When working with a time series, for example, comparisons with neighbouring weather or gauging stations will be completed to identify potential discrepancies. Data missing from a series will be replaced with data from neighbouring stations or from a multi-annual average. Before computing annual statistics, years with more than a certain percentage of missing data will be removed. When computing annual statistics, years when more than 5 to 7 per cent of data are missing will be eliminated (Golder Associates 2017; CBCL 2017). These methods follow best practices for working with observed data.

Some engineers have started to use homogenized/rehabilitated precipitation datasets from ECCC (Mekis & Vincent 2011; Vincent et al. 2002), as shown in Table 6-1. However, it is not a common practice, as the dataset is not well known outside the climatological community. There are also questions regarding homogenized data, such as, whether they are more or less representative of past conditions. For example, homogenized time hydro-climatic series yield significant differences (section 6.2.1a), as they address a common issue; weather stations tend to underestimate the first millimeters of a precipitation event. The difference in water balance can be 20 to 30 per cent higher with the use of homogenized data (Golder Associates 2017). Even if this product is documented through scientific articles, engineers call for better guidelines in the use of such data.

6.1.4 METHODOLOGIES USED TO ACCOUNT FOR REGIONAL/LOCAL CONDITIONS

Engineers may have to design infrastructure for locations with little or no record of observed data or observations derivatives. This can be less of a problem for comparative studies of design options (cf. section 6.2.1b). To account for missing data, engineers will calculate climate indicators, such as IDF curves, using data from the nearest ECCC station or multiple nearest stations. IDF curves are not calculated systematically at every weather station – some lack tipping-bucket rain gauges. Many engineers would rather calculate their own IDF curves using data from nearby weather stations than rely on pre-computed IDF curves based on other stations. When the record does not cover a long enough period of time, neighboring stations will be considered (Golder Associates 2017).

Private engineering firms may deploy river-gauging stations when working with very small watersheds. These gauging stations record data for one or two years before the project design is completed. These data are used during the calibration process of the hydrological model (section 6.2.1a) (Golder Associates 2017). Using such small records can be problematic, especially in areas having a high inter-annual variability and cannot be considered best practice. However, project spans are often short, and no workaround exists to gather the needed data.

Engineers might use hindcast or reanalyses data when no reliable observations exist. For example, ECCC's model MSC50 has generated information on waves and wind on Canada's Atlantic coast for the last 60 years (CBCL 2017).

6.2 USE OF CLIMATE INFORMATION FOR INFRASTRUCTURE DESIGN

6.2.1 INTEGRATION OF HISTORIC CLIMATE INFORMATION

a) Design Parameters for Infrastructure

Climate information is integrated into the design of infrastructure via design parameters. The nature of such parameters and their provenance depend mostly on the sector of interest, infrastructure type and best practices. Interviewees described the predominant climate-dependent design parameters used by different sectors, as listed below.

Buildings and Structures

This sector includes above-ground structures, such as buildings, pylons and bridges.

For buildings, design parameters such as wind, snow and rain loads are considered for the structural resistance of a building. These parameters are integrated into equations for basic designs or into a structural numerical model for more complex designs. Such equations and models are used to determine the individual characteristics of each structural element. Building codes prescribe the loads that these structural elements must meet.

In heating, ventilation and air conditioning (HVAC) systems, design parameters such as diffuse and direct solar-radiation intensity, level of cloud cover, wind speeds, wind direction, outdoor dry-bulb air temperature and relative humidity are also prescribed in the building code and vary by location.

For bridge design, engineers need information on a river's peak discharge. This parameter can be obtained through several methods, as explained in the next section, *Water Resources Infrastructures and Tailings Storage Facilities.* Peak discharge will be used in a hydraulic model to generate information about water levels and velocities at the bridge site, in order to design the freeboard above the river and the width between pillars. To compute the load, engineers also need information about the strength and thickness of ice that pushes on bridge pillars.

Water Resources Infrastructure and Tailings Storage Facilities

This sector includes underground and aboveground water-management structures, such as culverts, sewers, aqueducts, spillways, dams, and levees. It also includes tailings-storage facilities and all types of infrastructure located near rivers, as their design parameters are similar.

Peak discharge is a design parameter of interest for several types of infrastructure in this sector. Methods of obtaining peak discharge vary by type of infrastructure and level of engineering expertise. The period of return of peak discharges varies based on the potential consequences of a complete failure. For example, the period of return for culverts in New Brunswick is typically 1-in-100 years, while the period of return for spillways is typically much higher (Government of New Brunswick 2017).

Peak discharge can be obtained either through statistical analysis of nearby flow gauges; parametric relations (e.g. rational method); the runoff curve number (CN) method; or with runoff/hydrologic models. Peak discharge can be used directly to design basic infrastructure, such as small culverts. For more complex designs, engineers will use hydraulic models. For example, a hydraulic model is used to determine the level of water during a flood to establish the extent of flood zones. Hydraulic models are also used to design sewage systems; they provide information on the flow in the system with peak discharge at multiple entry points.

Weather data is needed to determine peak discharge. IDF curves are used as a basis for several of the cited methods. With runoff/hydrological models, engineers can use IDF curves or other types of data. Typically, data about observed precipitation, snow and river flow can be used to calibrate the model. Once calibration is complete, engineers can run precipitation scenarios using multiple sources, such as observed data, synthetic precipitation data or radar data, to obtain information on peak discharge.

Specific norms, standards and best practices vary by province and territory. Ontario and Quebec, for example, base sewer design on IDF curves. The curves are fed into parametric equations or runoff models to determine peak discharge and design sewer networks. In Ontario, once a network's base design is completed, it must be validated with historical storms, such as the intense 1954 Hurricane Hazel storm that struck the Greater Toronto Area. In Quebec, this validation phase is not mandatory.

Other design parameters related to climate come into play during the design of infrastructure in this sector. Low flows are important in the design of water intake for water-supply systems. Winds are also important to calculate the height of waves and seiches (the phenomenon of strong steady winds causing the inclination of a body of water) for the safety of dams, levees and tailings-storage facilities.

Coastal and Oceanic Infrastructure

This sector includes coastal infrastructure, such as ports and erosion-protection structures, along coastal cities. It includes oceanic structures, like breakwaters and drilling platforms.

Many design parameters come into play when designing coastal and oceanic infrastructure, such as water levels, tide cycles, storm surges, waves, currents, and winds. Information on these parameters is site specific and sparse. Advanced climate products are used in this field of practice to provide information for climate parameters.

Numerical models can be used to provide information on coastal water levels, storm surges and waves. Tide gauges are used in the calibration of these models.

Hindcast products are also used in this field of practice. ECCC's model MSC50, for example, has generated information about waves and winds on Canada's Atlantic coast for the last 60 years. Oil and gas organizations use regional climate-model hindcasts for drilling platforms and coastal installations. Hindcasts provide historical, high-resolution synthetic datasets for many variables. Oil and gas companies also use large ensembles of hindcasts and sometimes re-initialize the same model 10,000 times to better evaluate the risk of tropical cyclones (MetOffice 2017).

Transportation Infrastructure

This sector includes all infrastructure related to the transportation of people, such as roads, highways and train systems. It also includes infrastructure used for other types of transport, such as pipelines and electricity networks.

