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SENSITIVITY OF PERMAFROST TO CLIMATE WARMING IN CANADA

Sharon L. Smith and Margo M. Burgess

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Cover illustration

Massive ice in an esker at the site of the Ekati diamond mine near Lac de Gras, Northwest Territories. Photograph by M.M. Burgess, June 1998. GSC 2000-168

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FOREWORD

Change may be a welcomed or a feared challenge. It is welcomed when the outcome is known and expected to be positive. It is feared when the outcome is unknown or expected to be negative. Global climate change is the most significant change currently facing humanity. Climate change may be feared, because of the many unknowns that are involved. What will the rate and level of climate change be? How will global climate change be distributed, or impact on various regions? How will the complex Earth ecosystems be affected? Most importantly, how will humanity adapt?

One element of the global climate picture that resides within the mandate of the Geological Survey of Canada is surface geological processes, which include the various forces that act to change the Earth's surface. Climate plays a major role in driving these processes and changes in climate will result in changes in their nature and intensity. Through time we have gained knowledge which allows us to predict the impact of surface geological processes and hence to mitigate or avoid their harmful effects. For example, application of process knowledge has resulted in improved practices for site-selection of infrastructure such as transportation and pipeline corridors and buildings constructed on thaw-sensitive terrain. If climate warming results in changes in the distribution of permafrost, then it may be necessary to make adaptive responses to these changes. Developing and implementing new adaptation strategies requires research, planning, and time. Therefore, the sooner we gain information on what to expect, the better prepared we will be to take action when change occurs.

The Geological Survey of Canada has prepared overview reports on the more common geological processes occurring in Canada. Each of these reports includes a map showing the distribution of the process activity today and areas where this process is most sensitive to climate change. Each looks at how different factors control process activity, discusses the sensitivity to climate change, and considers the impact of different aspects of the process on human activity. These are not intended as research documents which predict what might be expected in each part of the country, but as warnings to draw attention to potential 'hot spots' or areas where the process in question is likely to be most affected by global climate change. The anticipation is that this first step will foster and focus further research which will determine potential impacts more precisely and provide information for planning adaptive measures.

AVANT-PROPOS

Le changement est un défi qui peut être bienvenu ou redouté. Il est bienvenu quand l'issue en est connue et que l'on s'attend à ce qu'il soit favorable; il est redouté quand l'issue en est inconnue ou que l'on s'attend à ce qu'il soit défavorable. Le changement du climat mondial est aujourd'hui le changement le plus important auquel doit faire face l'humanité. Le changement climatique peut faire peur en raison des nombreux impondérables qu'il recèle. Quelles seront sa vitesse et son ampleur? Comment sera-t-il réparti et quel impact aura-t-il sur diverses régions? Comment affectera-t-il les écosystèmes complexes de notre planète? Et surtout, comment l'humanité s'y adaptera-t-elle?

Les processus géologiques de surface, qui mettent en jeu les diverses forces modifiant la surface de la Terre, constituent un aspect du climat global qui relève du mandat de la Commission géologique du Canada. Le climat joue un rôle majeur dans l'activation de ces processus, et les changements climatiques vont modifier leur nature et leur intensité. Au cours des années, nous avons acquis des connaissances qui nous permettent de prévoir l'impact des processus géologiques de surface et, par conséquent, d'en atténuer les effets néfastes ou de les éviter. Par exemple, nos connaissances de ces processus nous ont amenés à améliorer la sélection d'emplacements pour les infrastructures, comme les voies de transport ou les couloirs de pipelines, et les immeubles construits sur des sols sensibles au dégel. Si le réchauffement climatique amène des changements dans la répartition du pergélisol, il nous faudra peut-être réagir de façon adaptative à ces changements. L'élaboration et la mise en œuvre de nouvelles stratégies d'adaptation exigent des recherches, de la planification et du temps. Par conséquent, moins nous tarderons à nous informer sur ce qui peut nous attendre, mieux nous serons préparés à intervenir quand des changements se produiront.

La Commission géologique du Canada a préparé des rapports offrant une vue d'ensemble sur les processus géologiques les plus communs au Canada. Chaque rapport renferme une carte montrant la répartition actuelle de l'activité du processus en question, et les régions où il est le plus sensible au changement climatique. Chacun présente une analyse de la façon dont différents facteurs contrôlent l'activité du processus, une discussion de la sensibilité de celui-ci au changement climatique et une évaluation de l'incidence de différents aspects du processus sur l'activité humaine. Ces rapports n'ont pas été conçus comme des documents de recherche contenant des prévisions sur les changements à venir dans chaque région du pays, mais plutôt comme des avertissements visant à attirer l'attention sur les «points chauds» éventuels, c'est-à-dire les régions où le processus en question est susceptible d'être le plus touché par le changement du climat mondial. Nous espérons que ce premier pas aidera à encourager et à circonscrire des recherches plus approfondies qui fourniront des déterminations plus précises des impacts possibles ainsi que de l'information pour la planification de mesures adaptatives.

The other reports in this series are: *Sensitivity of eolian processes to climate change in Canada* (GSC Bulletin 421), *Sensitivity of the coasts of Canada to sea-level rise* (GSC Bulletin 505), *Geomorphological processes in alpine areas of Canada: the effects of climate change and their impacts on human activities* (GSC Bulletin 524), and *The impact of climate change on rivers and river processes in Canada* (GSC Bulletin 555).

S.A. Wolfe
Co-ordinator
Impact of Global Climate
Change on Geological Processes
in Canada

Les autres rapports de cette série sont *Sensitivity of eolian processes to climate change in Canada* (Bulletin 421 de la CGC), *Sensitivity of the coasts of Canada to sea-level rise* (Bulletin 505 de la CGC), *Geomorphological processes in alpine areas of Canada: the effects of climate change and their impacts on human activities* (Bulletin 524 de la CGC) et *The impact of climate change on rivers and river processes in Canada* (Bulletin 555 de la CGC).

S.A. Wolfe
Coordonnateur
Répercussions du changement climatique
à l'échelle du globe sur les processus
géologiques au Canada

Preface

This is the fifth and final overview of the Geological Survey of Canada's project "Impact of Global Climate Change on Geological Processes". These overviews provide information on the possible impacts of global climate change and the potential magnitude of the problem.

This bulletin looks at the sensitivity of permafrost to climate change in Canada. The link to global climate change comes from the connection between climate and ground temperatures. Much of Canada is predicted to become warmer due to climate change, however, the greatest increases are expected to be felt in the North. If these predictions transpire, than large portions of northern Canada will be affected by thawing permafrost. Thus, it is essential that we draw our attention to the potential impacts of climate change on permafrost in Canada.

This report describes the nature and distribution of permafrost in Canada, and discusses the consequences of permafrost warming and thawing. The authors utilize their knowledge of permafrost to develop maps of the sensitivity permafrost to climate warming. These maps identify areas where the thermal response to warming and the physical impacts of permafrost thaw will be the greatest.

This report contributes to the Earth Science Sector program Reducing Canada's Vulnerability to Climate Change.

Irwin Itzkovitch
Assistant Deputy Minister
Earth Sciences Sector

Préface

Ce bulletin est le cinquième et dernier à présenter un tour d'horizon dans le cadre du projet «Répercussions du changement climatique à l'échelle du globe sur les processus géologiques au Canada» de la Commission géologique du Canada. Ces exposés sommaires fournissent de l'information sur les impacts possibles du changement du climat mondial et sur l'ampleur éventuelle du problème.

Ce bulletin examine la sensibilité du pergélisol au changement climatique au Canada. Le lien qui existe avec le changement climatique mondial vient de la connexion entre le climat et les températures du sol. On prévoit qu'une grande partie du Canada va se réchauffer en raison du changement climatique, et que c'est dans le nord du pays que les élévations de température seront les plus importantes. Si ces prévisions se réalisent, de grandes parties du nord du Canada seront perturbées par le dégel du pergélisol. Il est donc essentiel que nous portions attention aux impacts possibles du changement climatique sur le pergélisol au Canada.

Ce rapport comprend une description de la nature et la répartition du pergélisol au Canada et une discussion des conséquences du réchauffement et du dégel du pergélisol. Les auteurs ont utilisé leurs connaissances du pergélisol pour dresser des cartes de la sensibilité du pergélisol au changement climatique. Ces cartes identifient les régions où la réponse thermique au réchauffement et les impacts physiques du dégel du pergélisol seront les plus prononcés.

Ce rapport est une contribution au programme «Réduire la vulnérabilité du Canada au changement climatique» du Secteur des sciences de la Terre.

Irwin Itzkovitch
Sous-ministre adjoint
Secteur des sciences de la Terre

CONTENTS

Illustrations

SENSITIVITY OF PERMAFROST TO CLIMATE WARMING IN CANADA

Abstract

A major concern in climate-change impact studies in polar regions is the effect of climate warming on the permafrost environment. About half the present permafrost region in Canada contains permafrost at a temperature greater than -2°C and models suggest that most of this could ultimately disappear in response to climate warming.

Local environmental factors and ground-surface conditions will determine the response of the ground-thermal regime to increasing air temperature (thermal response), and also the impact of any permafrost thaw (physical response) that might occur. These factors have been combined to characterize and map, at a national scale, the potential thermal and physical response of permafrost in Canada to warming. These components have been combined into a sensitivity index map.

Within a large portion of the region containing warm permafrost, the sensitivity of permafrost to climate warming is considered to be moderate to high. In these regions, the potential for substantial thaw settlement exists and consideration of its impact on buildings, utilities, roads, railways, pipelines, and containment structures may be required.

Résumé

L'une des principales questions soulevées dans les études sur les impacts du changement climatique dans les régions polaires concerne l'effet du réchauffement climatique sur le pergélisol. Environ la moitié de l'étendue pergélisolée du Canada recèle du pergélisol dont la température est supérieure à -2 °C et, selon des modèles, la plupart de ce pergélisol pourrait dégeler en réponse au réchauffement climatique.

Ce sont les facteurs environnementaux locaux et les conditions à la surface du sol qui déterminent les comportements thermiques des sols en réaction à la hausse de la température de l'air (réponse thermique), ainsi que l'impact du dégel éventuel du pergélisol (réponse physique). Ces facteurs ont été combinés pour caractériser et cartographier, à l'échelle du pays entier, les réponses thermique et physique potentielles du pergélisol au réchauffement, et ces composantes ont elles-mêmes été combinées dans une carte des indices de sensibilité.

Dans une grande partie de la zone de pergélisol «chaud», la sensibilité de celui-ci au réchauffement climatique est évaluée comme étant moyenne à élevée. Dans ces régions, le dégel pourrait causer un important affaissement du sol, dont les impacts sur les immeubles, les installations, les routes, les chemins de fer, les pipelines et les structures de confinement devront possiblement être pris en considération.

