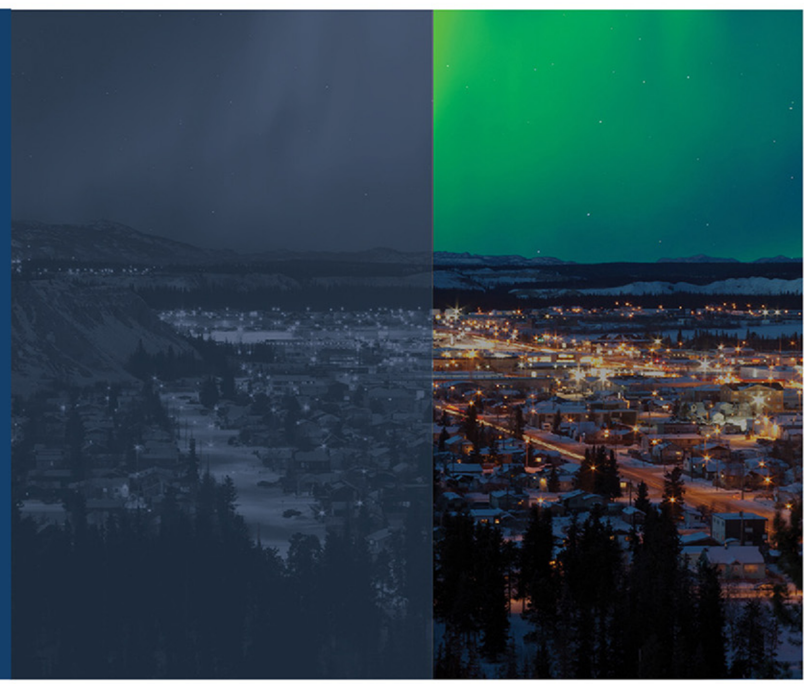
CSA PLUS 4011:19

Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation



Legal Notice

This document is provided by the Canadian Standards Association (operating as “CSA Group”) as a convenience only.

Disclaimer and exclusion of liability

This document is provided without any representations, warranties, or conditions of any kind, express or implied, including, without limitation, implied warranties or conditions concerning this document’s fitness for a particular purpose or use, its merchantability, or its non-infringement of any third party’s intellectual property rights. CSA Group does not warrant the accuracy, completeness, or currency of any of the information published in this document. CSA Group makes no representations or warranties regarding this document’s compliance with any applicable statute, rule, or regulation.

IN NO EVENT SHALL CSA GROUP, ITS VOLUNTEERS, MEMBERS, SUBSIDIARIES, OR AFFILIATED COMPANIES, OR THEIR EMPLOYEES, DIRECTORS, OR OFFICERS, BE LIABLE FOR ANY DIRECT, INDIRECT, OR INCIDENTAL DAMAGES, INJURY, LOSS, COSTS, OR EXPENSES, HOWSOEVER CAUSED, INCLUDING BUT NOT LIMITED TO SPECIAL OR CONSEQUENTIAL DAMAGES, LOST REVENUE, BUSINESS INTERRUPTION, LOST OR DAMAGED DATA, OR ANY OTHER COMMERCIAL OR ECONOMIC LOSS, WHETHER BASED IN CONTRACT, TORT (INCLUDING NEGLIGENCE), OR ANY OTHER THEORY OF LIABILITY, ARISING OUT OF OR RESULTING FROM ACCESS TO OR POSSESSION OR USE OF THIS DOCUMENT, EVEN IF CSA GROUP HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, INJURY, LOSS, COSTS, OR EXPENSES.

In publishing and making this document available, CSA Group is not undertaking to render professional or other services for or on behalf of any person or entity or to perform any duty owed by any person or entity to another person or entity. The information in this document is directed to those who have the appropriate degree of experience to use and apply its contents, and CSA Group accepts no responsibility whatsoever arising in any way from any and all use of or reliance on the information contained in this document.

Intellectual property rights and ownership

As between CSA Group and the users of this document (whether it be in printed or electronic form), CSA Group is the owner, or the authorized licensee, of all works contained herein that are protected by copyright, all trade-marks (except as otherwise noted to the contrary), and all inventions and trade secrets that may be contained in this document, whether or not such inventions and trade secrets are protected by patents and applications for patents. Without limitation, the unauthorized use, modification, copying, or disclosure of this document may violate laws that protect CSA Group’s and/or others’ intellectual property and may give rise to a right in CSA Group and/or others to seek legal redress for such use, modification, copying, or disclosure. To the extent permitted by licence or by law, CSA Group reserves all intellectual property rights in this document.

Patent rights

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CSA Group shall not be held responsible for identifying any or all such patent rights. Users of this document are expressly advised that determination of the validity of any such patent rights is entirely their own responsibility.

Use of this document

This document is being provided by CSA Group for informational and non-commercial use only. If you do not agree with any of the terms and conditions contained in this Legal Notice, you may not use this document. Use of this document constitutes your acceptance of the terms and conditions of this Legal Notice.

CSA GROUP™

Standards Update Service

CSA PLUS 4011:19
May 2019

Title: *Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation*

To register for e-mail notification about any updates to this publication
- go to **store.csagroup.org**
- click on **CSA Update Service**

The **List ID** that you will need to register for updates to this publication is **2427152**.

If you require assistance, please e-mail **techsupport@csagroup.org** or call 416-747-2233.

Visit CSA Group's policy on privacy at **www.csagroup.org/legal** to find out how we protect your personal information.

CSA PLUS 4011:19

Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation

Published in May 2019 by CSA Group
A not-for-profit private sector organization
178 Rexdale Boulevard, Toronto, Ontario, Canada M9W 1R3

To purchase standards and related publications, visit our Online Store at ***store.csagroup.org***
or call toll-free 1-800-463-6727 or 416-747-4044.

ISBN 978-1-4883-2163-4

Contents

Technical Committee on Northern Built Infrastructure

H. Auld	Risk Sciences International, Ottawa, Ontario, Canada *Category: Supplier/Contractor/Consultant Interest*	
S. Dueck	Yukon Government Community Services, Whitehorse, Yukon Territory, Canada *Category: Government and/or Regulatory Authority*	
D. W. Hayley	Hayley Arctic Geoconsulting, Kelowna, British Columbia, Canada *Category: Supplier/Contractor/Consultant Interest*	
C. Larrivée	OURANOS Impacts & Adaptation, Montréal, Québec, Canada	*Non-voting*
O. Lee	Government of the Northwest Territories, Yellowknife, Northwest Territories, Canada *Category: Owner/Operator/Producer*	
J. Oswell	Naviq Consulting Inc., Calgary, Alberta, Canada	*Non-voting*
N. Pisco	Government of Nunavut Dept of Community Services, Iqaluit, Nunavut, Canada *Category: Owner/Operator/Producer*	
B. Roy	Dept of Community & Government Services, Government of Nunavut, Pond Inlet, Nunavut, Canada *Category: Government and/or Regulatory Authority*	
T. Sheldon	Nunatsiavut Department of Lands and Natural Resources, Nain, Newfoundland and Labrador, Canada *Category: Government and/or Regulatory Authority*	
B. Sieben	Environment and Climate Change Canada/Canadian Centre for Climate Services, Yellowknife, Northwest Territories, Canada	*Non-voting*

J. Streicker	City of Whitehorse, Whitehorse, Yukon Territory, Canada *Category: General Interest*	
G. Strong	Dillon Consulting Limited, Yellowknife, Northwest Territories, Canada *Category: Supplier/Contractor/Consultant Interest*	
M. Tremblay	Aboriginal Affairs and Northern Development Canada (AANDC), Gatineau, Québec, Canada *Category: Government and/or Regulatory Authority*	
J. R. Trimble	Tetra Tech Canada Inc., Whitehorse, Yukon Territory, Canada	*Non-voting*
R. Van Dijken	Council of Yukon First Nations, Whitehorse, Yukon Territory, Canada *Category: General Interest*	
L. Jula Zadeh	CSA Group, Toronto, Ontario, Canada	*Project Manager*
M. Braiter	CSA Group, Toronto, Ontario, Canada	*Project Manager*

Subcommittee on Climate Change Adaptation for Infrastructure in Permafrost

C. Burn	Carleton University, Ottawa, Ontario, Canada	*Co-Chair*
D. W. Hayley	Hayley Arctic Geoconsulting, Kelowna, British Columbia, Canada	*Co-Chair*
H. Auld	Risk Sciences International, Ottawa, Ontario, Canada	
T. Engram	Government of the Northwest Territories, Yellowknife, Northwest Territories, Canada	
E. Hoeve	HoevEng Consulting Ltd., Yellowknife, Northwest Territories, Canada	
B. Roy	Dept of Community & Government Services, Government of Nunavut, Pond Inlet, Nunavut, Canada	
S. Smith	Natural Resources Canada, Ottawa, Ontario, Canada	
J. R. Trimble	Tetra Tech Canada Inc., Whitehorse, Yukon Territory, Canada	
L. Jula Zadeh	CSA Group, Toronto, Ontario, Canada	*Project Manager*

Preface

This is the second edition of CSA PLUS 4011, *Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation*. It supersedes the previous edition published in 2010.

Updates to the new edition are as follows:

a) Current climate change projections recommended for use in northern Canada are presented (Chapter 4);

b) Up-to-date information on ground temperature trends in permafrost throughout northern Canada are presented (Chapter 2);

c) Permafrost conditions critical for infrastructure foundations have been summarized, revised, and consolidated into a single chapter (Chapter 2);

d) Description and explanation of foundations used in northern Canada for buildings constructed on permafrost have been revised to improve readability (Chapter 3);

e) Current trends in climate (temperature and precipitation) throughout the North are presented (Chapter 4);

f) A range of climate projections available for northern Canada are presented graphically to allow assessment of current uncertainty in future climate projections (Chapter 4 and Annex C);

g) Minor revisions to the screening process have been made for clarity (Chapter 5).

CSA Group received funding for the development of this Guideline from the Standards Council of Canada, as part of the Northern Infrastructure Standardization Initiative with input from the Northern Advisory Committee (NAC).

This Guideline was prepared by the Technical Subcommittee on Climate Change Adaptation for Infrastructure in Permafrost, under the jurisdiction of the Technical Committee on Northern Built Infrastructure and the Strategic Steering Committee on Construction and Civil Infrastructure, and has been formally approved by the Technical Committee.

Notes:

1) *Use of the singular does not exclude the plural (and vice versa) when the sense allows.*

2) *Although the intended primary application of this Guideline is stated in its Scope, it is important to note that it remains the responsibility of the users of the Standard to judge its suitability for their particular purpose.*

3) *This Guideline was developed by consensus, which is defined by* CSA Policy governing standardization — Code of good practice for standardization *as "substantial agreement. Consensus implies much more than a simple majority, but not necessarily unanimity". It is consistent with this definition that a member may be included in the Technical Committee list and yet not be in full agreement with all clauses of this Guideline.*

4) *To submit a request for interpretation of this Guideline, please send the following information to* ***inquiries@csagroup.org*** *and include "Request for interpretation" in the subject line:*
   a) *define the problem, making reference to the specific clause, and, where appropriate, include an illustrative sketch;*
   b) *provide an explanation of circumstances surrounding the actual field condition; and*
   c) *where possible, phrase the request in such a way that a specific "yes" or "no" answer will address the issue.*

   Committee interpretations are processed in accordance with the CSA Directives and guidelines governing standardization *and are available on the* Current Standards Activities *page at* ***standardsactivities.csa.ca****.*

5) *This Guideline is subject to review within five years from the date of publication. Suggestions for its improvement will be referred to the appropriate committee. To submit a proposal for change, please send the following information to* ***inquiries@csagroup.org*** *and include "Proposal for change" in the subject line:*
   a) *Standard designation (number);*
   b) *relevant clause, table, and/or figure number;*
   c) *wording of the proposed change; and*
   d) *rationale for the change.*

EXECUTIVE SUMMARY

This Guideline outlines methods to estimate the sustainability of engineered structures on permafrost foundations over their service lives in northern Canada. The objective is to mitigate climate-change-induced risk of system failure at the design stage. The intent is to accommodate climate change effects anticipated throughout the Canadian North. This Guideline was developed initially in 2010 for community decision makers so that the impacts of climate change on permafrost are considered during the siting, design, and management of new community infrastructure. This updated version is more general and is applicable to all new infrastructure in permafrost regions, including those for resource development. The guideline will assist engineering design of new infrastructure to be built on permafrost.

Change in the climate is demonstrated by increases in mean annual air temperatures since the 1970s in the western Arctic and since the 1990s in the eastern Arctic, including northern Quebec and Labrador. At Inuvik, NT, for instance, the mean annual air temperature in 1961–70 was -9.7 °C but by 2009–18 it had increased to -6.3 °C. The temperature in 1998 (-4.6 °C) was considered an extreme value, with a return period estimated at 300 years, but the annual means in 2016–18 were -5.7, -4.8, and -6.1 °C suggesting such conditions are no longer unusual. These specific values all demonstrate warming, and in the last 15 years there have also been increases in precipitation, especially rainfall.

Warming and/or thawing of permafrost due to climate change have been recorded throughout the North. The most comprehensive Canadian data on ground temperatures in permafrost are available from the Mackenzie River valley and the western Arctic coastlands. Increases of about 3 °C in the uppermost 10 m of the ground have occurred since 1970 near the western Arctic coast and absolute change has been measured to depths of more than 50 m. In places, ground warming has further increased due to other consequences of climate change, such as growth of vegetation and a deeper snow cover.

At many locations in the southern part of the permafrost zone, the perennially frozen ground is discontinuous and its temperature is above -2 °C. This temperature approximates a threshold above which the permafrost in these regions is not resilient to the effects of climate change and may be susceptible to long-term thaw. Further north, the permafrost may be cooler and spatially continuous, but the prospect of continuing climate change means that commissioning and design of infrastructure throughout the permafrost regions must now consider the changes in ground temperature anticipated over the intended service life of structures. This involves determination of permafrost conditions and the consequences of climate change at sites proposed for development, and selection of an appropriate foundation design to mitigate warming of the ground beneath the structure. The consideration must also establish the consequences of foundation system failure and the likelihood of this occurring. It may lead to investigation of alternative sites for the infrastructure.

The guideline describes important aspects of permafrost terrain that contribute to its sensitivity following construction, especially the organic surface cover, the ground-ice content and near-surface temperature regime. The guideline also describes foundation types currently used in northern Canada: 1) to prevent heat from buildings compromising the integrity of permafrost by using gravel pads and ventilated crawl spaces; 2) to prevent frost heave or thaw settlement altering the structural integrity of the building by using pile foundations; and 3) to prevent thaw of permafrost foundation soils by installation of passive heat exchangers such as thermosyphons.

The guideline describes trends in climate observed in northern Canada and presents the most recent authoritative projections of climate for the 21st century available from global simulations used by the IPCC. These projections provide a range of potential adjustments to seasonal temperatures anticipated following continuing increases in greenhouse gas concentrations under increasing unrestricted future emission scenarios (Representative Concentration Pathway 8.5, RCP8.5) and with policy action taken to reduce emissions (RCP4.5). The rate of increase or decrease in greenhouse gas concentrations will depend upon societal behaviour, but regardless of this action, increases in air temperature are expected throughout the 21st century due to the residence time of gases in the atmosphere. RCP8.5 and RCP4.5 do not differ greatly in terms of CO_2 and N_2O concentrations over the next 20 years or in terms of radiative forcing of climate. The guide recommends that engineering design is based upon projected climate change over the next 20 years or for the projected life of the structure accompanied by effective monitoring to inform owners about performance of the infrastructure during its operating period.

The projected increases in temperature vary geographically across the Canadian Arctic, so the guideline presents tables for 11 sectors of northern Canada divided by latitude at approximately 60, 65, 70, and 75 °N and by longitude at approximately 59, 86, 114, and 141 °W. The projections are presented as the mean increases in seasonal and annual air temperatures in each sector for the periods 2011–40, 2041–70, and 2071–2100. Box plots indicate the range of increases projected for each sector and time period. The mean increases in annual air temperature projected for 2011–40 under an unrestricted increasing emissions scenario (RCP8.5) range from 1.2 to 2.0 °C, and from 2041–70 from 3.1 to 5.3 °C. The total ranges in projections from all climate simulations are greater than the ranges in means listed here, but almost all indicate climate warming throughout the 21st century. The increases are consistently highest in winter and lowest in summer. This is an important consideration that must be addressed during foundation design. These projected increases suggest considerable changes to permafrost conditions are likely over the 40- to 50-year service lives of structures to be designed and built in the next decade.

The guideline describes screening and design processes to determine the scope of site investigation and engineering design services required for effective adaptation of structures to climate uncertainty and warming. The screening process establishes the potential sensitivity of proposed structures to the effects of climate change on permafrost and assesses the associated risks. The process requires information on ground temperatures, ground materials, and ground ice contents at the proposed site. Screening also involves estimating ground temperatures at the end of the service life using extrapolation of recent temperature trends and/or evaluation of climate projections. In combination, these data are used to estimate the sensitivity of permafrost at the site to climate change. This sensitivity is combined with an assessment of the consequences of foundation system failure to determine the risk presented by the project.

Projects of low or moderate risk may proceed easily from preliminary to final design, while projects of high risk require more detailed quantitative assessment. This usually involves geothermal modelling of the foundation system throughout its service life, including the potential benefits of heat exchangers installed to cool the ground if the permafrost must be preserved. These complex foundation systems require that a detailed design basis report be prepared and approved by the Engineer of Record, then submitted to the owner. In addition, a monitoring and maintenance program must be developed, documented, and approved by the owner.

The key elements of the process presented in this Guideline are: 1) field assessment of permafrost materials and temperatures; 2) projection of foundation ground temperatures over the service life of the proposed structures; 3) determination of climate-induced risk presented by the project; 4) geothermal modelling of the proposed foundation over its service life; and 5) development of a comprehensive monitoring and maintenance plan.

CSA PLUS 4011:19
Technical Guide: Infrastructure in permafrost: A guideline for climate change adaptation

1 INTRODUCTION

CHAPTER AT A GLANCE

This Chapter introduces the second edition of a guideline for community decision makers and geotechnical engineers with roles in planning, designing, developing, or managing community infrastructure and development projects in permafrost regions. It concerns structures that require foundations. It is not a design textbook for building in permafrost regions. It is intended to equip community decision makers with the ability to ensure that the impacts of climate change on permafrost are considered during the siting, design, and management of new community infrastructure. The text has been revised to reflect changes in scenarios of future climate and new building standards that have become available since the first edition was published in 2010.

1.1 Need for this Guideline

Engineering projects in northern Canada often encounter permafrost in their foundation environment. The ability of frozen ground to support these structures depends mostly on local climatic conditions, ground temperatures, soil/rock material properties, and ground ice conditions.

Geographic range of permafrost in Canada

This Guideline is relevant to communities and development projects wherever permafrost occurs in the territories and the northern portions of most provinces (see Figure 2.1, p. 17).

Significant climate warming is occurring in the North. Community infrastructure should be located and foundations should be designed with careful consideration of the potential for **significantly different foundation environments** over the service lives of structures as permafrost warms and thaws. The analyses required to address permafrost and climate-change-related factors will vary between projects, depending upon the type of infrastructure, its design, location, intended service life, and purpose.

Infrastructure covered by this Guideline

The guideline relates to *structures that require foundations*, whether buildings, utilidors, water treatment plants, towers or tank farms, and bridges. Community water supply facilities (containment structures) require special design considerations, but climate change effects should also be considered for these structures. The Transportation Association of Canada (TAC) publication, *Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions* should also be consulted for specific guidance with respect to roads and permafrost (TAC, 2010, www.tac-atc.ca).

The guideline supports the appropriate consideration of climate-change-related factors during the planning, design, and management of a *range of community infrastructure* in permafrost regions. It sets out to:

a) provide an understanding of permafrost as an environmental variable, with a focus on how permafrost responds to climate and other environmental change;
b) provide a general assessment of trends in climate and permafrost conditions across northern Canada;
c) describe the most common foundation types used for community infrastructure in permafrost environments; and
d) outline a process for ensuring that the effects of climate change are incorporated, as appropriate, into the siting of community infrastructure projects and the design of their foundations.

This is the second edition of PLUS 4011. The first edition was published in 2010. Since then new scenarios of future climate have become available, and climate change has modified permafrost terrain by raising ground temperatures and changing conditions at the ground surface. A series of national standards for design and construction in permafrost terrain have been published under the Northern Infrastructure Standards Initiative. These are:

a) CAN/CSA-S500-14, *Thermosyphon foundations for buildings in permafrost regions*
b) CAN/CSA-S501-14, *Moderating the effects of permafrost degradation on existing building foundations*
c) CAN/CSA-S502-14, *Managing changing snow load risks for buildings in Canada's North*
d) CAN/CSA-S503-15, *Community drainage system planning, design, and maintenance in northern communities*
e) CAN/BNQ 2501-500, *Geotechnical site investigation for building foundations in permafrost zones*

The principal purpose of the second edition of this Guideline is to give more recent advice on climate change considerations than what was available in 2010. Elements of the guideline, especially the scenario tables in chapter 4 (Tables 4.2 – 4.3) may be updated more frequently as information becomes available. Such information is commonly released every five years with fresh assessments from the Intergovernmental Panel on Climate Change.

Permafrost and community infrastructure

Many northern communities are predominantly underlain by perennially frozen ground, or permafrost. The anticipation of significant climate change means that structures built on frozen ground will need to have their foundations designed not only for present conditions, but also for remarkably different foundation environments in the future. Professionals need to apply today's best practices and technologies, and to include monitoring programs for the performance of these foundations. The foundations may require adaptation in the future. Engineering of structures for permafrost environments with ground ice is a substantially different exercise than the design of foundations for similar structures in non-permafrost areas.

1.2 Target audience

This Guideline is for geotechnical engineers, planners, developers, and decision makers with a role in planning, purchasing, developing, or operating community infrastructure and other projects in permafrost regions. It is meant to assist people who are not experts in either permafrost engineering or climate-change science, by providing them with:

a) improved understanding of critical permafrost- and climate-change-related issues;
b) a means for locating key information sources on these topics; and
c) an ability to ask key questions of those they hire to carry out the planning, assessment, design, and construction of projects.

1.3 Limitations of this Guideline

This Guideline relates to those structures that require foundations. As such, it will not be of direct relevance to **all** types of infrastructure in permafrost terrain.

This Guideline is **not** a designer's textbook for foundations in permafrost, and it should not replace the expertise provided by geotechnical and other civil engineers, architects, planners, climatologists, and other environmental scientists who need to be engaged in all aspects of infrastructure planning, design, construction, and operation.

While the guideline focuses mainly on foundations and permafrost, it is critical to note that any infrastructure is best designed and operated as an integrated system comprising the infrastructure and the social and natural environment within which it operates. The guidance in this document should be used together with requirements and advice on structural design, heating systems, insulation, health and safety, and other aspects of infrastructure systems, to deliver assets that efficiently and effectively meet their intended purpose. The *National Building Code of Canada* (NBCC 2020) and the *Good Building Practices Guide*, published by the Government of the Northwest Territories (2019), are two important resources, as are the standards cited earlier in this chapter.

The knowledge base concerning permafrost, community infrastructure, and climate change and mechanisms for minimizing risks stemming from the interaction of these factors, will undoubtedly improve in the future. The principal conferences in North America where improvements to the practices presented in the guideline are discussed are the annual Canadian Geotechnical Conference, the periodic Canadian Permafrost Conference, and the biannual International Conference on Cold Regions Engineering. Users of the guideline may also wish to consult the *Infrastructure Climate Risk Protocol* (Engineers Canada, 2010) and *Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation* (Warren and Lemmen, 2014).

1.4 Important features of this Guideline

Readers will notice that there are few citations within the text of this Guideline. This approach has been taken to facilitate reading of the document. A list of key references for each chapter is included in Annex B.

Each of Chapters 2 through 5 finishes with a section called "conclusions and key messages". These sections highlight the elements of the chapter that are of greatest consequence.

The guideline contains both contextual information and guidance. Chapters 2 and 3 are predominantly contextual in nature, addressing among other things permafrost as an environmental variable, trends in climate and permafrost conditions, primary foundation types, and the effects of construction on the occurrence and condition of permafrost. This portion of the guideline establishes a common appreciation of key planning and design considerations for the task of construction in a changing permafrost environment.

Chapter 4 contains specific advice on climate change scenarios for northern Canada. This component of the guideline has been extensively revised from the material presented in 2010. The information presented provides the basis for assessing evolution of future climate in northern Canada and design-relevant parameters for distinct regions of the North. The data are divided by latitude and longitude because climate projections differ across the North.

Chapter 5 is the principal chapter that outlines how climate change considerations may be included in design of foundations built in permafrost. It provides both a screening tool for determining the character and extent of climate-change-related analytical requirements, and a step-by-step guide to the incorporation of climate-related analysis in planning and design processes.

Annexes are used to convey supplementary information. Two of the annexes are of particular importance for users: Annex A is a glossary that will assist readers in verifying their understanding of concepts and terms used in this Guideline. Annex B lists bibliographic information for each chapter.

1.5 Cautionary note

The guideline is published because the magnitude of recent climate change and the effects it has had upon ground temperatures warrant careful consideration during foundation design in permafrost regions. The details of the trajectory for climate change over the next 50 years are uncertain, but evidence from the last 20 years is that climate warming is substantial and increases in rainfall are occurring at some stations in northern Canada. There is greater scientific agreement over projected increases in temperature than for precipitation, and there is substantial variability in these projections across the North. Once permafrost degradation begins in any area, the rate of thaw characteristically slows with time as the depth of thaw increases. This means that permafrost thaw is a long-term phenomenon and associated loss of soil strength is to be expected over engineering time scales. Hence, the guideline emphasizes the importance of determining the intended service life of a structure at the outset of the design process. Owners of infrastructure should not assume that their assets can be replaced with similar foundations as in present operation.

1.6 Development of this Guideline

The guideline was developed by an Expert Working Group convened by CSA as part of its Northern Built Infrastructure Program. Members of the group were selected based upon their expertise with respect to the technical, environmental, socioeconomic, and cultural considerations of planning, designing, constructing, and managing community infrastructure in the Canadian North. Members of the Working Group for revision of the guideline are:

Mr Don Hayley, P.Eng. Hayley Arctic Geoconsulting, co-Chair

Dr Chris Burn, P.Geo. Carleton University, co-Chair

Ms Heather Auld, Risk Sciences International

Mr Todd Engram, P.Eng. Government of the Northwest Territories

Mr Ed Hoeve, P. Eng. HoevEng Consulting Ltd.

Mr Bhabesh Roy, P. Eng. Government of Nunavut

Dr Sharon Smith, Geological Survey of Canada Natural Resources of Canada

Mr Richard Trimble, P.Eng. Tetra Tech Canada Inc.