Climate-related design parameters for this practice sector may be based on established practices not linked to climate data; for example, the preferred temperature for railroad tracks in Canada is 90 °F (32.2 °C). This temperature is used to evaluate the dilatation of tracks during heat waves to prevent buckling. Track temperatures are influenced by ambient temperatures, which vary across Canada, but best practices demonstrate that 90 °F works fine for the entire country. Warmer countries use higher temperatures: South Carolina uses a preferred temperature of 100°F (37.8 °C).

b) Servicing Multiple Needs

Climate-design parameters are set to ensure the safety of people. Other economic, aesthetic or comfort considerations can be integrated to modify these design parameters. For example, although a building has to meet a minimal insulation value based on the building code, a client might want better insulation to reduce heating and cooling costs. Engineers will typically carry out a relative analysis, where the base scenario, minimal insulation, will be compared to an option with more insulation, to determine the benefits and costs of each option (AME Group 2017).

c) Accounting for Uncertainty

The uncertainty related to climate-design parameters is not always communicated; hence the engineering community does not typically make use of information about uncertainty provided by a climate data provider.

To prioritize safety, engineers consider the uncertainty associated with all parameters of a design. They generally consider uncertainty about future climate in the same way that they consider uncertainties about other factors, such as the structural resistance of building material. In many cases, uncertainty levels are pre-determined; for example, safety factors for a combination of loads are pre-determined in the design of a building or structure.

Engineers also have the flexibility to account for climate uncertainty by increasing safety factors. As they are liable for infrastructure design, engineers are typically conservative; they prefer higher safety factors, whenever possible. Some engineers will determine an appropriate safety factor by evaluating the risk of making a mistake on climate parameters.

Increasing the safety factor often also increases project costs, which influences decision-making. For example, enhanced safety may require the installation of stronger beams, larger spillways or bigger pipe sizes. At times, alternative solutions can be found that do not necessarily increase costs.

When major project cost increases are foreseen, a cost-benefit analysis can be carried out to evaluate the cost of adaptation over the cost of inaction (section 6.3.3.c).

Sensitivity analysis is another tool engineers use to evaluate the influence of uncertainty in climate and other design parameters. Sensitivity analyses can be carried out at many stages of the design to ensure safety and performance.

6.2.2 INTEGRATION OF CLIMATE CHANGE INFORMATION

a) The Service Life and Type of Infrastructure

The service life of infrastructure varies considerably, as shown in Table 6-2. This factor is significant when having to integrate climate change factors into infrastructure codes and standards. For infrastructure with a short service life of 10 to 20 years, it is not critical to integrate the climate change signal. The infrastructure can be designed based on recent climate information, which will not change markedly during this period. For infrastructure with a service life of 30 to 40 years, it becomes relevant to consider climate change, but it is not critical to look at multiple climate scenarios – general trends will suffice (Charron 2016). For infrastructure with a service life of more than 40 years, it is important to consider the climate change signal using multiple climate scenarios.

Table 6-2 *Service Life and End-of-Life Duration of Various Infrastructure in Canada (compiled from telephone interviews)*

Sector	Infrastructure types	Service life	End of life*
Buildings and Structures	HVAC systems	15-20 years	NA
	Hospitals	More than 100 years	NA
	Bridge	80 years	NA
	Nuclear power station	More than 100 years	NA
Water Resources Infrastructure and Tailings Storage Facilities	Tailings-storage facilities	10-20 years	Forever
Coastal and Oceanic Infrastructure	Ports	30-50 years	NA
Transportation Infrastructure	Railway tracks	More than 100 years	NA

**Some infrastructure, such as tailing storage facilities, end operations after their service life but remain in place.*

b) When Climate Data Are Not Needed

As stated in section 6.2.1a, *Transportation and Infrastructure,* some design parameters related to climate are based on established practices and are not linked to climate data. It is the case for preferred railway-track temperatures, where it can be tricky for engineers to use climate data to adjust design parameters; for example, Metrolinx (2017) chose to upgrade the preferred rail laying temperatures from 90°F to 100°F to account for increasing temperatures. Metrolinx is following the standard used in South Carolina, where the current climate is warmer. This decision comes with trade-offs, as raising the design threshold can cause rails to crack in cold temperatures. Metrolinx considered evidence that the number of cold days will drop significantly, and is confident in its internal standard modification.

Another example comes from the Bureau de Normalisation du Québec (BNQ). It recently issued a standard to help fight heat islands in populated areas, an issue expected to worsen with climate change. The standard calls for materials with greater reflectance properties to reduce heat absorption (BNQ 2017).

c) Managing Uncertainty

The uncertainty inherent in climate change projections can be daunting when compared to the uncertainty engineers typically manage. For a sensitivity analysis done on a climate indicator based on future precipitation, an uncertainty range of -5 to +200 per cent was reported (CBCL 2017). The decision-making process becomes much more complex in this context.

Climate change uncertainty is the result of a cascade of uncertainties coming from various sources: future greenhouse-gas emission scenarios, climate models formulation, downscaling and bias-correction methods, natural variability and impact models. Some engineers and organizations apply simplified hypotheses to reduce the range of projections and ease decision-making. The selection of a single RCP and a subset of models are two approaches followed by engineers to reduce uncertainty, as described below. Engineers also have other approaches, as discussed in section 6.2.2e to 6.2.2g.

Selection of an RCP and Climate Models

Organizations and engineers will sometimes decide on a single RCP and a subset of climate models. The decision can be made according to an organization's: beliefs, level of risk tolerance, budget for project design and construction, recent carbon-emission trends and type of infrastructure. RCP 8.5 and RCP 4.5 are used most often. Engineers reported using RCP 2.6 as a way to sensitize what GHG-mitigation measures could achieve. Some engineers used only a few climate models, instead of all available models (MetOffice 2017; Amec Foster Wheeler 2017).

Note that the selection of a single RCP and a subset of climate models is not considered best practice, as it underestimates climate change risk. It does not reduce the uncertainty of climate projections; it only hides it. However, it is among the current methods used by organizations and engineers, for the following reasons:

- it lowers the cost of climate analysis
- it is easier to consider one scenario for the design phase
- it facilitates discussions with clients and/or senior management.

d) Using Climate Information to Adjust Design

Use of a Single Climate Scenario

A method to account for climate change in the design of infrastructure is to add an additional safety factor to the historical design parameter. This safety factor is based on literature results, type of infrastructure and internal discussions concerning an organization's beliefs and tolerance for risk and expenses.

This approach is used in Canada to account for extreme precipitation events, which are expected to increase in frequency and intensity. Engineers add a safety factor to the IDF curve, based on literature results, such as Mailhot et al. (2012). Literature results for extreme precipitation events differ by region, return period, climate change scenario, and more factors. Most organizations make judgment calls and select a single safety factor for all designs, varying from 10 to 39 per cent (Government of New Brunswick 2017). The City of Montréal (2017), for example, decided to increase the safety factor for local sewer networks by 10 per cent. However, projects for major sewers (collectors), will not be subject to this safety factor, as the events generating extreme precipitation, summer convection cells, are typically smaller than a collector's drainage area. The City of Montréal has begun research to validate this hypothesis and has a real-time sewer-management system that can handle residual risk (section 6.2.2g.

An additional safety factor is used to address rising sea levels. Engineers refer to rates of sea-level rise found in the scientific literature. They consider historical sea level heights, then add safety margins based on the rates of sea-level rise and the expected life of an infrastructure (Government of New Brunswick 2017).