SUMMARY

Permafrost underlies about 4 000 000 km^2 of Canada's land surface. About half the current permafrost region contains permafrost warmer than -2°C and most of this could ultimately disappear under climate-warming scenarios predicted by general circulation models (GCMs). In areas of thicker and colder permafrost, warming would likely result in increases in active-layer thickness and thinning of permafrost. Thaw of ice-rich permafrost can result in ground instability and thaw settlement that can have impacts on the natural landscape and implications for engineering structures. An ability to characterize the sensitivity of permafrost to climate warming is important for planning future northern development projects, maintaining existing infrastructure, and adapting to changes in the natural environment.

The purpose of this study is to examine and map, at a national scale, the sensitivity of permafrost in Canada to climate warming. In contrast to previous national studies, which attempted to predict the new equilibrium permafrost boundaries that would eventually be established in response to warming, the present study focuses on the potential permafrost response during the transition to a warmer climate. The sensitivity of permafrost to warming has been characterized by considering: the present ground-temperature regime; the thermal response to warming (i.e. the relative rate and magnitude of ground-temperature change); and the physical response to warming (i.e. the relative impact of permafrost thaw).

The relationship between air temperature and ground temperature is complex, and is influenced by many local factors. The thermal response of permafrost depends on surface buffer factors, such as snow thickness, vegetation type and density, and organic ground cover that act to attenuate changes in air temperature. In addition, the transfer of heat through the underlying soil or rock depends on the thermal properties of the material. The likelihood of permafrost thaw is, in part, a function of the present ground-thermal regime. Permafrost that is currently at temperatures only a few degrees below 0°C would have a greater potential for thaw than colder permafrost at temperatures below -5°C.

There are many physical consequences of climate warming in permafrost, but only the effect of permafrost thaw on ground stability, in particular thaw settlement, is considered in this study. The impact of thaw of permafrost containing little or no ice is generally negligible. Melting of ice-rich permafrost can lead to a reduction in soil strength and ground instability resulting in thaw settlement, thermokarst development, and slope failures. The physical response therefore depends on the ice content, which is generally higher in organic and fine-grained sediments than in coarse-grained material or bedrock. The physical response will also be greater where massive ice is abundant.

SOMMAIRE

Le pergélisol s'étend sur environ 4 000 000 km^2 des terres émergées du Canada. Environ la moitié de la zone pergélisolée actuelle contient du pergélisol dont la température est supérieure à -2 °C et dont la plupart pourrait éventuellement dégeler, selon les scénarios de réchauffement climatique prévus par les modèles de circulation générale (MCG). Dans les régions où le pergélisol est plus épais et plus froid, il est probable que le réchauffement augmenterait l'épaisseur du mollisol (ou couche active) et réduirait l'épaisseur du pergélisol. Le dégel de pergélisol riche en glace peut entraîner l'instabilité ou l'affaissement du sol, ce qui peut avoir des impacts sur le paysage naturel et des conséquences pour les ouvrages de génie civil. La capacité de caractériser la sensibilité du pergélisol au réchauffement climatique est importante pour la planification de projets de développement dans le Nord, l'entretien de l'infrastructure actuelle et l'adaptation aux changements de l'environnement naturel.

L'objectif de cette étude était d'examiner et de cartographier, à l'échelle du pays, la sensibilité du pergélisol canadien au réchauffement climatique. Contrairement aux études d'envergure nationale parues antérieurement, qui avaient pour objet de prévoir les nouvelles limites du pergélisol qui s'établiraient en équilibre avec un climat plus chaud, la présente étude est axée sur la réaction possible du pergélisol durant la transition vers un climat plus chaud. Nous avons caractérisé la sensibilité du pergélisol au réchauffement en considérant la configuration thermique actuelle du sol, la réponse thermique au réchauffement (c.-à-d. la vitesse et l'ampleur relatives du changement de la température du sol) et la réponse physique au réchauffement (c.-à-d. l'impact relatif du dégel du pergélisol).

La relation entre la température de l'air et celle du sol est complexe et dépend de nombreux facteurs locaux. La réponse thermique du pergélisol dépend des caractéristiques de la «couche tampon» à la surface du sol, qui atténue les effets des variations de la température de l'air : épaisseur de la neige, type et densité de la végétation, présence ou absence d'une couche de matière organique. En outre, le transfert de chaleur dans le sol ou la roche sous-jacents dépend des propriétés thermiques du matériau. La probabilité de dégel du pergélisol dépend en partie de la configuration thermique actuelle du sol. Le pergélisol dont la température actuelle n'est que de quelques degrés sous le point de congélation risque plus de dégeler que le pergélisol plus froid, de température inférieure à -5 °C.

Le réchauffement climatique peut avoir plusieurs effets physiques sur le pergélisol, mais seul l'effet du dégel du pergélisol sur la stabilité du sol — l'affaissement du sol en particulier — est examiné dans cette étude. L'impact du dégel de pergélisol contenant peu ou pas de glace est généralement négligeable. Le dégel de pergélisol riche en glace peut mener à une réduction de la résistance du sol et à l'instabilité de celui-ci, entraînant son affaissement, la création d'un modelé thermokarstique et des ruptures de versants. La réponse physique dépend donc de la teneur en glace, qui est généralement plus élevée dans les sédiments organiques et les sédiments fins que dans les matériaux grossiers ou le substratum rocheux. En outre, la réponse physique sera plus prononcée dans les zones où la glace massive est abondante.

Factors considered important for the determination of the thermal and physical response to warming were identified and a rating scale was applied to each. These factors were then combined using Geographic Information System (GIS) techniques. The maps produced represent the summation of the factors influencing the thermal or physical response to warming, classified according to a low, moderate, or high response.

About 90% of the present permafrost region would have a moderate to high thermal response to increases in air temperature. Most of this area is located in the northern portion of the permafrost region where there is limited vegetation and/or snow cover (buffer layer). The thermal response to warming is generally low to moderate in the southern portion of the permafrost region due to the presence of a substantial buffer layer. Within this region however, ground temperatures are greater than -2°C and the potential for permafrost thaw is greater than in areas to the north where ground temperatures are lower. The physical response to warming is high in about 13% of the present permafrost region and most of this area is located in the southern portion of the permafrost region where the potential for thaw is the greatest. Throughout the rest of the permafrost region the physical response is generally low to moderate, but there are extensive areas where massive ice may be present and where the impact of permafrost thaw can be high.

The thermal and physical response to warming were combined into a sensitivity index. About 50% of the area within the zone containing warm permafrost (temperature >-2°C) is moderately to highly sensitive to warming. Included in this region are the Mackenzie valley and northern Manitoba where significant infrastructure presently exist and remedial action may be required to minimize damage to engineering structures. Planning and design for future development in these areas should also consider the impact of climate warming on permafrost.

A more detailed analysis is required to determine the sensitivity of permafrost to warming at local or regional scales. The results of this study can guide this future work by delineating areas where more detailed studies may be required and also provide an approach that may be applied to these detailed studies.

Les facteurs jugés importants pour déterminer les réponses thermique et physique au réchauffement ont été identifiés, et une échelle d'évaluation appliquée à chacun. Ces facteurs ont ensuite été combinés par des techniques de Système d'information géographique (SIG). Les cartes obtenues représentent la somme des facteurs qui influent sur la réponse thermique ou physique au réchauffement, laquelle a été classifiée comme étant faible, moyenne ou élevée.

Environ 90 % de la zone de pergélisol actuelle aurait une réponse thermique moyenne ou élevée à une hausse de la température de l'air. La plus grande partie de cette étendue se trouve dans le nord de la zone de pergélisol, où la végétation ou la couverture de neige (couche tampon) sont limitées. La réponse thermique au réchauffement est généralement faible ou moyenne dans le sud de la zone de pergélisol, grâce à la présence d'une couche tampon substantielle. Toutefois, dans cette région, la température du sol est supérieure à -2 °C et la probabilité de dégel du pergélisol est plus grande que dans les régions du nord où la température du sol est plus basse. La réponse physique au réchauffement est élevée dans environ 13 % de la zone de pergélisol actuelle, et la plus grande partie de cette superficie se trouve dans le sud de la zone de pergélisol, où la probabilité de dégel est la plus grande. Dans le reste de la zone de pergélisol, la réponse physique est généralement faible ou moyenne, mais il existe de grandes étendues qui pourraient receler de la glace massive et où le dégel du pergélisol pourrait avoir un impact considérable.

Les réponses thermique et physique au réchauffement ont été combinées dans un indice de sensibilité. Environ 50 % de la superficie de la zone de pergélisol «chaud» (température > -2 °C) a une sensibilité moyenne ou élevée au réchauffement. Cette étendue comprend entre autres la vallée du Mackenzie et le nord du Manitoba, où il existe actuellement une infrastructure importante et où des mesures correctives pourraient être nécessaires pour minimiser les dommages aux ouvrages de génie civil. Il faudra tenir compte, durant la planification et la conception de nouveaux programmes de développement pour ces régions, de l'impact du réchauffement climatique sur le pergélisol.

Une analyse plus détaillée sera nécessaire afin de déterminer la sensibilité du pergélisol au réchauffement à l'échelle locale ou régionale. Les résultats de cette étude pourront aider à guider ces futurs travaux, car les domaines où des études plus détaillées pourraient être nécessaires y sont identifiés, et une approche applicable à ces études y est présentée.

INTRODUCTION

Permafrost is defined as a thermal condition in which the temperature of earth material remains continuously below 0°C for two years or more (Brown and Pewe, 1973). Permafrost distribution in Canada may be divided into two zones of continuous and discontinuous permafrost (Heginbottom et al., 1995). The discontinuous permafrost zone may be further subdivided into widespread (or extensive), sporadic, and localized permafrost (Fig. 1). Considering the areal extent of permafrost within each of the zones, Kettles et al. (1997) estimated that about 4 000 000 km^2 or 42% of the total land surface of Canada is underlain by permafrost.

Climate is the main factor controlling the formation and existence of permafrost (Brown and Pewe, 1973). Although a general relationship exists between air and ground temperatures, local environmental factors play an important role in determining the permafrost distribution and its thermal regime. A change in air temperature may result in changes in ground temperature and permafrost distribution, but the magnitude and rate at which these changes occur will depend on the characteristics of the particular site such as snow cover, vegetation, and type of earth material.

Recently, there has been much concern about the impact that increasing atmospheric levels of carbon dioxide and other greenhouse gases may have on climate. Climatologists have shown that mean annual global air temperatures would increase in response to rising atmospheric greenhouse gas levels, although there is disagreement over the magnitude of this increase and the amount of regional variation. The globally averaged near-surface air temperature is projected to increase by 1.4°C to 5.°C between 1990 and 2100 (Intergovernmental Panel on Climate Change, 2001). These results are based on a number of climate models. The Canadian Climate Centre General Circulation Model predicts that mean annual air temperature increases in response to a doubling of atmospheric CO_2 expected in the first half of the 21st century, will range from 4°C in the southern portion of the Canadian permafrost region to 7°C in the high arctic (Berry, 1991; Maxwell, 1997; Flato et al., 2000).