Ms Leila Jula Zadeh, P.Eng. Canadian Standards Association

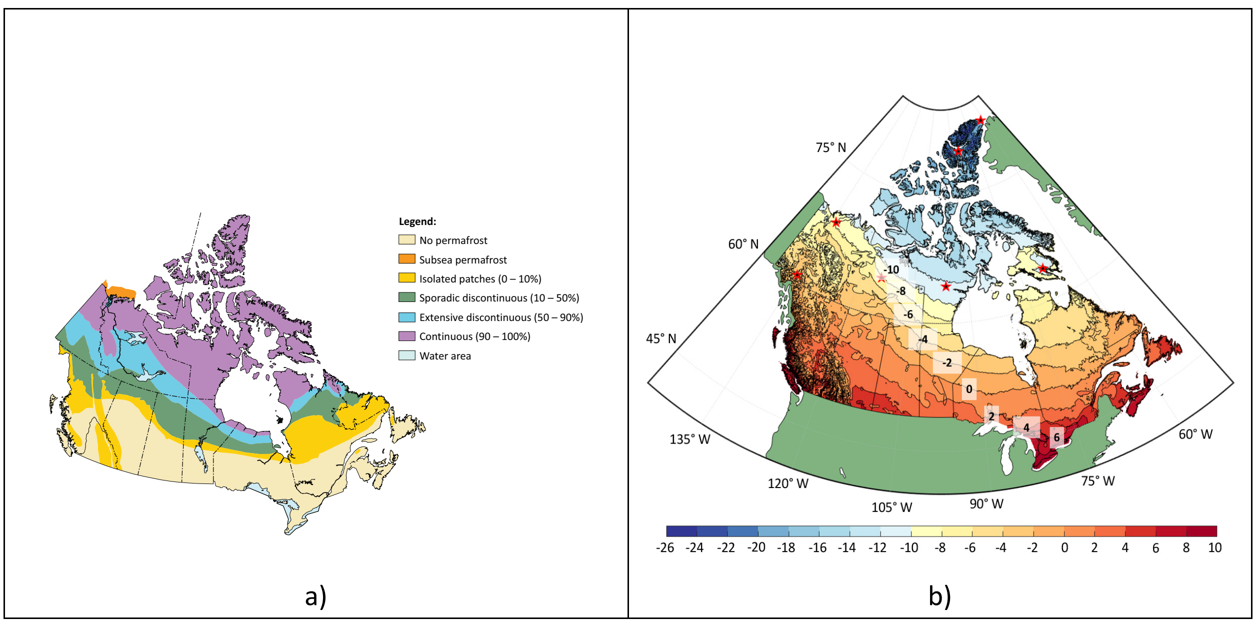
2 PERMAFROST

CHAPTER AT A GLANCE
This Chapter will provide users with an appreciation of a) the distribution of permafrost in Canada; b) the variation of ice content and temperature in permafrost; c) the environmental factors that control the temperature in permafrost; d) the effects of climate warming on permafrost; e) key indicators of ground ice; f) subsidence and reduction in soil strength when permafrost thaws; and g) significance of key permafrost characteristics for community infrastructure.

2.1 Definitions and distribution of permafrost

Permafrost is ground (soil or rock) that remains at or below 0 °C for two or more years. The ground above permafrost that thaws each summer and refreezes in autumn and winter is called the *active layer*. The permafrost region covers about half of Canada [see Figure 2.1a)]. North of tree line, in the continuous permafrost zone, permafrost underlies almost all the land area. South of tree line there are broad zones of discontinuous permafrost, where the proportion of land underlain by permafrost decreases southwards.

Figure 2.1
a) The permafrost zones of Canada [adapted from Heginbottom et al. (1995) with permission from Natural Resources Canada]; b) distribution of mean annual temperature (°C) in Canada for 1981–2010 using the Canadian gridded observation dataset (CanGRD). The historical CanGRD climate data has been developed through a partnership between Natural Resources Canada and Environment and Climate Change Canada (figure generated by Risk Sciences International).
(See Section 2.1.)



The discontinuous permafrost zones are subdivided into a more northerly, extensive discontinuous permafrost zone, where permafrost underlies 50 to 90% of the land area, and the southerly sporadic discontinuous permafrost zone, where 10 to 50% of the land area is underlain by permafrost. Further south, isolated patches of permafrost are found in peatlands and at high elevation in the mountains.

Permafrost is fundamentally a product of climate and there is direct correspondence at continental scale between the distribution of permafrost and air temperature (see Figure 2.1). The proportion of the ground that is underlain by permafrost and its thickness increase with latitude and the cooler climates found to the north. While the majority of permafrost in Canada is found in the territories, there is also considerable permafrost in the mountains of Alberta and British Columbia, and in the northern portions of the provinces from Alberta eastwards to Labrador.

Permafrost thickness at any location depends on climate, heat flow from the Earth's interior, geological history, and local site characteristics such as snow drifting, drainage, and soil conditions. Permafrost thickness varies from a few metres at the southern limits of the discontinuous zone to over 700 m in the outer Mackenzie Delta area and the Arctic Islands. In most of Canada, permafrost is deeper than the foundations of buildings.

The mean annual temperature of permafrost is generally above -2 °C in the discontinuous permafrost zone and may be as low as -15 °C in the High Arctic. The term "warm permafrost" generally refers to permafrost found within the discontinuous permafrost zone with a mean annual temperature between -2 and 0 °C, while "cold permafrost" refers to permafrost found in the continuous permafrost zone with a mean annual ground temperature lower than -4°C.

Active-layer thickness tends to decrease with the temperature of permafrost. The range of active-layer thicknesses in Canada is from a few metres, in dry bedrock, to a few tens of centimetres in the High Arctic. Commonly, the thickness in soils on the Canadian mainland varies from about 0.5 to 1.5 m. The active layer is relatively thin in peatlands.

2.2 Ground ice

The occurrence and character of ground ice is a key consideration in the siting and design of northern infrastructure. *Ground ice content* is a critical characteristic that may distinguish permafrost from unfrozen ground. Figure 2.2 shows a variety of core samples collected from permafrost soils and indicates how ground ice content may vary.

Figure 2.2
Examples of ground ice distribution in soils. a) Ice-bonded permafrost with no visible ice; b) ice-rich soil, supersaturated with ice; c) ice lenses distributed in frozen peat
(photographs courtesy of D. Fortier).
(See Section 2.2.)

a) **b)** **c)**

Ice content, temperature, and ground material are the key determinants of permafrost's strength as a foundation material (see Chapter 3). The strength of permafrost generally decreases as its temperature rises, and the salinity of the soil may reduce it further. Many northern communities, especially in the eastern Arctic, are situated at the coast, where salinity is an important consideration for strength of frozen ground.

The presence of ground ice contributes significantly to the sensitivity of a site to disturbance. Melting ground ice usually leads to ground instability, while the ability of permafrost to adhere and support pile foundations weakens as its temperature rises (see Chapter 3). Both warming and thawing of permafrost may affect infrastructure performance.

Instability is common following the melting of *excess ice*, that is, ice of greater volume than the soil pores in unfrozen ground. When excess ice thaws, the ground becomes wet and the water may pond on the surface. The accumulation or loss of excess ice is responsible for many of the landscape features associated with permafrost. These features are important to note when planning a municipal site or when assessing permafrost conditions with respect to a project.

Ground ice is normally present as *pore ice*, which fills the soil pores and bonds the soil particles together [see Figure 2.2 a)], horizontal *ice lenses* [see Figure 2.2 b) and c)], and vertical *veins* of more or less pure ice. The bodies of pure ice can range from lenses or veins that are less than a millimetre thick to massive icy beds several metres thick (see Figures 2.2 and 2.3). Fine-grained soils such as fine sands, silts, and clays are particularly susceptible to the development of such ice lenses. Excess ice contents of 30% or more are common in these soils, especially in the upper few metres of permafrost. Many settlements in the Canadian North are located close to water at sites with silt and clay-rich marine and floodplain soils containing significant ground ice.

Coarser-grained soils are generally less susceptible to ice lens formation and contain less excess ice than finer-grained sediments. However, the expansion of water as it turns to ice during freezing of coarse sediments (sand and gravel) may lead to the expulsion of water from such soils; if this water subsequently becomes confined, then large ice lenses may grow from such a reservoir. This can occur both within the active layer and during growth of permafrost.

Ice lenses are also found in bedrock fractures and may affect the use of the rock for rock-socketed piles (see Section 3.2.2). In general, the considerations required during design of foundations in permafrost are least for bedrock and greatest for ice-rich soils.

Figure 2.3
Examples of ground ice: a) massive lens of ice exposed near Tuktoyaktuk; b) buried glacier ice at Herschel Island; c) an ice wedge exposed near Tuktoyaktuk. These conditions pose challenges for successful foundation design (photographs courtesy of C.R. Burn).
(See Section 2.2.)

a) **b)** **c)**

Massive ice poses challenges for successful foundation design because of its loss of strength upon melting. Massive ice occurs most commonly near the surface as V-shaped wedges of ice in networks of polygons each about 10 to 15 m across [see Figures 2.3 c) and 2.4]. In flat terrain, these ice-wedge polygons are distinguishable in air photographs as indicators of ground ice at the site [see Figure 2.4 a)]. Commonly, ice wedges are 1 to 3 m wide at the top and penetrate up to 6 m into the ground. Ice-wedge polygons are easy to identify and avoid during construction in lowlands [see Figure 2.4 a)] but are less obvious on hillslopes where soil movement obscures the troughs. In the last decade, thawing of the ice has led to the appearance of many troughs on hillslopes and uplands, where they are clearly visible in tundra environments [see Figure 2.4 b)].

Figure 2.4
Ice-wedge polygons: Beneath the lines of the network lie ice wedges of almost pure ice (see Figure 2.3c), a) is from a lowland setting in Old Crow Flats and b) is from an upland in the outer Mackenzie Delta area (photographs courtesy of C.R. Burn)
(See Sections 2.2 and 2.3.)

a) b)

The distribution of massive ice and permafrost in various sediments has been documented for parts of northern Canada by the Geological Survey of Canada (GSC) and by other researchers. There is considerable detail available for regions where extensive geotechnical investigations have been conducted for major projects, such as the Mackenzie Valley. In regions with little or no industrial development, however, there has been little geotechnical investigation except for municipal projects. GSC databases and maps, including surficial geology maps, are suitable first sources for assessment of permafrost and ground-ice conditions. The following text box indicates some of the most important sources of permafrost data in Canada.

Main sources of permafrost data in Canada

Various agencies across Canada collect permafrost data.

a) **Geological Survey of Canada**
The Geological Survey of Canada (GSC) manages the greatest amount of permafrost data in Canada, much of which is available electronically. These data are included in historical databases and extensive geotechnical borehole compilations for regions such as the Mackenzie Valley. Other data products include ground temperatures and active-layer thicknesses for sites across northern Canada. The GSC also provides surficial and bedrock geology maps for northern Canada. All data products, reports, and maps published by the GSC are available for free download at https://geoscan.nrcan.gc.ca/geoscan-index.html

b) **Other government agencies**
Other agencies which also collect, receive, or manage permafrost-related data may also have relevant information. Among these are:
   i) *Provincial and territorial geological surveys*: The provinces and territories have geological agencies that may collect or receive permafrost-related data from other parties. Examples include the following:
      1) NWT Geological Survey Publications and Maps (http://www.nwtgeoscience.ca/our-data-and-searching-tools);
      2) NWT Discovery Portal (http://nwtdiscoveryportal.enr.gov.nt.ca/geoportal/catalog/main/home.page);
      3) Nunavut Permafrost Databank (http://www.climatechangenunavut.ca/en/climate-change/nunavut-permafrost-databank); and
      4) Yukon Geological Survey (http://www.geology.gov.yk.ca/publications.html).
   ii) *Regulatory agencies*: Regulatory agencies such as Land and Water Boards, Environmental Review Boards, and the National Energy Board maintain registries that include reports with environmental data submitted by project proponents as part of the environmental assessment process and in compliance with the terms and conditions of their licenses and permits.
   iii) *Public Works Departments*: Reports submitted to Public Works Departments by engineering consultants related to infrastructure planning and design of publicly owned infrastructure may contain information on permafrost conditions. Similarly, departments for transportation commonly commission geotechnical work.
   iv) *Northern Research Institutes*: The Nunavut Research Institute and the Aurora Research Institute (NWT) receive copies of reports with respect to all research undertaken in each of their respective territories, including research on permafrost. These reports generally consist of plain-language summaries and peer-reviewed publications.

c) **Consulting geotechnical engineers**
While their data is commonly proprietary, consulting geotechnical engineers with long-established practices in a region tend to have accumulated large amounts of site information from previous work.

d) **Other Sources**
Online databases associated with various academic research projects may also provide permafrost information such as:
   i) Nordicana D (Université Laval): http://www.cen.ulaval.ca/nordicanad/en_index.aspx
   ii) Northern Climate Exchange (Yukon University): https://www.yukoncollege.yk.ca/research/our-research/northern-climate-exchange/projects
   iii) Global Terrestrial Network for Permafrost (GTN-P): https://gtnp.arcticportal.org/

2.3 Detecting ground ice

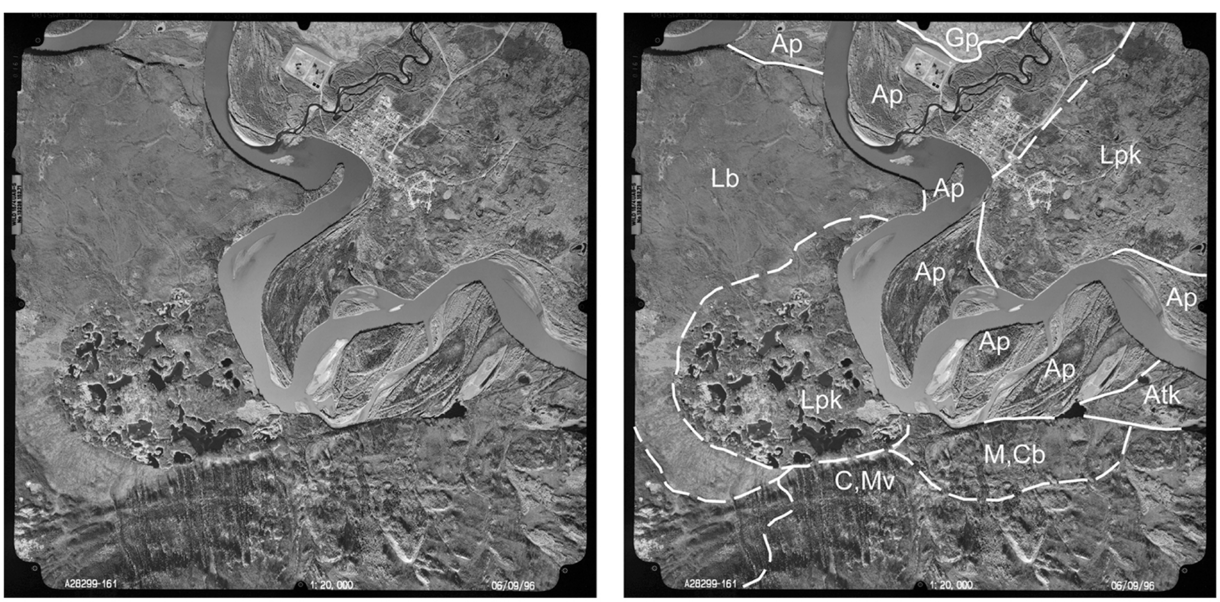
Several techniques are used to collect preliminary information on ground-ice conditions and terrain sensitivity to disturbance (see CAN/BNQ 2501-500/2017). In areas north of tree line, some of the more distinctive indicators of near-surface ground ice can be identified by consulting aerial photographs and, increasingly, through utilization of high-resolution satellite imagery or light detection and ranging (LiDAR) surveys. Among these indicators are *patterned ground* associated with ice-wedge polygons (see Figure 2.4); and *drunken forests* of trees tilted by ground movement associated with freezing and thawing of the active layer. At the southern fringes of the discontinuous permafrost zone, permafrost is largely limited to organic terrain, so forested peat plateaus may indicate ice-rich ground, because trees do not grow in the waterlogged bogs.

Uneven ground subsidence caused by the melting of near-surface ice, called *thermokarst* (see Figure 2.5), may also be used to determine areas of the terrain that may be thaw sensitive. Thawing may result from natural processes and related environmental disturbance such as wildfire, human activity such as the clearing of vegetation, extreme climatic events, or ongoing climate change. Differential thaw-settlement results in an irregular ground surface that is often poorly drained, with ponds or lakes. These phenomena can be identified on aerial photographs (see Figure 2.5) and high-resolution imagery.

Slope instability may also be used as an indicator of ice-rich permafrost. Evidence of mass movement due to the melting of near-surface ground ice on slopes, from shallow landslides and thaw slumps, is often visible on aerial photographs. Slower gradual movements due to creep may also occur on ice-rich slopes, creating lobe-shaped patterns on the hillside.

Office-based investigation techniques may include examination of surficial geology maps to delineate areas which are likely ice-rich due to their soil characteristics. Both photograph- and map-based exercises require expertise and should be carried out by a professional geoscientist or someone with similar knowledge and experience.

Figure 2.5
Use of aerial photographs to classify permafrost terrain. The photograph is of the Mayo area, central Yukon. a) Image as available; b) interpreted image with terrain units delineated as in the legend. The legend was calibrated by the author, the late O.L. Hughes, GSC. Lpk is a unit with thermokarst. (Aerial photograph A28299-161, 9 June 1996, reproduced with permission of Natural Resources Canada, courtesy of the National Air Photo Library)
(See Section 2.3.)



a)

b)

Legend:

Ap = alluvial plain (permafrost common, silt layer is generally ice rich and unstable when thawed)

Atk = alluvial terrace with thermokarst (permafrost common, silt layer is generally ice rich and unstable when thawed)

C, Mv = colluvial deposits, moraine veneer (sporadic permafrost)

M, Cb = moraine, colluvial blanket (sporadic permafrost, prevalent on most northerly facing slopes and on high plateau and mountain surfaces, less common on southerly facing slopes)

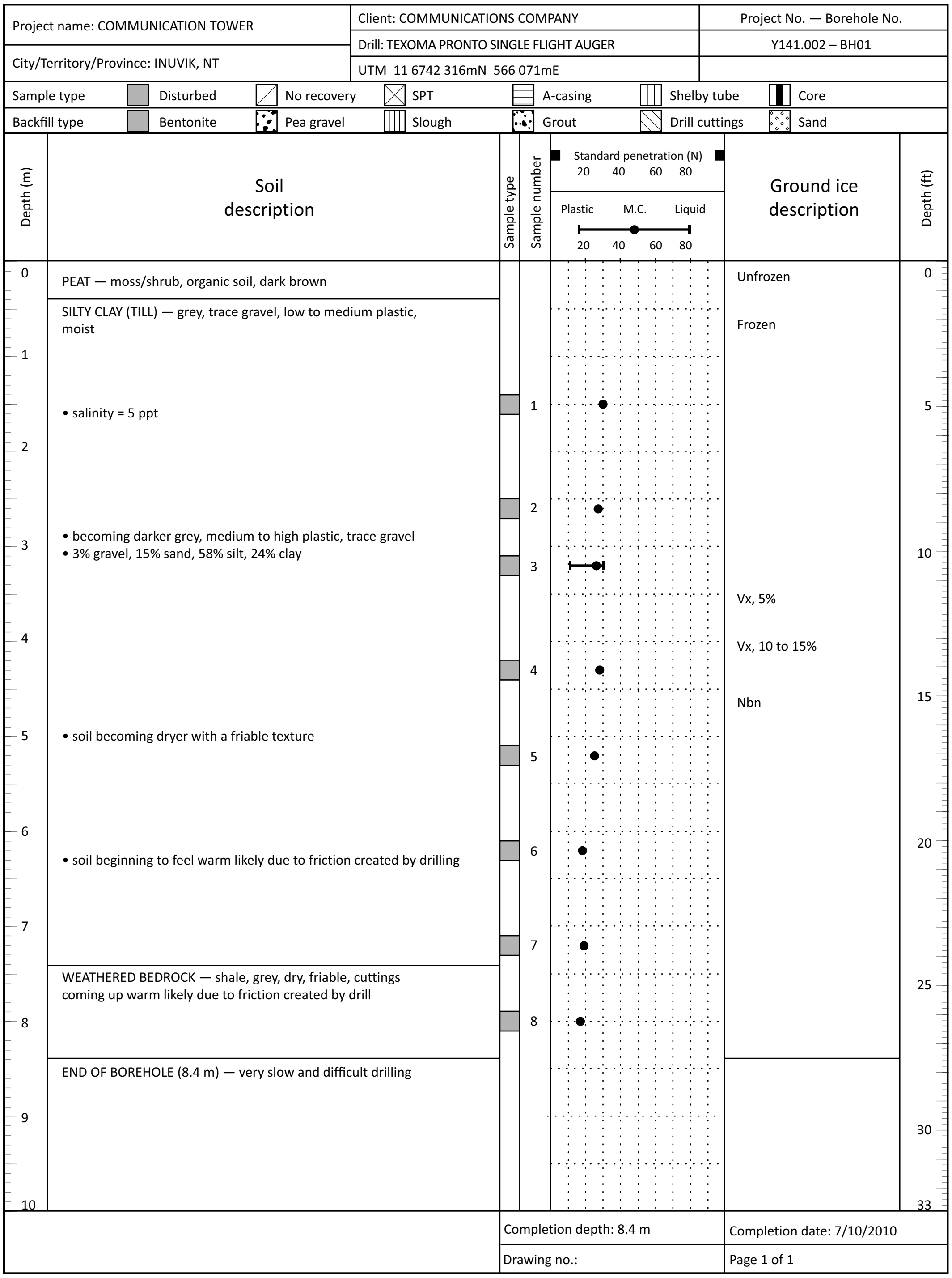
Gp = glaciofluvial plain (permafrost not common, but where present the deposits are mostly thaw stable)

Lpk = glaciolacustrine plain (permafrost present throughout, 15 to 50% segregated ice by volume common, highly unstable when thawed. Retrogressive thaw slumps and rotational failures are common where large streams are incised into glaciolacustrine sediments)

Lb = glaciolacustrine blanket (permafrost present throughout, 15 to 50% segregated ice by volume common, highly unstable when thawed)

The primary field-based technique for characterizing ground-ice conditions at a site is drilling to recover samples of permafrost for geotechnical testing (see Figure 2.2). Figure 2.6 shows a (hypothetical) borehole log. Descriptions of ground materials at different depths are recorded, including ice content, rock or soil type, and soil plasticity. Site investigations vary from project to project depending upon the needs of the client, the nature of the proposed design, previous information available about the site, and complexity of site conditions. Additional guidance on site investigation is provided in CAN/BNQ 2501-500/2017.

Figure 2.6
Typical format for a borehole log
(courtesy of Ed Hoeve)
(See Section 2.3.)



Note: *Borehole data are a function of samples retrieved during drilling. Some drilling techniques provide generalized information about ground conditions while others provide more detailed data. The notation for ground* *ice description follows the system published by the National Research Council of Canada in 1963. Vx refers to individual ice crystals or inclusions visible in the sample; Nbn refers to frozen soil with no excess ice.*

Drilling to recover samples for geotechnical testing is a critical step in understanding the potential permafrost-related vulnerability of a site. However, drilling only provides data from point sources. For some projects it is necessary to extend the investigation between drill holes with geophysical surveys. Ground penetrating radar (GPR) and electrical resistivity tomography (ERT) may be used. GPR is useful for defining the geometry of the underlying sediment layers. It can be used to determine the depth to bedrock, where there is a shallow surface layer, and the presence and shape of massive icy bodies. Resistivity surveys are particularly useful for delineating unfrozen ground within continuous permafrost. ERT can also be used to determine the thickness and lateral extent of permafrost bodies in the discontinuous zone. The use and interpretation of results from GPR and resistivity surveys require significant expertise and may require the involvement of professionals such as geophysicists, geotechnical engineers, or geoscientists.

2.4 Temperatures in permafrost

The essential features of the ground temperature regime in permafrost are shown in Figure 2.7. Near-surface ground temperatures vary through the year, driven by the annual cycle in surface temperature. The total variation declines with depth, at a rate that depends on the ground's *thermal conductivity* and *heat capacity.* The annual ground temperature envelope is defined by the maximum and minimum temperatures experienced at each depth during the year. In most permafrost, the seasonal *variation* in ground temperature decreases with depth to a level where the variation is almost imperceptible at the *depth of zero annual amplitude*. This is of significance for infrastructure since fluctuations in ground temperature affect the load-bearing capacity of foundations in frozen soil.

The depth of zero annual amplitude varies with material type and the moisture content of the soil. If the ground temperature is within a few tenths of a degree of 0 °C, the variation is also reduced by the energy requirements for freezing or thawing within the soil. In discontinuous permafrost, the annual variation does not generally extend below a depth of 10 to 15 m because of these effects (see Figure 2.7). In thinner permafrost, the depth of zero annual amplitude may even be at the base of permafrost, which stays continuously very close to 0 °C. It may be at a depth of 20 m or more in bedrock or dry granular materials with high quartz content, a mineral with high thermal conductivity. In continuous permafrost, the depth of zero annual amplitude is commonly 15 to 25 m below the surface.

Under equilibrium conditions, that is when the effects of climate warming are not included, ground temperatures increase with depth *below* the depth of zero annual amplitude (see Figure 2.7). The base of permafrost occurs where the temperature profile crosses 0 °C. The rate of change in temperature with depth is the geothermal gradient. Mean annual ground temperatures close to the level of zero annual amplitude near selected communities are provided in Table 2.1.

Figure 2.7
The equilibrium ground thermal regime of permafrost terrain, based on data collected from a site in southern Yukon (with permission from Natural Resources Canada).
(See Sections 2.4 and 2.5.)

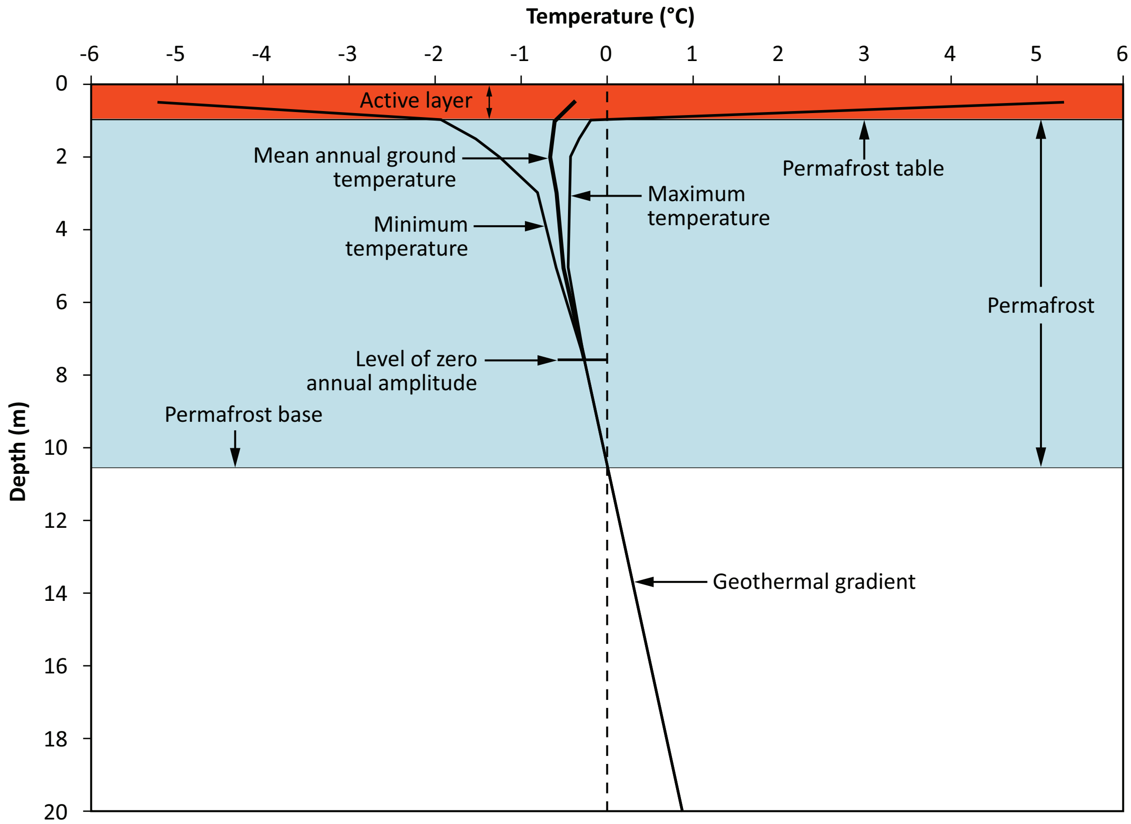


Table 2.1
Mean annual ground temperature at the measurement depth closest to level of zero annual amplitude for selected communities in northern Canada. Data for NWT and Nunavut are used with permission of Natural Resources Canada. Data for northern Quebec are from Allard et al. (2016). Data for Yukon from various sources compiled by C.R. Burn.
(See Section 2.4.)