Engineers can use a worst-case climate scenario to start a discussion with a client or to evaluate the need for further analysis. For example, passive buildings do not rely on typical HVAC systems; they are designed to use minimal amounts of energy and to leverage natural conditions for ventilation. A rise in temperature can have a significant impact on interior comfort levels. Engineers can use the worst-case climate scenario to initiate a discussion about future comfort levels in the building. This analysis will not necessarily lead to design modifications, but will raise a client's awareness of the issue (AME Group 2017).

Use of Multiple Climate Scenarios

Engineers now use multiple climate scenarios in the design process. Most of the time, this takes the form of a sensitivity analysis. For example, engineers designing sewer networks will find IDF curves for a specific location based on several emission scenarios and climate models. The engineer replaces the historical values in the numerical model and runs all future IDF values. This generates multiple scenarios of peak discharge and system performance. The engineer is left with multiple possibilities and a judgment call is required to determine whether the design should be modified to take future conditions fully into account (Amec Foster Wheeler 2017; CBCL 2017; MetOffice 2017).

Engineers will sometimes pre-select the scenarios they want to run in numerical models to diminish the use of human resources and computation time. Engineers reported using the median and the maximum scenarios of two distinct methods to produce future rainfall projections (MetOffice 2017; CBCL 2017).

e) Using a Risk-Based Approach

Canadian engineers have begun to use a risk-based approach to address the vulnerabilities of infrastructure to extreme events and a changing climate. The Public Infrastructure Engineering Vulnerability Committee (PIEVC) of Engineers Canada developed this protocol. "The Protocol systematically reviews historical climate information and projects the nature, severity and probability of future climate changes and events. It also establishes the adaptive capacity of an individual infrastructure as determined by its design, operation and maintenance. It includes an estimate of the severity of climate impacts on the components of the infrastructure (i.e. deterioration, damage or destruction) to enable the identification of higher risk components and the nature of the threat from the climate change impact. This information can be used to make informed engineering judgments on what components require adaptation, as well as how to adapt them, e.g. design adjustments, changes to operational or maintenance procedures" (PIEVC 2017).

To date, this protocol has been applied 45 times in Canada (PIEVC 2017). Engineers report using it to raise awareness and understanding of climate change in their organizations. Metro Vancouver (Metro Vancouver 2017) did a PIEVC study, and the project manager stated: "It is a stepping stone; once the analysis is finished, people need to dive into more detailed analysis."

Engineers must have climate data to apply the protocol. These data take the form of climate indicators relevant to the infrastructure assessed. Indicators are often related to the likelihood of exceeding a certain threshold. For example, how likely is it that the temperature is going to exceed 40°C? Information is needed for recent, past and future climate data, and the protocol provides guidelines for their calculation.

f) Adaptive Designs

When possible, engineers use adaptive designs that can accommodate future adaptation to climate change. An adaptive design is one that can easily be retrofitted, modified or expanded. This approach offers some advantages in addressing the uncertainty of climate projections. Indeed, instead of making a costly adaptation to uncertain future conditions, adaptation decisions and investments are deferred to a time when more information is likely to be available. The key is to design infrastructure so that it can accommodate the range of adaptation measures that might be required in the future. Because adaptation expenses are postponed, adaptation costs have a lesser impact on the net present value of the investment (Amec Foster Wheeler 2017).

g) Managing the Residual Risk

Another strategy to address the high uncertainty of climate projections is managing residual risks during the operation phase of the infrastructure. This strategy is used when operational management is more efficient than structural mitigation. It applies for extreme events with very high recurrence periods and can be implemented through emergency protocols.

Three examples of this strategy follow:

- Organizations install back-up systems in case of a major electricity blackout (Metrolinx 2017).
- When freezing rain is forecast, companies run their streetcars 24 hours per day to prevent ice accretion on the Overhead Contact System (Metrolinx 2017).
- The City of Montréal manages sewer-network flows in real time. According to *the Canada-wide strategy for the Management of Municipal Wastewater Effluent*, the city has to comply with performance standards for sewer overflows; the real-time management system is therefore well developed. The residual risk of extreme precipitation (the one not accommodated by the 10 per cent increase in the IDF curves, section 6.2.2d will be accommodated by the real-time management system (City of Montréal 2017).

6.3 CHALLENGES AND NEEDS RELATED TO INTEGRATING CLIMATE INFORMATION INTO INFRASTRUCTURE DESIGN

6.3.1 CLIMATE DATA

a) Observed Data and Climate Products Based on Observed Data

Interviewed engineers perceived a decreasing level of services at ECCC, which began in the 1980s. They stated that in the past, more data were validated and made available more quickly, and more research was conducted that met the needs of engineers. Moreover, as highlighted in section 5.4.1, the shift toward automated weather stations resulted in a degradation of the estimation of some variables, such as precipitation type (liquid, solid, freezing rain, sleet).

During recent decades, there have been multiple academic and professional initiatives to meet the needs of the engineering community regarding IDF curves. Engineers have started to use sources other than ECCC to obtain IDF curves; some perhaps less reliable than others; some include climate change projections and some don't; some use the Gumbel distribution, and others use an alternative Generalized Extreme Value (GEV) distribution; some use sophisticated spatial models, and others rely on the nearest-neighbor method for ungauged sites. Intercomparison projects of IDF products were carried out at the regional scale (ex.: Coulibaly et al. 2016). According to Engineers Canada (2017), there is a lot of confusion in this field, and it is a top priority to clarify IDF curves and how to use them, especially for climate change projections. Developing a standard on IDF curves was identified as a second priority by engineers at the 2017 SCC-Ouranos workshop (SCC-Ouranos Workshop 2017) .

Another challenge for engineers is the low spatial density of weather and gauging stations in some regions of the country (SCC-Ouranos Workshop 2017). Some projects rely on data from neighbouring stations that are hundreds of kilometres away. Engineers dealing with ocean models (section 6.2.1a) make use of tide gauges for the calibration phase. They make use of the tide gauge in Halifax, for example, although the site is 300 km away. The low spatial density is particularly problematic for rain, tides and river-flow gauges. It would be useful to have gauges on watersheds with areas less than 50 km^2, as most stations are located on watersheds with areas greater than 700 km^2 (Government of New Brunswick 2017).

To be useful to engineers, weather and gauging stations must be operational for long periods, and records must be stable and continuous. The minimum length of record-keeping required varies according to the application: 10 years is a minimum for mean values; 20 years is usually the minimum for IDF curves. When the length of record-keeping of nearby stations is inadequate, engineers tend to combine records from multiple stations to compute statistics of interest.

Temporal resolution of weather data is also a challenge. There is a need for weather stations to generate records for variables, like precipitation, at sub-daily scales. Sub-daily extremes of precipitation are particularly important for the design of water systems in watersheds with concentration times of less than 24 hours.

Engineers also indicated a need to have more information about specific variables; for example, more wind, snow, radiation and lightning data would be useful (SCC-Ouranos Workshop 2017). The coefficient of reduction for rain would complement IDF curves, as it provides information on the scale of storms. This information would help engineers design rain collectors in highly populated areas without systematically over-sizing entire networks in an effort to accommodate climate change. High quality, readily accessible and readable radar data would also contribute to better designs for water-related infrastructure.