Large areas of the Canadian north are underlain by permafrost at temperatures greater than -2°C (Fig. 2) and it is expected that most of this permafrost, which is generally less than 75 m thick (Burgess et al., 2000; Smith and Burgess, 2000, 2002; Smith et al., 2001), may ultimately disappear under anticipated climate warming. In areas of thicker and colder permafrost, warming would likely result in a thickening of the active layer, an increase in permafrost temperature, and a decrease in permafrost thickness. The impacts of permafrost warming and degradation will be important in regions where permafrost is ice-rich. Thawing of ground ice can result in loss of soil strength and lead to ground instability. The melting of ground ice will also affect the hydrological regime of arctic regions and alter drainage patterns. As permafrost warms, groundwater storage capacity will increase and as active layers deepen, infiltration will increase (Woo et al., 1992). Large amounts of carbon are stored in northern peatlands and these may emit carbon in the form of greenhouse gases as peat materials thaw and subsequently decompose in response to warming (Kettles et al., 1997). An ability to characterize the sensitivity of permafrost to climate warming is important to ensure the integrity of existing northern infrastructures, to adequately design future developments, and to assess and adapt to climate-change impacts on the natural environment.

In contrast to recent national studies such as those of Woo et al. (1992) and Kettles et al. (1997), this study focuses on the potential permafrost response during the transition to a warmer climate, rather than on delineating the new equilibrium conditions that would eventually be established. The main purpose of this study is to examine and map permafrost sensitivity (Fig. 3, in pocket) to climate warming in Canada using national data sets. Permafrost sensitivity consists of two components, the potential for permafrost thaw and the impact of thaw. The potential for permafrost thaw depends on the thermal response to warming (i.e. the relative rate and magnitude of ground-temperature change) and the present ground-temperature regime. The second component of permafrost sensitivity considers the physical response to warming (i.e. the relative magnitude of the impact of permafrost thaw).

The first objective was to map, at a national scale, the thermal sensitivity of permafrost to climate warming. This study considered the main environmental factors that influence permafrost stability. The approach taken recognized the transient nature of the thermal response of permafrost to climate warming and the uncertainties associated with various climate-warming scenarios. Therefore no attempt was made to project boundaries of permafrost zones or the future extent of permafrost under specific climate-warming scenarios, but rather the study identified areas where the thermal response to warming would be greatest under general climate warming. The second objective was to delineate areas where the physical impacts of permafrost thaw will be the greatest. Although there are many physical impacts of permafrost warming as outlined above, only that of thaw settlement was considered here. The maps produced were subsequently used to characterize the sensitivity of permafrost to a general climate warming.

NATURE AND DISTRIBUTION OF PERMAFROST

Only a brief description of the nature and distribution of permafrost, of its associated ground-ice conditions and stability, and the main features of the permafrost thermal regime will be presented here. Further information on the distribution of permafrost in Canada can be found in Heginbottom (1995) and Smith et al. (2001). A discussion of the factors influencing the shallow ground-temperature regime is presented by Burgess and Smith (2000). The terminology and definitions used throughout this discussion generally follow those found in the *Multi-Language Permafrost Glossary of Permafrost and Related Ground Ice Terms* produced by the International Permafrost Association (1998).

Permafrost thickness ranges from a few metres or less at the southern limit of the permafrost zone to over 700 m on the islands of the Arctic Archipelago (Fig. 3d). At any location, permafrost thickness depends on the temperature at the ground

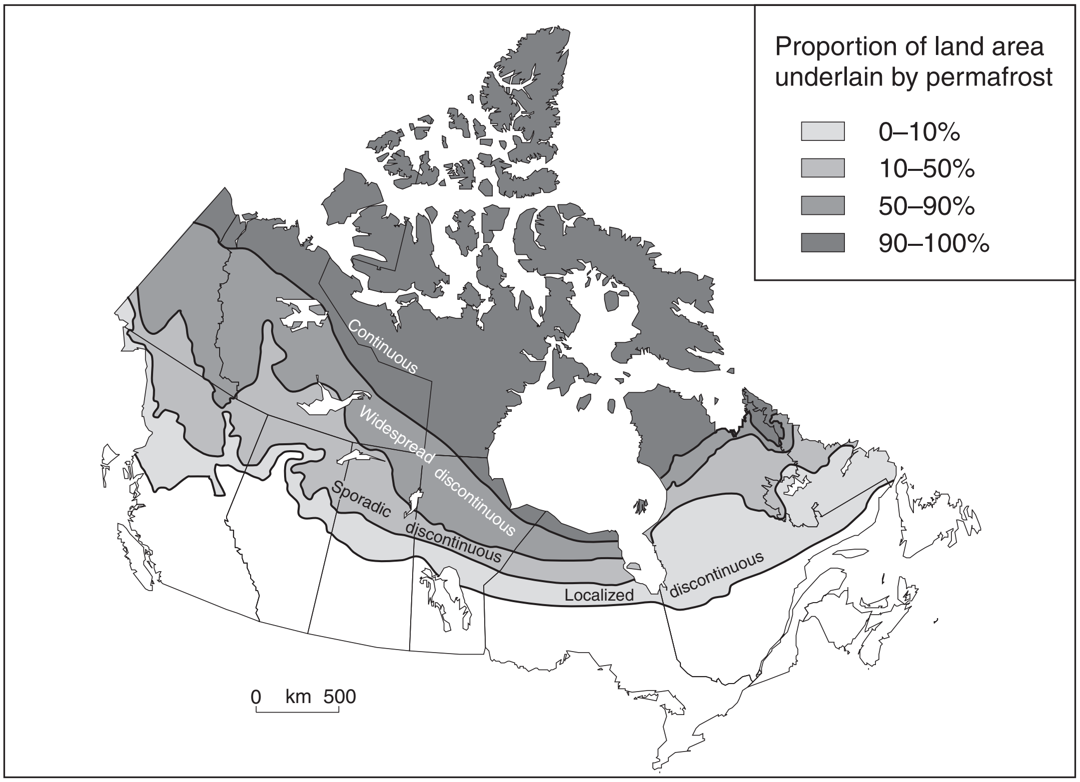

Figure 1. *Permafrost zones of the Canadian permafrost region (*after *Kettles et al., 1997).*

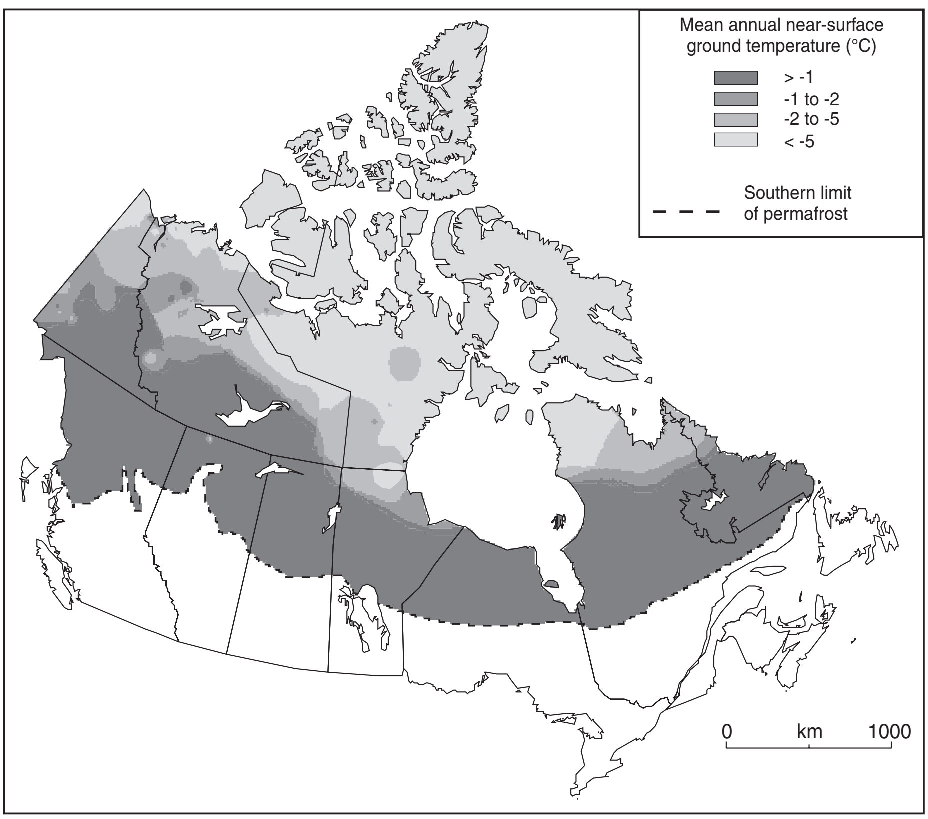

Figure 2. *Spatial variation in mean annual near-surface ground temperature within the Canadian permafrost region (*after *Smith and Burgess, 1998). Ground temperature within the zone classified as greater than -2°C will only be colder than 0°C where permafrost is present; this zone is within the discontinuous permafrost zone. This map was produced from ground-temperature data extracted from a GSC database (Smith and Burgess, 2000).*

surface, the geothermal heat flow from the Earth's interior (which is a function of the geological environment and history), the climate history, and the ground-thermal properties.

The ground-temperature regime in a permafrost setting is illustrated in Figure 4. The maximum and minimum temperature experienced at each depth during the year define the annual ground-temperature envelope. The average temperatures at each depth define the mean annual ground-temperature profile. The mean annual ground temperatures within the upper 10 m range from about 0°C at the southern limit of the permafrost zone to about -20°C at the northern limit (Fig. 3e). The diurnal cycle of air temperature penetrates only a few tens of centimetres below the ground surface. At depths of a few metres, only the seasonal variation in temperature is observed. The seasonal variation in ground temperature decreases with depth such that the annual wave is completely dampened out at depths of approximately 10 m to 15 m. The depth at which there is no observed seasonal variation in ground temperature is defined as the level of zero annual amplitude. Below this depth, temperatures increase according to the geothermal gradient.

The upper part of the ground that freezes and thaws each year (i.e. where the maximum temperature exceeds 0°C) is referred to as the active layer. The active layer may be several metres thick in areas of exposed bedrock due to its high thermal conductivity. In vegetated organic terrain, under similar climatic conditions, the active layer may be less than 0.5 m thick because of the insulation supplied by the surface organic layer that restricts the flow of heat into the ground during summer. The zone beneath the active layer, where the ground temperature remains permanently below 0°C, is permafrost.

Climate is the main factor determining the occurrence of permafrost, but the actual relationship between climate and ground temperatures depends on site-specific conditions that determine the surface-energy balance. Factors such as slope, aspect, vegetation, snow cover, surficial materials, the presence or absence of an organic layer, soil moisture content, and drainage influence the local surface-energy balance and therefore, ground-surface temperatures on which the spatial distribution, temperature, and thickness of permafrost are highly dependent. The mean annual near-surface ground temperatures for over 500 sites in Canada are shown in Figure 3e. The general spatial patterns of mean annual ground temperature and mean annual air temperature are similar (Fig. 3f), but ground temperature is generally 2°C to 4°C higher and exhibits much greater local variation due to variation in the ground-surface factors listed above.