Community	Depth (m)	Temperature (°C)	Period		Community	Depth (m)	Temperature (°C)	Period
Nunavut					***Yukon***			
Pond Inlet	15	-8.1	2015-16		Whitehorse	5	-0.8	2009-10
Resolute Bay	15	-12.1	2014-15		Mayo	16	-1.1	2009-18
Arctic Bay	15	-10.6	2016-17		Dawson	5	-0.4	2014-18
Pangnirtung	15	-4.9	2016-17		Old Crow	16.5	-3.1	2009-13
Taloyoak	15	-9.4	2010-11		Beaver Creek	7	-1.5	2012-13
Igloolik	15	-8.3	2010-11		Herschel Island	14	-8.0	2002-07
Gjoa Haven	15	-8.7	2012-13					
Kugaaruk	15	-8.0	2010-11		***N. Quebec***			
Repulse Bay	15	-8.0	2012-13		Salluit	20	-5.3	2015
Clyde River	15	-6.2	2016-17		Akulivik	5	-2.7	2014
Iqaluit	15	-5.6	2010-15		Tasiujaq	20	-2.7	2015
Rankin Inlet	12	-5.6	2017-18		Quaqtaq	19.6	-3.0	2015
NWT								
Norman Wells	12–15	-1.1 to -1.2	2016-17					
Wrigley	15	-0.7 to -0.9	2016-17					
Fort Good Hope	20	-1.1	2016-17					
Inuvik	10	-2.2	2014-15					

2.5 Site-specific factors that affect permafrost conditions

There is a general relationship between latitude and permafrost thickness, but there may be considerable local variation in permafrost temperature. Such site characteristics determine the mean annual ground surface temperature, which is critical for the spatial distribution, thickness, and temperature of permafrost (see Figure 2.7). A change in climate will result in a change of ground temperature, but the magnitude and rate at which this will occur may vary depending on site conditions, so the design, construction, and management of infrastructure foundations must recognize the importance of local site characteristics.

The four main factors affecting the site-specific occurrence and characteristics of permafrost are: snow cover, site vegetation, the soil surface organic layer, and the presence of water bodies.

Snow is an effective insulator due to its low thermal conductivity. Under natural conditions, snow acts to reduce heat loss from the ground to the air, and results in higher winter ground temperatures beneath relatively deep snow packs of 50 cm or more. Construction activities and the establishment of new structures commonly change the distribution and accumulation of snow at a site by altering drifting patterns. As a result, ground temperatures will be modified from pre-construction conditions. Potential changes in snow cover expected due to construction may be investigated by wind and snow modelling during project siting and design.

Vegetation has an important influence on permafrost distribution in the discontinuous permafrost zone, providing shade in summer and affecting the amount and pattern of snow accumulation. North of the tree line, warmer permafrost conditions are often found where shrubs trap snow during the winter. The effects of vegetation are variable because snow trapping tends to raise ground temperatures but shading and promotion of evaporation in summer lowers them.

Mosses and peat at the ground surface critically moderate the transfer of heat in and out of the ground, and strongly influence the thickness of the active layer and near-surface ground temperatures. Evaporation within the peat absorbs much of the heat otherwise available to warm the ground in summer. Dry peat also acts as an effective insulator. Commonly the peat becomes wet in autumn after rainfall, and when the wet peat freezes, it is no longer an effective insulator. As a result, permafrost at the southern fringe of the discontinuous zone may be found in organic terrain.

Water bodies, including smaller water bodies that accumulate on the side of roads or where drainage is not adequate, have a significant impact on ground temperatures, primarily by slowing the rate of seasonal ground freezing. Migrating river channels leave *taliks* behind them as they move across the landscape, and these zones subsequently freeze back. Taliks are sources of heat in the permafrost landscape, so permafrost temperatures nearby increase in response to the available energy.

These four factors all influence the temperature of permafrost at a site and generate locally a range of ground temperatures. In discontinuous permafrost, these site conditions can control the presence or absence of frozen ground. In continuous permafrost, the local factors alter the temperature of the permafrost. The range of temperatures due to local factors within a landscape is about 4 °C.

Changes in these factors influence ground temperatures and the condition of permafrost. Changes in air temperature by themselves may lead to permafrost warming, but climate change will include changes in snowfall and rainfall, and these will contribute further to changes in vegetation and snow cover. Over the long term, these cumulative effects of climate change may have a significant impact on permafrost.

2.6 Effects of surface disturbance on permafrost

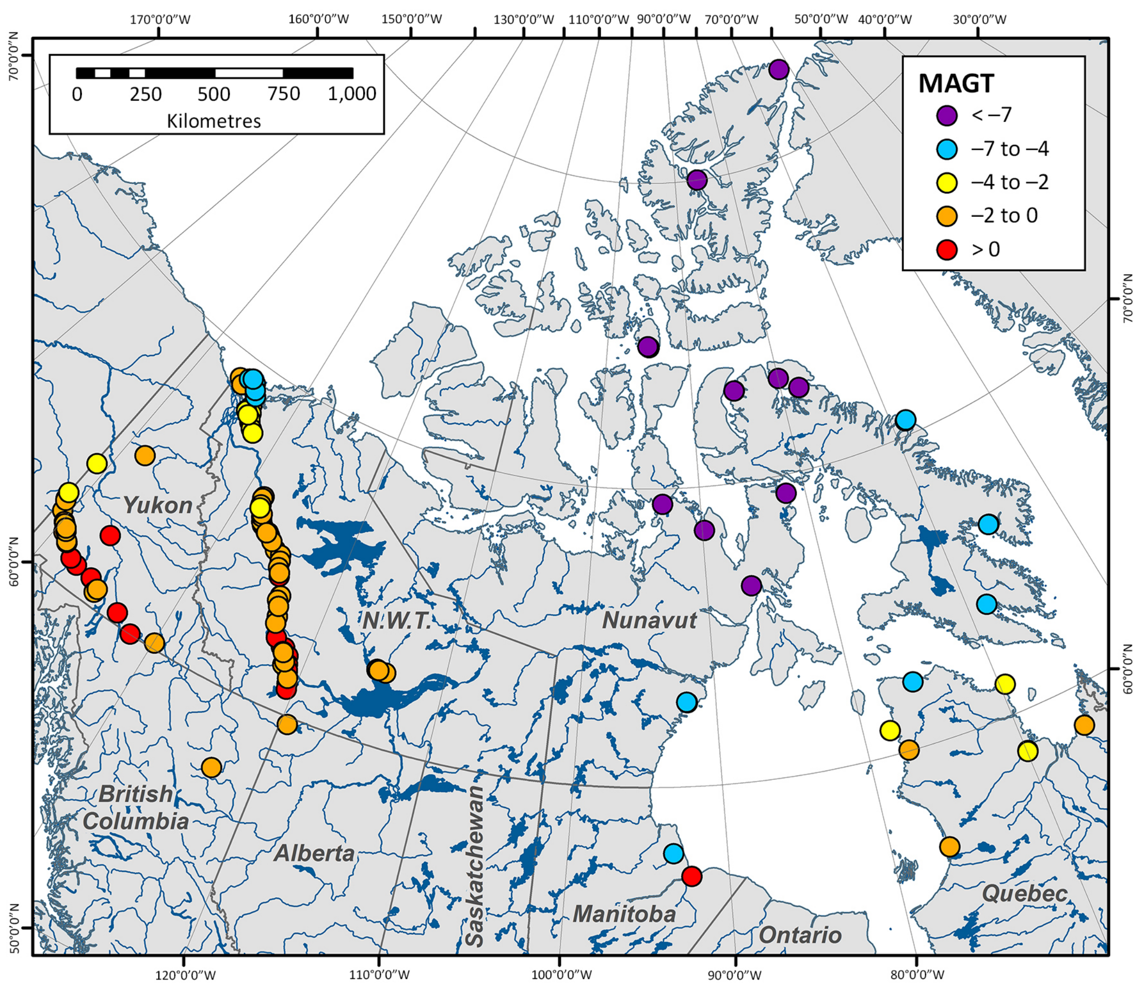
During site preparation and infrastructure construction, significant disturbance will occur at the ground surface and to near-surface soil, usually resulting in an increase of ground temperatures, irrespective of the effects of climate change. Site preparation and construction activities include vegetation clearance, grading of the surface, and removal or compression of the organic layer.

Structures themselves influence microclimatic conditions, particularly by shading and by altering snow accumulation. However, once built, the most significant impact on permafrost normally occurs immediately beneath the building. Other chapters in this Guideline give detailed information on foundations and methods used to preserve permafrost beneath infrastructure.

2.7 Climate-permafrost relations

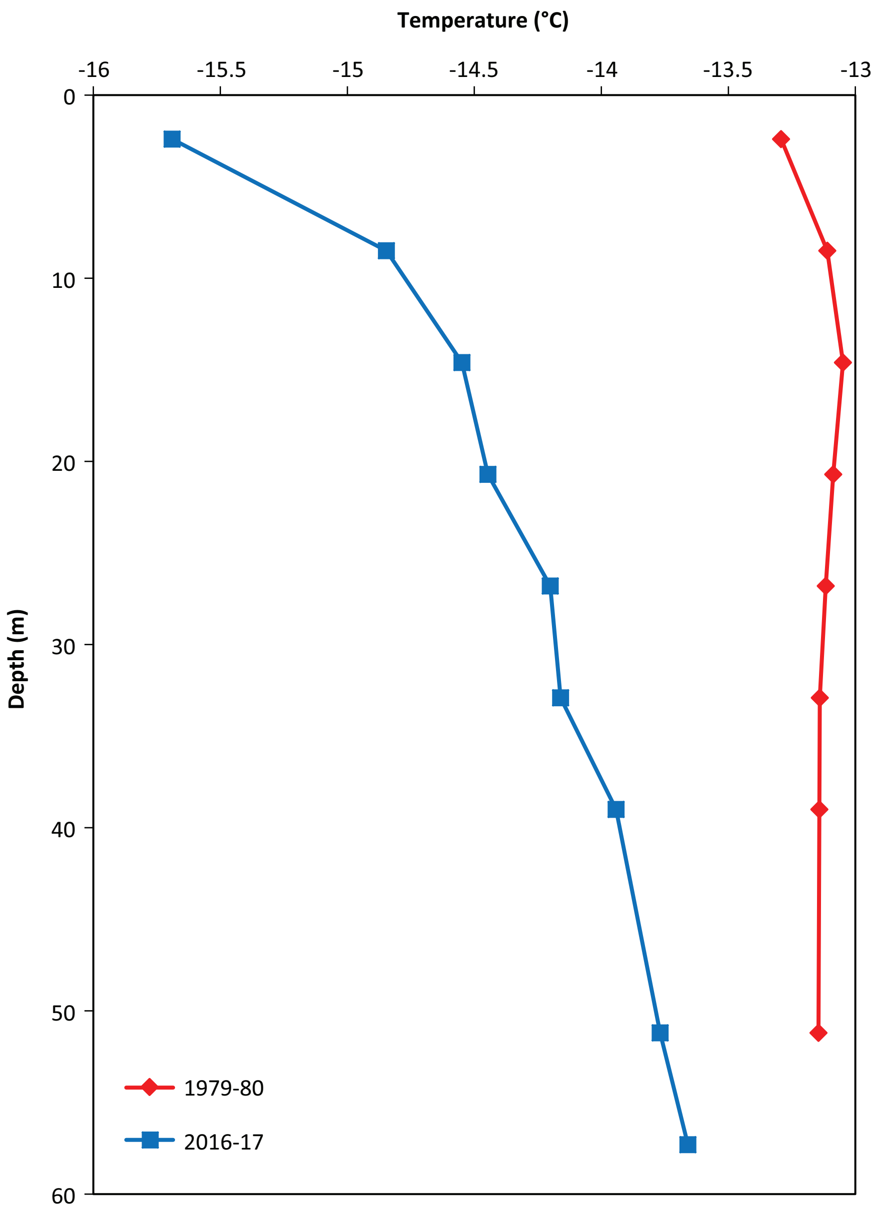
Climate is the principal factor controlling the formation and persistence of permafrost in Canada. As air temperatures decline northwards in Canada, so do ground temperatures (see Figure 2.8). The association of permafrost with climate means that as the climate warms, we also expect permafrost to warm.

Figure 2.8
Mean annual ground temperatures across northern Canada based on ground temperatures measured in 2013–2017 (updated from Smith et al., 2010, 2013, 2015 with additional data from Duchesne et al., 2016; Allard et al., 2016)
(See Section 2.7.)



An increase in temperature at the surface of the ground, due to a disturbance or to a change in climate, will lead to gradual and generalized increases in temperatures throughout the permafrost (see Figure 2.9). Permafrost close to 0 °C responds more slowly to the effects of surface warming than permafrost below about -2 °C, since near to 0 °C a significant amount of the incoming heat is used to melt ice in the ground. In the colder permafrost, nearly all the heat coming from the surface is used instead to raise the temperature of the ground. In this case, temperatures at depth increase more quickly in *cold* permafrost than in *warm* permafrost environments after warming at the ground surface. This is important with respect to the planning and design of foundations for two reasons: first, while warm permafrost may not appear to be warming rapidly, its strength will be reduced significantly as the ice melts; second, in colder permafrost the strength of the bond between permafrost and the foundation may decrease as the temperature of the ground rises. Of these, the first is the most difficult to detect and monitor.

Figure 2.9
Mean annual ground temperature profiles for cold permafrost at CFS Alert, northern Ellesmere Island for 1979–80 and 2016–17: the mean annual ground temperatures increased during the 37-year period between observations. The greatest warming occurred close to the surface, where built structures are founded (with permission from Natural Resources Canada)
(See Section 2.7.)



Latent heat, permafrost warming, and thaw

Latent heat is the energy needed to melt ice, rather than warm the ground. In frozen ground, the ice in soil pores melts over a range of temperature close to, but below, 0 °C. As heat flows into the ground following climate warming or due to changes in surface conditions, some of the heat is used to melt ice when the soil temperature approaches 0 °C. This reduces the strength of the soil and lowers its bearing capacity. If all the ice melts, then the soil may subside, as excess water drains away. The distribution of latent heat with temperature, the ability of the soil to conduct heat, and the amount of energy needed to raise the temperature of the soil are the main thermal properties of the soil which influence how soil temperatures change in response to changes in surface temperature.

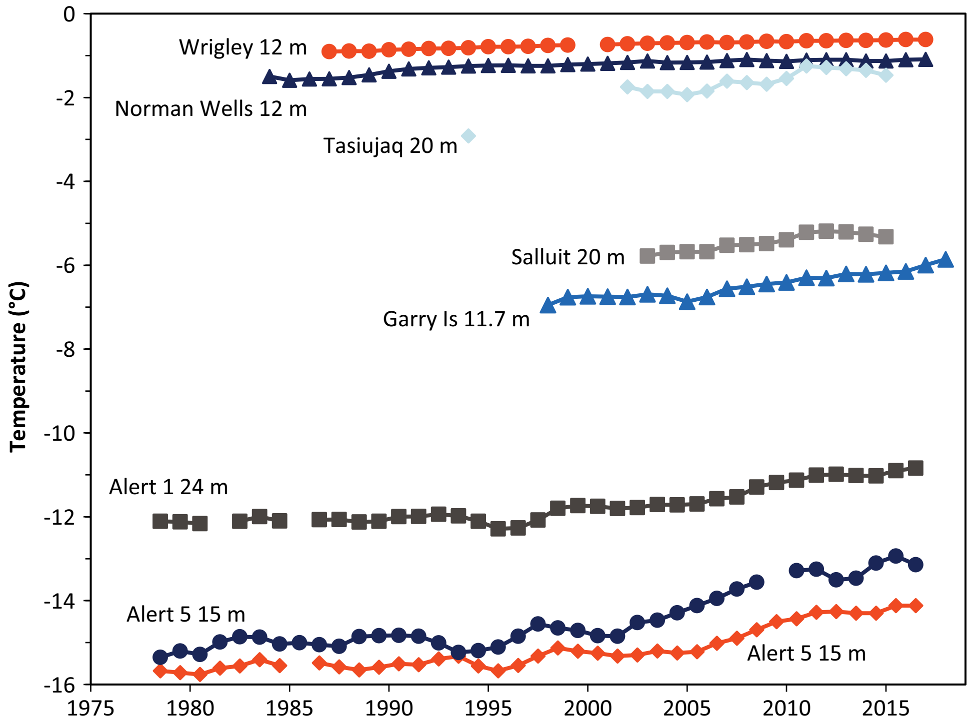
An increase of temperature at the ground surface will gradually increase the thickness of the active layer. Permafrost that is only a few metres thick may completely thaw in response to climate warming in the next century, but thicker, ice-rich permafrost will take much longer to thaw completely.

2.8 Observed trends in permafrost conditions

The temperature of permafrost is responding to climate warming in northern Canada. The warming has been occurring since 1970 in Yukon and the western Arctic and began about 20 years later in the eastern Arctic. The effects of climate warming on permafrost terrain are most easily seen over large areas of ground when ponds appear at the surface due to subsidence after melting of ground ice. These are visible most clearly in the High Arctic, where the active layer is thinnest and ground ice is close to the surface. Permafrost monitoring sites have been developed and maintained in Canada over the past three decades. Data from this network illustrate how permafrost in Canada is responding to climate change (see Figure 2.10).

Figure 2.10 shows ground temperature records for the period 1985 to 2017 at depths of about 10 m in the Mackenzie Valley. In the central Mackenzie Valley near Norman Wells, warming of about 0.1 °C per decade since the mid-1980s has been observed, where permafrost is up to 50 m thick and about -1 °C (see Table 2.2). Less warming has been measured further south near Wrigley where permafrost is warmer. Further north in the Mackenzie Valley near Inuvik and in the tundra uplands where permafrost is colder, recent increases in ground temperature have been greater (see Table 2.2).

Figure 2.10
Examples of permafrost temperature in central Mackenzie Valley (Norman Wells and Wrigley), Nunavik (Tasiujaq and Salluit), at the western Arctic coast (Garry Island), and in the high Arctic (Alert), 1978–2018. Temperatures are shown for the measurement depth closest to the depth of zero annual amplitude. All locations represented are at coastal sites, with the exceptions of Wrigley and Norman Wells [updated from Smith et al. (2010, 2015); data from Allard et al. (2016) for northern Quebec; unpublished data for Garry Island from C.R. Burn]
(See Section 2.8.)



Ground temperature records for the eastern and high Arctic indicate that permafrost warming has occurred since the early 1990s. At Alert (Figure 2.10) the rate of increase in ground temperature since 2000 is double that for the entire 40-year record. This increase reflects a period when air temperatures have been among the highest ever recorded at Alert.

Table 2.2
Change in annual ground temperatures in each region of northern Canada (based on data from GSC monitoring sites and Allard et al., 2016)
(See Section 2.8.)

Region	**Period**	**Ground temperature change (°C per decade)**
Central Mackenzie Valley	1985–2017	Up to +0.1
Northern Mackenzie Valley	2007–2017	+0.5 to +0.9

(Continued)

Table 2.2 (Concluded)

Region	Period	Ground temperature change (°C per decade)
Baffin Island	2008–2017	+0.5 to +0.7
High Arctic (Alert)	1978–2017	+0.5 (15 m), +0.3 to +0.4 (24 m)
Northern Quebec (Nunavik)	1994–2015	Up to +0.7

2.9 Impact of warming on frozen soil strength

For construction design, a principal difference between unfrozen soils and permafrost is the short-term strength presented by ice lenses and the pore ice, which binds the soil particles together. The strength of soils due to ice bonding increases at lower temperatures. Frozen soils weaken as they warm, and ice-rich soils may lose all strength due to melting of ground ice and the high pore-water pressures that occur before the soil drains. The long-term strength of frozen ground depends on the mineral matrix of the soil or rock and the presence and structure of ice, which may deform gradually, or *creep*, under sustained loads. However, the creep resistance of ice decreases as it approaches the melting point. In many cases, piles are used for foundations in permafrost, in order to transfer the weight of a structure from surface soils to a load-bearing layer at depth that is less susceptible to changes in soil strength due to seasonal warming and cooling or freezing and thawing (see Chapter 3).

Saline pore water in soils, for example in sediments of marine origin, is an additional factor that must be considered in assessments of soil strength. Saline soils contain dissolved salts in the pore water which lower its freezing point. Depending on the salinity or concentration of salts, saline soils may contain a significant amount of unfrozen water at temperatures below 0 °C. Since ice-bonding is the primary source of strength for frozen soils, the strength of saline permafrost will be less than freshwater permafrost at the same temperature.

Soils with excess ice undergo considerable transformation upon thawing. Initially, the excess water content raises the pore-water pressure and reduces the strength of the soil. On sloping ground this may lead to landslides, but in all ground, as excess water from thawing permafrost drains, the soil settles (consolidates), and its volume is reduced. In flat terrain, such settlement is noticed as subsidence at the ground surface, and the excess water may appear as ponds. Spatial variation in excess ice contents and soil drainage can result in differential thaw settlement. This is a design factor for larger structures which may cover patches of different materials, as it may lead to deformation of the structure. The terms “thaw sensitive” or “thaw unstable” are used to refer to frozen soils that exhibit significant settlement and consolidation upon thawing. Fine-grained soils such as silt and clay and organic material are thaw sensitive because they may contain significant amounts of excess ice, are generally drained poorly, and are compressible. Soils containing massive icy bodies are highly thaw sensitive and can exhibit significant settlement upon thawing. Thaw-stable soils tend to be coarser-grained, granular material (sands and gravels) with negligible excess ice. Most bedrock is thaw stable, but ice may be found where the bedrock is fractured.

2.10 Conclusions and key messages

The main conclusions and key messages of this Chapter are:

a) Permafrost is widely distributed across the northern portions of most Canadian provinces and the territories.

b) The ice content of permafrost can range from near zero to 100%.

c) Office-based investigations may help determine whether a site is likely to have ice-rich permafrost. These studies may include interpretation of aerial photographs (for key indicators or ground ice) and interpretation of high-resolution satellite imagery and maps.
d) Field-based investigations concentrate on characterization of near-surface conditions, mapping surficial geology, permafrost drilling operations, and geophysical investigations.
e) Field measurement of ground temperatures is an essential contribution to the foundation design process for community infrastructure, in order to establish initial conditions for geothermal modelling and to determine the strength characteristics of the ground.
f) Climate is the principal factor determining the occurrence and persistence of permafrost, but a range of other site-specific variables also play critical roles in determining the characteristics of permafrost important for foundation design. These include: snow cover, vegetation, the organic cover of the ground, the thermal properties of the soil or rock, and proximity to water bodies.
g) Ground temperatures are affected by warming at the ground surface, either due to natural or construction disturbance or a changing climate, and the warming of permafrost at depth may occur more quickly in cold permafrost (less than -4 °C) than in warmer permafrost environments.
h) The impact of climate change on permafrost can be seen in the ground temperature profile or may be apparent through monitoring of ground temperatures. Ground temperature profiles from many sites in northern Canada show curvature towards higher temperatures close to the ground surface as a result of recent warming of permafrost. Monitoring also shows that ground temperatures in permafrost are rising.
i) Since the relatively small climate change of the 20th century has had a noticeable impact on permafrost, we must expect these effects to develop further under the climate change scenarios discussed in Chapter 4 of this Guideline.
j) During monitoring of structural performance, it is important to obtain high-resolution measurements that may be used to detect small changes in ground temperature that may signal significant adjustments in ground properties.
k) The ground ice content of the construction site and the temperature of the ground are the main determinants of the load-bearing capacity of the permafrost.

3 NORTHERN INFRASTRUCTURE FOUNDATIONS

CHAPTER AT A GLANCE

This Chapter will give readers an appreciation of
a) the challenges that frozen and thawing ground can pose to foundations and associated structures;
b) the foundations in common use that are designed to address the potential instability of the ground in permafrost regions; and
c) considerations related to the function of these foundations.

Long-lasting community infrastructure in permafrost regions must accommodate potential instability of the ground. Foundations that rely directly on frozen ground must be designed to ensure the ground does not thaw following construction, and all foundations must accommodate changes that are anticipated throughout the service life of the structure. Engineering design needs to consider that changes in ground thermal regime, including thawing of permafrost, may accompany both construction and operation of infrastructure. Fundamental guidance is presented in Table 3.1.

Table 3.1
Classification of permafrost based on temperature
(See Chapter 3.)

Classification	Ground temperature range	Resilience to climate change
Warm permafrost	Warmer than -2 °C	Not resilient
	Permafrost between -2 °C and -4 °C will behave as either warm or cold permafrost depending upon ground ice content and soil composition. Foundation designs that rely on frozen ground should not be used in warm permafrost unless they include an active or passive heat exchanger as appropriate for the ground conditions and infrastructure purpose.	Possibly resilient
Cold permafrost	Colder than -4 °C	Presently resilient

This chapter discusses factors that affect foundation design and their modes of failure, and then reviews common foundation types used in Canada to manage permafrost conditions. The relations between foundation design and the uncertainty presented by climate warming are discussed in Chapter 5.

The following discussion focuses on buildings, but it is generally applicable to tower foundations, with the distinctions that these structures are unheated and that the tension loads commonly encountered with such foundations need to be adequately considered. For roads, the reader should refer to TAC (2010). Design of dam foundations in permafrost is an area of specialization for which no guidelines have yet been developed. Such work should only be undertaken by experienced practitioners.

While some of the principles described in this Guideline are applicable to existing buildings, the primary focus is on design of new structures. CAN/CSA-S501-14 should be consulted for specific guidance where existing buildings exhibit distress as a result of permafrost degradation.

3.1 "Failure modes" associated with foundations in permafrost

Conventional foundation design primarily considers two factors: bearing capacity and settlement. Settlement results from deformation of one or more of the support elements beneath a structure. "Failure modes" in permafrost terrain differ in important ways from their occurrence at non-permafrost locations, primarily because of the variable distribution of ground ice in permafrost. This can give rise to differential settlement and structural distortion (see Figure 3.1) and may compromise the serviceability of the structure. Foundation design in permafrost imposes several challenges for control of deformation and differential settlement. The predicted magnitude of differential settlement is usually the principal factor that controls foundation design in permafrost. Bearing capacity may become more important as permafrost thaws but bearing capacity does not normally control design.

Figure 3.1
A building in Yellowknife with the effects of differential settlement (photograph courtesy of Ed Hoeve)
(See Section 3.1.)

3.1.1 Soil strength and creep displacements

Soil is almost always stronger when frozen than thawed. The loss of strength as permafrost thaws is the greatest risk associated with soil warming, but there can be a significant reduction in strength as the soil temperatures rise gradually towards 0 °C. The strength of frozen soil not only depends on temperature but also on the duration of loading. Under constant load, ice or ice-rich soil will deform, or creep, at a predictable rate. The creep rate increases as the soil temperature approaches 0 °C. The extent of predicted ground warming during a structure's service life is critical for determining design loads that will restrict deformations to within predefined acceptable limits.

3.1.2 Thaw settlement

Segregated ice lenses and pore ice are the most common forms of ground ice. Segregated ice lenses make up the principal excess ice in fine-grained soils (fine sand, silt, and clay). Once thaw of ice-rich soil is initiated, permanent subsidence of the ground surface results, as the excess water released from the permafrost drains away. Normally permafrost thaws gradually and it takes time for the excess water to drain from the soil. The process is called *thaw consolidation*. Dense frozen granular soils will generally be free of excess ice but may still exhibit small deformations on thawing because of the 9% volumetric reduction in pore ice as it changes phase.

Ground-ice volumes and distribution can be linked directly to the thaw-settlement potential of a site. The following are examples of rules-of-thumb that are used when judging site conditions:

a) The ice content of permafrost generally decreases with depth.
b) Granular solids are generally free of excess ice.
c) There is commonly a high concentration of ground ice at the bottom of the active layer.

Such rules can be useful in assessing thaw-settlement potential but do not apply in every region. For instance, rules-of-thumb that apply in the Mackenzie Valley may need adjusting in central Yukon, where deep, infilled valleys may have substantial accumulations of ground ice at depths below 30 m.

Permafrost and climate information for site selection and design

Information relating to the extent of the permafrost, the physical and mechanical properties of the soils, and the thermal regime of the ground are essential for assessing the most appropriate foundation design and construction approach. Chapter 5 of the guideline provides a step-by-step approach for combining these types of information with preliminary data relating to the changing climate in order to evaluate the risks associated with development of the chosen site and the extent of any further climate-change-related analysis required for site selection and foundation design.

3.1.3 Accentuated frost heaving/jacking

Frost heave is the expansion of the soil that occurs during freezing and growth of ice lenses. The active layer commonly heaves in autumn and winter as it freezes back. The magnitude of frost heave depends on the type of soil, the rate of freezing, and the availability of water to form ice lenses. Structures that are supported on the ground will move with the ground. Structures that are embedded through the active layer may be pulled upwards as the ground freezes unless restrained by the permafrost below. The following summer, as the active layer settles around the structure, the foundation element may not return to its original position. In this way, structures may be progressively jacked out of the ground as shown in Figure 3.2. Deepening of the active layer and greater availability of groundwater may lead to greater frost heave potential.