Finally, to be comfortable with new observation-based products, engineers need the metadata and an understanding of production methodologies. The numbers must be verifiable. Engineers also called for clarification on how to use climate products (SCC-Ouranos Workshop 2017); for example, how to use ECCC's homogenized data, to better determine appropriate usages for them.

b) Climate Change Data and Resources

Engineers said they struggle to find adequate climate change data and products. Results are published in scientific journals, but these are not always readily accessible to practitioners. Engineers follow the research on climate change, but when it comes time to make decisions, it can be difficult for them because different articles reach different results (Amec Foster Wheeler 2017). Also, the information contained in scientific articles is not always relevant to the design of infrastructure or the region of interest, and sometimes it uses innovative methods that have yet to be validated.

There are journal articles that drive discussions to integrate the climate change signal into the design of infrastructure; for example, the article of Mailhot et al. (2012) initiated a discussion at the City of Montréal to increase rain intensity in sewer design by 10 per cent. The City of Montréal continues the discussion with Alain Mailhot and Ouranos on how to enhance integration of climate change into drainage-system design.

Good climate change products have been produced at the project scale for risk analysis (section 6.2.2e). For example, PCIC provided a set of climate indicators for the PIEVC study of Metro Vancouver, and Risk Sciences International provided open access to its climate portal, which attracted interest from Metrolinx. Except for these few examples, however, the type of information available about climate change still does not meet the infrastructure-design needs of the engineering community. The situation is similar in the United States: “A central challenge is to understand how weather events relevant to civil engineering practice may change in terms of frequency, duration and intensity of climate change. While various approaches to converting output from GCMs to scales of relevance to civil engineering practice have been explored, converting such information to insights regarding changes in meteorological phenomena at the project scale has not been successfully demonstrated” (Olsen 2015).

The type of indicator, the graphic representation and the resolution of each climate product must be adequate for engineers. Most of the time, annual means are publicized widely, but these indicators are not always useful for engineers. Engineers need information about precipitation extremes, indicators with thresholds (e.g. number of days above 40°C), wind speeds and orientation, and more. Graphic representation is also important. Some engineers are interested in only one value; others want to see uncertainty ranges. As for spatial resolution, there is no consensus regarding engineers’ needs. Some prefer high-resolution maps for each indicator, while others feel that these are not necessary, due to significant regional differences in climate change.

As suggested in section 5.3, many engineers consider climate models as black boxes and would appreciate guidance on their proper use. The guide of Charron (2016) can increase confidence in climate model projections. Sometimes, the science is just not mature enough for the engineers’ needs; for example, the need for high resolution, waves, hourly climate model data, and other variables.

To address the need for climate change data, several resources and services have emerged in the last two decades. ECCC, Ouranos, PCIC, RSI, OCC, Amec Foster Wheeler and other consulting firms are providing climate change services. In the last few years, the number of free and readily accessible climate change scenarios on the web has increased, along with the number of climate change models, data and downscaling/bias correction methods. There is no central authority to help engineers determine whom to trust, where to find data and which data to use. Some engineers and organizations have started working in close collaboration with CSPs, such as PCIC with Metro Vancouver and BC Hydro, and Ouranos with Hydro-Quebec and Manitoba Hydro. These collaborations generally increase the confidence of engineers in climate data providers by co-producing needed data. Once this type of collaboration is established, engineers then confront limitations related to the state of the science. However, the collaborative model is not transferable at a large scale to all engineering consultants involved in infrastructure design. There is a need for guidance and data at the national and provincial/territorial levels. Engineers have proposed national or provincial/territorial climate standards. Engineers Canada (2017) stated “it would be a tremendous leap forward to get the climate indicators and thresholds organized to produce standardised datasets at the national and provincial level.” The ASHRAE heating and ventilation climate standard is often cited as a good example.

Finally, Engineers Canada (2017) emphasizes that “it is accuracy that matters, not precision.” For the purpose of design, engineers do not need a point decimal value; they need an accurate representation of what the climate will look like based on the best science available. The level of confidence climate scientists have in climate change information would be useful to engineers (section 5.4.2).

c) Data Access and Extraction

Interviewed design engineers agree that ECCC's data can be hard to obtain (CBCL 2017). ECCC representatives report that the volume of data is enormous and, as such, dissemination is problematic. ECCC publishes its data on the DataMart. However, DataMart is neither well known nor user-friendly; for example, engineers struggle to get river levels that match river flows and timely access to radar data.

Another challenge is that, as data are available through many varied organizations, gathering it takes time. For example, after a big storm in the Toronto area, it took engineers eight weeks to collect data from 60 rain gauges owned by various organizations in the area (Amec Foster Wheeler 2017). In other cases, data are recorded but few people are aware of it to access it. For example, The Weather Network has a system that monitors pavement and ambient temperatures, and dew points for an Ontario maintenance company. These data could be useful for scientists and engineers, if they were aware it existed.

The extraction of data and the creation of products can be time consuming. Some systems require extracting data point-by-point instead of for entire regions (CBCL 2017). Extraction by region, when available, necessitates programming skills. The extraction problem is particularly true for climate change projections. The extraction and manipulation of data consume much of a consultant's time, which can lead to the development of fewer climate scenarios and fewer climate models for impact studies.

6.3.2 TECHNICAL CHALLENGES FOR ENGINEERS

a) Decision-Making and Uncertainty

Uncertainty related to climate change is a challenge. Previous methods used to deal with uncertainty cannot be readily applied today, because uncertainty levels are now much larger (SCC-Ouranos Workshop 2017). Using safety factors that accommodate the full range of uncertainty could lead to oversizing all infrastructure and greater costs for organizations and society.

Systemically designing infrastructure for the worst-case scenario (highest emissions and greatest sensitivity of climate to GHG) is perhaps the safest solution, but can add significant costs to projects. Designing for a stable climate can expose infrastructure to greater risk and potentially significant costs, if retrofits are later needed. Engineers must use design parameters that balance the costs of mitigating risk through adaptation against the potential consequences of failure.

There are many ways that engineers deal with uncertain climate-design parameters: by carrying out sensitivity analyses and considering safety factors (section 6.2.2.d), using a risk-based approach (section 6.2.2.e), planning for adaptive designs (6.2.2.f) and managing residual risks during infrastructure operation (6.2.2.g). Decision science also proposes various schemes to manage uncertainty, such as the Robust Decision-Making Approach (Kalra et al. 2014).

Currently, the client or the design engineer decides which approach to use, often based on intuition. Some relevant regulations have emerged, such as the technical circular on climate change from British Columbia's Ministry of Transportation and Infrastructure (2015). However, the requirements remain vague to most engineers, who would prefer a more prescriptive approach that clearly indicates appropriate types of climate change assessment.

Finally, approaches such as the PIEVC protocol and Robust Decision-Making ones are not adapted to small-scale projects. Future climate should be considered for projects of all scales, but not necessarily using the same methodology.

Reducing Uncertainty

As explained in section 6.2.2c, engineers and organizations make hypotheses to manage climate uncertainty. Interviewees reported that the selection of an RCP was the most challenging part of climate change analysis. This selection engages personal values and is based less on proven science and more on a plausible socioeconomic future.

Some engineers reported that industry cannot deal with uncertainty using the same methods as the academic world because of a lack of time and resources (section 6.3.3b). According to best practices, impact analyses should consider every RCP and every available climate model. The selection of a low RCP at the beginning of an analysis can lead to an underestimation of risk, while the selection of a high RCP can lead to the oversizing of infrastructure. Selection of climate models can also skew estimations of risk. Ouranos (Casajus et al. 2016) and PCIC use clustering methods to lower the number of simulations required while covering most uncertainty.