Permafrost is essentially continuous across the arctic regions of Canada and underlies virtually all exposed land areas (Fig. 1). To the south of the continuous permafrost zone lies a broad zone of discontinuous permafrost, in which the proportion of unfrozen ground generally increases southwards. The discontinuous zone is commonly subdivided into a zone of widespread discontinuous permafrost, wherein over 50% of the land area is underlain by permafrost, and a zone of sporadic discontinuous permafrost in which 10% to 50% of the land area is underlain by permafrost. Within the localized permafrost zone, permafrost is confined to isolated patches of terrain, in locally favourable locations such as areas of elevated organic terrain (Kettles et al., 1997). Conditions favouring the existence of permafrost also prevail at high altitudes, mainly in the mountains of western Canada. Permafrost also underlies areas of the seabed in the western Arctic (Judge et al., 1987) and possibly the inter-island channels of the Arctic Archipelago.

The national permafrost map of Heginbottom et al. (1995), on which Figure 1 is based, provides a classification of permafrost that is essentially based on the proportion of land that is underlain by permafrost within a given area. Boundaries of permafrost regions are mainly derived from

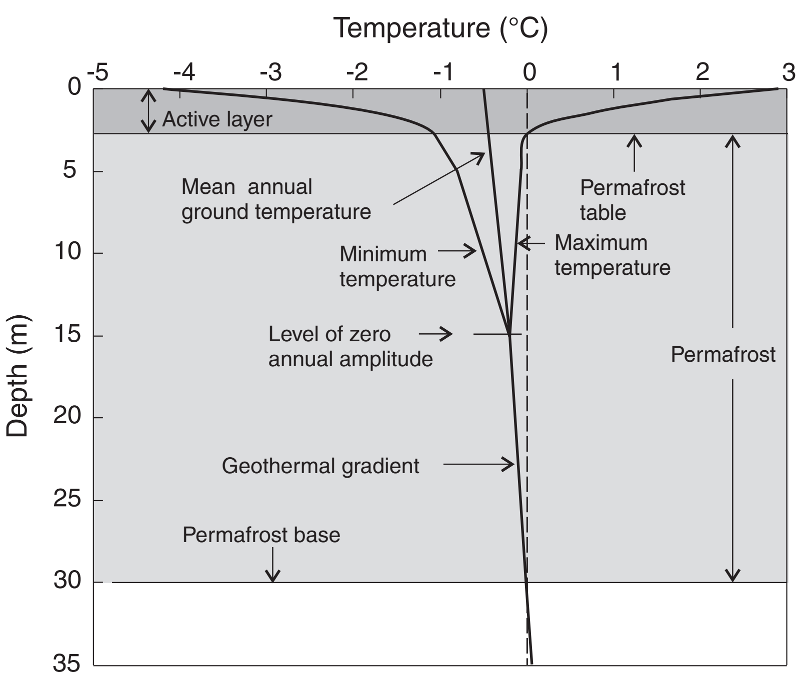

Figure 4.

Features of the ground-thermal regime in permafrost based on data from a Yellowknife site (data from Brown, 1973).

physiographic boundaries. This map gives only a general idea of the permafrost distribution. Although the permafrost thickness at a number of points has been mapped (Fig. 3d) as well as the presence or absence of permafrost in several boreholes (*see* Smith and Burgess, 2002), no map exists at present that delineates areas that are actually underlain by permafrost.

Permafrost has traditionally been defined on the basis of temperature, but the ground may not necessarily be frozen or bonded by ice at temperatures below 0°C. This situation may occur due to a depression of the freezing point of water related to the presence of dissolved salts. Also, water within the soil pores may freeze gradually over a range of temperature below 0°C due to pressure effects. Water and ice can coexist in frozen soils and in the case of fine-grained soils such as silt and clay, appreciable amounts of water may remain unfrozen at temperatures several degrees below 0°C (Williams and Smith, 1989).

In contrast to most other earth materials, ground ice exists at temperatures comparatively close to its melting point. In the permafrost region, the presence of ground ice is an important influence on topography, geomorphic processes, vegetation, and the response of the landscape to environmental changes. Ground ice also presents challenges to development in the permafrost region. The engineering properties of permafrost soils are dependent on their unfrozen water and ice contents and therefore on ground temperature. An important concept in understanding the role of ground ice in permafrost areas is that of excess ice, the volume of which when melted, exceeds the void volume or pore volume of the enclosing sediments (French, 1996; International Permafrost Association, 1998). Freezing and thawing processes and the presence of excess ice are responsible for the variety of landscape features associated with permafrost.

Ground ice may occur as structure-forming ice that bonds the enclosing sediment, or as larger bodies of more or less pure ice referred to as massive ice (Heginbottom et al., 1995). Structure-forming ice includes pore ice, icy coatings on soil particles, ice veins, ice lenses (Fig. 5), and intrusive ice. Massive ice (Mackay, 1972) occurs as ice wedges, as the ice-core in pingos, and other massive ice beds (Fig. 6). Massive ice beds may form as water migrating from warmer unfrozen soil accumulates and freezes within the frozen soil. Massive ice beds formed by this process, referred to as ice segregation, are

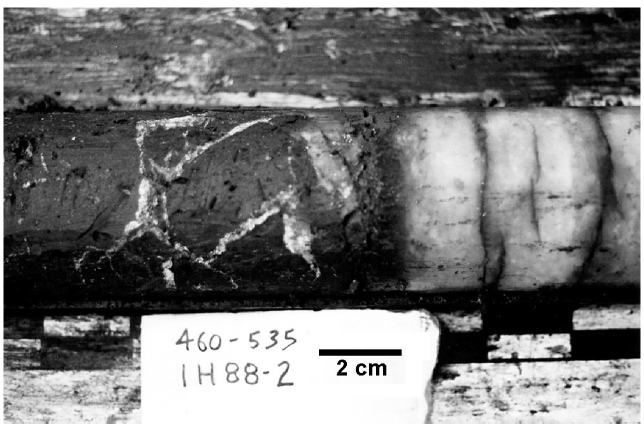

Figure 5. *Ice lenses in a sediment core sample. Photograph by S.R. Dallimore, March 1988, GSC 2000-169*

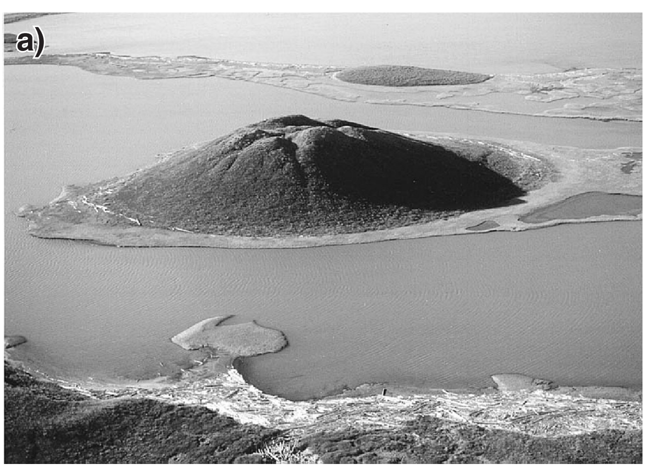

Figure 6. a) *Ice-cored pingo on the Tuktoyaktuk Peninsula. Photograph by S.L. Smith, September 1999. GSC 2003-017* ***b)*** *Massive ice in an esker at the site of the Ekati diamond mine near Lac de Gras, Northwest Territories. Photograph by M.M. Burgess, June 1998. GSC 2000-168*

Figure 7. Thermokarst terrain in Yellowknife. Photograph by S.A. Wolfe, August 1997. GSC 1998-006L

commonly found at the base of fine-grained sediment and above coarse-grained material (e.g. Mackay, 1971). Massive ice beds may also be buried deposits of surface ice such as glacier ice (Dyke et al., 1992; Wolfe, 1998). The distribution of ground ice is strongly influenced by soil texture and the local geological and geothermal history. In general, organic soils and fine-grained soils that are rich in clay and silt, contain more ground ice (structure-forming ice in particular) than coarse-grained material consisting of sand and gravel.

Ice bonding is an important component of the strength of frozen, fine-grained soils. As ground temperature increases, the unfrozen water content increases, resulting in a decrease in ice-bonding. Frozen soils weaken as warming occurs and lose all strength due to ice bonding when completely thawed (Ladanyi et al., 1996). Thaw of permafrost containing excess ice can result in thaw settlement as water drains away, and the volume formerly occupied by excess ice is lost. Frozen soils that are subject to significant settlement during thaw are referred to as thaw unstable or thaw sensitive. Thaw unstable soils include those containing massive ice as well as fine-grained material such as silt and clay or peat, that generally have high ice contents and are also compressible in the unfrozen state.

Thermokarst topography (Fig. 7), which is characterized by irregular terrain containing ponds or lakes, may develop where differential thaw settlement occurs (Smith, 1988; Burn and Smith, 1993). Ground instability and thaw settlement are a major concern for development in permafrost regions, especially where permafrost temperature is close to 0°C. The removal of vegetation or the insulating organic cover and other disturbances to the ground prior to construction can alter the ground-thermal regime and may lead to warming and melting of permafrost. Permafrost may also be warmed by heat generated from buildings, or buried water and sewage, or hydrocarbon pipelines. Ground subsidence due to the melting of ground ice can cause damage to structures such as buildings and pipelines, roads, and railways especially if differential settlement occurs (Brown, 1970; Johnston, 1981). Warming of ice-rich soils and melting of ground ice on slopes can cause instability (Aylsworth and Duk-Rodkin, 1997; Dyke et al., 1997) resulting in flows and slides (Fig. 8). Warming of frozen ground may also decrease the strength of the frozen material and lead to increased rates of soil creep (Bennett and French, 1990), which is a slow, time-dependent deformation of the frozen ground.

PERMAFROST AND CLIMATE CHANGE

Permafrost is a thermal condition and therefore its occurrence depends on climate. Climate, however, is not constant and has undergone significant changes detectable at time scales from decades or centuries to millennia. Under cooling conditions, permafrost may increase in both areal extent and thickness, whereas a warmer climate may cause an increase in active-layer thickness, permafrost thinning, and in some cases, complete disappearance of permafrost.

The body of subsea permafrost beneath the Beaufort Shelf is a relic from periods of lower sea level during the glacial maxima of the Quaternary Period. During this period, large areas of the continental shelf were above sea level (Blasco et al., 1990) and thus were exposed to air temperatures that were as much as 18°C lower (Allen et al., 1988) than those currently occurring at the seabed. This allowed the formation of permafrost up to 700 m thick. During interglacial periods and in postglacial time, these areas were covered by Arctic Ocean water having seabottom water temperatures between 0 and -2°C. The thermal regime of the subsea permafrost is thus in disequilibrium with the present marine environment (Taylor, 1991) such that the sediments are warming gradually, and the permafrost is slowly degrading.