Figure 3.2
Frost jacking of bollards
(photograph courtesy of Ed Hoeve)
(See Section 3.1.3.)

3.2 Foundation types

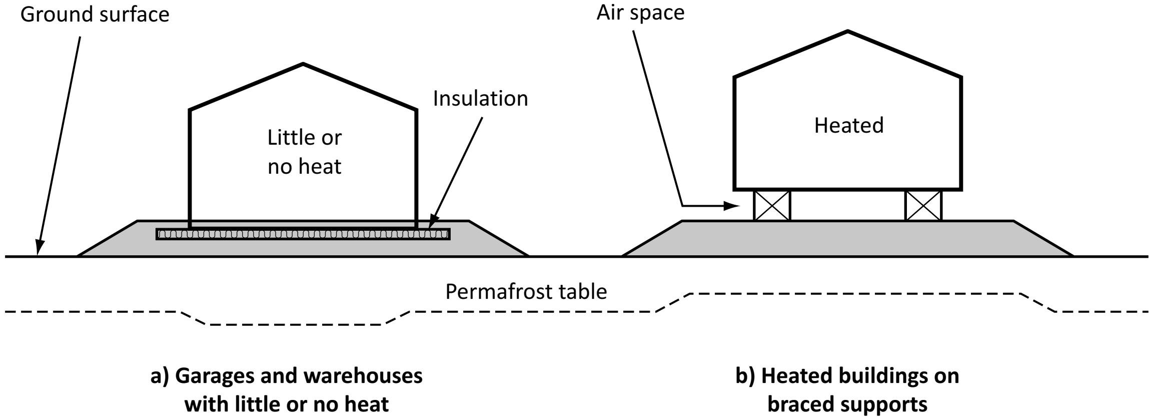
The following are the three principal foundation types commonly used in permafrost terrain:

a) shallow foundations;
b) deep foundations; and
c) foundations with heat exchangers.

3.2.1 Shallow foundations

A pad of granular material is normally placed on the ground surface as a platform for the development of many buildings on permafrost. As a minimum the pad improves trafficability and facilitates access to the site and building. With additional material, the surface pad can be configured to protect the underlying permafrost. These pads are generally composed of gravel or crushed rock placed to remain stable during annual freeze-thaw cycles (see Figure 3.3). The pad must be of sufficient thickness and material type to protect the underlying permafrost from thawing. Permafrost aggradation upward into the base of the pad may be facilitated, causing the original active layer at the site to join the perennially frozen ground beneath. It is important that the pad surface is protected from heat flowing out of the building. This may be achieved by elevating the structure at least 1 m above the surface of the pad and allowing air to circulate freely below the insulated floor of the building [see Figure 3.3 b)]. Where buildings must be placed directly on the pad surface, an alternative heat exchanger must be used (see Section 3.2.3).

Figure 3.3
Two basic pad foundation designs
(See Section 3.2.1.)



Surface footings on a granular pad with an open space below the building is an extensively used foundation type above permafrost, particularly for smaller buildings, such as homes. This foundation type can be expected to move with the ground. Therefore, the ability to compensate for differential settlement or heave of a footing by jacking and shimming is normally provided. If future settlement is likely, due to known thaw-sensitive permafrost, screw jacks may be permanently installed at each footing to simplify re-levelling [see Figure 3.4 a)].

Figure 3.4
a) Screw jacks or wedges offer relatively simple means of re-levelling structures;
b) pad and wedge foundation
(photographs courtesy of Igor Holubec and John Watson)
(See Section 3.2.1.)

a) **b)**

There are other variations of this simple footing system that use prefabricated steel or aluminum trusses to transfer the load to an interconnected network of bearing points designed for re-levelling. This system of shallow footings is called a multipoint foundation. A TRIODETIC® foundation (also referred to as a space frame) is a specific, proprietary type of multipoint foundation that is commonly used in the North [see Figure 3.5 a)]. The design premise is for the stiff framework to move as a plane, so that if there is differential movement of the pad, it will not be directly transmitted to the structure. This foundation type has been commonly used in northern Canada for light structures of one or two storeys such as houses [see Figure 3.5 b)] but has also been used for a power station.

Figure 3.5
a) A multipoint foundation situated on a rock and gravel pad; b) a building situated atop a multipoint foundation
(photographs courtesy of Robert Chapple and Ed Hoeve)
(See Section 3.2.1.)

a)

b)

Figure 3.3 is a schematic diagram showing one structure founded directly on a gravel pad and another raised off the pad. Unheated buildings such as warehouses, fuel tanks, and, with limited success, garages have been placed on granular pads. In these cases, a layer of insulation may be placed beneath the floor slab cast directly on the pad surface. This type of design is only effective if the structure is unheated and well ventilated. Garages with this type of foundation system have had a poor history, because these spaces are frequently converted to mechanical shops and subsequently heated without recognition of the design limitations. Insulation reduces the heat flux into the ground but does not eliminate it, no matter how thick the insulation is. Heat loss from such buildings will eventually initiate thaw of the pad and the underlying permafrost. Furthermore, insulation is vulnerable to degradation from the hydrocarbon spills associated with equipment garages and power stations.

A variant of a surface footing is a buried spread footing. In this case, the footing is buried with insulation either above or below it, such that it is situated near the top of permafrost (an example shown in Figure A.4 of CAN/CSA-S501-14). This foundation type still requires an air space to maintain permafrost. An objective of such foundations is to limit seasonal movements. The construction of this foundation type is more labour-intensive than surface footings, and the success depends on timing of construction and workmanship. Because of these challenges, buried spread footings are not commonly used.

3.2.2 Deep foundations

Structures may also be erected on a series of piles embedded in the ground to carry the load. There are two pile types commonly used in the Canadian North: adfreeze piles and rock-socketed piles. The designs and their applications are fundamentally different.

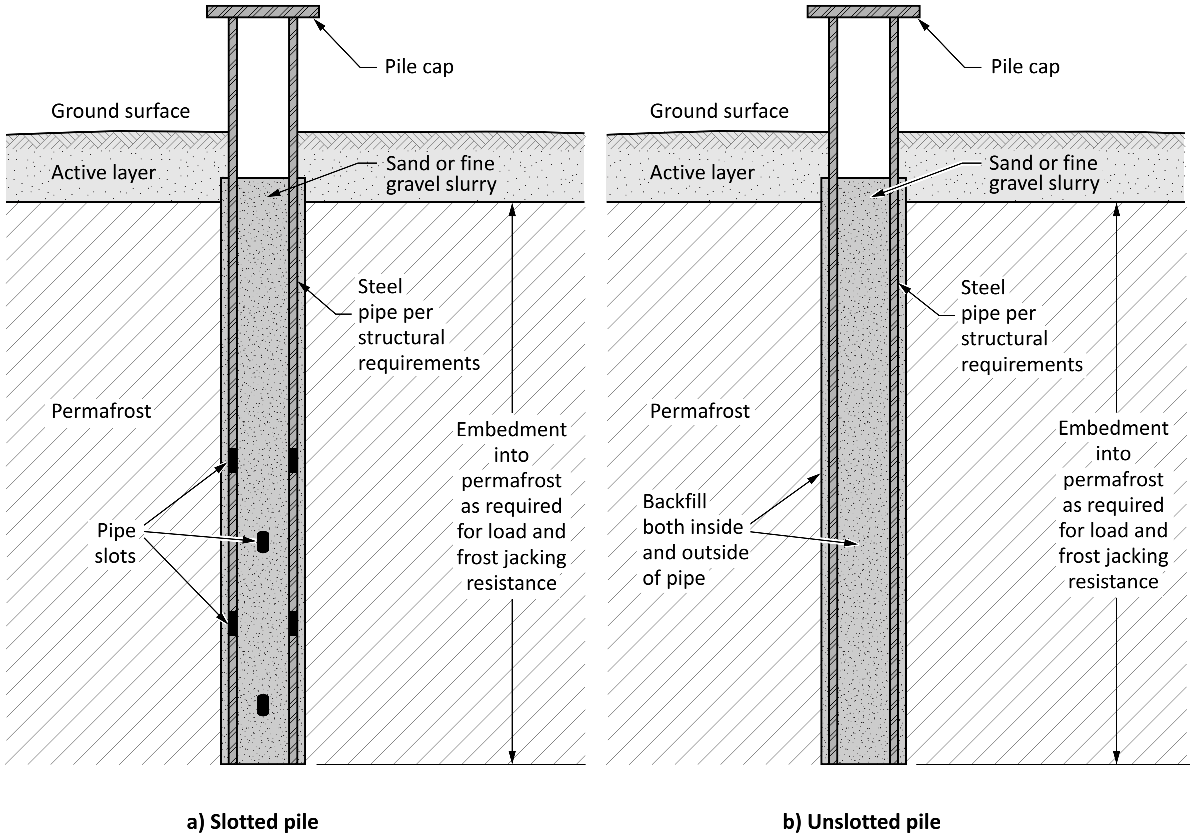
a) **Adfreeze piles**
Adfreeze piles are embedded and frozen into permafrost where they transfer their load to the frozen ground by developing a shear, or adfreeze, bond between the pile shaft and the surrounding ground. An air space must be maintained between the structure and the ground to help preserve

permafrost (see Figure 3.6). These piles are commonly installed where permafrost soils extend to substantial depths without encountering bedrock. The piles should preferably be installed at ground temperatures below -4 °C. Relatively small concentrations of salt or other ions in the pore water reduce the strength of the adfreeze bond. The salinity of the ground must be carefully assessed during site investigation at Arctic coastal communities. Adfreeze piles are commonly designed so that the nominal creep settlement is less than 30 mm over 30 years; however, this criterion may be negotiated with the building owner.

Figure 3.6
A building on adfreeze piles under construction in Inuvik, NT, where permafrost soils extend to substantial depths
(photograph courtesy of Igor Holubec)
(See Section 3.2.2.)

An oversized hole is drilled to a depth determined by the designer. The preferred piles are steel pipe with an open bottom (see Figure 3.7). Timber piles are seldom used because the shaft within the active layer may rot. The piles are placed and backfilled with a sand slurry (see Figure 3.7), then vibrated to densify the slurry, and allowed to freeze. Testing has shown that the frozen bond between the steel pipe and the sand backfill can be substantially improved by roughening the surface of the pipe. Amongst several alternatives, one method is to weld steel collars on the pipe before installation. Commonly, holes are cut in the pipe wall [see Figure 3.7 a)], allowing sand slurry placed inside the pile to migrate through the holes, enhancing the bond between the pile wall and the frozen backfill.

Figure 3.7
Sketch of adfreeze pile alternatives installed in permafrost (dimensions in mm)
[See Section 3.2.2 a).]



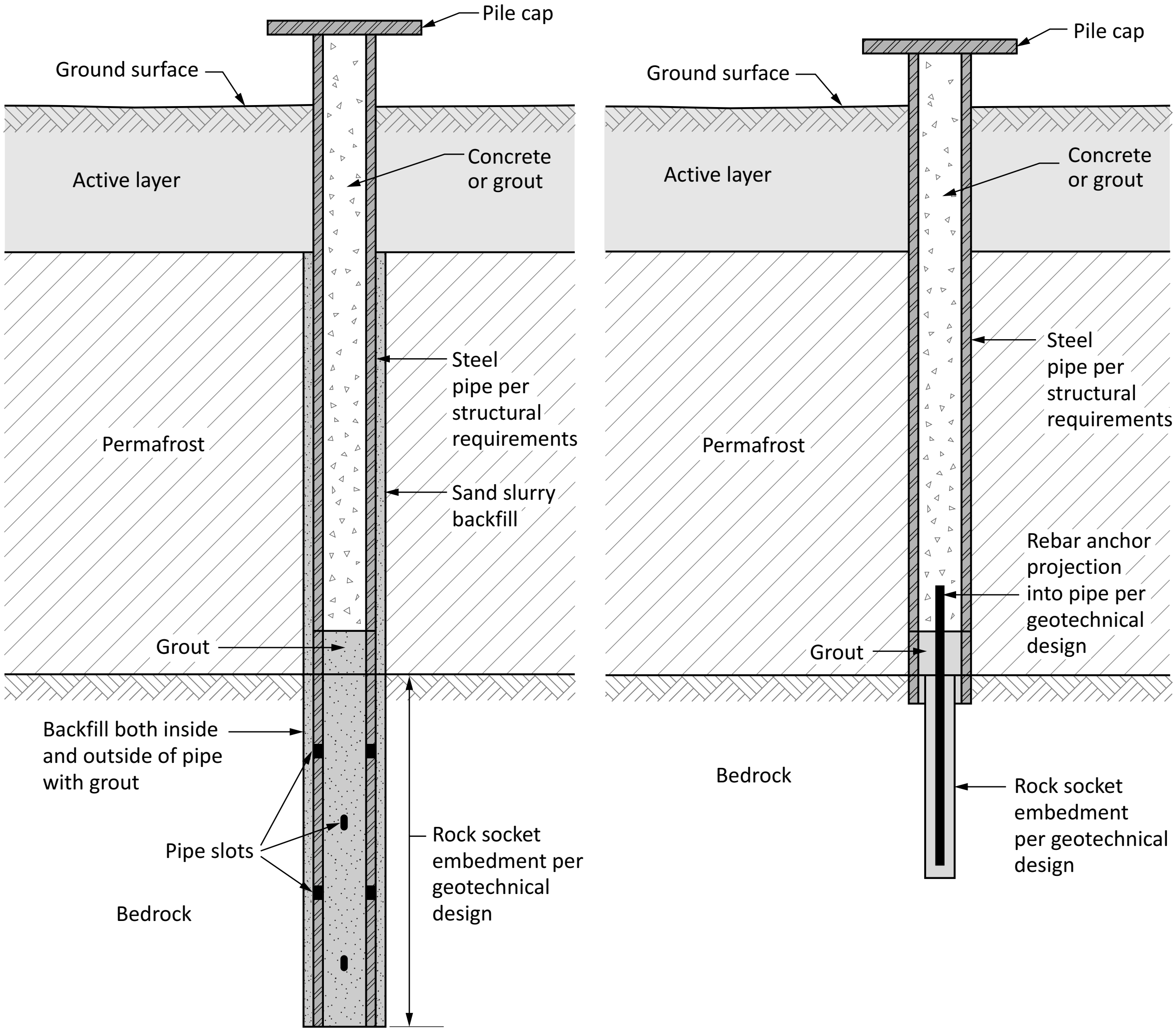
b) **Rock-socketed piles**

Where bedrock is found at relatively shallow depths (typically less than 10 m) a pile of substantially greater capacity can be keyed into competent bedrock [see Figure 3.8 a)]. Rock-socketed piles are designed to transfer the entire load of the supported structure to the underlying rock. It is not good practice, except in exceptional circumstances, to count on both adfreeze and end-bearing loads in the same pile. Load distribution from a pile to surrounding frozen soil by adfreeze requires some pile deformation that will seldom occur in a pile bearing directly on rock. These piles are typically capable of supporting much higher load capacities than an equivalently-sized adfreeze pile.

Compression loads are supported through a combination of end-bearing and grout to pile/rock bond. Resistance to uplift from frost jacking is mobilized entirely from the grout to pile/rock bond. Piles of this type must be well anchored into the underlying rock to provide appropriate resistance to uplift. The pile can be grouted into the rock socket if it is possible to maintain an open hole with either no casing or temporary casing, as is common when the piles are installed during the winter or spring, when the active layer is frozen.

It is difficult to maintain a clean, dry rock socket, therefore a specialized down-the-hole drilling system (such as Odex) is often used to advance a permanent steel casing through the permafrost and seat it into the underlying bedrock. The concept is shown in Figure 3.8 b). A smaller bit is used inside the casing to advance an uncased hole into the bedrock one metre or more. Steel reinforcing is placed into this rock socket and the entire assembly is grouted from the bottom up with a quick setting, high heat-of-hydration grout. The design of this type of pile is based on the bond between the rock-socket wall and the grout column within the socket length. The specific requirements for a grout and steel pile require the designer to collaborate with the contractor to establish an acceptable methodology.

Figure 3.8
Rock-socketed pile secured in bedrock
[See Section 3.2.2 b).]



a) "Conventional" rock-socketed pile **b) Rock-socketed pile anchored to bedrock**

Rock-socketed steel piles are not normally affected by ground thermal conditions. They are therefore not sensitive to long-term behaviour of the permafrost and how it might be affected by climate warming. There is no requirement to maintain an open space beneath a building supported on rock-socketed piles, but the designer must recognize that other ancillary aspects of a development such as stairs and ramps, utilities, and parking lots, aprons, and sidewalks will be affected by permafrost degradation or seasonal frost action.

c) **Driven piles**

Driven piles can be considered in warm permafrost with high unfrozen moisture content. They have been installed either without predrilling or by predrilling a slightly undersized pilot hole. Care must be taken to avoid inadequate embedment or damage to the pile from hard driving conditions. The design and installation of driven piles in permafrost should only be undertaken by experienced practitioners.

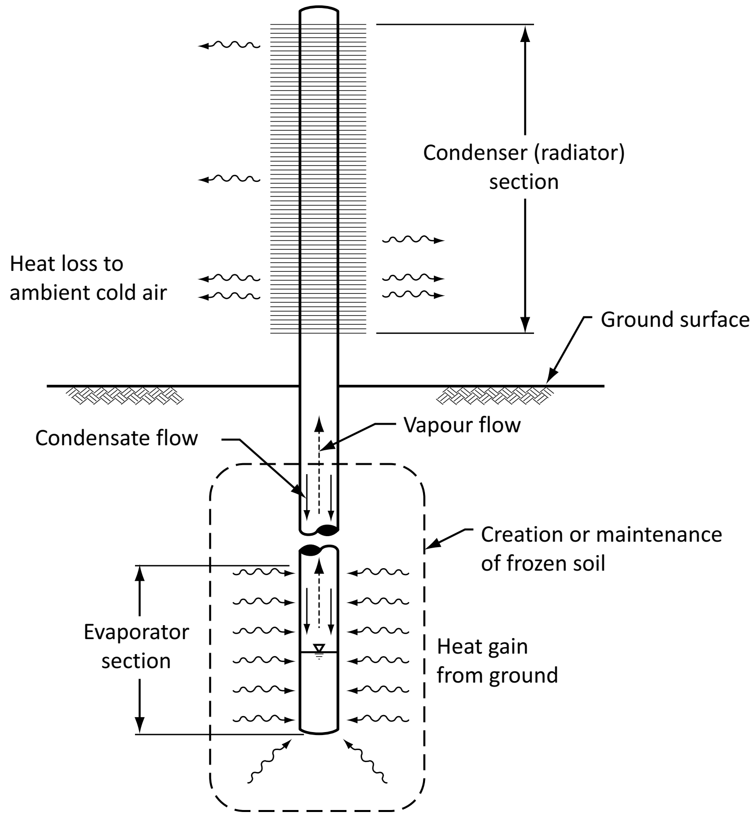
3.2.3 Foundations with heat exchangers

Foundations that use heat exchangers to maintain permafrost beneath structures are now widespread in Canada’s North. Improvements to northern communities have led to public buildings such as schools, hospitals, and airport terminals that cover large areas and are regional gathering locations. Additionally, designers favour at-grade access for institutional buildings, which facilitates compliance with Building Code requirements for barrier-free access. In communities where rock-socketed piles are not feasible, the foundation for an at-grade structure must incorporate a heat exchange system that will operate below the heated building on a prepared surface. The system must intercept heat that would otherwise flow into the ground and protect the underlying permafrost.

The use of heat exchangers, other than an open space below the structures, is not new. Free and forced ventilation pipes have been used for many years in gravel pads below bulk fuel storage tanks, and they have also been used for industrial buildings such as airport hangars. However, heat exchangers were not commonly incorporated in the design of public buildings before 2000. Active refrigeration systems and heat pumps have been used in the past but were not popular because of their high operating cost and complex maintenance requirements. These systems have been replaced by thermosyphons that are now widely used across the North American Arctic.

Thermosyphons use a fluid that evaporates at temperatures below 0 °C. Figure 3.9 shows a pool of this fluid at the bottom of the thermosyphon. The fluid evaporates into the pipe and rises upwards. The evaporation requires heat, which is extracted from the surrounding ground. The gas rises to the above-ground radiator where, in winter, it cools and condenses, releasing heat to the atmosphere. As a result, the ground beneath the building loses heat, and it may be possible to preserve the permafrost.

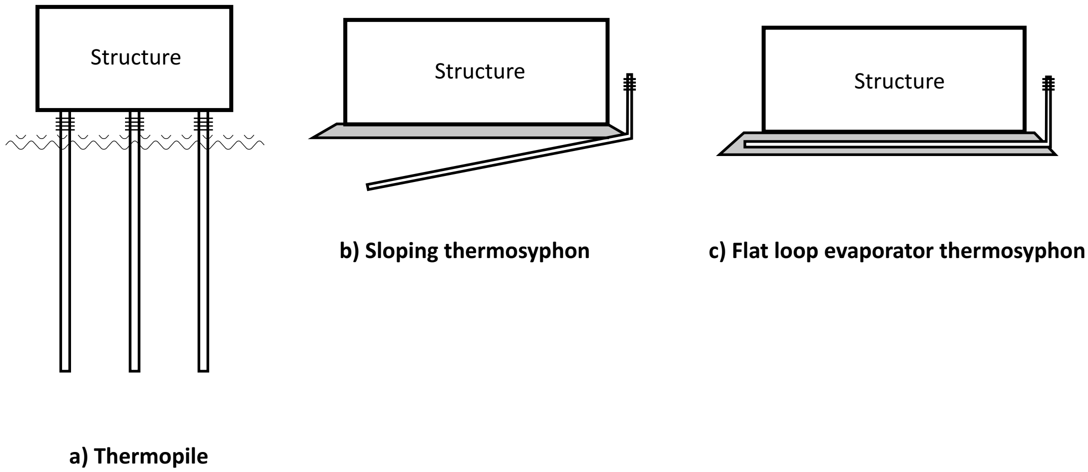
Figure 3.9
Thermosyphon components and their functions (diagram courtesy of Don Hayley)
(See Section 3.2.3.)



Thermosyphons operate effectively in the cold winters that prevail in northern Canada. An advantage of a thermosyphon foundation is that it can be configured to be resilient to climate change impacts. The design, construction, and maintenance of thermosyphon foundations is described in CAN/CSA-S500-14.

Three concepts for incorporating thermosyphons into a foundation system are shown in Figure 3.10. The sloping thermosyphon and flat loop evaporator are the most common type in Canada [Figures 3.10 b) and c)]. Thermosyphons are used in Alaska within other structural elements such as piles [thermopile; Figure 3.10 a)] to enhance the adfreeze bond. Thermopiles have now been installed in Canada.

Figure 3.10
Three thermosyphon foundation design options
(See Section 3.2.3.)



While thermosyphons are passive cooling devices and relatively maintenance free, they require annual inspection to verify that they are working as intended. Their effectiveness needs to be monitored by ground temperature measurements. Should one or more pipes fail, it could take several years for obvious distress to appear, and by then, it is usually too late to develop an effective low-cost mitigation strategy.

Inspection and maintenance of complex foundations in small communities

Complex foundations should be inspected annually and receive periodic maintenance. In order to carry out these activities, special technical expertise is required. Many smaller communities will likely need to contract outside professionals in order to secure these services. This can become expensive, but the cost of skipped inspections or delayed maintenance may be far greater. Without inspections, issues that may be easily addressed will likely not be detected, and irreversible failure of the system may subsequently occur.

Typical design sketches for a pad foundation stabilized with thermosyphons are shown in Figures 3.11 and 3.12. The thermosyphon evaporator pipes are buried under the slab at a spacing of 1 to 2 m, and a row or group of radiators is supported along one side (or more) of the building (see Figure 3.13). Gravity returns the liquid from the condenser to the bottom of the evaporator.

A system of this type requires a geothermal analysis, which considers the spacing of thermosyphon tubes and the placement and thickness of the insulation layer. The objective is to maintain the active layer within the gravel pad, which should not be susceptible to movements resulting from seasonal freezing and thawing. The inclusion of climate warming in the design process is an essential component of the design that requires careful consideration of the service life of the structure. System performance is highly dependent on winter monthly temperatures that drive heat removal from the foundation pad through the thermosyphons.

The slope thermosyphon system, illustrated in Figure 3.10 b), has generally been replaced in current foundation designs with thermosyphon loops [Figure 3.10 c)]. A closed loop allows continuous flow of both gas and liquid from the radiator around the buried evaporator loop with return of gas to the radiator for condensation (Figure 3.11). These systems use smaller diameter piping and do not rely on gravity. Therefore, they can be installed on a level pad prepared below the entire building footprint. The design principles are the same as for a single-pipe sloped system once appropriate parameters are applied to the selected system geometry to determine heat flux.

Figure 3.11
Typical thermosyphon design sketch showing insulation placement and evaporator pipes in an engineered foundation pad
(diagram courtesy of Don Hayley)
(See Section 3.2.3.)

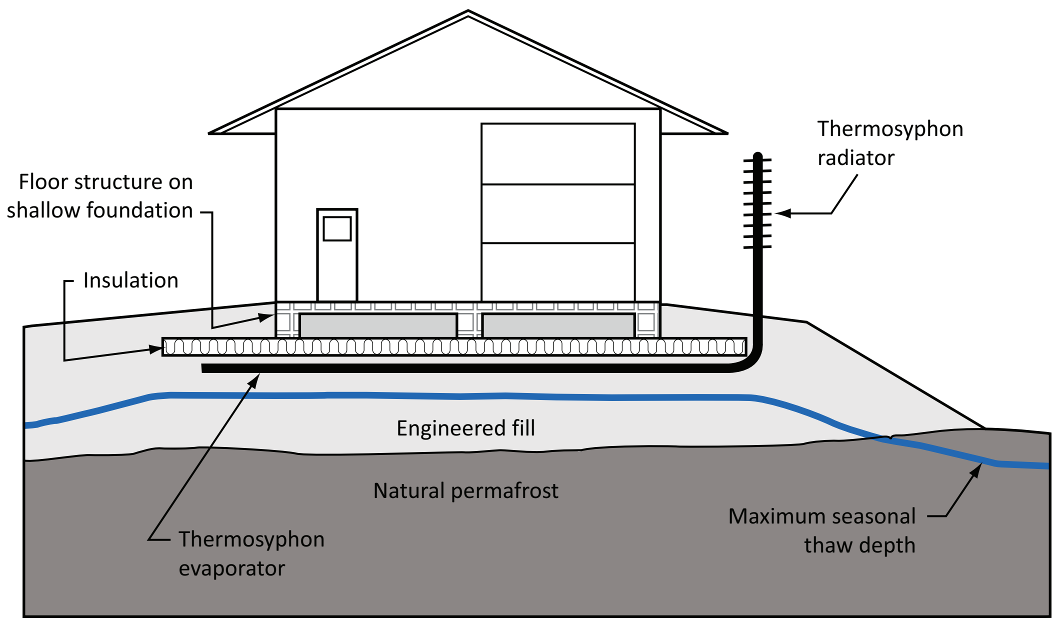
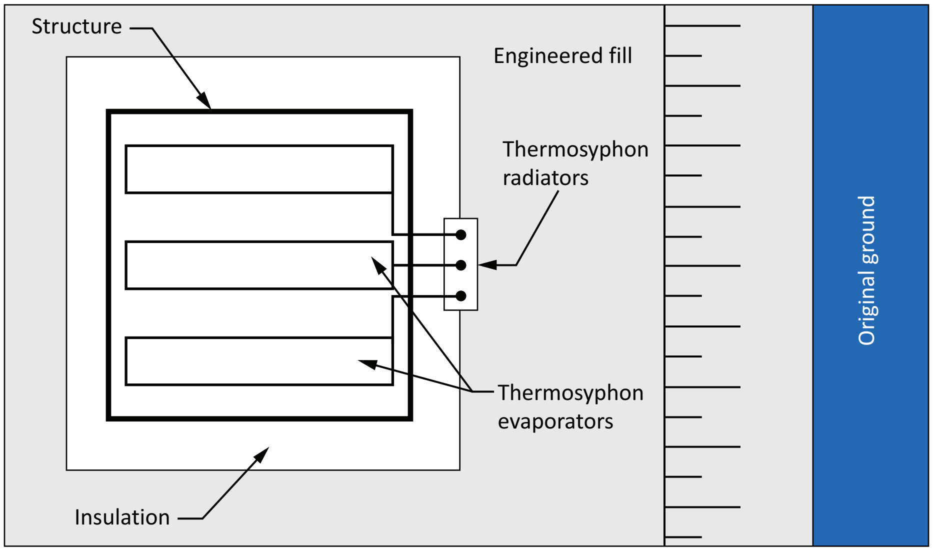


Figure 3.12
Plan view of a flat loop thermosyphon system (CAN/CSA-S500-14)
(See Section 3.2.3.)