There is a need to agree on a methodology to assess the impact of climate change on infrastructure. The methodology must be practical for engineers and acceptable to scientists.

Types of Decisions

Engineers who conduct sensitivity analyses, with climate parameters based on multiple climate models and RCPs, face two types of decisions.

The first is, when the uncertainty and/or the worst-case scenario necessitate only small changes in base design. For example, flood zones in very steep areas will not be much impacted, even if future peak discharges are greater. There are also situations when the worst-case scenario necessitates only larger pipes, or more freeboard, on a control pond. These modifications are not costly, and are easier to make and justify.

There is, however, another type of decision, when uncertainty and worst-case scenarios call for many modifications to or even a complete revision of the base design. This typically involves significant additional costs. Engineers will have trouble making decisions in these situations and might adopt other strategies, such as following a risk-based approach, using adaptive designs and managing residual risks with emergency protocols; these situations are challenging.

Current Tools and Methodologies

Engineers reported that their tools and current methods are not adequate for the consideration of such large uncertainties. For example, numerical models for the estimation of peak discharge in sewers can run multiple scenarios. However, they always take discrete rainfall as an input; it would be helpful to provide a probability-distribution function.

No Agreed-Upon Methodologies for Climate Change Considerations

Engineers agreed that having a methodology to factor climate change into the design of infrastructure would be a significant step forward. Some called for a prescriptive approach, while others wanted something non-prescriptive. Engineers emphasized that the methodology should take into account an infrastructure’s lifecycle. Some engineers have studied guidelines and best practices in the field, but find them hard to standardize.

British Columbia's Ministry of Transportation and Infrastructure issued a technical document on the integration of climate change into the design of infrastructure; the document provides high-level guidance for proponents of capital projects. It is one of the first initiatives of its kind in the country and directs consultants to climate data providers and resources. Engineers have called for other initiatives of this kind.

b) Tipping Points

Natural thresholds, or tipping points, represent a significant challenge for engineers (Government of New Brunswick 2017). They can materialize in many ways, such as an extreme event that disrupts the normal behavior of a system. For example, a 1-in-100 year storm creates high flows in a river, erodes river banks and uproots trees; the trees float down the river and block a culvert, causing an overflow that destroys a road. Even if the culvert were designed for a 1-in-200 year storm, the natural threshold uproots the tree, blocks the culvert and destroys the road.

These kinds of natural thresholds were observed when climate was relatively stationary and will continue as climate changes. Over-designing infrastructure in anticipation of future climate change might be part of the solution, but as the above example shows, residual risks will always exist and should be addressed.

c) Interdependencies

Interdependencies between networks are a challenge, not only for engineers, but also for urban planners, public-security officials and others. For example, after a storm, the ability of a railway to deliver service on time depends largely on the capacity of the electric utility to provide adequate power. This relationship can make it more difficult for engineers trying to build a business case for adaptation, as the performance of their adaptation actions depends on the actions of others. In some cases, the interdependency of networks requires that upgrades be made to the entire system to realize the potential benefits of adaptation (see example, section 6.3.3c) (Metrolinx 2017).

6.3.3 OTHER CHALLENGES FOR ENGINEERS

a) Expertise

Climate change is a relatively new consideration in engineering. The number of people and engineers able to navigate climate change information and data remains low throughout the country (Metrolinx 2017). Some engineers are becoming familiar with climate models and understand them as sophisticated, but imperfect, tools. Those engineers do not doubt the science behind climate change or what the models project (Metro Vancouver 2017; Amec Foster Wheeler 2017; AME Group 2017; CBCL 2017).

To meet their needs in this area, engineering consultants are starting to form teams. Some organizations are creating jobs that require skills in adaptation and resilience (Metrolinx 2017).

b) Time and Budget

In many cases, time and budget dictate the exhaustiveness of climate change analysis. A low budget can force a design team to use existing information, even if it is not adequate for its intended purpose and even if it does not follow best practices. When specific analyses of climate models are needed, low budgets can lead to the consideration of only one climate model and/or one emission scenario. On the design side, larger budgets enable the consideration of more parameters in conjunction with the engineer's numerical model.

c) The Benefits are Neither Clear Nor Immediate

For many engineers, the benefits of climate change adaptation are not clear. "To justify the economic cost of adaptation, you have to be able to estimate the cost of inaction" (Metrolinx 2017). These studies are not trivial; however, examples have emerged in the last few years (Circé et al. 2016).

The fact that the benefits of adaptation are not apparent quickly is even more challenging. For example, Metrolinx might not see the benefits of an increased preferred rail laying temperature before the entire track network is upgraded. As multiple projects and needs compete for time and resources in an organization, it can be tempting to prioritize investments that yield short-term benefits.

d) Liability

For engineers, it is important that climate data come from authoritative sources. The information must be recognized in the field of practice and be scientifically defensible, as the engineer is liable for infrastructure design. There is an underlying assumption in engineering that the information used is the best available at the time of design. Scientists providing the information have a moral obligation to disclose its limitations, and there are few cases where courts have addressed scientists' legal responsibilities (Engineers Canada 2017a).

This creates an asymmetry: engineers are more cautious with new methods or new data that do not align with historical results. From a pragmatic point of view, choices made need to be defensible in court. One analogy suggested in the interviews is the "scarcity of data in design" and "integration of climate change in design." For example, consider a case when weather and climate data for a particular project are not available. Two general options exist to circumvent the problem: use data from the nearest neighbouring station; or estimate the data using algorithms. The former might be a bad choice in terms of precision, if the closest station is far away and this choice does not create new data – it merely uses what is available. The latter option, even though it might result in better data for the ungauged site, involves choosing among methods – a choice subject to potential future court challenges. It is worth noting that the inclusion of climate change into weather and climate data might be just as vulnerable in court, as it involves a choice of method and may lead to differing results. As a result, various expert witnesses could reach different conclusions. Interviewees highlighted this liability problem, stressing the need for proper legal approaches to the inclusion of climate change information into infrastructure design.

7 BARRIERS AND RECOMMENDATIONS

The incorporation of climate change information into infrastructure design faces numerous challenges throughout the infrastructure-design process. This chapter lists barriers to the effective incorporation of climate change into the design, construction and maintenance of infrastructure, followed by recommendations to address these challenges. It is important to note that since each sector uses its own set of design methods, each will require a particular method to consider climate change information.

7.1 BARRIERS

7.1.1 EDUCATION

To overcome the challenges of integrating climate change information into the design process, the need for education has been highlighted (SCC-Ouranos Workshop 2017). More formal educational guidelines and /or continuous education courses relating to climate science would be useful for engineers (SCC-Ouranos Workshop 2017). Engineering experts highlighted that climate change knowledge in engineering departments was almost inexistent (SCC-Ouranos Workshop 2017); for example, Engineers Canada could foster climate change courses in the curriculum of engineering programs.

7.1.2 A COMMON LANGUAGE FOR SCIENTISTS, ENGINEERS AND STAKEHOLDERS

Interviewees spoke about the difficulty of establishing a common language among scientists, engineers and stakeholders (SCC-Ouranos Workshop 2017). The same words carry different meanings in the various disciplines, creating misunderstandings and hampering collaboration. This is where CSPs play an important role, albeit only recently.