A general warm period followed the disappearance of glacial ice with temperatures peaking during the middle Holocene between 9000 BP and 6000 BP (uncalibrated radiocarbon years). Zoltai (1995) presented a reconstruction of the permafrost distribution 6000 BP in western Canada, based on data from macrofossil analysis and radiocarbon dating of peat cores, that indicate whether permafrost was present or absent at the time of peat formation. The results of this analysis suggest that mean annual temperatures were about 5°C warmer than present and the southern limit of permafrost was 300–500 km northward of its current position. Much of the present discontinuous permafrost zone may have been free of permafrost. Where permafrost did exist during this time, active-layer thickness was probably greater than at present. Studies by Burn et al. (1986) suggested that the active layer in the Mayo area of Yukon Territory was twice as thick about 9000 BP than it is currently. This period of maximum active-layer development coincides with active-layer deepening that began between 11 000 BP and 10 400 BP (Murton et al., 1998) and the development of thermokarst lakes in the Mackenzie Delta (e.g. Rampton, 1973, 1982; Mackay, 1978; Vardy et al., 1997). Peat accumulation was also the greatest during this relatively warm period (Rampton and Bouchard, 1975; Vardy et al., 1998).

Permafrost became more extensive during cooler conditions following the mid-Holocene Warm Period. Zoltai (1993) presented evidence suggesting that permafrost was established in northwestern Alberta by 3700 years ago and the climate at this time probably resembled the present climate regime. In the Mackenzie Delta region, permafrost aggradation and pingo development occurred in response to cooling that began about 5000 BP (Rampton, 1973; Rampton and Bouchard, 1975; Vardy et al., 1998).

Frozen peatlands occurring today at the southern fringe of the discontinuous permafrost zone exist at relatively warm ground temperatures (>-0.5°C). Permafrost in these peatlands likely formed when slightly colder climatic conditions prevailed in the northern hemisphere during the Little Ice Age (Thie, 1974; Vitt et al., 1994). Between 1550 AD and 1850 AD, temperatures were about 1°C cooler than present and permafrost occurred farther south than it does today (Vitt et al., 1994). Much of this permafrost has generally degraded in response to warming, but has been preserved in some areas due to the insulating properties of the thick peat cover (Halsey et al., 1995).

Evidence also exists for climate-induced changes to permafrost during the last several decades to a century. Analysis of borehole temperatures in Alaska by Lachenbruch and Marshall (1986) indicate a general warming trend. During the last 100 years, air temperatures in the western Arctic have warmed by about 1.5°C (Maxwell, 1997). This warming has caused the eradication of thin permafrost and an apparent northward displacement of the southern boundary (Kwong and Gan, 1994) of the discontinuous permafrost zone, and an increase in permafrost temperatures in Yukon Territory and western Northwest Territories (Burn, 1992, 1998a; Halsey et al., 1995). A general warming of ground temperatures in the discontinuous permafrost zone of Alaska has also been observed (Osterkamp and Romanovsky, 1999). In Manitoba, permafrost continues to degrade in the southern fringe of the permafrost region, especially where there is no surface peat layer (French and Egorov, 1998). Extensive permafrost degradation also appears to have occurred in the subarctic and boreal peatlands of Quebec, especially between 1957 and 1973 (Laberge and Payette, 1995). In the eastern Arctic, however, recent cooling and aggradation of permafrost has occurred. Records for northern Quebec, show a decrease in air temperature between 1947 and 1992 ranging from 0.02–0.03°C per year. An analysis of ground temperatures in the upper 20 m for the period 1988–1993 indicate that permafrost also cooled over this time period (Allard et al., 1995).

Permafrost conditions are also dynamic under the current climate. Changes in the permafrost environment can be caused by inter-annual variability in rainfall, snowfall, or the occurrence of drought or fires. Soil temperature and active-layer thickness may temporarily increase following a fire (Viereck, 1973; Liang et al., 1991). The increase in temperature is not due to the heat of the fire, but rather to the loss of the shading effect of trees, the removal of the insulating organic layer, and a decrease in the reflectivity of the surface, that results in greater absorption of radiation by the ground surface (Viereck, 1982; Johnson and Viereck, 1983). Deeper active layers are found at more severely burned sites where the organic layer has been completely removed (Johnson and Viereck, 1983; Racine et al., 1983). Active-layer thickness may return within a few years to pre-burn levels if the fire was not severe and vegetation regeneration occurs over a short period. Where vegetation regeneration is slow, long-term permafrost degradation may continue (Burn, 1998b). The effect of fire on the permafrost landscape is illustrated by the marked increase in active-layer detachment slides along the banks of the Mackenzie River (Fig. 8) following forest fires near Tulita in the warm spring of 1995 (Aylsworth and Duk-Rodkin, 1997). Extreme climatic events, for example higher than normal air temperatures associated with El Niño events, may also affect the permafrost environment and can lead to increases in active-layer thickness, thaw settlement, and slope instability. This is illustrated by the occurrence of active-layer detachments on the Fosheim Peninsula of Ellesmere Island during an unusually warm summer in 1988 (Edlund et al., 1989; Lewkowicz, 1990).

The local distribution and extent of permafrost also varies in response to changes in the surface-thermal regime caused, for example, by the lateral migration of river channels, shoreline erosion, lake drainage, and coastal emergence (Dyke et al., 1997). The Mackenzie Delta region and the Mackenzie valley illustrate the close links between the local permafrost

Figure 8.

Numerous active-layer detachments along a bank of the Mackenzie River between Norman Wells and Tulita, Northwest Territories. The area was burned by a forest fire in June 1995. Photograph by M.M. Burgess, September 1996. GSC 2000-034C distribution and the history of river migration (Smith and Hwang, 1973). In these areas, channel courses are continually changing and as scouring occurs on the outside of river bends, warming and thawing of permafrost occurs. On the inside of river bends, deposition occurs and sediments are exposed to lower air temperatures and permafrost becomes established (Dyke, 2000a). In coastal regions, for example near Tuktoyaktuk, erosion resulting from wave action and storm surges exposes frozen sediment to warm sea water. Melting of massive ice and subsidence results in rapid retreat of the coastline (Nairn et al., 1998; Wolfe et al., 1998). Permafrost aggradation occurs along emergent coastlines such as those in the Arctic Archipelago. As new land emerges from the ocean due to isostatic rebound and is exposed to lower air temperature, subsurface temperatures decrease, and permafrost forms (Taylor, 1991).

Human activity may also have an impact on global climate that may result in changes in the permafrost environment in addition to the natural influences discussed above. The international Intergovernmental Panel on Climate Change (IPCC) declared in 1996 that "the balance of evidence suggests a discernable human influence on global climate" (Houghton et al., 1996). This statement was reinforced in the Third Assessment Report of the IPCC (Intergovernmental Panel on Climate Change, 2001) that concluded that there is strong evidence that most of the warming observed over the last 50 years of the 20th century is attributable to human activities. Doubling of atmospheric carbon dioxide (CO_2) is expected to be realized between 2050 AD and 2100 AD, after which it is likely that CO_2 levels will continue to increase, especially if emission reduction targets are not met. A doubling of the atmospheric content of CO_2 is expected to result in an increase in global air temperature of 1°C to 3.5°C. Warming is not predicted to be uniform, with greater increases in air temperature expected at high latitudes. The coupled general circulation model of the Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment Canada (Flato et al., 2000) predicts an increase in mean annual air temperature ranging from 2°C to 6°C, for the Canadian permafrost region in response to the doubling of atmospheric CO_2 (Fig. 9).

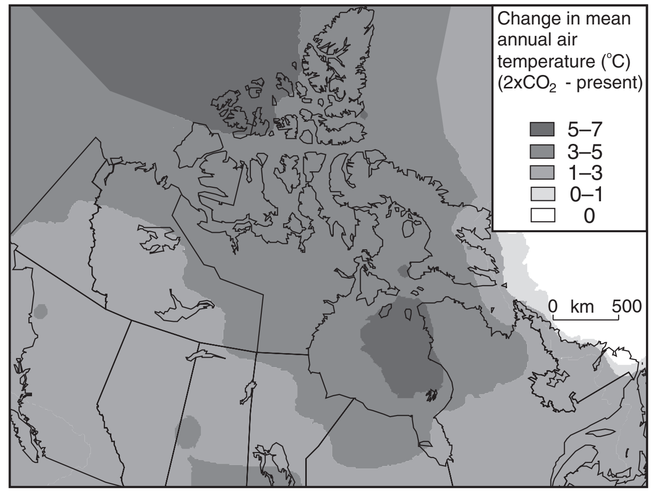

Figure 9. *Increase (2040–2060 mean minus 1975–1995 mean) in mean annual air temperature in response to doubling of CO_2, predicted by the Canadian Centre for Climate Modelling and Analysis first generation coupled GCM (Flato et al., 2000).*

CONSEQUENCES OF PERMAFROST WARMING AND THAW

The physical response of the terrain to permafrost degradation is mainly dependent on the ice content of the frozen material (Dyke et al., 1997). Where ice-rich materials are present, an increase in thaw settlement and thermokarst activity will probably accompany climate warming. Soil strength due to ice bonding will be reduced as unfrozen water content of the frozen ground increases in response to a rise in ground temperature. This may lead to ground instability and an increased incidence of slope failure. An increase in the frequency of wild fires may accompany climate warming. In peatland areas, fires could consume some of the dry peat in the active layer of peat plateaus, initiating widespread permafrost degradation (Zoltai, 1993) and thaw settlement. An increase in active-layer detachment slides can also be a consequence of increased fire frequency and burn extent (Dyke, 2000b).

Climate warming may also have important effects on the hydrology of permafrost areas. Permafrost provides an impermeable layer that impedes drainage, supports a high water table, and constrains infiltration and groundwater movement to the active layer (Dingman, 1973; Kane and Slaughter, 1973; Mackay and Loken, 1974). Wetlands and ponds, therefore, are prevalent in the permafrost region (Wright, 1979). Patchy wetlands may even exist in the polar desert of the high arctic because of the shallow active layer and high water table (Woo and Young, 1998). Increases in active-layer thickness will improve drainage and may lead to a loss of these wetlands. This can result in a change in vegetation patterns and the potential loss of breeding habitats for wildlife (Michel and van Everdingen, 1994).