Plan view

Figure 3.13
An array of thermosyphon radiators beside a school with slab-on-grade foundation overlying thick insulation and thermosyphon evaporator loops (photograph courtesy of Don Hayley)
(See Section 3.2.3.)

3.3 Conclusions and key messages

The main conclusions and key messages of this Chapter are

a) Foundation design in permafrost imposes several challenges for control of differential settlement and the resultant deformation of dependent infrastructure.
b) Choice of foundation type should be contingent upon an array of factors, principally the permafrost and thermal characteristics of the ground, the building function, as well as a community's capacity for ensuring that monitoring and maintenance requirements can be met.

c) Structures on shallow foundations will typically move with the ground, but structures on deep foundations should be stable, within design parameters.
d) Rock-socketed piles are resilient to climate change because the rock into which they are embedded is typically insensitive to climate change impacts.
e) Thermosyphon foundations are resilient to climate change because the cooling capacity can be configured to accommodate predicted climate warming over the design life of the structure.

4 PAST AND FUTURE CLIMATE CHANGE IN NORTHERN CANADA

CHAPTER AT A GLANCE

This Chapter provides, for the 21st century, projected changes to climate variables significant for the engineering properties of permafrost. The data are relevant to planning and development of infrastructure foundations in northern Canada.

Information in Tables 4.2 and 4.3 should be considered in the screening stages of siting and design for community infrastructure in permafrost regions.

4.1 Observed changes in the northern climate

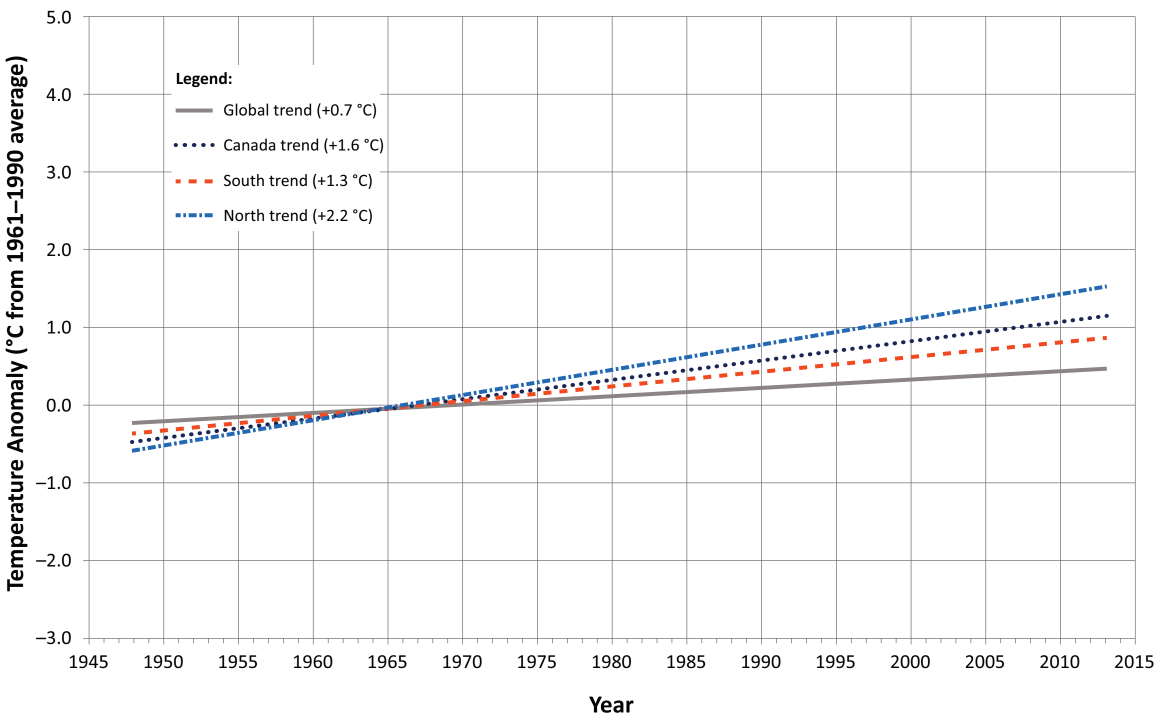
Over the past few decades, the Canadian North has warmed more than any other region in Canada and more than most regions on Earth. Over the past 50 years, climate warming in the Arctic has been about three times the global average. Much of the warming has occurred since the 1970s, with the most recent projections indicating that such climate changes will continue and, potentially, accelerate. The effects of these changes in air temperatures, along with changes in precipitation and typical weather patterns, include warming and thawing of permafrost, decreasing sea ice thickness and extent, decreasing land ice volume, melting glaciers and ice sheets, and reduced spring snow cover extent and duration. Some of these effects further magnify regional air temperature increases. As indicated in Chapter 2, changes in air temperatures, precipitation patterns, ice and snow cover, and the landscape in general can all significantly affect the characteristics of permafrost.

4.1.1 Surface air temperatures

Evidence from long-term climate data, together with other regional observations, shows warming in Canada's North that is unprecedented over the last few centuries. An international assessment in 2017 of changing Arctic climate, snow, water, ice, and permafrost conditions noted that the Arctic is evolving towards a new climate state that will be warmer, wetter, and more variable.

The ongoing and rapid warming of Arctic regions is enhanced by an atmospheric-ocean-landscape feedback process known as Arctic amplification. As shown in Figure 4.1, Arctic temperature trends and fluctuations, calculated using differences from longer-term averages, are significantly greater than for global temperatures. Research indicates that Arctic warming and changes to its ice and snow conditions may be influencing the changing weather patterns commonly noticed in southern Canada and around the northern hemisphere.

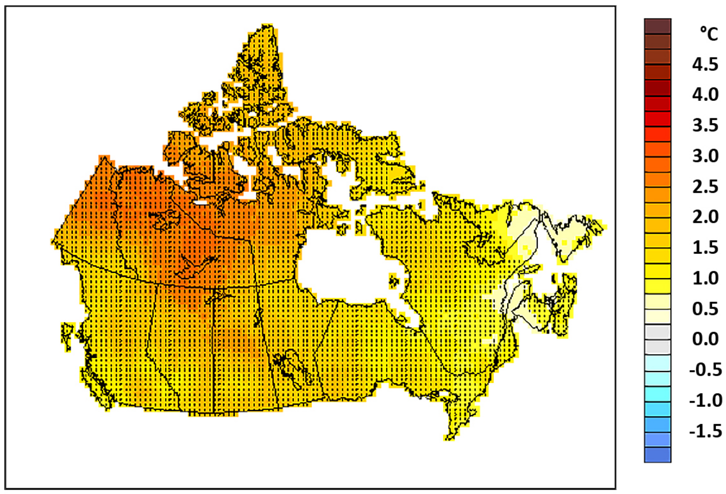
Figure 4.1
Trend lines of annual mean temperature differences relative to the average for 1961–1990 and overall change for the globe, all of Canada, northern Canada (i.e., north of 60°N) and southern Canada (i.e., south of 60°N), over 1948–2013 (Revised from Environment and Climate Change Canada, 2013: Climate data and scenarios for Canada: synthesis of recent observation and modelling results: Chapter 2. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/publications/data-scenarios-synthesis-recent-observation/chapter-2.html)
(See Section 4.1.1.)



Climate records for Canada's North are generally shorter and less complete than those for southern parts of the country. Surface air temperatures in the North also tend to be more variable than in the rest of Canada, with large changes in mean annual and seasonal temperatures from year-to-year and from decade-to-decade. This complicates analysis of trends because climate trends or variability over periods of a few decades are sensitive to the precise period of record used. Professional climatologists can provide guidance whenever extrapolating, detecting, and interpreting climate trends.

Warming trends over the Canadian Arctic indicate regional differences, with average surface temperature increases of 2 °C or more since the 1950s. Figure 4.2 illustrates the change in annual mean temperature for stations across Canada using "homogenized" temperature records obtained from Environment and Climate Change Canada's Adjusted and Homogenized Canadian Climate Data (AHCCD). These adjusted or homogenized datasets represent climate records that have been carefully examined and adjusted for non-climatic influences such as station moves, settlement influences, and site disturbances. Only the climate pattern changes or signals remain in the homogenized data.

Figure 4.2
Change in mean annual temperature (°C) in Canada over the period 1948–2013, as computed from gridded or CANGRD data. Regions with statistically significant warming are noted with dots. The northern regions have lower station density and higher uncertainty in gridded temperature anomalies (© Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment, 2019)
(See Section 4.1.1.)



Winter warming rates in some regions are up to four times greater than summer warming, as shown in Table 4.1. The warming in the western and central regions since 1950 has contributed to increases in the length of the thaw season of about 1.2 days/decade. Note that in Table 4.1, the period of record can have a significant influence on the changes in mean temperature. The relatively complete portion of the data record for Iqaluit is shorter than for the other territorial capitals. Warming for Iqaluit has been greater over the past couple of decades than during the past 50 years.

Table 4.1
Change in annual summer (June, July, August) and winter (December, January, February) mean temperatures for the three territorial capitals over 1947–2016 for Whitehorse and Yellowknife and 1951–2015 for Iqaluit. The changes in mean annual temperatures have been computed from the homogenized monthly temperature datasets developed by Environment and Climate Change Canada (Adapted from Environment and Climate Change Canada, 2017: https://www.canada.ca/en/environment-climate-change/services/climate-change/science-research-data/climate-trends-variability/adjusted-homogenized-canadian-data/surface-air-temperature-access.html).
(See Section 4.1.1.)

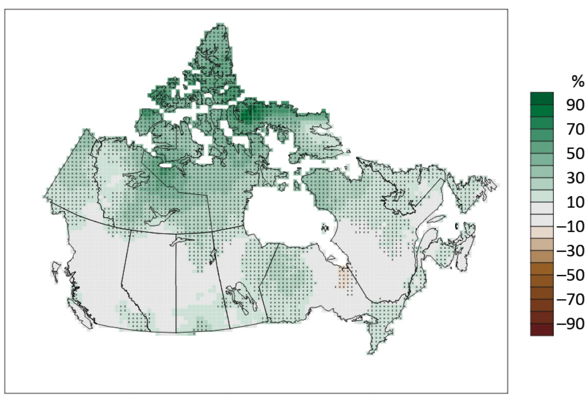
City	Period of record	Mean annual temp. change (°C)	Summer (JJA) temp. change (°C)	Winter (DJF) temp. change (°C)
Iqaluit, NU	1951–2013	1.1	1.1	0.7
Yellowknife, NT	1947–2016	3.0	1.8	5.3
Whitehorse, YT	1947–2016	1.9	0.6	5.9

Significant increases in extreme temperatures have also been observed in the North. Warming of winter extreme low temperatures across Canada from 1961 to 2010 has been stronger and more widespread than for summer extreme high temperatures, with the increases much greater in the North than in southern Canada. North of 56°N, the warming rates for one-in-20-year temperatures are estimated up to 6.8 °C per *century* for the extreme yearly minimum temperature and 1.7 °C per *century* for the extreme yearly maximum temperature.

4.1.2 Precipitation

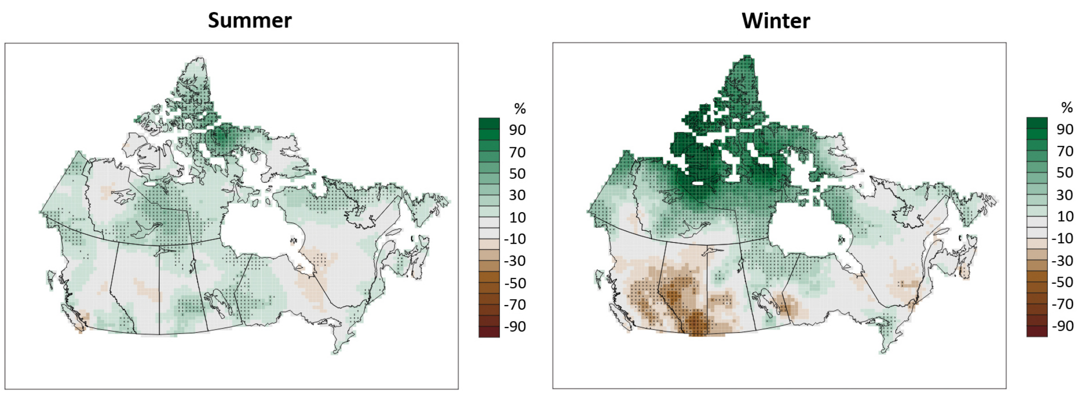
Precipitation changes tend to be more difficult to detect and interpret than temperature trends. The climate observing network in Canada has changed considerably since the 1990s with station closures and relocations. Nonetheless, during the last few decades, total precipitation in the North has generally increased. The greatest increases have been measured in the High Arctic, although average annual precipitation is typically low there (see Figure 4.3). The greatest increases in precipitation have been observed in winter, with High Arctic regions showing increases of more than 50% since 1950.

Figure 4.3
Change in annual total precipitation for the period 1948–2012, shown as percent change over 65 years. Coloured grid squares are marked with a dot when the change is statistically significant at the 5% level. Increases in precipitation have been statistically significant in most of the North (Vincent et al., 2015 and © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment, 2019).
(See Section 4.1.2.)



Analysis of snow cover in the North is significantly constrained by the limited number of stations with long records, while monitoring is impeded by the challenges of obtaining reliable estimates of changes in snowfall and accumulation over large areas. In addition to sparsely distributed measurements, there have been inconsistencies with data collection due to under-catch of snow by snow gauges, and changes in measurement practices including automation. Nonetheless, analyses of daily snow depth measurements show that the annual period with snow on the ground in the North has decreased by approximately 15 days since 1950, with most of the change due to earlier snowmelt. Observations by satellites confirm this trend in all Arctic countries. As shown in Figure 4.4, winter precipitation increases have been greater and more widespread than summer precipitation changes, with more total winter snowfall now across the North, except for southeastern Yukon. These increasing snowfall amounts over a generally shorter snowfall season have been linked to winter warming and increasing frequency of storms.

Figure 4.4
Changes in total precipitation for the period 1948–2012, expressed as percent change over 65 years. Coloured grid squares are marked with a dot when trends are statistically significant at the 5% level (from Vincent et al., 2015 and © Her Majesty the Queen in Right of Canada, as represented by the Minister of the Environment, 2019)
(See Section 4.1.2.)



Snow cover duration is projected to decrease by about one month by the 2050s, although annual maximum snow depth is projected to change only slightly in many regions due to increased snowfall, potentially offsetting the shorter snow accumulation period. Large reductions in snow accumulation are projected during the fall and spring due to a later start to the snow season and earlier melt.

4.1.3 Changing storm tracks

Storm systems or cyclones pass through the Arctic year-round. More cyclones cross the North in summer than winter, with the summer cyclones typically weaker in intensity and longer in duration. However, deeper and more intense cyclones are three times more frequent in winter than in summer.

The Arctic may have become stormier over the past several decades, but there is large variability in these trends from year-to-year and over longer timescales. Wind speeds over the Arctic Ocean may increase in all seasons later this century, but especially in autumn and winter. The occurrence of the highest wind speeds may increase in frequency by up to 100%.

4.2 Future climate change: The Arctic context

Climate change models are the principal tools used to understand future climate change. The outputs of climate models are called scenarios—the range of plausible or possible future climate conditions that vary with assumptions about the economic, social, technological, and environmental conditions driving increases in global greenhouse gas (GHG) emissions. The climate scenarios are referred to as **projections** (not predictions) and indicate the changes in the climate system that could result under different sets of GHG emissions. These sets of emissions are agreed upon internationally to provide standard pathways for the models. Although the global-scale climate models can simulate global- or broad-scale aspects of the existing climate, they remain limited in their ability to capture regional variations and describe the details of climate variability and extremes.

Arctic regions pose particularly significant challenges for climate models, as sea ice, seasonally frozen ground, snow cover, and permafrost conditions must be included in the simulations. Since our scientific appreciation and knowledge of climate change is ever increasing, decisions that require consideration of climate change are best taken with up-to-date information.

Background on climate modelling

Scientists develop their projections of future climate using selected outputs from about 40 different global-scale climate models developed for the most recent IPCC assessment (i.e., AR5). These global- and regional-scale climate models depict the physical processes of the atmospheric system and include future projected concentrations of GHGs and aerosols.

All climate simulations require a projection of greenhouse gas emissions in the future. The concentration of these gases in the atmosphere follows a specific representative concentration pathway (RCP) in each climate simulation. Two RCPs are considered in this Guideline. RCP8.5 is a pathway that follows from little effort to limit the emission of greenhouse gases into the atmosphere and projects increases in concentration that are associated with economic and population growth. RCP8.5 is sometimes called the *business-as-usual* RCP. RCP4.5 is a pathway that represents substantial efforts to curb emissions so that emissions decline after about 2040. Temperatures rise during the 21st century under both RCPs, but the rate is higher with RCP8.5.

Current climate trends should not be extrapolated into the future for periods greater than about 15 to 20 years due to the large variability of climate signals, Arctic amplification of changes, and difficulties in selecting appropriate sub-periods for trend analysis. Climate change projections should be used to help evaluate future permafrost stability for community infrastructure projects planned for a long service life.

4.2.1 Climate change projections

All of the climate models project that future air temperatures in the North will continue to rise, with many models indicating that autumn and winter temperatures will rise the most. The projected increases for the North are about twice those for the Northern Hemisphere as a whole, under either medium or high greenhouse gas emission scenarios. Most of these mid-century increases in temperature are already locked into the climate system from past greenhouse gas emissions and from heat storage in the oceans. They would likely occur even if global GHG emissions could be greatly reduced soon. If emissions continue to increase, which is likely, future changes in the Arctic will be even greater and longer lasting.

Climate models continue to be improved but their projections are still subject to significant uncertainties. There are three main sources of uncertainty in the climate model projections, namely

a) large natural year-to-year and decade-to-decade variability in the climate;
b) the rate of future GHG emissions; and
c) unresolved weaknesses in the climate models themselves, such as the size of the units used in each simulation to represent the Earth's surface.

There is no scientific consensus on how to select the best performing climate models or how to weigh many models in combination, so best practice involves examining results from multiple climate models. This, known as using an *ensemble* of climate models, is preferred because each model summarizes the complexity of the atmospheric system in a unique way. Increasing the network of climate measurements, improving regional-scale climate change projections, and using ensemble projections help to improve understanding of current and future climate.

It is possible that the warming shown by the climate change projections may underestimate potential future changes. The recent seasonal declines in Arctic sea ice extent and thickness have occurred faster than projected by climate models.

Climate change model projection uncertainties

The different climate change models typically provide different future climate projections for specific regions. Differences or uncertainties are noted among the models, even when given similar initial conditions, model physics, and assumptions about future GHG emissions. We expect these and other differences between models because the models summarize the behaviour of a global-scale system, and each model represents aspects of the system, such as topography or other regional characteristics, in different ways. Scientists have gained significant insight into how the climate system functions, and they have increasing confidence in their simulations of the climate under each emission scenario.

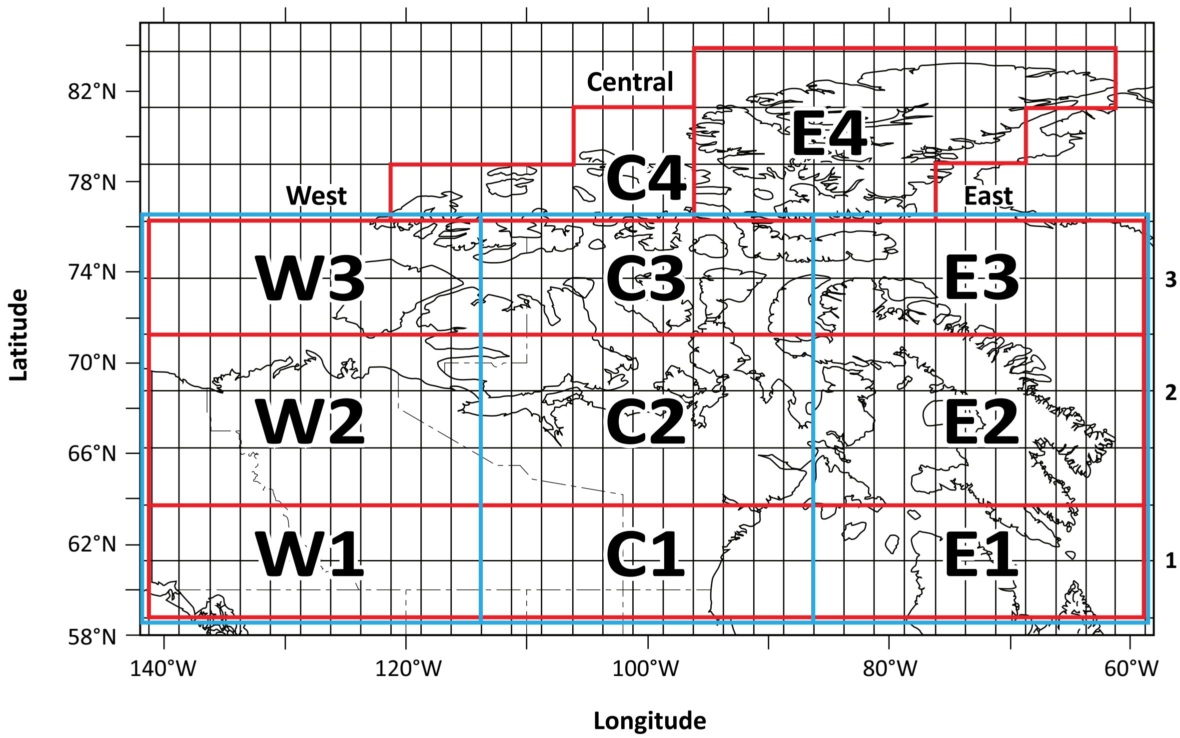
4.2.2 Climate change projections for the North

The rates and amounts of future climate warming in the North depend strongly on ongoing and future GHG emission rates. For example, if there are limited efforts to reduce GHG emissions globally (i.e., business-as-usual emission assumptions known as RCP8.5), an ensemble of the most recent climate projections indicate annual mean air temperature increases in the Canadian Arctic of 3 to over 5 °C by mid-century. By the latter part of the 21st century, the average increases range from 5 to over 9 °C, with considerably greater warming in winter. With aggressive efforts to reduce global GHG emissions (RCP4.5), the average annual warming is reduced to 2 to under 4 °C by mid-century. Generally, warming projections increase with latitude for each zone, except around Hudson Bay.

4.2.2.1 Temperatures

As in the first edition of this Guideline, the climate projections presented are based on internationally peer-reviewed climate model results from the most recent IPCC assessment. The projections have been averaged across eleven Arctic zones. Figure 4.5 shows the delineation of these zones using a matrix of longitudinal and latitudinal bands. Two high Arctic zones have been added in this edition of the guideline.

Figure 4.5
The eleven zones in northern Canada with climate scenarios presented in this Guideline
(See Section 4.2.2.1.)



The guideline provides updated, gridded future projections of air temperatures derived from an ensemble of current generation or IPCC *Fifth Assessment Report* (AR5) climate models. Tables 4.2 and 4.3 provide a useful starting point for desk-top evaluations of permafrost sensitivities to warming. Where longer asset lifespans are desired, greater spatial or temporal resolutions of projections are needed, or more detailed understanding of climate-change uncertainties is required, the designer should consult with a professional climatologist with expertise in climate-change projections and climate data analysis.

Higher emission scenarios may need to be considered for some projects, given that climate projections may underestimate future regional warming and current progress in controlling GHGs globally is limited. Higher emission scenarios lead to more conservative assumptions about future climate, which is important when considering high-risk permafrost foundations. The projections included in Table 4.2 (RCP4.5) and Table 4.3 (RCP8.5) likely are sufficient for a screening-stage assessment. Decision makers needing a more in-depth analysis for high-risk projects may need to refer to climate specialists to obtain the most recent appropriate data (Section 4.3).

Table 4.2
Seasonal mean temperature change from 1986 to 2015 baseline, under a moderately reduced (RCP4.5) greenhouse gas emission scenario [ensemble of all model outputs — AR5 GCM models regridded to common 2.5° × 2.5° (lat. & long.) NCEP grid]

(See Sections 4.2.2.1, 4.3, and 5.2.3 and Annex C.)

	WESTERN ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector W1)					**65–70 (Arctic Sector W2)**					**70–75 (Arctic Sector W3)**				
Year	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**
2011–2040	1.2	1.0	0.9	1.0	1.0	1.7	1.3	0.9	1.6	1.4	2.2	1.4	0.6	2.6	1.7
2041–2070	2.9	2.1	1.8	2.1	2.2	4.0	2.6	1.8	3.3	2.9	5.0	2.8	1.2	5.2	3.6
2071–2100	3.6	2.6	2.3	2.7	2.8	5.1	3.3	2.2	4.0	3.7	6.5	3.6	1.5	6.4	4.5
Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*															
	CENTRAL ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector C1)					**65–70 (Arctic Sector C2)**					**70–75 (Arctic Sector C3)**				
Year	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**
2011–2040	1.7	1.2	0.9	1.2	1.3	1.8	1.3	1.0	1.7	1.4	2.1	1.3	0.6	2.5	1.6
2041–2070	3.9	2.3	1.8	2.5	2.6	4.1	2.6	1.9	3.6	3.0	4.7	2.7	1.3	5.1	3.5
2071–2100	5.0	3.0	2.4	3.2	3.4	5.4	3.4	2.3	4.5	3.9	6.2	3.5	1.6	6.4	4.4
Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*															

(Continued)

Table 4.2 (Concluded)

	EASTERN ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector E1)					**65–70 (Arctic Sector E2)**					**70–75 (Arctic Sector E3)**				
Year	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
2011–2040	2.2	0.9	0.8	0.9	1.2	1.9	1.0	0.8	1.6	1.3	1.7	1.1	0.7	2.1	1.4
2041–2070	4.8	2.2	1.5	1.9	2.6	4.3	2.3	1.5	3.1	2.8	4.0	2.3	1.3	4.1	2.9
2071–2100	6.4	2.9	1.9	2.4	3.4	5.7	3.1	1.9	3.8	3.6	5.2	3.0	1.6	5.1	3.7

Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1971 to 2000.*

	HIGH ARCTIC: Latitude (deg N) — Ensemble results									
	75–82 (Arctic Sector C4)					**75–85 (Arctic Sector E4)**				
Year	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
2011–2040	2.2	1.4	0.4	2.7	1.7	1.8	1.2	0.6	2.2	1.4
2041–2070	4.9	2.9	0.9	5.8	3.6	4.0	2.7	1.2	4.6	3.1
2071–2100	6.4	3.7	1.1	7.4	4.6	5.3	3.4	1.5	5.9	4.0

Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*

Table 4.3
Seasonal mean temperature change from 1986 to 2015 baseline, under "high" (RCP8.5) greenhouse gas emission scenario (ensemble of all model outputs — AR5 GCM models regridded to common 2.5° × 2.5° NCEP grid)

(See Sections 4.2.2.1, 4.3, and 5.2.3 and Annex C.)