The meaning of the word “rare”, for example, differs for climate scientists and engineers. The connotation familiar to scientists is demonstrated in this quote: “extreme weather events would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function (e.g. annual or seasonal timescale)” (IPCC 2012). Engineers define “rare” in terms of acceptable frequency of failure; for example, dams may be designed for events with an average recurrence interval of 1,000 or 10,000 years.

The word “model” provides another example. An engineering “model” is often calibrated on observations and is generally linear: running the model twice, using the same input and parameters, yields the exact same results. Probabilistic approaches are often used, providing the whole probability distribution of the engineering model output, but the solutions remain linear. Climate models describe non-linear systems (i.e. chaotic systems). Running the same “model” twice, with only slightly different parameters or initial conditions, yields similar long-term climate normals, but an entirely independent time series. Although climate models are evaluated using observed data, their parameters are not calibrated in the usual sense. For many engineers, this creates confusion and leads to skepticism.

A formal, interdisciplinary glossary would help the groups to better understand one another.

7.1.3 CLIMATE CHANGE IMPACTS IS AN EVOLVING SCIENCE

Although the science underlying climate change traces its roots back to the 19th century and gained wide scientific acceptance during the 1980s, the consensus about the accuracy of detailed regional impacts based on regional-scale processes is not strong. In practice, this means that conclusions are subject to revision and cannot be considered authoritative until they have been confirmed by independent analyses and the test of time. It is important to note that engineers need the best available science and recognize that there is no best or correct answer (SCC-Ouranos Workshop 2017).

An example of such revision is the fate of Great Lake levels and St-Lawrence River flows. Studies in the early 2000s suggested that the doubling of CO2 concentrations would lead to significantly lower lake levels (2.5 m lower for Lake Michigan and Lake Huron) and reductions in outflows from Lake Ontario of about 30 per cent (Mortsch et al. 2000). Later studies found that simplifications in the calculations of lake evaporation had exaggerated water losses due to higher temperatures, and that a more realistic approach yielded results closer to current realities.

One interviewee discussed the experience of a provincial ministry financing a study to quantify future design criteria for road construction. The study was completed and new standards prescribed, but both became outdated quickly when new research was published. The standards were perceived as overly prescriptive, given the evolving nature of the underlying science. The balance between a prescriptive approach – which defines new design standards – and a guidance approach – which sets objectives and leaves the implementation to practitioners – should depend on the maturity of the science.

7.1.4 ACCESS TO DATA

Access to weather and climate data remains problematic (SCC-Ouranos Workshop 2017). For example, the spatial density of weather networks is low and inadequate for engineering projects located away from populated areas. Canada's size makes it impractical to densify the weather network enough to meet engineering standards; it would be too expensive to install and maintain such a large number of weather stations. Climate providers and engineers have started to develop solutions to this issue. Some engineers use reanalysis data (CBCL 2017), while climate scientists are working on spatial models (McKenney et al. 2011), corrected reanalysis products (Alain Mailhot and INRS-ETE) and spatial statistical models to compute IDF curves (Perreault & Jalbert 2016).

The temporal resolution of the data is also often inadequate, for example, not every station records heavy rainfall events at a high enough resolution. This is particularly true for rainfalls of short duration. Adequate estimations require a temporal resolution of at least 15 minutes; the data, which is available from ECCC's web portal, has a resolution of 60 minutes, even though some stations record the results from tipping-bucket rain gauges more than once an hour. Other requested climate variables or indices are not readily available, such as those related to wind, radar, wave height and river discharge.

The type of climate change information currently available does not meet the needs of engineers involved in the design and risk analysis of infrastructure projects. Main problems include the type of indicator, the robustness of methodology to compute the data, the graphic representation, spatial and temporal resolutions, and missing metadata or guidelines. Also, because climate change information comes from multiple parties, engineers sometimes have difficulty knowing whom to trust.

Finally, weather and climate data is scattered among multiple portals where access is often limited to technically-inclined professionals, thereby rendering their use challenging for most.

7.1.5 UNCERTAINTY AND DECISION-MAKING

The size of Canada makes it difficult to install and maintain enough weather stations to monitor weather and climate processes at adequate spatial and temporal resolutions. The resulting lack of data often means uncertainty in the historical data is important, at least in areas where spatial density is low. Engineers have historically coped with the inherent uncertainty of Canadian weather data by incorporating safety factors and conducting sensitivity analyses. While a denser weather station network has been identified as an important priority (SCC-Ouranos Workshop 2017), it is doubtful that resources are available to make it happen.

The amount of uncertainty in climate change projections is significant compared to what engineers previously had to consider (SCC-Ouranos Workshop 2017). Interviewees reported an uncertainty range of -5 to +200 per cent for a derived climate indicator based on precipitation and a sensitivity analysis (CBCL 2017). To diminish uncertainty and ease decision-making, engineers and organizations make hypotheses, even though best practices require that all uncertainty be considered. Climate change information is still relatively new to the engineering community, and guidance on how to use it properly needs to be well vetted and properly explained, and to acknowledge the underlying uncertainty.

Updating historical information can be difficult, due to unforeseen circumstances. Presently, the flood map of southern Ontario is based on a single 1954 tropical storm, Hurricane Hazel; engineers use the data from Hazel as their "design storm." There is no consensus on how to adjust the flood map to a future climate, given that the baseline is founded on a single event. Current storm events exceed Hazel, and a change of paradigm in Ontario must take place to consider alternative design methods (Amec Foster Wheeler 2017).

The decision-making process becomes much more complex in the context of climate change; historical best practices for infrastructure design are hardly applicable.

7.1.6 NO AGREED-UPON METHODOLOGIES

Multiple methodologies exist for the development of climate change information, such as IDF curves and climate scenarios. In recent decades, for example, the paucity of updates to IDF curves from ECCC led to a multiplication of academic and professional initiatives to meet the needs of the engineering community. The variety of methodologies and conclusions add uncertainty and create confusion.

The multiplication of methodologies is also happening in the climate change projection field. Estimates of future climate may be based on an ensemble of RCMs or GCMs. There are various methods for downscaling and bias-correction, as explained in section 5.3.1. In addition, some providers incorporate climate information using the delta approach (Charron 2016), some use bias-corrected climate simulations (PCIC 2017b; Charron 2016), while others use climate simulation as explicative variables in a statistical model (Perreault & Jalbert 2016).

7.1.7 POTENTIAL COST OF CLIMATE CHANGE ADAPTATION

The benefits of climate change adaptation are not always readily evident. It is tempting for organizations to prioritize projects and investments that yield short-term benefits. Among the proposed solutions that could diminish the cost of adaptation are adaptive design (section 6.2.2f) and the low-regret approach (Braun & Fournier 2016).

In a recent comprehensive study by Hughes and collaborators, the authors found that: "the cost of adapting to climate change, given the baseline level of infrastructure provision, is no more than one to two per cent of the total cost of providing that infrastructure" (Hughes et al. 2010). In other words, the marginal cost of design adaptation can be low overall; such findings should be communicated broadly. However, it should be highlighted that estimates found in the Hughes et al. report vary across regions and economic sectors. Their conclusions were also challenged during the SCC-Ouranos workshop (SCC-Ouranos Workshop 2017).

7.1.8 LIABILITY

Interviewees expressed concern about liability. Scientists develop multiple methods to understand weather data, climate information and climate change projections, with varied results. Engineers try to apply this research in a diligent manner that enables them to defend their choices in court, if necessary. Interviewees explained that it can be easy to find experts who will contradict other experts in court and create reasonable doubt in the minds of a judge or jury (ECCC 2017b).