Rivers normally exhibit a quick response to snowmelt and rainfall events where permafrost is present. The active layer is easily saturated and most of the water reaches streams as overland flow (Woo, 1976). Drainage basins in the permafrost region therefore, generally have high runoff-to-rainfall ratios (Kane et al., 1998; Lilly et al., 1998). Once the precipitation event is over, however, stream flow quickly decreases because permafrost restricts groundwater flow to the stream (Dingman, 1973). As permafrost degrades and active layers thicken, subsurface flow will become a more important contribution to baseflow and streamflow will become more uniform throughout the year (Woo et al., 1992; Michel and van Everdingen, 1994; Ashmore and Church, 2001). An unfrozen zone or talik may develop between the base of the active layer and the permafrost table allowing streamflow to be sustained in winter (Hinzman and Kane, 1992). Enhanced winter streamflow may, however, result in more extensive river-ice formation and the possibility of more serious flooding during break-up in the arctic river ice (Michel and van Everdingen, 1994).

A deeper active layer will be associated with a greater variation in the amount of water stored in the soil as well as an increase in the movement of subsurface water downslope (Hinzman and Kane, 1992).

Groundwater will play a more important role in the hydrology and landscape processes especially in areas currently underlain by continuous permafrost (Michel and van Everdingen, 1994). Frost heave in the active layer may increase due to a greater availability of unfrozen water and this has important engineering implications. Frost blisters, which are formed as frost heave occurs, may become more numerous in the arctic region. Icing activity, which can present a serious road hazard, may also increase in the continuous permafrost zone. Greater exchanges between surface water and groundwater may lead to a greater dissolved solids content in rivers and this may have an effect on fish and other aquatic life. As permafrost thaws, increased regional groundwater flow may promote further warming and thawing of permafrost. Groundwater may also be discharged offshore (through the sea floor) where it may influence nearshore circulation and sea-ice cover.

Terrestrial carbon sinks are an important, yet poorly understood component of the global CO_2 budget (Sundquist, 1993). Northern peatlands are a significant global carbon sink and it is estimated that 200 Gt to 500 Gt carbon are sequestered within them (Kuhry and Zoltai, 1994). The Canadian permafrost region currently represents an important carbon sink that may become a carbon source as climate warming progresses. Tarnocai (1998) estimates that about 104 Gt of carbon are stored in soils (cryosols) within the permafrost region of Canada, and a substantial portion (47 Gt) of this is stored in frozen organic soils found mostly in peatlands in western Canada and the Mackenzie valley (Vitt et al., 1994; Aylsworth and Kettles, 2000). Carbon that was sequestered in organic matter during a warmer period has been preserved in the frozen material (Oechel et al., 1995; Vardy et al., 1997, 1998; Peteet et al., 1998). The amount of carbon stored in the permafrost regions will likely change in response to climate warming, but the response will be complex (Moore et al., 1998). A change from a carbon sink to a carbon source has been suggested, but this will not be caused directly by an increase in temperature. An increase in active-layer thickness, enhanced drainage and soil aeration, and a decrease in water-table level will favour peat decomposition and release of CO_2 to the atmosphere, constituting a potentially significant positive feedback leading to additional climate warming (Oechel et al., 1993; Bubier et al., 1998; Schraeder et al., 1998). Following an initial outgassing of CO_2, an increase in primary productivity related to tree and shrub growth may lead to a general increase in carbon storage (Oechel et al., 1993, 1995; Waelbroek et al., 1997). If increased precipitation or poor drainage lead to higher water tables, methane, which is also a greenhouse gas, may be released from northern peatlands (Roulet et al., 1992). Thawing of permafrost in dry peat plateaus will create collapsed bogs and fens that will emit additional amounts of methane (Moore et al., 1998). An increase in the incidence and severity of fire would also modify the carbon balance of permafrost-affected peatlands. The role of fire in the peatland carbon cycle, however, is poorly understood.

Large amounts of methane may currently be stored within and beneath permafrost as natural gas hydrate bodies that are ice-like solids that are stable under conditions of low temperature and high pressure. Recent estimates by Smith and Judge (1995) indicate that about 100 Gt of methane gas may be stored as gas hydrate in terrestrial and marine sediments in the Mackenzie Delta–Beaufort Sea region. Warming of these sediments may result in gas hydrate decomposition and the eventual release of methane to the atmosphere, further enhancing climate warming (Kvenvolden, 1988, 1994; Nisbet, 1989). Methane hydrate is generally only stable at depths greater than about 200 m at locations where permafrost thickness exceeds 200 m. A substantial amount of time (hundreds of years) may be required for gas-hydrate-bearing sediments to become sufficiently warm for decomposition to take place (Taylor, 1999). As permafrost thaws, however, potential increases in regional groundwater circulation would further enhance warming of deep sediments and degradation of gas hydrate (Judge and Majorowicz, 1992; Michel and van Everdingen, 1994). Evidence also exists for the occurrence of gas hydrate at depths shallower than the theoretical minimum determined for methane hydrate stability (Dallimore and Collett, 1995; Smith, 1998). This gas hydrate could be affected by warming over a shorter time period. Permafrost may act as an essentially impermeable barrier to the migration of hydrocarbons from below. Permafrost thaw and the formation of taliks may create conduits for gases such as methane to reach the surface and be released to the atmosphere.

PREVIOUS STUDIES ON PERMAFROST RESPONSE TO CLIMATE CHANGE

Several approaches have been used in the past to predict the effect of climate warming on permafrost. These range from physically based, energy-budget models to semi-empirical permafrost index models. Energy-budget models such as that presented by Anisimov (1989) attempt to account for all the energy exchanges involved in determining the surface heat balance and therefore the ground-surface temperature (or snow-surface temperature in winter). A large number of radiative, thermal, and aerodynamic parameters are required as inputs for these models. Ground temperatures are calculated using a heat-transport equation that requires the thermal properties of each soil layer as well as the snow layer in winter (Anisimov, 1989). Simple relations based on conductive heat transfer have been used by Osterkamp (1984) and Lunardini (1996) to predict transient effects of surface temperature on the thermal state of permafrost, but information is required on the original thermal state of the permafrost, thermal properties of the earth materials, geothermal heat flow, and the magnitude and timing of warming. These models are generally unsuitable for regional studies due to the large number of input parameters required, but they may be used for local studies where accurate information on the thermal regime and physical characteristics of permafrost are available. Riseborough and Smith (1993) and Burgess et al. (2000) for example, used a one-dimensional conduction model to predict the transient response of the ground temperature to warming at a number of sites in the Mackenzie valley for which detailed information was available.

To model the response of permafrost to climate warming on a regional scale, the heat-transfer computations must be simplified in order to reduce the number of site-specific variables that are required (Jorgenson and Kreig, 1988). These simpler approaches relate soil temperature to air temperature through the use of empirical n-factors (Lunardini, 1978). Rather than using heat-transport equations to determine the response of the ground-thermal regime, a frost number or index is calculated that is based on the ratio of the depth of freezing and thawing (Nelson and Outcalt, 1983; Nelson, 1986). This index is dependent on the surface thawing and freezing degree day indices and the thermal conductivity of the frozen and thawed soil. Surface thawing and freezing indices are determined from air thawing and freezing indices using empirical n-factors that are related to vegetation and snow cover. This approach has been used to determine the equilibrium permafrost distribution following climate warming at a regional scale (Jorgenson and Krieg, 1988; Wright et al., 2000) and on a global scale (Anismov and Nelson, 1996, 1997). Wright et al. (2000) used GIS techniques and empirical relations between the frost index and permafrost thickness to predict the effect of warming on permafrost thickness at a regional scale in the Mackenzie valley. These index methods, however, do not contain explicit relationships between climate and the temperature conditions of permafrost that are more suitable for the assessment of climate-change impacts (Smith and Riseborough, 1996). An approach similar to that used to compute the frost index, however, can be used to determine the temperature at the top of the permafrost or at the base of seasonally frozen layer (Romanovsky and Osterkamp, 1995; Smith and Riseborough, 1996; Riseborough and Smith, 1998). This model (referred to as the TTOP model) may be used to assess the impact of warming on the permafrost thermal regime as well as determine the extent of permafrost under current and future climate conditions.

Recent national-scale studies such as those of Woo et al. (1992) and Kettles et al. (1997) attempted to project the new positions of boundaries of discontinuous and continuous permafrost that would result from climate warming. Woo et al. (1992) considered the change in permafrost boundaries that would occur in response to a greenhouse warming of 4°C to 5°C. It was assumed that this caused a spatially uniform increase in ground-surface temperature of the same magnitude. This increase in surface temperature was then superimposed on a national ground-temperature map to produce a generalized map of future permafrost distribution (Woo et al., 1992). In studies such as this, actual ground-temperature data are not usually considered. Ground-surface temperatures are generally inferred from air-temperature data. The new positions of permafrost boundaries are assumed to reflect conditions of thermal equilibrium and the approach also assumes no change in the type of vegetation cover or other climatic factors. Environmental factors that influence the rate of ground-temperature change or the present permafrost distribution are generally not considered.

The frost-index approach (e.g. Nelson, 1986) and the national-scale studies of Woo et al. (1992) and Kettles et al. (1997) do not include the dynamics of permafrost change and assume that sufficient time has passed to allow the permafrost distribution to equilibrate with the new climatic conditions. These approaches, therefore, do not take into account the rate of permafrost warming or provide an assessment of the changes in the permafrost environment over time periods as short as 50–100 years (Anisimov, 1989; Lunardini, 1996). Changes in permafrost conditions over these shorter time periods are important in evaluating the environmental and economic consequences of climate warming, because significant changes in the physical and thermal characteristics of permafrost may take place long before equilibrium is reached. More sophisticated, physically based models can predict the changes in the permafrost temperature regime during the transition to a warmer climate, but these models are not feasible for evaluating the permafrost response to warming at a national scale due to the large number of site-specific variables that are required. Therefore, the approach used in the present study focuses on the potential permafrost response during the transition to a warmer climate by considering the major climatic and environmental factors that influence the response of the ground to a general climatic warming. This work is conducted at the national scale and has minimal data input requirements.

APPROACH FOR CHARACTERIZING PERMAFROST SENSITIVITY TO CLIMATE WARMING ON A NATIONAL SCALE

Geographic Information System method

The aim of the present study was to map areas of the Canadian permafrost region that are most sensitive to climate warming. Both the thermal and physical response of permafrost to warming were considered in preparing Figure 3c. Several factors determine the thermal response to changes in air temperature and the physical response or impact of any permafrost thaw that occurs. For each factor considered, a rating scale was applied that assigns a high ranking to the condition for which the response will be greatest. The factors were then combined using an added factor analysis (Environmental Conservation Service Task Force, 1981) in which there is a progressive adding of the ranks for each factor. The highest totals correspond to the greatest response. Separate maps were produced representing the summation of the factors influencing the thermal and physical responses of permafrost to climate warming.

A series of input map layers representing dominant climate and terrain factors influencing the response of permafrost to warming were produced at a resolution of 10 km (each pixel covers 100 km^2). This resolution is considered appropriate for this national-scale study since the quality of data used or available for each layer is variable and, for some regions, sparsely available. The input map layers were combined using a raster-based GIS (Geographic Information System) to produce the maps depicting the thermal and physical response of permafrost to climate warming.