	WESTERN ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector W1)					**65–70 (Arctic Sector W2)**					**70–75 (Arctic Sector W3)**				
Year	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**
2011–2040	1.5	1.1	1.0	1.1	1.2	2.0	1.5	0.9	1.9	1.6	2.6	1.6	0.6	3.0	2.0
2041–2070	4.0	2.8	2.6	3.1	3.1	5.8	3.6	2.5	4.6	4.1	7.6	4.1	1.9	7.2	5.2
2071–2100	6.9	5.0	4.7	5.2	5.5	10.2	6.4	4.5	7.1	7.1	14.3	7.3	3.6	10.8	9.0
Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*															
	CENTRAL ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector C1)					**65–70 (Arctic Sector C2)**					**70–75 (Arctic Sector C3)**				
Year	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**	**Win-ter**	**Spri-ng**	**Sum-mer**	**Au-tumn**	**An-nual**
2011–2040	2.0	1.3	1.0	1.4	1.4	2.1	1.5	1.0	2.0	1.7	2.4	1.5	0.7	2.8	1.9
2041–2070	5.6	3.3	2.7	3.7	3.8	6.1	3.8	2.7	5.1	4.4	7.0	4.0	2.0	7.2	5.1
2071–2100	9.8	5.9	4.9	6.1	6.7	11.1	6.7	4.7	8.2	7.7	13.2	7.2	3.7	11.3	8.8
Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*															

(Continued)

Table 4.3 (Concluded)

	EASTERN ARCTIC: Latitude (deg N) — Ensemble results														
	60–65 (Arctic Sector E1)					65–70 (Arctic Sector E2)					70–75 (Arctic Sector E3)				
Year	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
2011–2040	2.6	1.2	0.8	1.1	1.4	2.3	1.3	0.8	1.8	1.6	2.1	1.3	0.7	2.3	1.6
2041–2070	7.1	3.4	2.3	2.8	3.9	6.5	3.6	2.3	4.4	4.2	6.0	3.4	1.9	5.8	4.3
2071–2100	11.9	6.4	4.3	4.8	6.8	11.7	6.4	4.1	6.9	7.3	11.5	6.3	3.5	9.1	7.6

Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*

	HIGH ARCTIC: Latitude (deg N) — Ensemble results									
	75–82 (Arctic Sector C4)					75–85 (Arctic Sector E4)				
Year	Winter	Spring	Summer	Autumn	Annual	Winter	Spring	Summer	Autumn	Annual
2011–2040	2.5	1.6	0.5	3.1	1.9	2.0	1.5	0.7	2.5	1.7
2041–2070	7.4	4.3	1.3	8.3	5.3	6.0	3.9	1.8	6.8	4.7
2071–2100	14.2	7.6	2.7	13.2	9.4	11.5	7.1	3.3	11.3	8.3

Note: *The value displayed in each cell represents the average change in mean seasonal or annual temperature for the specified 30-year period when compared to the average mean seasonal temperature from 1986 to 2015.*

Box and whisker plots of projected annual mean air temperature changes are provided in Annex C for each of the 11 zones in northern Canada. These plots highlight the differences between the many climate model projections for different future periods. Sample box and whisker plots (see Figures 4.6 and 4.7) highlight the full range of projections for increases in mean annual temperature for 2010–2039, 2040–2069, and 2070–2099. The top and bottom dots (and horizontal bars) for each time period mark the highest and lowest of all the projected temperature values, respectively. The shaded box represents the inter-quartile (inner 50%) range of the models. The top of the shaded box shows the higher end or the 75th percentile value of all the models while the bottom of the box shows the lower end or the 25th percentile value. The median (the middle value of all the projections) is represented by the horizontal line in the centre of the shaded box. Since different climate models project different rates of warming for the same location, it is good practice to consider these differences, especially for projects at higher risk from permafrost warming. The differences or spread between the model projections increase with time as the influence of GHG emissions increases. Higher emissions lead to greater warming, with the warming becoming more pronounced after the 2050s.

Figure 4.6
Projections of change in mean annual temperature for a region near Yellowknife from all available models for three different 30-year periods. These climate models assume reductions in global GHG emissions during the 21st century (RCP4.5)
(See Section 4.2.2.1.)

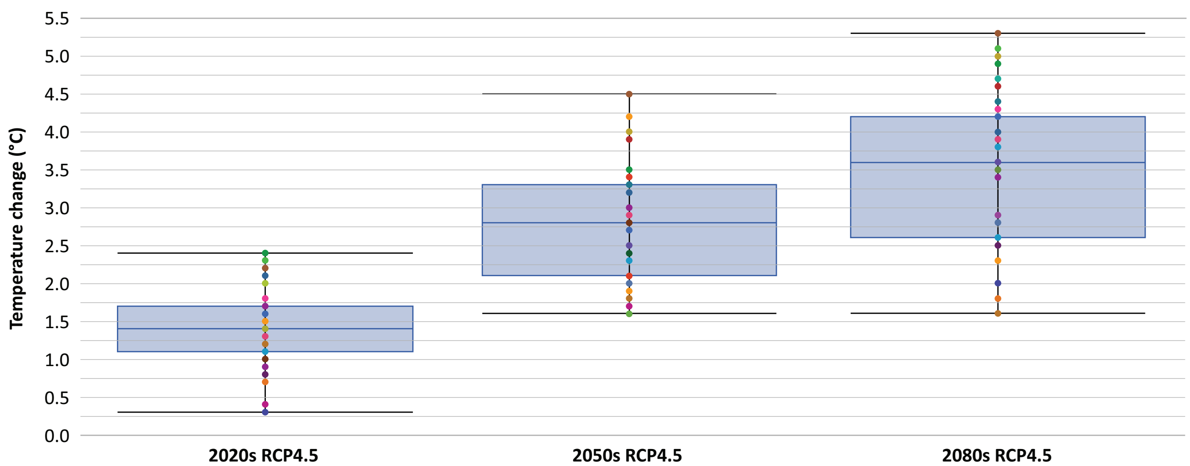
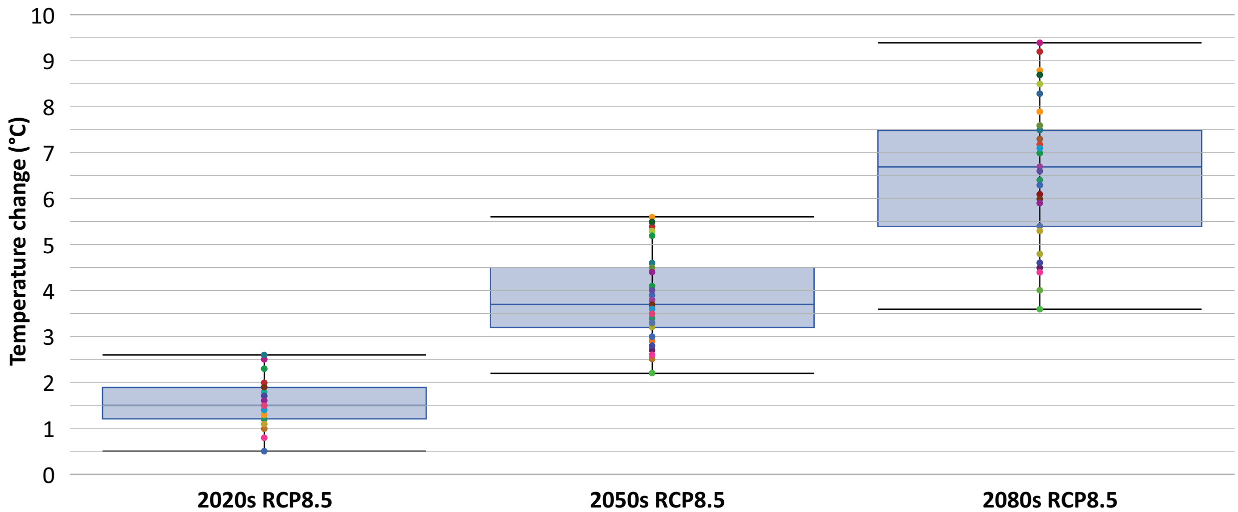


Figure 4.7
Projections of change in mean annual temperature for a region near Yellowknife, as in Figure 4.6, but with "business as usual" or high GHG emission assumptions. Note the different scale or higher range (spread) in projection differences under the "business as usual" or RCP8.5 GHG emission assumption
(See Section 4.2.2.1.)



4.2.2.2 Precipitation

Climate change projections indicate that the Arctic water cycle is expected to continue intensifying during this century, so mean precipitation and daily precipitation extremes may increase, especially over the mid- and high latitudes. There also is a growing consensus among scientists that decreasing Arctic sea ice will lead to further increases in Arctic precipitation. Precipitation increases of 50% for some Arctic regions are projected by the end of this century under higher GHG emission scenarios due to both global warming and sea-ice decline. These marked precipitation increases, peaking in late autumn and winter, are among the highest projected globally. As sea ice declines, more moisture evaporates from Arctic waters and contributes more heavily to regional precipitation. It is unclear how much of the North's increased total precipitation will fall as snow or rain.

Resources for the development and interpretation of climate change scenarios

Climate change science studies on climate trends typically monitor and detect the changes with homogenized climate data, representing adjusted climate data that account for artificial influences such as weather equipment changes, new monitoring procedures, weather station moves, and other monitoring site changes. The adjusted or homogenized climate data are available across Canada for several climate variables, including temperature and precipitation. These values are updated regularly and available publicly. Adjusted and Homogenized Canadian Climate Data (AHCCD) for daily and monthly temperature and precipitation can be found at the following sites:

a) http://www.ec.gc.ca/dccha-ahccd/ Canadian Blended Precipitation, version 0 (CanBPv0) https://open.canada.ca/data/dataset/5d49713a-fe56-48a8-887f-c0ca3e4aebfe;
b) Canadian Gridded Temperature and Precipitation Anomalies (CANGRD) at 50 km resolution http://data.ec.gc.ca/data/climate/scientificknowledge/canadian-gridded-temperature-and-precipitation-anomalies-cangrd/canadian-gridded-precipitation-anomalies/.

Good climate science practice uses a range of projections from multiple climate change models (ensembles) and emission scenarios. The websites below can provide various projections for Canada as well as documentation on the development and interpretation of climate change scenarios. Some of these sites are national in scope, while others are regionally focused. Many of the sources assume an advanced level of climate change model knowledge:

a) an overview of climate change scenarios in Canada can be found at: http://climate-scenarios.canada.ca/?page=main and https://www.canada.ca/en/environment-climate-change/services/climate-change/publications/data-scenarios-synthesis-recent-observation/chapter-2.html;
b) Environment and Climate Change Canada has a complete set of outputs from one Canadian climate model (CanESM2) at: http://www.cccma.ec.gc.ca/data/cgcm4/CanESM2/index.shtml;
c) projection maps from many other climate models are available from the Canadian Climate Data and Scenarios website at http://climate-scenarios.canada.ca/?page=cmip5-intro;
d) details on one new higher-resolution model or Regional Climate Model, CanRCM4, which is based on the larger scale "physics" used in CanESM2, can be accessed at: http://climate-modelling.canada.ca/climatemodeldata/canrcm/CanRCM4/index_cordex.shtml;
e) for British Columbia, see https://www.pacificclimate.org/analysis-tools/plan2adapt;
f) for fact sheets on projects and other programs in Quebec and selected other regions, see https://www.ouranos.ca/en/program/scenarios-services-climatiques/;
g) the Prairie Climate Atlas provides user-friendly general information on climate change for regions across Canada: http://prairieclimatecentre.ca/2017/10/the-prairie-climate-atlas-making-climate-science-meaningful/; and
h) in Ontario, regional climate change projections have been developed by several academic institutions, as described on https://www.ontario.ca/data/climate-data-high-resolution-projections.

Other agencies and firms can provide customized climate change projections and analyses for specific climate-sensitive issues, e.g., Risk Sciences International has a customizable Climate Change Hazards Information Portal.

4.3 Conclusions and key messages

The main conclusions and key messages of this Chapter are

a) Historical records show significant, positive, long-term trends in temperature and precipitation across most northern regions, and climate models suggest that warming over much of the North will continue at a rate that may increase.
b) Climate in the Canadian Arctic, as in other Arctic regions, is evolving towards a new state and increasingly is characterized by warmer, wetter, and more variable conditions.
c) It is important that updated climate and climate change information be used in decisions for community infrastructure planning and foundation designs in the North.
d) Tables 4.2 and 4.3 provide projected changes in air temperature for screening-level analysis of the potential impacts of climate change on permafrost and foundation performance. For more detailed

analyses in support of potentially high-risk permafrost projects, decision makers are advised to refer to climate specialists in order to obtain the most up-to-date information available.

e) Higher GHG emission scenarios provide more conservative assumptions for applications with high-risk permafrost foundations.

f) The average of a group of models or use of any one climate model may bias important information on the future climate, particularly on the ranges of future projected changes. Multiple climate models or ensembles should be used for projections and, where possible, the ranges or differences between the climate model projections taken into consideration. Annex C illustrates the ranges or differences between the various climate change model projections for defined zones in northern Canada.

5 ADDRESSING CLIMATE CHANGE IN SITE SELECTION AND THE DESIGN OF FOUNDATIONS

5.1 General

This Chapter describes the planning and design of infrastructure in permafrost regions as a two-stage process. In **Stage One,** the *climate change screening* stage, the potential sensitivity of the proposed structure to the effects of climate change on permafrost is determined, and associated risks are assessed. The screening can be conducted either for a specific project or at the town-site level for the expansion or establishment of a settlement. The climate change screening *determines the design services* required to define and address risks attributable to climatic uncertainty and change.

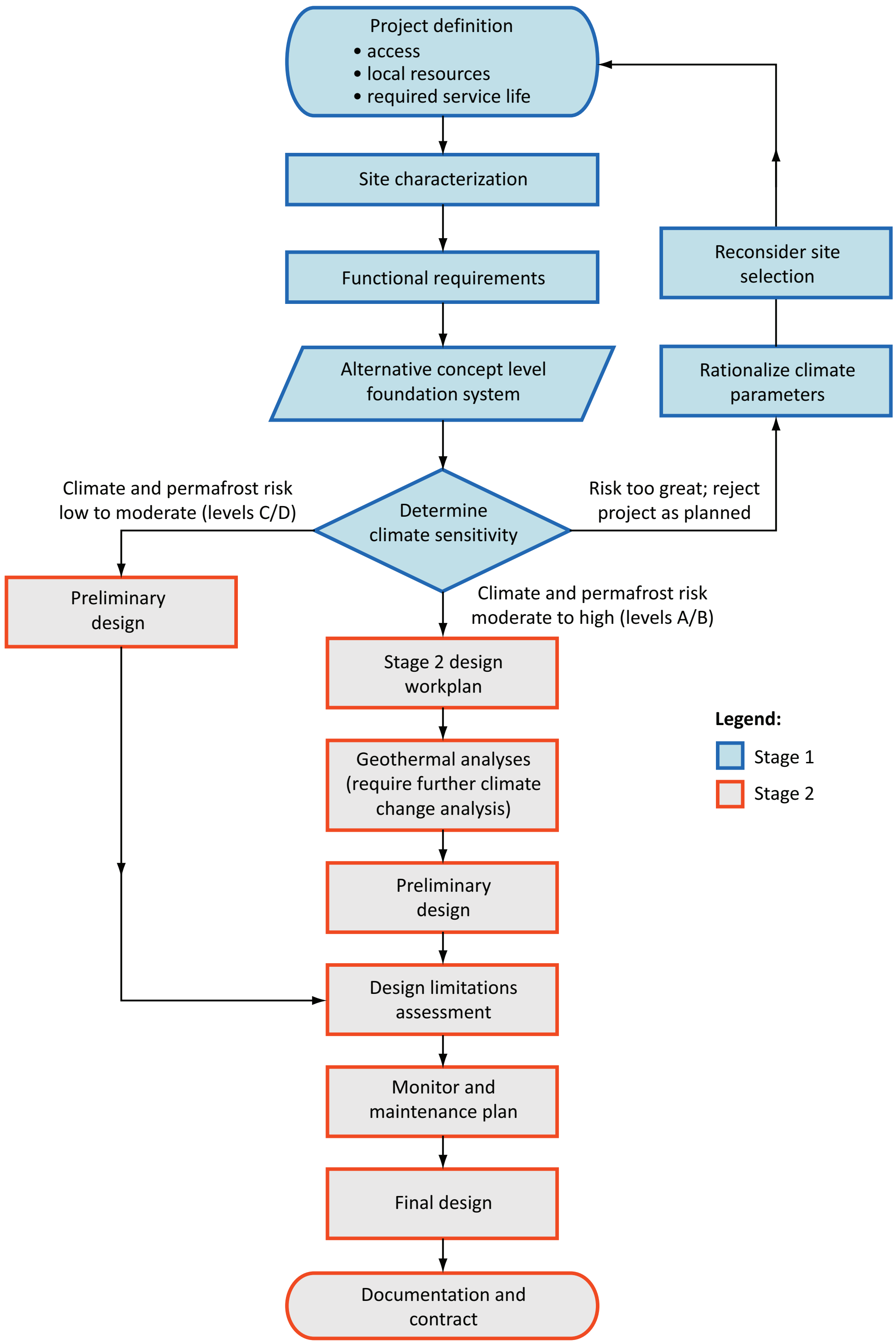
Stage Two allows the project manager to assess the foundation design required in order to construct a project. The services described are normally contracted to geotechnical engineers specialized in permafrost conditions.

Applying the screening tool at different scales

The climate change screening process provides a rational basis for determining the scope of the site investigation and design services required for effective adaptation of a structure to climatic uncertainty and warming. When applied to an individual structure at a predetermined site, the screening process establishes the level of detail required for the geothermal analysis used in foundation design. At the town-site level, the screening process can guide the assessment of different development options with respect to the effects of climate change.

Figure 5.1 presents Stages One and Two in a single flow chart, providing an overview of the planning and design process for community infrastructure projects in permafrost. Stage One results in a choice of three different options, depending upon the determined level of climate change and permafrost-related risk. Two of these are Stage Two options: a) proceed with the project, with significant further climate-change-related analysis; or b) proceed with the project with limited further climate-change-related analysis. In some cases, the third option, c), is to reject the project as currently planned, especially if the site chosen for a structure is incompatible with its intended function. In this case, Stage One is initiated again from the outset at a new site.

Figure 5.1
Flow chart for planning and design of community infrastructure in permafrost terrain. Risk levels ("A/B" and "C/D") shown in this Figure are clarified below in Tables 5.1 and 5.2
(See Section 5.1.)



5.2 Stage One: Climate change screening

5.2.1 Introduction

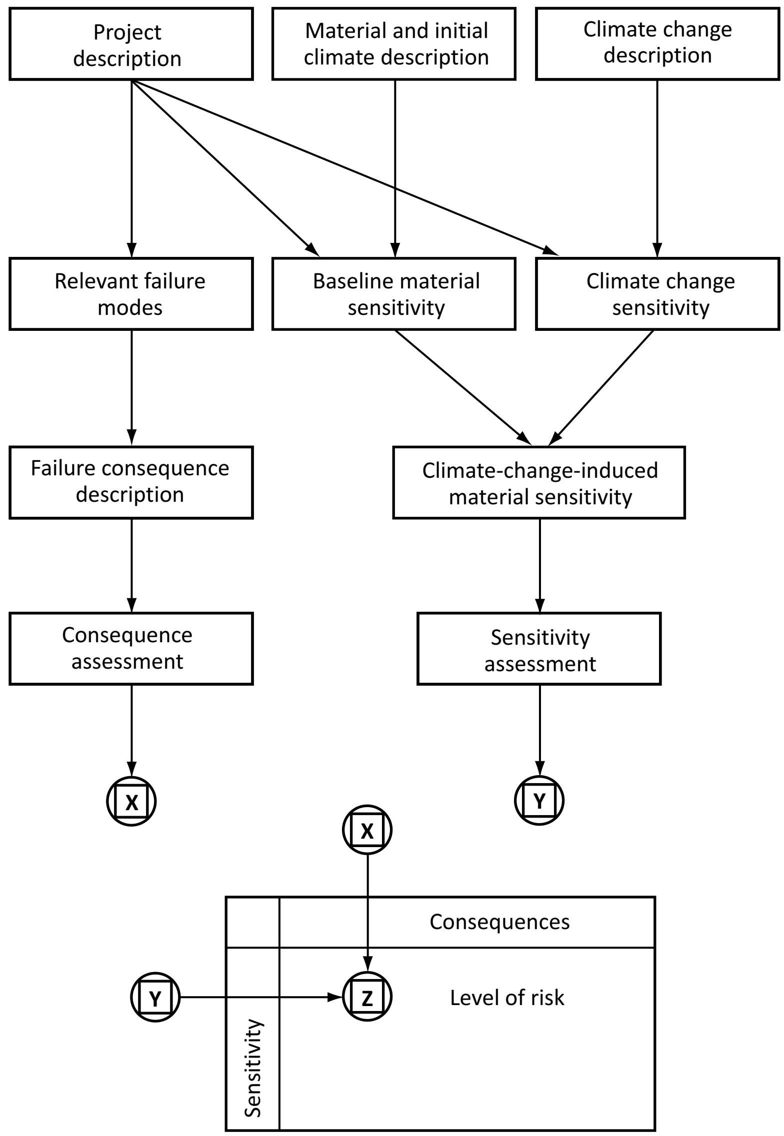
Chapter 4 described the magnitude of climate warming projected for Canada's North. Such climate change increases the complexity of site selection and foundation design for community infrastructure throughout the region. The owner/developer must specify an acceptable minimum service life for the project so that planners and engineers may estimate the climate trends and annual extremes a project may be exposed to over its operational life. This estimate, considered with the project's functional criteria, should then guide the extent and character of site investigation and ground thermal analyses required for foundation design.

A process that considers both the climate change sensitivity of permafrost and the consequences of failing to ensure the long-term stability of foundation design was developed in 1998 by Environment Canada and a committee of experts for the Panel on Energy Research and Development (PERD) of Natural Resources Canada. It has been applied in engineering practice to several structure types over the past decade, as described by Hayley and Horne (2008). The climate change screening process described below draws significantly upon and adds to the PERD process.

5.2.2 Risk-based framework

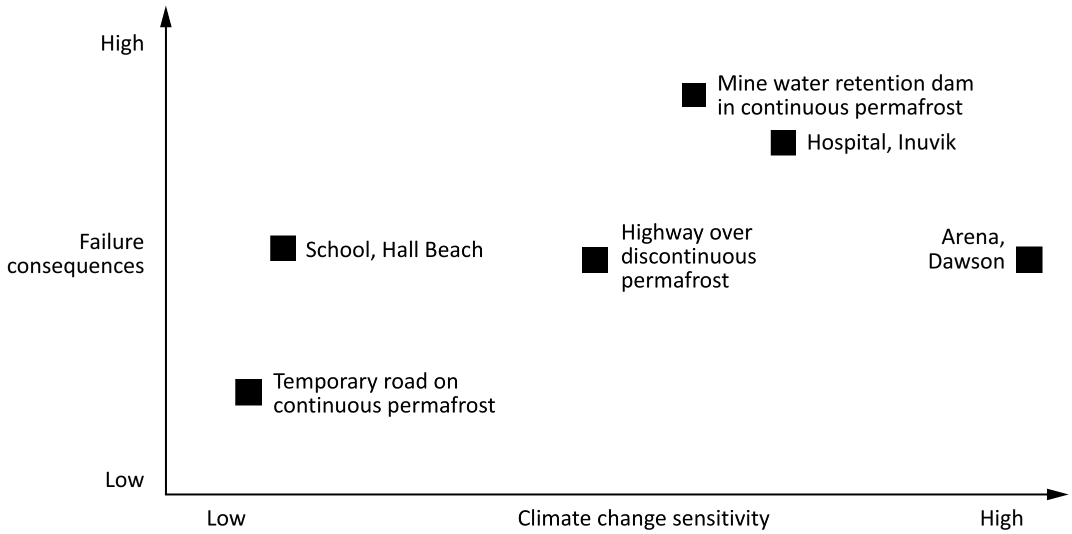
The screening process places a project, whether an individual component of infrastructure or a larger town-site expansion, within a risk-management framework. Figure 5.2 indicates that a project is assessed for both the climate-warming-induced *sensitivity* of its permafrost environment (*material sensitivity*) and the eventual *consequence* of any permafrost-induced impact or failure. For the purpose of this Guideline, *sensitivity* reflects the extent to which the permafrost may settle, lose bearing strength, or initiate accentuated frost heave as a result of climate warming. The likelihood of operational or structural problems developing in infrastructure built on climate-change-sensitive permafrost will normally be high, unless steps are taken to mitigate such vulnerability.

Figure 5.2
Framework for the assessment of permafrost and climate-change-related risks (adapted from Environment Canada, 1998)
(See Section 5.2.2.)



Consequence is a qualitative assessment of the degree to which structural or operational problems, were they to occur, would affect use of the structure. For example, structural and operational issues might be expected to impair personal safety, quality of life, the surrounding environment, social well-being, or financial affairs within a community. Figure 5.3 situates a set of representative northern projects with respect to *sensitivity* and *consequence* measures which, taken together, allow for an assessment of risk. The rankings in Figure 5.3 are presented solely for illustration.

Figure 5.3
Infrastructure ranked according to permafrost *sensitivity* and failure *consequences* (adapted from Environment Canada, 1998)
(See Section 5.2.2.)



A qualitative risk-ranking scheme is provided in Table 5.1 using the concepts of *sensitivity* and *consequence*.

Table 5.1
Risk-based screening matrix (adapted from Environment Canada, 1998)
(See Sections 5.2.2 and 5.2.3.)

Categories A and B imply "high" and "moderate" risk, while categories C and D suggest "low" and "negligible" risk.

	Consequence			
Sensitivity	**Negligible**	**Minor**	**Major**	**Catastrophic**
High	C	B	A	A
Medium	D	C	B	A
Low	D	C	C	B

Defining rankings

Words like *sensitive* may mean different things to different people or to the same person in different situations so corresponding quantitative rankings should be established whenever possible. For example, parties might decide to agree that "insensitive" equates to a one-in-ten chance of permafrost-induced impacts, and that "sensitive" will equate to a four-in-ten chance.

As shown in Table 5.2, each risk category is matched to a suggested level of climate-change-related analysis, ranging from "not required" to "qualitative", "semi-quantitative", and "detailed quantitative". Precise definitions of each level of analysis are provided in Table 5.5.

Table 5.2
Degree of climate change and permafrost-related analysis suggested for projects in each risk category (adapted from Environment Canada, 1998)
(See Sections 5.2.2 and 5.2.3.)

Risk level	Analysis prescribed
D	Not required
C	Qualitative
B	Semi-quantitative
A	Detailed quantitative

5.2.3 Step-by-step through Stage One

This section addresses each step in Stage One of the planning and design process for community infrastructure in permafrost, including application of the above risk-based framework. The first step in the Stage One screening process is to characterize the site proposed for the project.

Step 1 — Characterization of the site

Knowledge of site conditions is a prerequisite for proceeding to the planning and design process. The information required to characterize a site includes

a) site development history — previous structures, site clearing, and fill placement;
b) topography, geology, and surface cover;
c) soil stratigraphy, permafrost, and ground ice;
d) snow cover and drainage;
e) initial ground temperature;
f) materials available for site grading; and
g) access restrictions that may limit construction equipment and available operating periods, such as construction season, sealift, or winter roads.

Note: *For more information, consult CAN/BNQ 2501-500, Clause 7.2.*

Step 2 — Development of project functional criteria

The owner's project manager must have a clear understanding of the intended function of the project and must convey this to the design engineer. The manager and engineer should discuss and agree on a functional service life for the project. The choice of foundation type (described in Clause 3) must satisfy both site conditions and project function. The elements of project function that have the greatest effect on foundation design include

a) The *site grading plan*, as it affects initial fill placement in preparation for building construction and the main floor elevation relative to the original and final surface elevation.
b) *Slab-on-grade type* of foundations are commonly preferred for heavily loaded floors such as maintenance garages and for sports facilities such as gymnasiums.
c) Some public buildings have *crawl space restrictions* that require heated enclosures precluding natural air convection below the structure.
d) *Sensitivity to deformation* as determined by the nature of the structural elements and column spacing. The settlement tolerance for the structure over its agreed service life is a criterion provided by the structural engineer that will be required for sensitivity screening.

Step 3 — Characterization of permafrost sensitivity to climate change

The overall sensitivity of permafrost can be classified based upon ground material, ice content, and an estimate of the ground temperature at the *end* of the project's service life. Initially, future permafrost temperatures should be estimated by assuming that the current permafrost temperature will change at the same rate and magnitude as air temperature. In the field, ground temperatures tend to lag behind air temperature changes and will vary with depth and other factors. Nevertheless, a conservative assumption is used for screening purposes. For moderate-to-high risk structures (ranked "A" or "B" in Table 5.1), a more refined estimate of ground temperature response must be developed in Stage Two of the planning and design process.