7.1.9 REQUIREMENTS

The lack of policies in the procurement processes of a project is a challenge for the integration of climate change into infrastructure design. In most cases, the choice to integrate climate change into the design of infrastructure is left to the design engineer.

Recently, public agencies like British Columbia and Quebec's ministries of transportation have started to require climate change assessments for specific projects; Interviewees pointed out that this requirement is nebulous, as the stipulation is to "assess climate change," which can mean different things to different people. Current legislative requirements are vague; typical wording is, "new infrastructure projects should take into account climate change."

When developing the technical circular on climate change from British Columbia's Ministry of Transportation and Infrastructure (2015) and APEGBC's guidelines (APEGBC 2016), engineers asked for specific and detailed requirements. However, these bodies quickly realized that making specific tangible recommendations would be difficult because it is a new field of practice. Practitioners are at the stage of considering climate change the best way they can and then documenting what they did. Leaving practitioners with flexibility in how to include climate change into project designs will lead to literature to derive best practices. Best practices will then be used to make specific tangible recommendations for standards (PCIC 2017).

7.2 RECOMMENDATIONS

This section offers recommendations to strengthen the uptake of climate information into engineering practice:

- Increase the practicality of data collected at weather and climate monitoring stations so that it is usable for multiple purposes
- Improve the consistency and comprehensiveness of climate information gathered across Canada
- Ensure that climate change informs infrastructure design and that the relevant risks are understood and articulated
- Enhance communication of the uncertainty inherent in climate scenarios when used in the design process.

7.2.1 NATIONAL DATA PORTAL

Interviewees cited the difficulty of accessing relevant data for a given project (SCC-Ouranos Workshop 2017). It is, therefore, recommended that a national data portal be developed to catalogue relevant weather, climate and earth-observation data, along with user-oriented materials derived from these data. The portal would leverage existing initiatives, such as the NoN (section 5.2.2a), the planned Canadian Centre for Climate Services and the Federal Geospatial Platform.

To be effective, the portal would have to meet a number of criteria. It must include a diverse array of raw, quality-controlled and properly documented datasets. It must also provide a diversity of output formats and machine interoperability, facilitate posting by external data providers, and feature smart search capabilities.

Data Coverage

The data available on the portal would cover the majority of commonly-used earth-observation and climate products. At a minimum, the portal would present data from federal departments; ideally, it would also feature data from other governmental, private and academic sources. Similar to what is done in the remote-sensing community, data would be available at different stages of processing, from instrument readings to heavily processed and quality-controlled analyses. The portal should provide observation data such as weather-station time series, radar precipitation maps, satellite imagery, as well as interpreted products, such as maps of climate normal over historical and future periods, IDF curves, engineering design values by city, and more.

Documentation and Quality Control

To adequately inform end users about data sources and characteristics, standardized documentation would accompany each dataset. Data providers would provide metadata, such as variable name, unit, measurement apparatus, time resolution of recordings, along with accuracy, data history, contact details, and more.

It is also recommended that a mechanism be put in place to evaluate data quality and report errors. A third-party data assessment would provide an initial evaluation, and users would be able to submit assessments and comments, leading to a rating for each dataset; for example, the portal could let end users identify potential weaknesses within datasets to alert other users and help data providers continuously improve the quality of resources.

File Format and Machine Interoperability

To convert files from formats commonly used by climate-data providers to formats preferred by end users is time-consuming and a potential source of error in the integration of climate products into practice. The portal should enable end users to select a format compatible with engineering software, like HEC-RAS and MIKE11 and other more general formats, like CSV, XLS, XML, JSON, and netCDF.

The same idea applies to machine-to-machine communications. The portal could become a source for third-party online applications that embed climate data into custom products. The portal should have a documented Application Programming Interface (API) that enables software developers to query, catalogue and stream data to custom applications, as well as enable data providers to update content.

Portal Services

A common challenge for data portals is that as they grow in coverage, they become more difficult to search effectively. The portal must include an efficient, smart search engine. A suite of basic processing services should be available to perform common operations, such as spatial and temporal subsetting and averaging. Services such as a communication channel for updated databases should also be implemented.

7.2.2 PROVIDING ENGINEERS WITH GUIDANCE ON DECISION-MAKING AND UNCERTAINTY

Decision-making for engineers is more complex in the context of climate change, in part because the limited relevance of historical best practices and norms introduces significant uncertainty about design parameters. This situation is not unique to climate change, however, engineers and society make many crucial decisions despite uncertainty and a lack of authoritative guidance; for example, calculating the feasibility of a hydroelectricity facility. Responsibility for determining acceptable levels of risk should fall to society, and not to engineers and organizations.

It is, therefore, recommended guidelines and best practices be developed to help engineers cope with climate uncertainty. It is also a top priority, according to participants of the SCC-Ouranos Workshop (SCC-Ouranos Workshop 2017). The guidance could be incorporated into a standard that answers questions, such as:

- When must climate change be considered in infrastructure design?
- Which method(s) should be used to derive climate information (e.g. indicators, climate scenarios) and to integrate climate information into infrastructure design, with detailed and reproducible steps?
- How should climate uncertainties be translated into safety factors?
- When is a risk-based approach preferable to a standards-based approach?
- How should adaptive design be regulated?

Guidance should be applicable to a wide range of infrastructure types, and various project sizes and phases.

7.2.3 CLIMATE CHANGE ALMANAC FOR ENGINEERS

This report indicates that available climate change information does not meet the needs of engineers involved in infrastructure design (SCC-Ouranos Workshop 2017). To maximize the value of the guidelines discussed above, they must be accompanied by design parameters informed by climate change projections into an almanac. The science is already mature enough to be used in standards for some design parameters. Inspiration can be derived from the ASHRAE Climatic Data for Building Design Standards – a resource highly valued by engineers across North America.

The new standard would offer guidance on design values, based on the type, projected lifespan and strategic importance of infrastructure, along with the consequences of failure, and more. The standard would correlate safety factors with methodological choices that accommodate the uncertainties of climate projections. The values would feature uncertainty assessments that capture the level of confidence of climate data providers and the signal-to-noise ratio. The levels would differ by variable, region and algorithm used to derive the design value. A practical standard would include tables and maps showing design values for each Canadian region, as well as for various time periods and risk-tolerance levels.

Finally, the climate change almanac should adapt readily to new data from the IPCC and the scientific community. New data should affect only design parameters and not the standard itself. The standard should be flexible, and provide general and reproducible guidance on how to use climate simulations and scenarios to design various types of infrastructure and to accommodate various levels of risk.

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APPENDIX A. DATA PROVIDERS' GRID INTERVIEW

The following analysis grid was used to guide semi-directed interviews with 16 data providers.

General information

- Who is the interviewee?
- What is his role in the organization? Since when?
- Experience and expertise?
- What is their experience with weather and climate data?
- Examples of projects
- Examples of climate services provided

Current supply chain

- General description
    - How, where, why are you providing data?
- Instrument deployment?
    - Deployment strategy/ closure, moving, goal (behind these decisions)
    - Factors/criteria/existing standard/rules
    - Spatial distribution strategy (cost-benefit analysis?)
    - Case-by-case request
    - Choice of instrument type/model
    - Variables and their temporal resolution
        - temperature, precipitation, wind, ice, freezing rain, sticking snow
    - Is monitoring of instruments done? Improvements/modifications?
    - **Strengths and weaknesses**
- Data collection and operation
    - Automated collection
    - Manual collection
        - Frequency of manual collection (snow)
    - Issues with existing stations
    - **Strengths and weaknesses**
- Management and maintenance of weather stations network
    - What kind of maintenance?
    - Challenges?
    - **Strengths and weaknesses**
- Data storage
    - Where are the data stored, by whom, for how long?
    - Under what format are the data stored?
    - Security? Back ups?