The distribution of available point data describing ground-temperature and snowcover data is not uniform and there are large areas of northern Canada for which no data are available. Interpolation of point data employed a weighted moving average technique in which estimates of the value of the interpolated surface at any point are based on the values of neighbouring observations and their distance from that point (Branson, 1989). Actual observed values are not likely to be retained since a generalized surface is created by averaging all values within an area. Since the location of climate stations and other measurement sites are arbitrary and values recorded at these sites are not necessarily critical values (may not represent maxima or minima), the maintenance of actual observed values is not important. Point data used in this study represent average values over time, and in some cases, the average of several points within a small area. These data therefore are statistical in nature rather than exact values, and thus are suitable for the weighted-average technique (Branson, 1989). Data points are irregularly spaced and it is desirable to give reduced weights to data points that are farther from the estimation location (Burrough, 1986). An exponential weighting function was used so that points closer to the location being estimated will have a greater effect on the estimate than points farther away.

Thermal response

The boundary layer interactions affecting the ground-thermal regime have been summarized by Luthin and Guymon (1974) in a buffer-layer model that links the atmospheric climate to the subsurface-thermal regime. A modified version of this model (Fig. 10) is used to characterize the ground-thermal response to climate warming. The buffer zone component considers the factors that act as thermal buffers between the atmosphere and the ground. These factors determine how direct the link is between climate and ground temperature and therefore influence the rate and magnitude of heat transfer between the atmosphere and the ground. The mineral soil component considers the rate of heat transfer through the underlying soil or rock. The buffer zone and mineral soil components determine the rate and magnitude of the response of the ground-thermal regime to a change in air temperature.

Buffer zone

The vegetation canopy, snow cover, and the surface organic layer act as thermal buffers between the atmosphere and the ground. Any changes in the atmospheric climate must be transmitted through the buffer layer before they can affect the ground-thermal regime. The link between climate and ground temperature is more direct in areas of sparse vegetation, of thin snow cover, or lacking an organic layer (Smith, 1988). The physical and thermal characteristics of the buffer layer will therefore determine the rate and magnitude of the response of the ground-surface temperature to changes in air temperature. Information on snow cover, vegetation cover, and the distribution of organic material has been assembled and rating scales developed as described below and outlined in Figure 10.

Although changes in vegetation or snow cover will also likely occur as climate warms, no attempt has been made to consider these changes or feedbacks in this study. For the purposes of this analysis, these conditions are assumed to remain constant. General circulation models generally have difficulties in simulating seasonal snow cover under global-change scenarios and there is variation between models (Houghton et al., 1996). Models generally predict increases in winter precipitation for high latitudes, but uncertainties exist in the prediction of snowfall amounts, snow depth, and duration of snow cover.

Snow cover

Snow is an effective insulator due to its low thermal conductivity (Nicholson and Granberg, 1973). A snow cover acts to reduce the energy exchanges between the air and the ground surface. The presence of a thick snow cover therefore insulates the ground from changes in air temperature. Shamanova and Parmuzin (1987) found that if mean winter air temperature increases, the greatest change in mean annual ground- surface

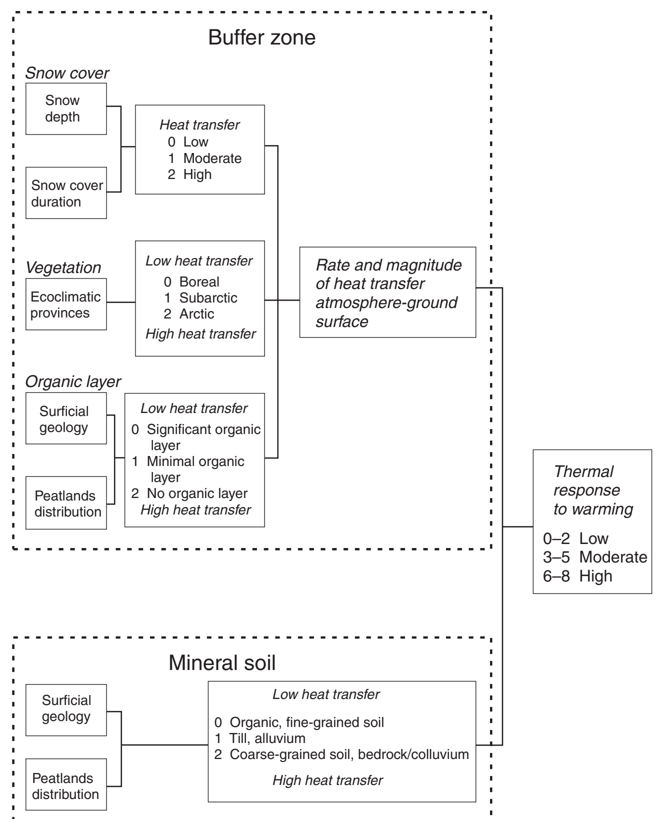

Figure 10. *Approach used to characterize the thermal response of permafrost to climate warming, based on the buffer-layer model of Luthin and Guymon (1974).*

temperature will occur in areas of low snow cover. The duration of the snow cover is also a factor and the insulating effect of snow becomes more important as the duration increases.

The 1961 to 1990 normals of annual maximum snow depths for 300 Canadian sites were extracted from Environment Canada's "snow climate normal database" (Braaten, 1996) and used to produce a map of mean maximum snow cover (Fig. 11a). The point data were interpolated spatially using the weighted moving average technique. Snow depth may vary significantly over short distances. Wind, temperature, and the vegetation distribution can all play a part in the character of the snowpack (McKay, 1968). Melting of snow and subsequent freezing in the snowpack and settling of snow, for example, result in an increase in snow density and a decrease in snow depth. Wind may redistribute snow and vegetation may act like a snow fence and block the movement of wind-blown snow. Vegetation may also intercept snow and prevent a considerable amount of snow from reaching the surface before it is lost to sublimation. The map of snow-cover depth produced from the climate-station data thus only represents general regional patterns of snow cover.

The rating scale used for depth of snow cover reflects the decrease in heat transfer between the atmosphere and ground surface that accompanies an increase in snow depth (Fig. 12). Areas that have little snow cover were given a higher rating than those with a thick snow cover because the ground-surface temperature response will be greater for a given change in air temperature. Several studies examining the relationship between the ground-thermal regime and snow cover were reviewed to determine the class limits to be used for the rating scale. Nicholson and Granberg (1973) suggested that ground temperatures in Schefferville, Quebec are insulated from changes in air temperature when the snow cover is 75 cm thick, whereas Annersten (1966) suggested 40 cm is sufficient. Harris (1981) gave a critical value of 50 cm for western Canada. Studies done by Stuart et al. (1991) in the Mackenzie valley indicated that while the insulating effect of snow depends on its density, the threshold thickness, which they refer to as the thermal damping depth, is generally between 40 cm and 50 cm. The threshold value will depend on location and air temperature and is expected to be greater as latitude increases. Taking these results into account, class limits of 40 cm and 80 cm were chosen for this study.

Information on snow-cover duration was also extracted from the Environment Canada database to produce the map in Figure 11b. A high heat-transfer rating was given to areas where a snow cover exists for only a short period of time because the ground will be insulated from changes in air temperature for a shorter period of time. Information on snow depth and snow-cover duration were combined into a single index (Fig. 12). Areas having a thin snow cover for a short period of time have been given a high rating because the thermal response of the ground to warming is expected to be greater in these areas than in those having a thick snow cover that persists for a longer period of time. The map layer used to represent the snow-cover component is shown in Figure 11c.

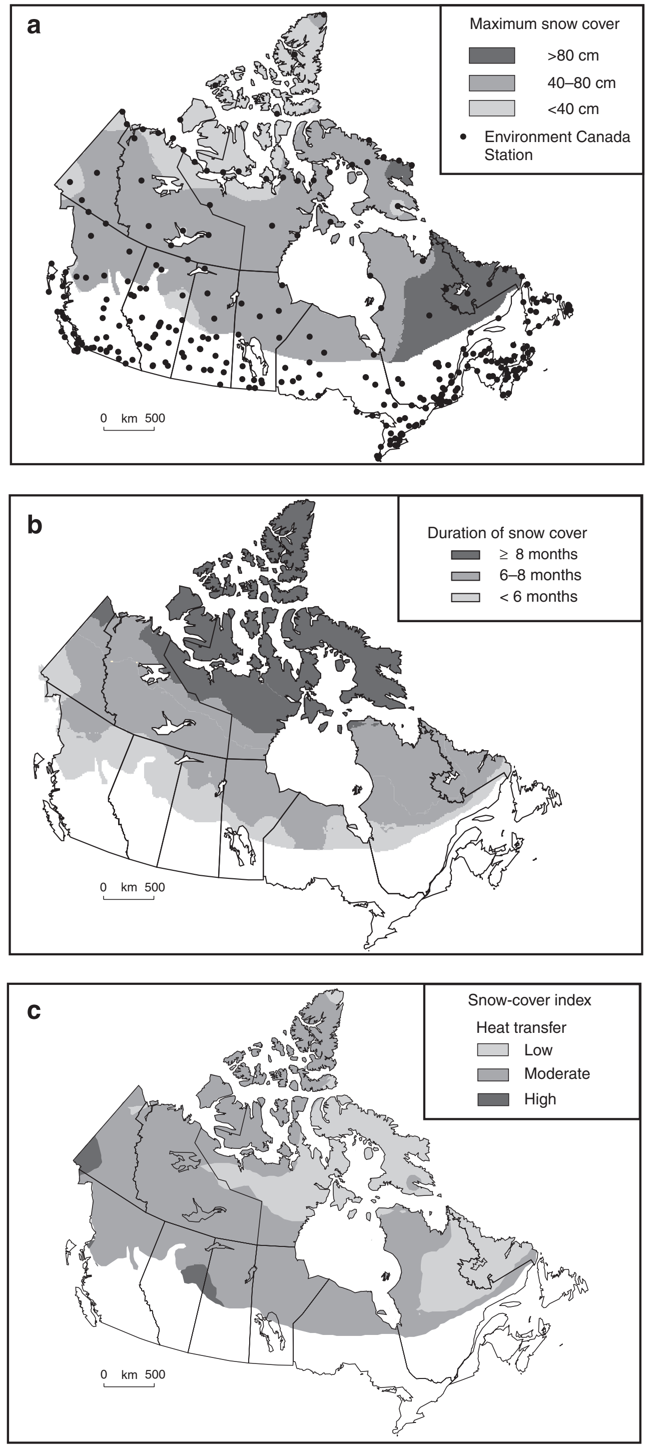

Figure 11. ***a)*** *Mean maximum snow depth based on data extracted from an Environment Canada database (Braaten, 1996).* ***b)*** *Mean annual snow-cover duration.* ***c)*** *Map used to represent the snow-cover component of the buffer layer.*