Air temperature is assumed to be the primary driver of changes to permafrost conditions when a project is initially screened

While the influence of snow cover may be important in determining the effect of climate change on permafrost, changes in precipitation patterns and amounts are not explicitly included in the screening process. This is partially due to the relatively low confidence in projected changes in precipitation and snow cover. Snow accumulation pattern changes as a result of the development may have an even greater effect on the results. Such changes must be considered when examining the results and applying judgment to their inclusion in decision making. Projects that are determined to be particularly sensitive will advance to a higher level of analysis where snow cover is an important parameter in the geothermal evaluation of the chosen design and may be studied through wind and snow modelling exercises.

For the purpose of climate change screening, permafrost sensitivity is derived by considering the following three main factors:

a) the likelihood of thaw settlement due to active-layer deepening;
b) the potential for a reduction in bearing strength and creep resistance due to warming of the frozen ground; and
c) the potential for accentuated frost heaving (see Section 3.1 for a description of failure modes).

The sensitivity rankings in Table 5.3 take all three of these factors into consideration. The rankings, qualitative in nature, are provided in accordance with the *ground materials* and *temperature* of permafrost. Ground materials have been classified by physical characteristics (predominantly grain size) or by material origin (with physical characteristics assumed). The concept of permafrost temperature zones (Vyalov et al., 1988) has been slightly modified to reflect North American practice. The temperature of permafrost is the mean annual ground temperature (see Figure 2.7). Sensitivity is classified as high (H), medium (M), or low (L).

Table 5.3
Sensitivity of permafrost material by temperature zone and ground material (adapted from Environment Canada, 1998)
(See Section 5.2.3.)

Ground material	Permafrost temperature zone			
	Zone 4 (T < −7 °C)	**Zone 3 (−7 ≤ T < −4 °C)**	**Zone 2 (− 4 ≤ T < −2 °C)**	**Zone 1 (−2 ≤ T < 0 °C)**
Any soil containing massive ice	M	H	H	H
Peat and organic	L	M	H	H
Lacustrine (silt or clay)	M	M	M	H
Diamiction (dominantly fine grained)	M	M	M	H
Diamiction (dominantly coarse grained)	L	L	L	M
Marine soils with salinity	M	M	H	H
Alluvial and glaciofluvial (sand or gravel)	L	L	L	M
Frost-shattered rock	L	L	M	M
Hard, intact rock	L	L	L	L

Using the final year of the design life of the project, an "estimate" for ground temperature change should be determined. In Chapter 4, estimates for changes to air temperature are provided for each combination of time period, latitude, and season for moderate (see Table 4.2) and high (see Table 4.3) GHG emission scenarios. The estimate should be added to the initial permafrost temperature to arrive at the final temperature for each material. By locating the permafrost material and final temperature in Table 5.3, the permafrost sensitivity—high (H), medium (M), or low (L)—can be determined. The final sensitivity measure corresponds to the indices in Table 5.1.

Addressing permafrost terrain sensitivity through land-use planning

Most northern communities were established with little consideration for the range of biophysical hazards affecting their locations. They were located for ease of access to transportation routes, proximity to water sources, and links with major natural resource development projects. Over time, many northern communities have required protection from flooding. Permafrost degradation must also be considered a natural hazard and is likely to further affect communities as climate warming continues.

Permafrost terrain sensitivity should be determined where possible when new town sites or expansions are being considered. Table 5.3 can be used at the town-site scale, as the spatial segregation of terrain units can be mapped using aerial photographs, as shown in Figure 2.5, and further refined using supplementary information as available. In some cases, drilling programs or other surveys to establish ground-ice content in the proposed expansion might be needed.

Step 4 — Identification of relevant failure modes and consequences

The potential failure mode of a project depends both on the nature of the frozen ground used for support and how loads are transmitted to it. Relevant failure modes for various foundation types are indicated in Table 5.4.

Table 5.4
Index of relevant failure modes by foundation type (adapted from Environment Canada, 1998)
(See Section 5.2.3.)

Failure mode	Foundation type			
	Roads	Foundations/ piles	Foundations (thermosyphons)	Elevated utilidors
Thaw settlement	YES	YES	YES	NO
Loss of strength/creep	NO	YES	YES	NO
Accelerated frost effects	YES	YES	NO	YES
System failure	NO	NO	YES	YES

Note: *"System failure" in this Table refers to structural failure of a mechanical component, such as the depressurization of a thermosyphon.*

Given the relevant failure modes and the project description, a set of possible failure scenarios can be generated, and their consequences qualitatively rated as: catastrophic, major, minor, or negligible (see Table 5.1). Failure means that distortions in a structure or system prohibit its function at the level of efficiency or safety for which it was constructed. In devising failure scenarios and their consequences, social, environmental, and cultural factors should be broadly considered.

Step 5 — Climate change analysis resulting from screening

A prescribed level of climate change analysis may be assigned from the qualitative measures of sensitivity and consequence in Tables 5.1 and 5.2. Experts involved in the screening of projects may have reasons for higher or lower levels of analysis based on factors not identified in this screening process. Table 5.5 describes in more detail the analyses associated with each level of risk.

Table 5.5
Recommended analyses based on level of risk related to permafrost and climate change
(See Section 5.2.3.)

Risk level	Analysis prescribed
D	No action required.
C	Apply "qualitative analyses" and expert judgment. This requires a comparison of the project with other built structures in the region (the same or similar community) to judge their performance. The person assessing the options and making the judgment should be able to demonstrate directly related experience, both with the selected foundation design and with permafrost conditions in the community. This level of

(Continued)

Table 5.5 (Concluded)

Risk level	Analysis prescribed
	analysis will normally add only insignificantly to the normal schedule and budget associated with the engineering design services.
B	This level of analyses includes those measures suggested for Level C, while adding the restriction that there should be a good comparison both of structure type and foundation system on a similar site within the same community. Sufficient performance data must be available for the particular foundation system to provide a reasonable level of confidence in the judgment that arises from the comparison. If a direct comparison is not available, as would be the case for a "greenfield" site or an innovative, untested foundation system, the design should be elevated to a Level A analysis. In either case, a systematic performance-monitoring program is recommended to identify if corrective action is required at some future time.
A	The highest risk level requires that special care and attention be paid to assuring the integrity of permafrost used for structural support. This requires a full quantitative analysis of the ground thermal regime that will persist below the structure over its **projected service life**. This screening process outcome pushes the project into Stage Two of the design process. A significant level of complexity is added to the design, usually necessitating that up to an additional two (2) months of time be added to the planning schedule. Engineering costs will typically increase proportionally. Ongoing monitoring and assessments should be included among planned operating costs.

5.3 Stage Two: Design implementation where climate change poses a significant risk

5.3.1 Overview

Where rigorous design analysis is required (Level A or B in Table 5.5), the project passes to Stage Two. In Stage Two, the design process will generally include a thorough, quantitative, future-looking analysis of the ground thermal regime beneath the structure. The analysis requires that the design life of the infrastructure must be clearly established by the owner with guidance provided by the **Engineer of Record**. The service life for purposes of design may be different from the occupancy period. It should be anticipated that near total reconstruction may be required at the end of a service life in order to extend the occupancy period. With some notable exceptions, the service life of northern buildings is usually shorter than comparable southern buildings.

Foundation systems involving engineered heat exchangers, such as thermosyphons (see Figure 3.9), commonly require the Stage Two design process. The heat exchangers must intercept building heat before it enters the ground. Elevated structures on surface foundations or shallow piles with an ambient air temperature crawl space seldom require geothermal analyses during design. Large structures, such as hospitals or schools with structural components supported on the surface or in direct contact with the underlying permafrost, require the greatest attention during design analyses. A ground thermal model is used to predict the temperature at any time and location below the structure throughout its design life. The results are then used to refine the configuration of the supporting elements and any systems required to offset heat transfer into the permafrost foundation.

5.3.2 Foundation design parameters

Shallow foundations

Those features that can be controlled within the design process for shallow foundations include the following:

a) Configuration of a crawl space that separates the ground from the heated interior space. The crawl space provides access for utilities that service the building and may have an ambient temperature above 0 °C. Effective use of insulation and protection from water inflow are important design variables.
b) A heat exchanger may be required to intercept building heat that escapes from the crawl space into the ground. The heat exchanger may be air ventilation pipes, thermosyphons, or refrigeration piping connected to a heat pump or compressor. The design of these systems typically includes sizing and spacing of pipes in a manner that is capable of extracting heat from the ground at a rate that exceeds the predicted heat flux from the building.
c) The building and its heat exchanger must be separated from the natural permafrost with an engineered pad of granular fill. That pad is particularly important for surface foundation types where near-surface ground movements due to freezing or thawing can be transferred directly to the building structure. The pad material and construction methods must be specified so that the pad remains stable during seasonal freezing and thawing.

Deep foundations

Deep (pile) foundations separate the structure from near-surface soils. The loads are transmitted to the surrounding ground along the pile shaft or at the tip if it is embedded in bedrock. The design variables include the following:

a) *Pile dimensions and spacing*. Steel pipe piles are the most common pile type for Arctic structures. They must be installed in pre-drilled holes. Pile diameters and wall thickness are often limited by the available drilling equipment, so it is common to use smaller diameter piles at more frequent spacing than in conventional southern practice.
b) *Pile length*. The pile length must be sufficient to dissipate the load to the surrounding frozen ground by shear at the frozen bond. The calculation accounts for creep-like displacement of the pile relative to the surrounding frozen ground over the life of the structure. Since creep is highly dependent on ground ice and ground temperature, changes in these conditions during the life of the structure and their effects must be predicted.
c) *Active-layer thickness, soil type, and drainage*. The active layer is an important design parameter for deep foundations because it freezes and thaws annually along the pile shaft. The process of refreezing each fall and winter will exert an uplift force on the piles that could result in damaging heave. Persistent small annual heave displacements can accumulate into substantial heave over time. In conditions where gradual warming of the permafrost is predicted during structure life, the risk of heave will rise as the proportion of the pile shaft subject to seasonal freezing increases while the anchorage offered by the frozen bond decreases.

5.3.3 Analytical tools

Analytical tools for predicting future ground temperatures below the structure, taking into account the various design variables, are based on numerical methods that solve the equations for heat flow in the ground. These analyses are readily available for desktop use by engineers who specialize in design for permafrost conditions.

Typically, finite difference or fine element models are utilized for geothermal analyses. Examples of models that are commercially available or current utilized by Canadian engineers are

a) TEMP/W: a commercial finite element model marketed by Geo-Slope International;

b) SVHEAT: a finite element model marketed commercially by Soil Vision Systems;
c) GEOTHERM: a finite element model developed and used by EBA Engineering Consultants (now Tetra Tech Canada); and
d) THERM2: a finite difference model developed by Nixon Geotech.

A geothermal model must be able to simulate two-dimensional heat conduction with change of phase (solid-to-liquid and vice versa) within the elements for a variety of boundary conditions. Two-dimensional analyses are commonly satisfactory for modelling buildings, as the thermal regime can be effectively represented by a cross-section of width and depth beneath the structure. The algorithm that deals with freezing or thawing is critical, as it must capture the exchange of latent heat as a thaw or freeze boundary migrates through the model’s grid. Another important consideration is the simulation of ground surface heat flux. Some models simply represent the ground surface temperature as a function of air temperature. More refined models represent the solar radiation, heat transfer by convection in the air, and snow cover at the ground surface.

Input parameters for any model must represent the soil conditions, boundary conditions, and initial temperature conditions. The soil parameters for each element in the site stratigraphy must include thermal conductivity of frozen and thawed soils, the specific heat, and latent heat. These properties are sensitive to the soil moisture or ice content and the bulk density of the soil. It is seldom necessary to measure soil thermal properties in the laboratory, as there are published values available for the experienced geotechnical engineer to use once common soil properties are known. Certain soils, such as relatively dry sand and gravel, may be strongly influenced by the mineralogy of the constituents. Gravels used for site grading and road construction that have a high quartz content will have relatively high thermal conductivity and low water content.

The initial conditions for the simulation are the current soil temperatures. This information comes from the site investigation and is obtained from ground temperature sensors that are installed in drill holes where the stratigraphy has been determined. It is desirable to have a year of ground temperature data or a minimum of four sets of readings representing the late winter (coldest ground conditions) and the late summer or fall (warmest ground conditions).

Boundary conditions must simulate the heat flow into and out of the soil. These are the external thermal drivers that maintain the current or initial ground temperature. These parameters are generally considered at the ground surface and at the lowest level in the model. They represent the heat exchange at the ground surface and the flow of heat upwards into the soil along the geothermal gradient.

Geothermal models used for design assume that the structure is to be built where ground temperatures before disturbance do not vary significantly over the site and that heat flow in the ground is by conduction. Local conditions, especially in discontinuous permafrost, may indicate that ground temperatures vary over the site. Heat transfer by ground water may also be important, especially where the permafrost is thin. In these cases, more extensive site investigations may be needed to characterize the initial and boundary conditions for the model.

5.3.4 Derivation of climate parameters

The climatic input can be developed using data available from
a) Environment Canada’s Weather Office (www.weatheroffice.gc.ca) has details on the historical climate data.
b) Projection maps from several climate change models are available from the Canadian Climate Data and Scenarios website at http://climate-scenarios.canada.ca/?page=main.

c) Environment and Climate Change Canada has a complete set of outputs from one Canadian climate model (CanESM2) at: http://climate-modelling.canada.ca/climatemodeldata/cgcm4/CanESM2/index.shtml. A higher-resolution model (i.e. one model, CanRCM4) is also available from http://climate-modelling.canada.ca/climatemodeldata/canrcm/CanRCM4/index_cordex.shtml.

Other agencies and firms can provide customized climate change projections and analyses for climate-sensitive issues. These include Ouranos for Quebec, Pacific Climate Impacts Consortium, Prairie Climate Centre, and Risk Sciences International among others. The process will generally include the following steps, and may consider annual or seasonal climate warming:

a) Review and plot all available mean annual air temperature data for the closest meteorological station(s).
b) Plot current published Canadian Climate Normals (temperature) for reference.
c) Develop a "dynamic normal" by averaging the most recent 30 years of air temperature data for comparison with the plotted Canadian Climate Normals.
d) Develop trend analyses using a least squares fitting technique for the entire data set as well as for the past 30-year dynamic normal period.
e) Derive air temperature projections from an ensemble of global climate models (GCMs) evaluated and verified for the project region (as described in Chapter 4). Site-specific projections from regional models considered to be reliable within the project area will be obtained.
f) Extrapolate the linear trends to the end of building life, or 30 years, whichever is the *shorter* time period. Take into consideration that because changes in air temperature are highly variable from year-to-year and decade-to-decade, they should be expected to depart from linear trends of previous decades (see text box below). When analyzing climate and the atmosphere, the present trajectory should be considered as only one of various pieces of evidence, and one that, like most others, becomes much less precise as the time span for prediction exceeds 20 years, as discussed in Chapter 4.
g) Compare the end-of-life projections from the GCM ensemble with the extrapolated historical trends. A comparison of this type is considered reasonable for sites where a comprehensive historical database exists and when the comparison is over a service life not exceeding 30 years. Climate model projections become uncertain beyond this timeframe, but projections from the historical record will be more unreliable because climate change is expected to accelerate.
h) Using all these results, make a value judgment regarding an appropriate design climate at the end of structure life.
i) Convert the mean annual air temperature at the end-of-life to projected design mean monthly air temperatures, recognizing the seasonal variation in climate change described in Chapter 4.

Extrapolation of air temperature trends: further explanation

Climate scientists (Chapter 4) have indicated that due to the natural variability of air temperature trends, especially in the Arctic, extrapolation of currently accessible air temperature models in excess of 15 to 20 years will be subject to significant uncertainty even when based on long-term datasets. Most community infrastructure is expected to remain in service much longer than 15 years from the time of construction. The methodology in Section 5.3.4 suggests that a range of evidence, including temperature normals, model projections, and historical trends, should be evaluated in order to estimate a probable mean air temperature at the anticipated end-of-life of a structure. This estimated design basis end-of-life air temperature will ultimately be combined with other site-related factors for dynamic modelling of the most probable ground temperatures that the structure will experience over time. A level of uncertainty must therefore be associated with all temperature inputs.

5.3.5 Calibration and use of geothermal models

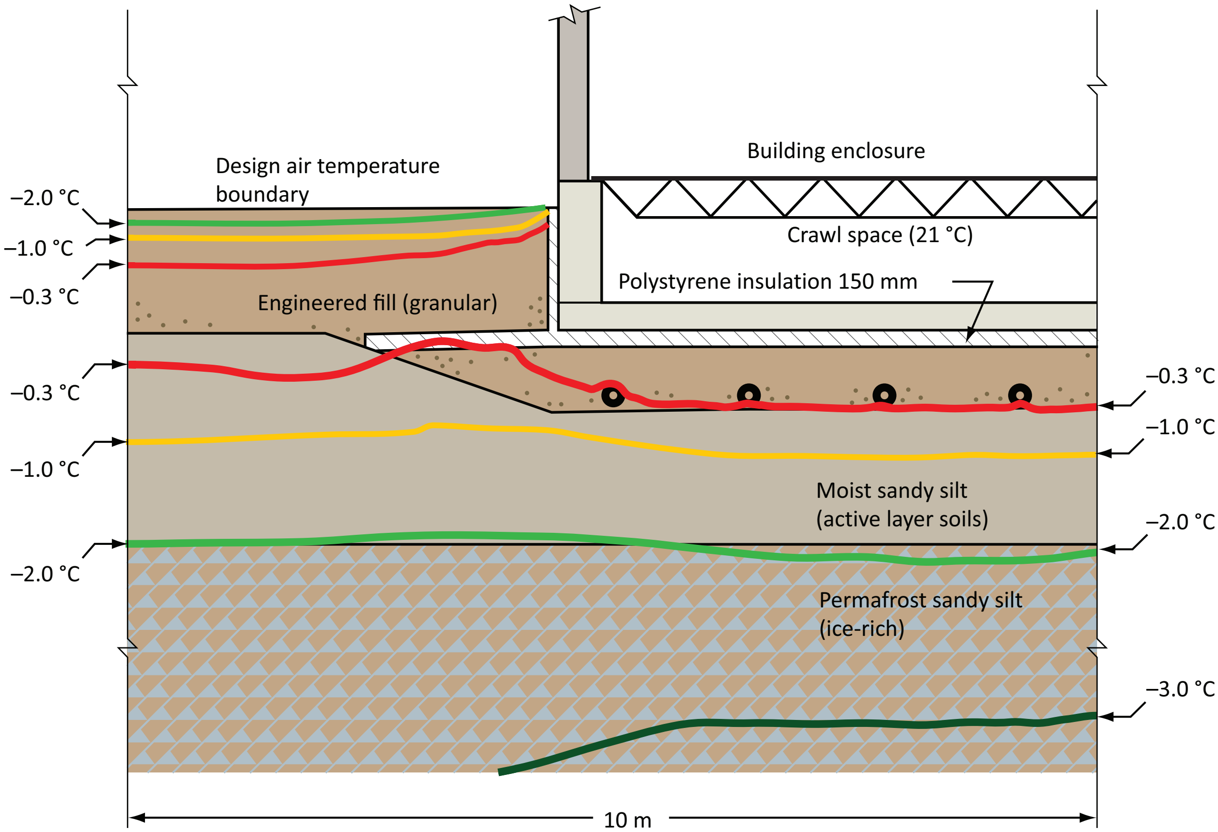
Once the ground thermal model has been selected and appropriate input parameters determined, the simulation must be calibrated to current conditions. The model should be set up and run for the present site conditions and the ground temperature at the site should be simulated. The predicted ground temperatures should be compared with available measured values. Deviations between predicted and observed ground temperatures must be rationalized and, in some cases, minor adjustments to the input parameters made. The interpretation of calibration runs and minor adjustments of the input parameters must be made with considerable judgment by an experienced engineer.

The site-calibrated model must be set up in a two-dimensional grid with temperature-controlled boundaries that include the contact of the building with the ground. The climate surface boundaries can be set to change annually along a linear trend from the present climate to the climate at the end of the service life. The simulation proceeds in set time intervals during which heat flow between points in the grid is calculated, and changes in ground temperature are determined. The results are normally presented as ground temperature isotherms at chosen times during the analyses. The temperature prediction must be examined at the end of service life for conditions in September-October when the ground is expected to be warmest. This condition will usually be the initial basis for judging adequacy of the design.

A foundation configuration that provides an acceptable result for a design linear climatic warming trend must also be tested for extreme weather events. The historic database can be analyzed statistically to determine the frequency of extreme annual mean temperatures. Mean monthly temperatures representative of these conditions may be developed. The design based on the trend analyses or GCM should then be checked for robustness against a combination of extreme conditions.

An example of output from a geothermal model is shown in Figure 5.4. The figure shows the predicted temperature distribution below a structure with a warm crawl space embedded in permafrost at Inuvik, NT. This case history from 2001 (EBA Engineering Files) is actual design output for the Inuvik Hospital described by Hayley and Horne (2008). The results show the warmest predicted ground temperature (September) following 30 years of linear climatic warming. This building has been monitored from 2001 to 2007 by Arctic Foundations of Canada and results are reported by Holubec (2008). The measured data matches predictions of warmest ground temperatures (within 0.5 °C). Winter temperatures below the foundation at a depth of 4 m drop to -7.5 °C each year.

Figure 5.4
Example output from geothermal design of the Inuvik Hospital in 2000 showing the predicted warmest ground temperatures after 30 years of operation (courtesy of Don Hayley)
(See Clause 5.3.5.)



The predictions shown in Figure 5.4 provide marginal design security because the 0 °C isotherm is close to the bottom of the frost-stable engineered fill at the end of service life. Consequently, the insulation thickness below the building was increased from 150 mm to 200 mm for final design.

5.3.6 Critical evaluation of design limitations

A design that has been analyzed and refined in order to meet the tests established in the geothermal analysis must be assessed to confirm that a logical and practical construction plan can be prepared to meet limitations imposed by location and schedule. The evaluation must address at a minimum the following key principles:

a) *Constructability.* The construction logistics must fit with local contractor experience and the ability for equipment, supplies, and manpower to reach the site in a timely manner.

b) *Schedule*. The design may impose schedule constraints. For example, if excavation into permafrost is required, there will be preferred seasons for this.

c) *Contingency planning*. There is never complete understanding of site conditions, especially on northern projects where geotechnical investigation is often restricted by budgetary conditions. It should be recognized at the outset that adaptation of the design during construction will be a field requirement. Contingency planning for changed conditions should be a requirement for any northern project.

d) *Robustness review*. The final step is to review the entire design and construction plan for robustness. The review must examine the design within the context of the overall site development and should consider site drainage and snow management both during the construction and operational phases. This may entail an independent review by an experienced person who has not been part of the design process.

5.3.7 Monitoring and maintenance plan

All projects that proceed to Stage Two of the design process are sensitive to minor variations in permafrost conditions that are integral to foundation support. Where thermosyphons and other complex elements are used in the foundation design, there must be sufficient monitoring to determine that they function as intended. Foundation systems that depend upon thermosyphons to maintain the permafrost are described in detail in CAN/CSA-S500-14.

There are no formal procedures for developing a monitoring program, but the principal features to be measured are ground temperature, air temperature, and soil deformation. Deformation can be detected by setting plates on structural elements, such as piles, for periodic elevation survey. Ground temperature measurements need to target those areas of the foundation system that are most vulnerable to temperature changes, and the collected data must be compared over time to the values predicted in the planning and design processes.

The requirement for monitoring, reporting, and reacting to any changes that are noted must be recognized early in the project. The responsibilities need to be defined at the project outset and budgets allocated to collect and summarize the data. An annual review by the geotechnical engineer is recommended with more frequent reviews if undesirable trends appear. Monitoring is pointless unless the data collected are evaluated.

5.3.8 Design and construction documentation

Documentation of the design and construction process for complex foundation systems in regions of permafrost is an essential component of the project. The documentation should include

a) a design basis document;
b) a thermal design report stamped and signed by the geotechnical engineer of record;
c) specification for materials and fabrication of buried features integral to foundation performance such as piles, pads, and thermosyphons;
d) operating limitations knowingly accepted by the designer and the owner and their role in ongoing maintenance;
e) issued-for-construction drawings and specifications;
f) as-built drawings and quality control procedures that are supported by inspection reports and test data;
g) monitoring plan documentation with reporting procedures; and
h) non-routine maintenance and operating procedures that arise from the design process.

Project documentation must be thorough and written for ease of interpretation by future owner-representatives who were not involved in either design or construction. The unique features of foundations on permafrost are seldom understood by those without a history in the region. Owners must be able to recognize when to request expert review of any sign of building distress. The design analyses must be reproducible in order to test contingency plans should they be required.

5.4 Conclusions and key messages

The main conclusions and key messages of this Chapter are

a) The planning and design of community infrastructure in permafrost regions must include design basis prediction of local climate conditions throughout the service life of the facility as described in Chapter 4.
b) A site investigation as per Chapter 8 of CAN/BNQ 2501-500 should be conducted;
c) Application of the screening process, described in Section 5.2, results in a preliminary determination of the level of climate-warming-related risk associated with a project. The risk is determined through an assessment of the sensitivity of the project's permafrost environment to climate warming and the potential consequences associated with any permafrost-induced failure of the eventual infrastructure.
d) The potential failure mode of a project depends on the nature of the frozen ground used for support and how loads are transmitted to it.
e) One outcome of the screening process may be to determine that a project is too risky if constructed where planned and that a new site is required.
f) Projects that are assessed as presenting high climate-warming-related risk require full quantitative analysis of the ground thermal regime that will persist below them over their service life. This assessment in Stage One will push the project into Stage Two of the design process, adding a significant level of complexity to the design and usually requiring two (2) months to be added to the planning schedule.
g) Projects that are assessed through the climate change screening process as presenting lesser levels of risk may still require further related analysis, ranging from qualitative to semi-quantitative.
h) Stage Two of the design process comprises the following steps:
   i) refinement of design parameters;
   ii) selection of ground thermal modelling tools;
   iii) derivation of climate design parameters;
   iv) calibration of ground thermal modelling tools;
   v) two-dimensional geothermal analyses of the building footprint, including an exterior perimeter zone, over the service life of the structure;
   vi) critical evaluation of design limitations;
   vii) development of a monitoring and maintenance plan; and
   viii) production of design and construction documentation.

Annex A
Glossary of terms

Active layer — ground above permafrost that thaws each summer and refreezes in autumn and winter.

Adfreeze/adfreezing — the process by which two objects are bonded together by ice formed between them. Generally, adfreeze is considered a combination of the ice-to-surface bonding (adhesion), mechanical interaction, and friction.

Clay — particles of soil less than 0.004 mm in size.

Condenser — the upper part (above ground) of a thermosyphon where cold CO_2 gas flowing upward from below the ground surface is cooled and condenses into a liquid (see **Evaporator**).

Creep — movement of snow, ice, or frozen soil by internal deformation after application of a load.

Creep resistance (also "**Creep strength**") — the failure strength of a material at a given strain rate or after a given period under differential stress. Under heavy loads and at relatively high freezing temperatures, most frozen soils creep and eventually fail in a plastic manner.

Depth of zero annual amplitude — the distance below the ground surface beneath which there is practically no annual fluctuation in ground temperature.

Drunken forests — trees leaning in random directions in a permafrost region. A descriptive term for areas of the boreal forest where leaning trees are found growing on ice-rich terrain due to repeated differential frost heave or thermokarst subsidence.

Electrical resistivity surveys — surveys to determine the configuration of frozen ground that rely on the substantial difference in resistance between water, a conductive medium, and ice, a resistive material.

Evaporator — the underground part of a thermosyphon in which liquid evaporates and in so doing extracts heat from the surrounding soil.

Excess ice — the volume of ice in the ground that exceeds the porosity of the ground under natural unfrozen conditions.

Failure modes — the process or means by which the integrity or function of an engineered structure is adversely affected as the result of changing conditions in the underlying permafrost.

Frost heave — the upward or outward movement of the ground surface or of objects on, or in, the ground caused by the formation and growth of ice in the soil.

Frost jacking — cumulative upward displacement of objects embedded in the ground, caused by frost action.