- **Strengths and weaknesses**

- Weather and climate data diffusion
  - Types of diffusion
  - Distribution strategy
    - Targeted audience
    - Only your data or data from other parties?
  - Licence type (is it for free?)
    - Why this licence?
  - How do you decide the information format
    - Type of indicators
    - Type of file
  - Web platform
    - FTP
    - Data hub
  - Feedback from users
  - Need for consistency?
    - Do you coordinate with other organizations?
    - Presentation format
    - File format
    - Web platform
  - **Strengths and weaknesses**
- Climate services provision
  - Assistance? Kind of team, kind of assistance.
  - Mechanism/factors to ensure that end users have the information they need
  - Raw data/Metadata/climate products made available
  - Cost/quality. Membership.
  - **Strengths and weaknesses**
- Climate change service?
  - Scenario, indicators
  - Assistance
  - Data from elsewhere
  - What, how, why, ...
  - Coordination/linkages with other networks
- Quality control during each step of workflow
  - What kind
    - Following any procedure/documentation
    - Manual/Algorithm?
  - Missing data
  - **Strengths and weaknesses**
- Challenges

Opportunities for improvement of datasets

- Are you able to identify important gaps in supply chain?
  - Your supply chain
  - General supply chain (from other organizations)
  - Communication with users
- What are the options to fill identified gaps?
  - Low-hanging fruit
  - Exhaustive solutions
- Are you planning actions to upgrade current supply chain?
  - Usability (more data, better format?)
  - Consistency
  - Quality
  - Through partnership with other organizations? (RMCQ,ECCC or MDDELCC)
  - Easier access to data (web or through requests)
- What is the strategy for improvements?
  - Cost-benefits?

Norms and standards

- Is the information provided used for deriving infrastructure design value?
  - Indicators
    - IDF curves
    - Temperature normal
    - PMP/PMF
    - Wind information
    - Freezing rain information
    - Mean and extreme conditions
    - Snow water equivalent
    - Freeze depth
    - Thaw cycle
  - How to choose indicators?
    - Needs of users?
    - Guidelines from existing standards?
    - Expert judgment?
- Are you integrating climate change signal in this information?
  - How could it be integrated?
  - Standards in terms of climate change information
  - Integration through internal expertise or external expertise?
  - Feedback from users
- Issues and challenges to integrate climate change

APPENDIX B. ENGINEERS' GRID INTERVIEW

The following analysis grid was used to guide semi-directed interviews with 17 end users.

General information

- Who is the interviewee?
- What is his role in the organization? Since when?
- What is his experience and expertise with climate data?
- What is his experience and expertise with infrastructure design?
- Examples of projects (sewers, aqueducts, bridges, roads, railroad, dams, dikes, etc)
- Example of engineering services provided

Sources of weather data

- What type of climate data are you using in infrastructure design? (length of data record)
    - Climate variables, indicators and statistics
        - Temperature
            - Statistics (mean, extreme)
            - Spatial and temporal resolution
        - Precipitation
            - Statistics (mean, extreme)
        - Spatial and temporal resolution
        - Wind
            - Statistics (mean, extreme)
            - Spatial and temporal resolution
        - Freezing rain
        - Other
    - Climate indicators
        - IDF curves
        - PMP/PMF
        - Snow water equivalent
        - Frost depth
        - Freeze/thaw cycle
        - Others
    - Weather station data, gridded data
    - Radar data
    - Reanalysis data
    - Climate change projection
- Where does the climate data come from (sources) ?
    - Handbooks

    - Scientific articles
    - External consultant (climate services provider)
    - Public organization (website, personal contact)
    - Internal climate service team
- Type of data: already formatted or manipulation is needed?
    - Manipulation of data (interpolation, quality control)
    - Tailored data for project needs
- Is uncertainty communicated with the data?
    - If yes, how?
    - If no, is this missing? Would you use the data differently, if uncertainty was communicated?
- Greater confidence in data provided by local regional/provincial/federal sources?
- General confidence in the data you are using

How climate information is used in design?

- Methodologies to use the data
    - What are you doing when data are missing?
    - Accounting for regional and local conditions
    - Aggregation of stations
    - Other transformations?
- How do you integrate (with confidence) historical climate information in infrastructure design?
    - The value is used directly in equation/numerical model
    - Sensitivity analysis
    - Safety factor
    - Holistic decision-making protocol
    - Vulnerability assessment
    - Other
- Do you need to manipulate the data before doing so?
    - What are you doing when data are missing?
    - Accounting for regional and local conditions
    - Aggregation of stations
    - Other transformations?
- Are you integrating climate change information in infrastructure design?
    - Is it on your initiative or because your client requests it?
    - Challenges
    - Barriers
- How do you consider/integrate (with confidence) future climate change information in infrastructure design?
    - The value is used directly in equation/numerical model
    - Sensitivity analysis

- ☐ Safety factor
- ☐ Holistic decision-making protocol

- Do you need to manipulate the data before doing so?
  - ☐ Downscaling? What methodologies? Who is doing it?
- How do you deal with intrinsic uncertainty of climate change data?
  - ☐ Estimation
  - ☐ Consideration
    - o Greenhouse gases scenario selection and other details
    - o Climate models' imperfections
    - o Natural climate variability

How do you communicate climate information with your client?

- What kind of communication /validation of climate information takes place with your client?
  - ☐ Validation of climate hypothesis with client
  - ☐ Written documentation of hypothesis
  - ☐ Criteria selection with client
- How do you communicate climate uncertainty with client?
  - ☐ Risks (Do not say this word during interview!)

Interviewee needs for better integration of climate information

- How could climate providers improve their services?
  - ☐ Datasets
  - ☐ Uncertainty communication
  - ☐ Spatial resolution
  - ☐ Tailored services for consultants/association/specific project
  - ☐ other
- Are you able to identify important gaps in the climate services supply chain?
  - ☐ General supply chain
  - ☐ Communication
  - ☐ Guidelines
  - ☐ other
- How are you filling the gaps in data?
- What are the improvement pathways considered for your organization concerning climate services?
- What would you need to integrate climate change information into infrastructure design?
  - ☐ Inclusion in norms
  - ☐ Accessibility of data
  - ☐ Internal expertise
  - ☐ Accessible climate services
  - ☐ Better awareness of client and stakeholders

- According to your organization, is there a need for norms and standards in the provision of climate change information?

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Ouranos was born from the shared vision of the Government of Quebec, Hydro-Québec and Environment Canada, with financial support of Valorisation-Recherche Québec in 2001. Incorporating a network of some 450 scientists and professionals from various disciplines, the consortium focuses on two main themes: climate science and vulnerabilities, impacts and adaptation. Its mission is the acquisition and the development of knowledge on climate change and its impacts, as well as socio-economic and environmental vulnerabilities, in order to inform policy makers about climate change and advise them on how to identify, evaluate, promote and implement local and regional adaptation strategies.