General circulation model (GCM) — a global, three-dimensional computer model of the climate system that can be used to simulate human-induced climate change. GCMs are highly complex and represent the effects of such factors as reflective and absorptive properties of atmospheric water vapour, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures, and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface.

Geothermal gradient — the increase in temperature with depth below the depth of zero annual amplitude. The gradual increase in temperature is due to heat from the Earth's interior.

Ground penetrating radar (GPR) — a geophysical method that uses radar pulses to image the subsurface. This non-destructive method uses electromagnetic radiation in the microwave band (UHF/ VHF frequencies) of the radio spectrum and detects the reflected signals from subsurface structures. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements, and structures. It can detect objects, changes in material, and voids and cracks.

Grout — cement-like material used to anchor piles to rock.

Heat capacity — heat involved in raising or lowering the temperature of a medium (soil or rock) by a given amount. It is normally given as the heat required to raise 1 kg or 1 m^3 of a substance by 1 °C ($J\ kg^{-1}\ °C^{-1}$ or $J\ m^{-3}\ °C^{-1}$).

Hummocks — small mounds of soil, commonly about 1 m in diameter, pushed up by repeated freezing and thawing, often found uniformly spaced in large groups. Hummocks can form in areas of permafrost or seasonally frozen ground and are one of the most common surface features of the Arctic.

Ice lens(es) — a predominantly horizontal, lens-shaped body of ice of any dimension.

Lacustrine — pertaining to lakes.

Latent heat — the heat required or released in melting of ice or freezing of water ($J\ kg^{-1}$ or $J\ m^{-3}$).

Patterned ground — a term used to describe distinct geometric shapes formed at the surface of the ground.

Peat plateau — a generally flat-topped expanse of peat, elevated above the general surface of a peatland, and containing segregated ice that may or may not extend downward into the underlying mineral soil.

Permafrost — ground (soil or rock) that remains at or below 0 °C for two or more years.

Continuous permafrost — permafrost that occurs beneath more than 90% of the exposed land surface.

Discontinuous permafrost — permafrost occurring in some areas beneath the exposed land surface in a region where other areas are permafrost-free. Widespread discontinuous permafrost underlies 90–50% of the exposed land surface. Sporadic discontinuous permafrost underlies 50–10% of the land surface, where less than 10% of the exposed land surface is underlain by permafrost is in isolated patches.

Ice-rich permafrost — permafrost containing excess ice.

Piles — posts made of wood or steel driven into the ground or placed in drilled holes to provide support for buildings.

Sand — soil particles with a diameter greater than 0.05 mm.

Silt — soil particles with a diameter of 0.002 to 0.05 mm.

Talik — a layer or body of unfrozen ground within a permafrost area.

Thaw consolidation — time-dependent compression resulting from thawing of frozen ground and subsequent drainage of pore water.

Thaw settlement — a lowering of the ground surface resulting from the melting of ground ice with volume greater than soil pore spaces. Ground settlement will occur if thawing of ice-rich permafrost takes place. It also occurs annually during the summer when excess ice melts during thawing of the active layer.

Thermal conductivity — ability of a medium (soil or rock) to conduct heat (W m^{-1} $°C^{-1}$).

Thermokarst — the pitted relief formed from the melting of ground ice. In areas that have appreciable amounts of ice, small pits, ponds, and valleys are formed when the ice melts and the ground settles unevenly.

Annex B
References

Chapter 1

CSA Group; CAN/CSA-S500-14, *Thermosyphon foundations for buildings in permafrost regions*

CSA Group; CAN/CSA-S501-14, *Moderating the effects of permafrost degradation on existing building foundations*

CSA Group; CAN/CSA-S502-14, *Managing changing snow load risks for buildings in Canada's North*

CSA Group; CAN/CSA-S503-15, *Community drainage system planning, design, and maintenance in northern communities*

Department of Government Works and Services. 2019. Good Building Practices for Northern Facilities 2019. Government of the Northwest Territories, Yellowknife, NT.

Engineers Canada. 2010. Infrastructure Climate Risk Protocol. Engineers Canada, Ottawa, ON.

NRCC. 2015. *National Building Code of Canada*. National Research Council of Canada, Ottawa, ON. NRCC 56190. 2 vols.

Romanovsky V., Isaksen K., Drozdov D., Anisimov O., Instanes A., Leibman M., McGuire A. D., Shiklomanov N., Smith S. L., Walker D. (2017) Chapter 4, Changing permafrost and its impacts. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Program (AMAP), Oslo, Norway, pp. 65–102.

The BNQ; CAN/BNQ 2501-500, *Geotechnical site investigation for building foundations in permafrost zones*.

Transportation Association of Canada. 2010. Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions. Transportation Association of Canada, Ottawa, ON.

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., and Wang, X. L. 2015. Observed trends in Canada's climate and influence of low-frequency variability modes. Journal of Climate, 28: 4545–4560.

Chapter 2

Allard, M., Sarrazin, D., and L'Hérault, E. 2016. Borehole and near-surface ground temperatures in northeastern Canada. Nordicana D8, v, 1.4 (1988–2016). doi:10.5885/45291SL-34F28A9491014AFD.

Andersland, O. B. and Anderson, D. M. (ed.). 1978. Geotechnical engineering for cold regions, McGraw-Hill Book Company, 566 pp.

Andersland, O. B. and Ladanyi, B. 2004. An introduction to frozen ground engineering. 2nd edition, Hoboken, NJ: Wiley, 363 pp.

Burgess, M. M. and Smith, S. L. 2000. Shallow ground temperatures. In Dyke, L. D. and Brooks, G. R. (ed.), The physical environment of the Mackenzie Valley, Northwest Territories: A baseline for the assessment of environmental change. Geological Survey of Canada Bulletin 547, pp. 89–103.

Duchesne, C., Morse, P. D., Wolfe, S. A., and Kokelj, S. V. 2016. Report on 2010–2015 Permafrost thermal investigations in the Yellowknife Area, Northwest Territories, Geological Survey of Canada Open File 8093 and NWT Open Report 2016-019. doi: 10.4095/299189.

Heginbottom, J. A., Dubreuil, M. A., and Harker, P. A. (compilers). 1995. Canada — Permafrost; National Atlas of Canada (fifth edition), Plat. Natural Resources of Canada, Geomatics Canada, National Atlas Information Service, and Geological Survey of Canada Map MCR 4177, scale 1:7 500 000.

Johnston, G. H. (ed.). 1981. Permafrost — Engineering, design and construction: Toronto, John Wiley and Sons, 540 pp.

Lachenburch, A. H., Cladouhos, T. T., and Saltus, R. W. 1988. Permafrost temperature and the changing climate, in Senneset, K., ed., Proceedings of the Fifth International Conference on Permafrost, Volume 3: Trondheim, Norway, Tapir Publishers, Norway, p. 9–17.

O'Neill, H. B., and Burn, C. R. 2017. Impacts of variations in snow cover on permafrost stability, including simulated snow management, Dempster Highway, Peel Plateau, Northwest Territories. Arctic Science, 3: 150–178. dx.doi.org/10.1139/as-2016-0036.

Pihlainen, J. A. and Johnston, G. H., 1963. Guide to a Field Description of Permafrost for Engineering Purposes. National Research Council Canada Associate Committee on Soil and Snow Mechanics, Technical Memorandum 79 (NRC 7576).

Smith, S. L. and Riseborough, D. W. 2010. Modelling the thermal response of permafrost terrain to right-of-way disturbance and climate warming. Cold Regions Science and Technology, 60: pp. 92–103. doi:10.1016/J.coldregions.200908.009.

Smith, S. L., Burgess, M. M., and Heginbottom, J. A., 2001. Permafrost in Canada, a challenge to northern development, in Brooks, G. R., ed., A Synthesis of Geological Hazards in Canada, Geological Survey of Canada Bulletin 548, pp. 241–264.

Smith, S. L., Burgess, M. M., and Riseborough, D. W. 2008. Ground temperature and thaw settlement in frozen peatlands along the Norman Wells pipeline corridor, NWT Canada: 22 years of monitoring, in Kane, D. L., and Hinkel, K. M., eds., Ninth International Conference on Permafrost, Volume 2: Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, pp. 1665–1670.

Smith, S. L., Burgess, M. M., Chartrand, J., and Lawrence, D. E. 2005. Digital borehole geotechnical database for the Mackenzie Valley/Delta region, Geological Survey of Canada Open File 4924.

Smith, S. L., Burgess, M. M., Riseborough, D., and Chartrand, J. 2008. Permafrost and terrain research and monitoring sites of the Norman Wells to Zama pipeline — Thermal data collection and case histories, April 1985 to September 2001, Geological Survey of Canada Open File 5331.

Smith, S. L., Lewkowicz, A. G., Duchesne, C., and Ednie, M. 2015. Variability and change in permafrost thermal state in northern Canada. Paper 237 In GEOQuébec 2015 (Proceedings 68th Canadian Geotechnical Conference and 7th Canadian Conference on Permafrost). Québec. GEOQuébec 2015 Organizing Committee.

Smith, S. L., Riseborough, D. W., Ednie, M., and Chartrand, J. 2013. A map and summary database of permafrost temperatures in Nunavut, Canada, Geological Survey of Canada Open File 7393.

Smith, S. L., Romanovsky, V. E., Lewkowicz, A. G., Burn, C. R. Allard, M., Clow, G. D., Yoshikawa, K. and Throop, J. 2010. Thermal State of Permafrost in North America — A Contribution to the International Polar Year. *Permafrost and Periglacial Processses* 21: 117–135.

The BNQ; CAN/BNQ 2501-500, *Geotechnical site investigation for building foundations in permafrost zones*.

Chapter 3

CSA Group; CAN/CSA-S500-14, *Thermosyphon foundations for buildings in permafrost regions*

CSA Group; CAN/CSA-S501-14, *Moderating the effects of permafrost degradation on existing building foundations*

CSA Group; CAN/CSA-S502-14, *Managing changing snow load risks for buildings in Canada's North*

CSA Group; CAN/CSA-S503-15, *Community drainage system planning, design, and maintenance in northern communities*

The BNQ; CAN/BNQ 2501-500, *Geotechnical site investigation for building foundations in permafrost zones*

Transportation Association of Canada (TAC), 2010. Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions.

Chapter 4

AMAP, 2017. *Snow, Water, Ice and Permafrost (SWIPA): Summary for Policy-makers*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. 20 pp.

AMAP, 2017. *Snow, Water, Ice and Permafrost in the Arctic (SWIPA)*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 269 pp.

Chapin, F. S., III, Trainor, S. F., Cochran, P., Huntington, H., Markon, C., McCammon, M., McGuire, A. D., and Serreze, M., 2014: Ch. 22: Alaska. In *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T. C.) Richmond, and G. W. Yohe, eds. U.S. Global Change Research Program, pp. 514–536. doi: 10.7930/J00Z7150.

IPCC, 2013. Climate change 2013: the physical science basis. In Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley P. M. (eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, and New York, NY (2013), p. 1535.

Kopec, Ben G., Feng, Xiahong, Michel, Fred A., and Posmentier, Eric S., 2015: Influence of sea ice on Arctic precipitation. *Proceedings of the National Academy of Sciences*, 2015; 201504633 DOI: 10.1073/pnas.1504633113.

Mioduszewski, J., Vavrus, S., and Wang, M., 2018: Diminishing Arctic Sea Ice Promotes Stronger Surface Winds. *Journal of Climate*, 31, pp. 8101–8119.

Vincent, L. A., Zhang, X., Brown, R. D., Feng, Y., Mekis, E., Milewska, E. J., Wan, H., and Wang, X. L., 2015: Observed Trends in Canada's Climate and Influence of Low-Frequency Variability Modes. *Journal of Climate*, 28, pp. 4545–4560. doi: http://dx.doi.org/10.1175/JCLI-D-14-00697.1.

Wang, X. L., Feng, Y., and Vincent, L. A., 2014: Observed changes in one-in-20 year extremes of Canadian surface air temperatures. *Atmosphere–Ocean*, pp. 52, 222–231, doi: https://doi.org/10.1080/07055900.2013.818526.

Chapter 5

Environment Canada, 1998. Climate change impacts on permafrost engineering design. Panel on Energy Research and Development, Ottawa, ON, Canada.

Hayley, D. W. and Horne, B. 2008. Realizing climate change for design of structures on permafrost: A Canadian perspective. In Ninth International Conference on Permafrost, Kane D. L., Hinkel K.M. (eds). University of Alaska, Fairbanks, pp. 681–686.

Holubec, I. 2008. Flat Loop Thermosyphon Foundations in Warm Permafrost. Available at: www.pws.gov.nt.ca/pdf/publications/Thermosyphon%20Foundations%20in%20warm%20permafrost%20.pdf.

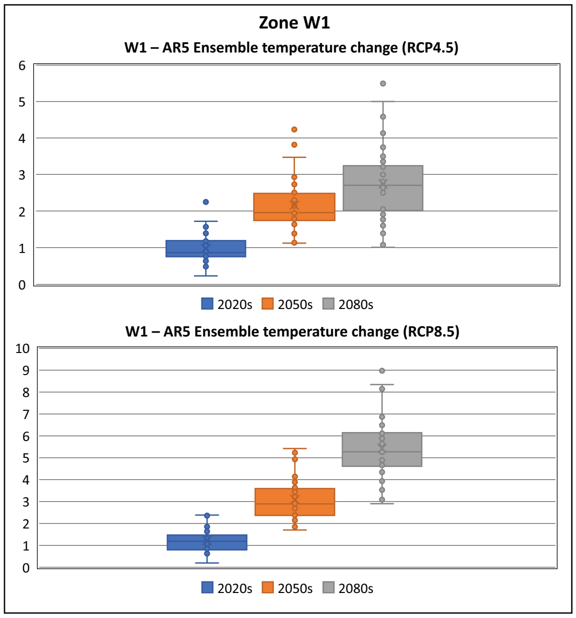
Vyalov, S. S., Gerasimov, A. J. and Fotiev, S. M. 1988. Ensuring stability and durability in permafrost ground areas at global warming of the earth's climate. In Proceedings of the Sixth International Conference on Permafrost, Beijing, pp. 955–960.

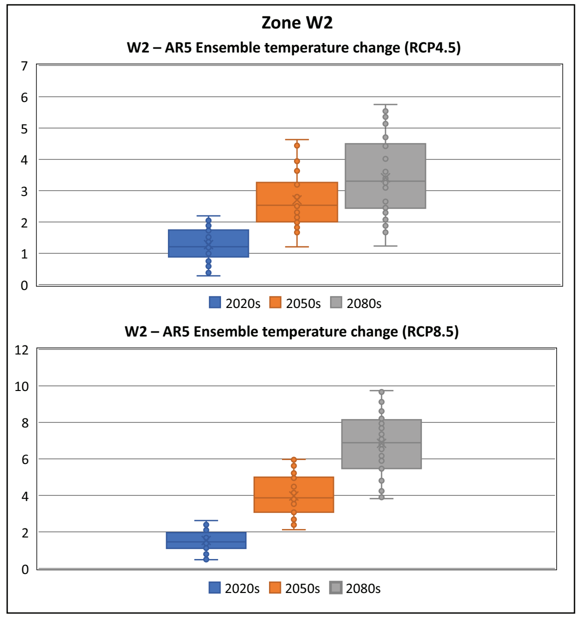
Annex C
Box and whisker plots of projected future temperatures

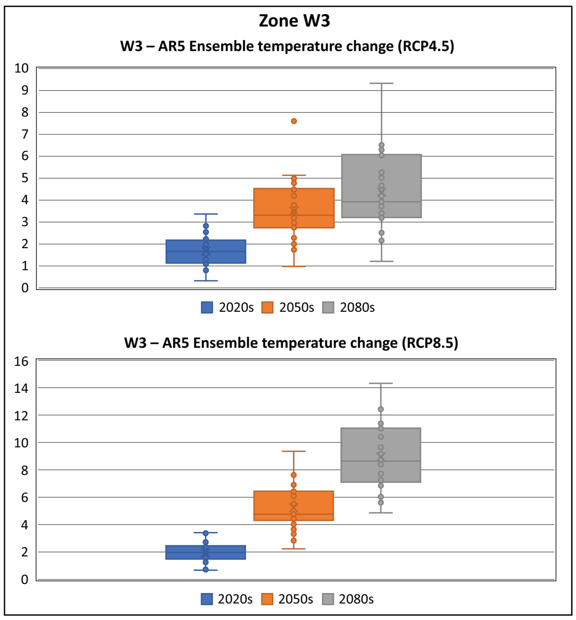
Box and whisker plots of projected annual mean air temperature changes are provided for the 11 zones referenced in Tables 4.2 and 4.3. These plots highlight the differences between the many climate model projections for different periods.

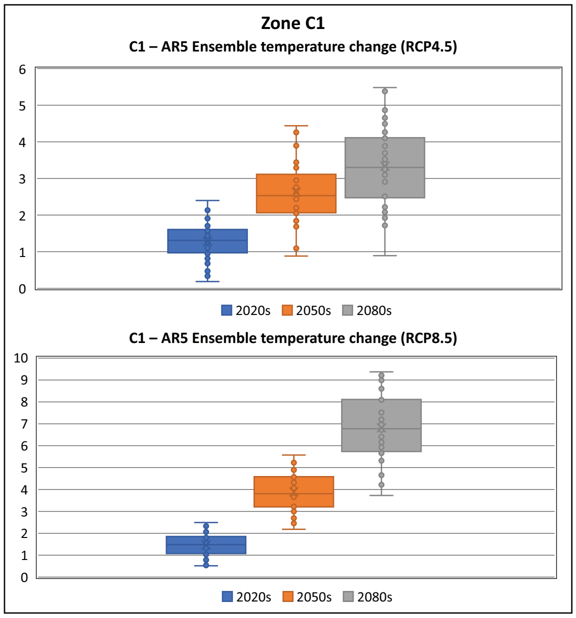
For each of the zones, the top figure indicates the full range of all model projected mean annual temperatures for three different periods: 2010–2039; 2040–2069, and 2070–2099. The shaded box represents the inner range of 50% of the models. The top of the shaded box shows the higher end or the 75^{th} percentile value of all the model projected temperature changes, while the bottom of the box shows the lower end or the 25^{th} percentile value of the model temperature projections. The median (the middle value of all the temperature projections) is represented by the horizontal line in the centre of the shaded box. Outlier model dots lie outside the whiskers or shaded box, with the top dot representing the highest projected model temperature change and the bottom dot the lowest projected temperature change. Note when comparing results that the scales for temperature changes are different between the two emission scenarios, RCP4.5 and RCP8.5. The greater temperature increases are generally associated with the highest GHG emission scenario.

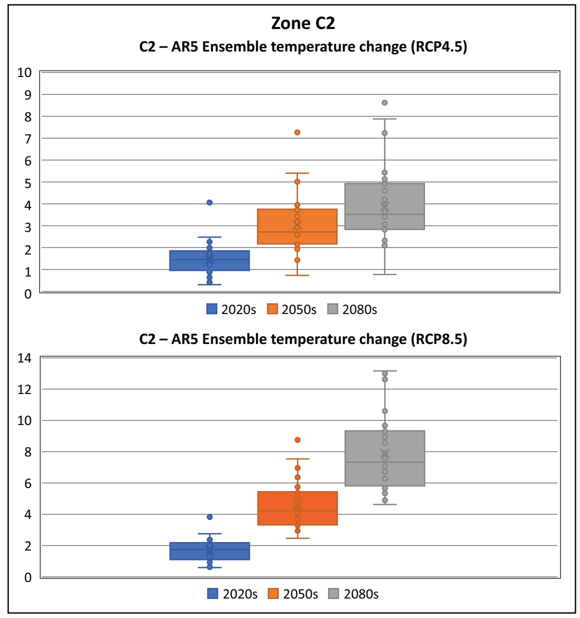
The differences between the model projections increase with time as the influence of GHG emissions increases. Higher emissions lead to faster rates of warming, with the warming more pronounced after the 2050s.

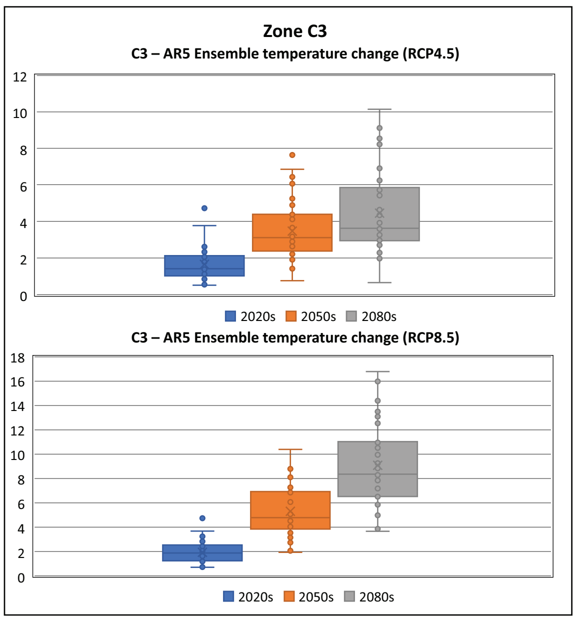

Zone W1
W1 – AR5 Ensemble temperature change (RCP4.5)
0
1
2
3
4
5
6
2020s 2050s 2080s
W1 – AR5 Ensemble temperature change (RCP8.5)
0
1
2
3
4
5
6
7
8
9
10
2020s 2050s 2080s

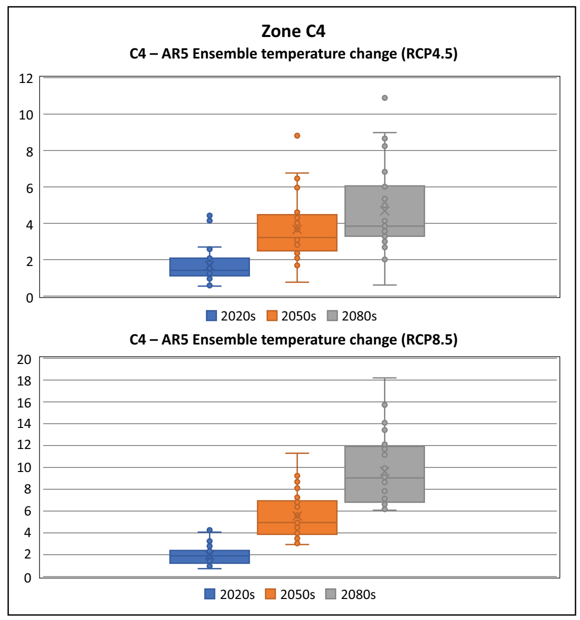

Zone W2
W2 – AR5 Ensemble temperature change (RCP4.5)
0
1
2
3
4
5
6
7
2020s 2050s 2080s
W2 – AR5 Ensemble temperature change (RCP8.5)
0
2
4
6
8
10
12
2020s 2050s 2080s

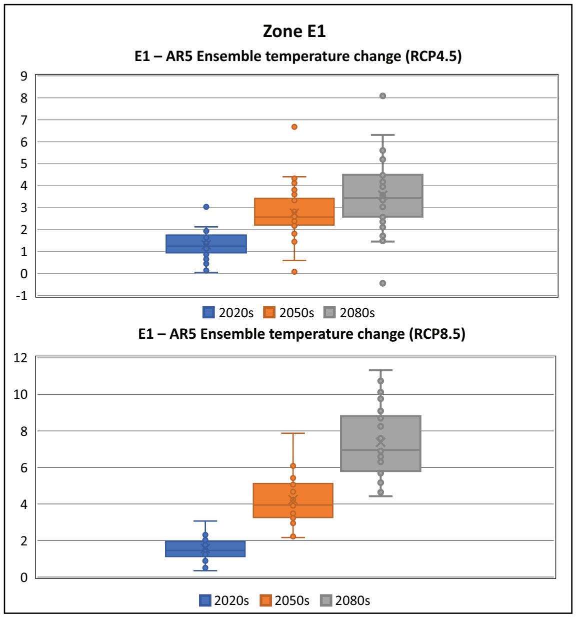

Zone W3
W3 – AR5 Ensemble temperature change (RCP4.5)
0
1
2
3
4
5
6
7
8
9
10
2020s 2050s 2080s
W3 – AR5 Ensemble temperature change (RCP8.5)
0
2
4
6
8
10
12
14
16
2020s 2050s 2080s

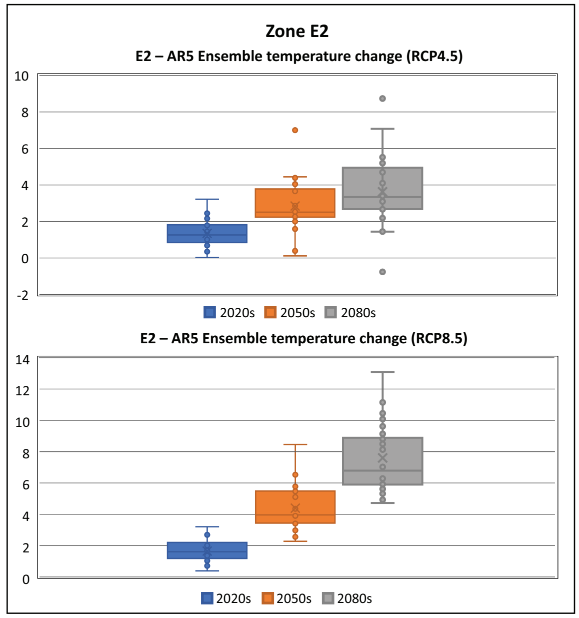

Zone C1
C1 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
C1 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s

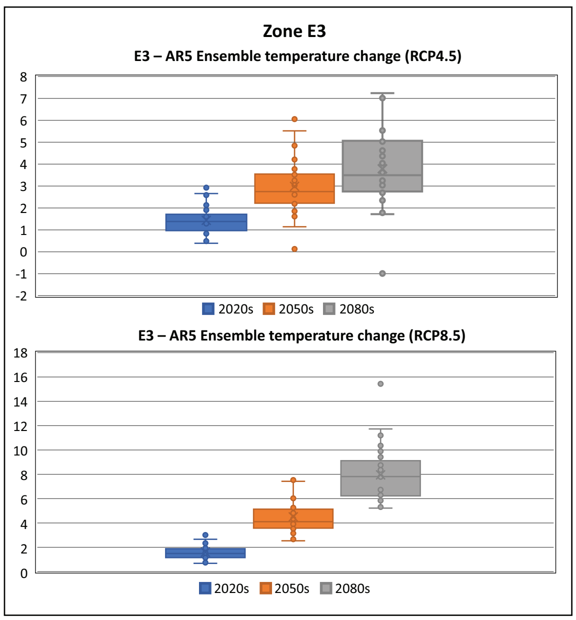

Zone C2
C2 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
C2 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s

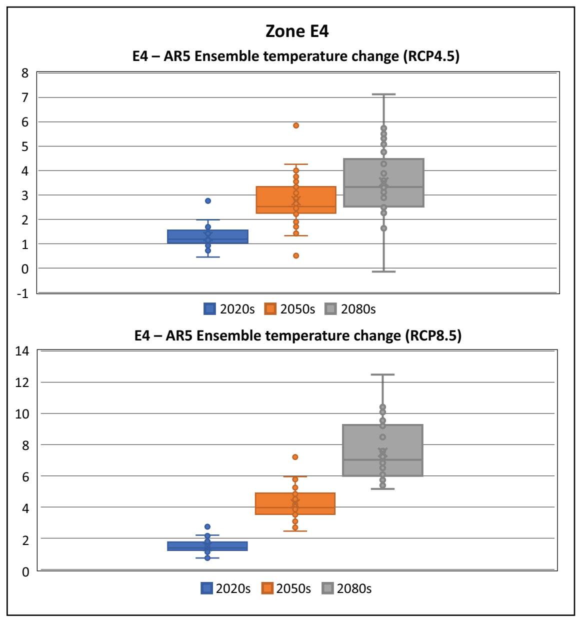

Zone C3
C3 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
C3 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s


Zone C4
C4 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
C4 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s


Zone E1
E1 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
E1 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s


Zone E2
E2 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
E2 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s


Zone E3
E3 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
E3 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s


Zone E4
E4 – AR5 Ensemble temperature change (RCP4.5)
2020s 2050s 2080s
E4 – AR5 Ensemble temperature change (RCP8.5)
2020s 2050s 2080s

ISBN 978-1-4883-2163-4