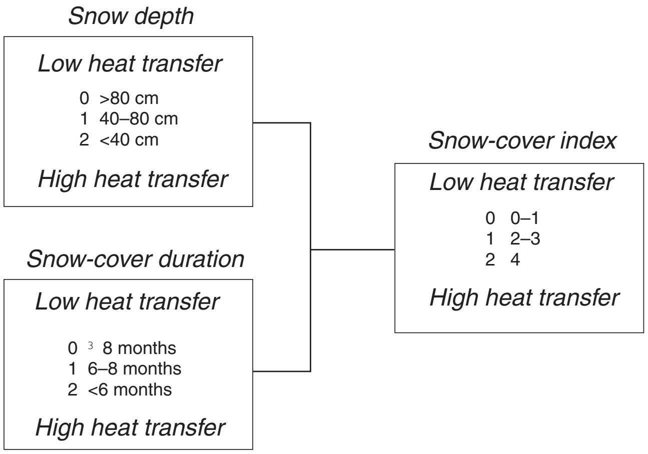

Figure 12. *Approach used to determine rating scale used for snow-cover component of the buffer-layer model.*

Vegetation canopy

The vegetation canopy affects the amount of net radiation at the ground surface by providing shade in summer and modifies the advective heat available for transfer to the soil (Luthin and Guymon, 1974). In the discontinuous permafrost zone, vegetation is an important influence on the distribution of permafrost (Brown and Pewe, 1973). Ground temperatures tend to be lower in areas shaded by trees compared to adjacent treeless areas (Brown, 1965). Permafrost may therefore be thin or nonexistent in treeless areas compared to forested areas within the discontinuous zone. Removal of vegetation can lead to permafrost warming and degradation (Linell, 1973; Burgess and Riseborough, 1990). The thermal link between the atmosphere and the ground is less direct where a significant vegetation canopy exists and therefore, a reduced response of the ground-thermal regime to climate warming would be expected in these areas compared to those with little vegetation cover.

The map layer used in this study to represent the vegetation component (Fig. 13) is based on the map of ecoclimatic regions at a scale of 1:7 500 000 (Ecoregions Working Group, 1989). Within ecoclimatic regions, the ecologically effective climate will result in the development of similar trends in vegetation succession under similar soil conditions and topographic setting. A total of 73 distinct ecoclimatic regions are represented in Canada, with these further generalized into ten ecoclimatic provinces. Vegetation type is variable within a given ecoclimatic province, but there is a resemblance in the vegetation that distinguishes each from its neighbouring provinces. The ecoclimatic provinces that are found within the permafrost region of Canada may be characterized as: 'Arctic': treeless, with tundra, polar semi-desert, or polar desert; 'Subarctic': open-canopied conifer woodlands, with tundra patches; and 'Boreal': close-canopied forests of conifer or mixed conifer-hardwood.

In addition to these, there are a group of ecoclimatic provinces associated with the Cordilleran region. The vegetation within the Cordillera is highly variable and is dependent on elevation. The Cordilleran, Interior Cordilleran, and Pacific Cordilleran provinces are similar to the Boreal ecoclimatic province and have thus been placed in this category. The Subarctic Cordilleran province has been placed in the Subarctic category.

The rating scale used (Fig. 10) assigns the highest rating to the Arctic ecoclimatic province because it has a sparse vegetation cover and thus the rate and magnitude of heat transfer between the atmosphere and the ground will tend to be greater than that in the forested areas of the Boreal ecoclimatic province.

Organic layer

The presence and nature of organic material or peat at the ground surface are important factors controlling permafrost occurrence and persistence in the southern margins of the permafrost zone where mean annual ground temperatures are close to 0°C (Zoltai, 1971; Thie, 1974; Zoltai and Tarnocai, 1975; Vitt et al., 1994). Permafrost may exist in areas with thick surface peat cover, but be absent in adjacent areas with little or no peat cover. The insulation offered by peat, especially when dry in summer, acts to thermally buffer the ground from the effects of climate change (Smith, 1988; Woo et al., 1992; Halsey et al., 1995).

Tarnocai et al. (1995) produced a map of peatlands in Canada at a scale of 1:6 000 000, showing the percentage of land area covered by various types of peatlands. This map was used in combination with the surficial geology map (Fig. 14) of Fulton (1995), prepared at a scale of 1:5 000 000, to delineate areas most likely to have a surface organic layer (Fig. 15). For this study, a region was considered to have a dominant organic cover if the areal coverage of bogs or fens was greater than 50%. Within these regions, areas underlain by fine-grained material, and therefore poorly drained, are more likely to have a surface organic layer than those underlain by coarser grained materials. Areas deemed to have a significant organic cover were assigned a low heat-transfer rating (Fig. 10) because the rate and magnitude of heat transfer between the air and the ground will be lower than that in areas where an organic layer is not present.

Mineral soil component

This component considers the transfer of heat through the underlying soil or rock, the amount of which is partly dependent on its thermal conductivity. The thermal conductivity will generally be lowest for organic soils and fine-grained material consisting of clay and silt. Sand and bedrock will generally have higher thermal conductivity and should respond more rapidly to climate warming.

The thermal stability of permafrost is also dependent on the ice content of the material. For ice-rich material, the latent heat effects of thawing are important in determining the rate of permafrost degradation (Riseborough, 1990). The apparent thermal diffusivity of ice-rich permafrost is low due to the high amount of latent heat required for thaw. The response to

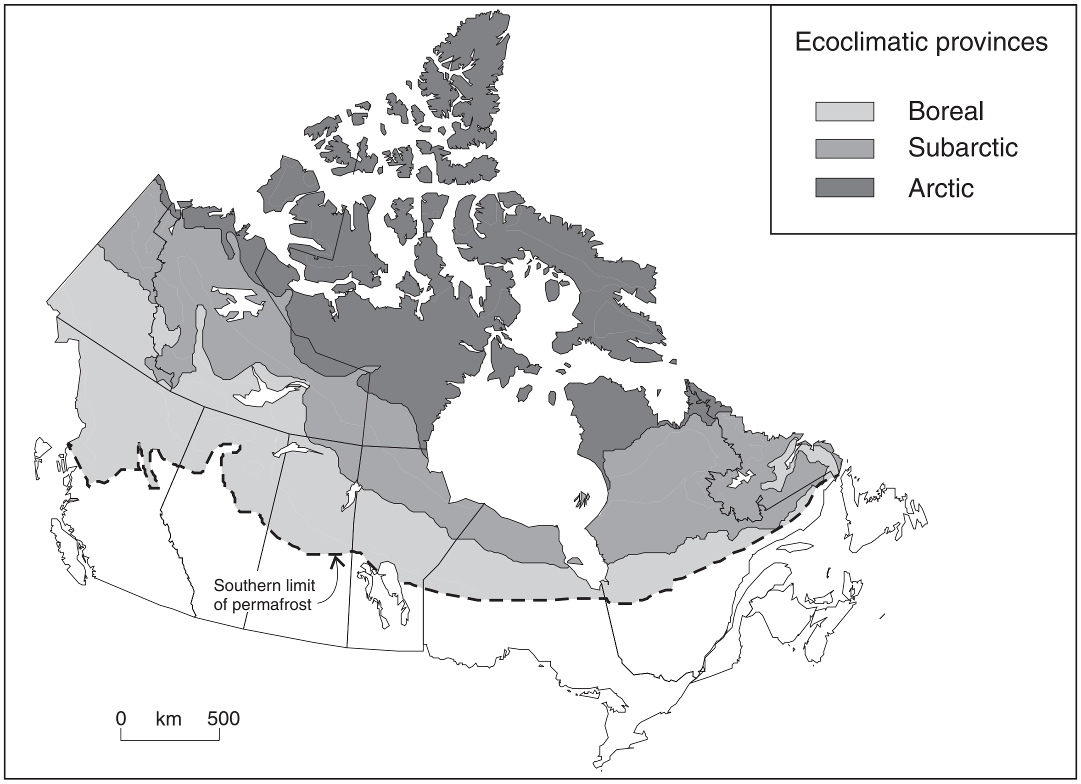

Figure 13. *Ecoclimatic provinces (Ecoregions Working Group, 1989) of the Canadian permafrost region.*

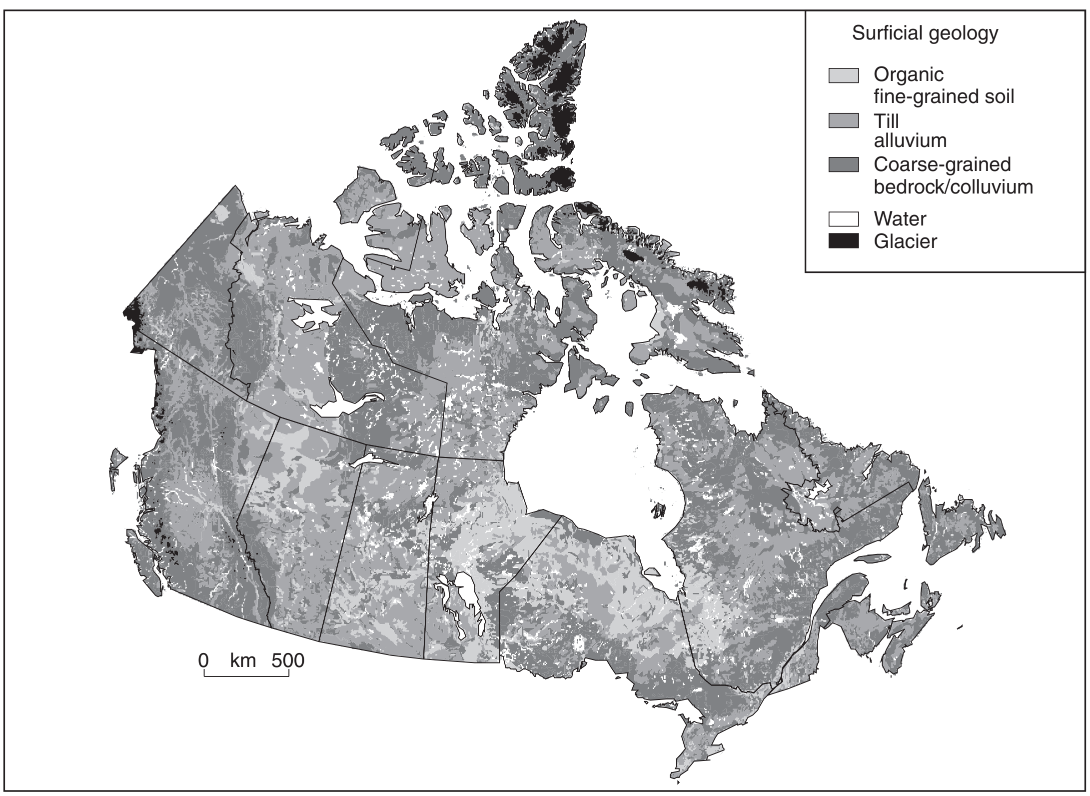

Figure 14. *Simplified surficial geology map (based on Fulton (1995)).*

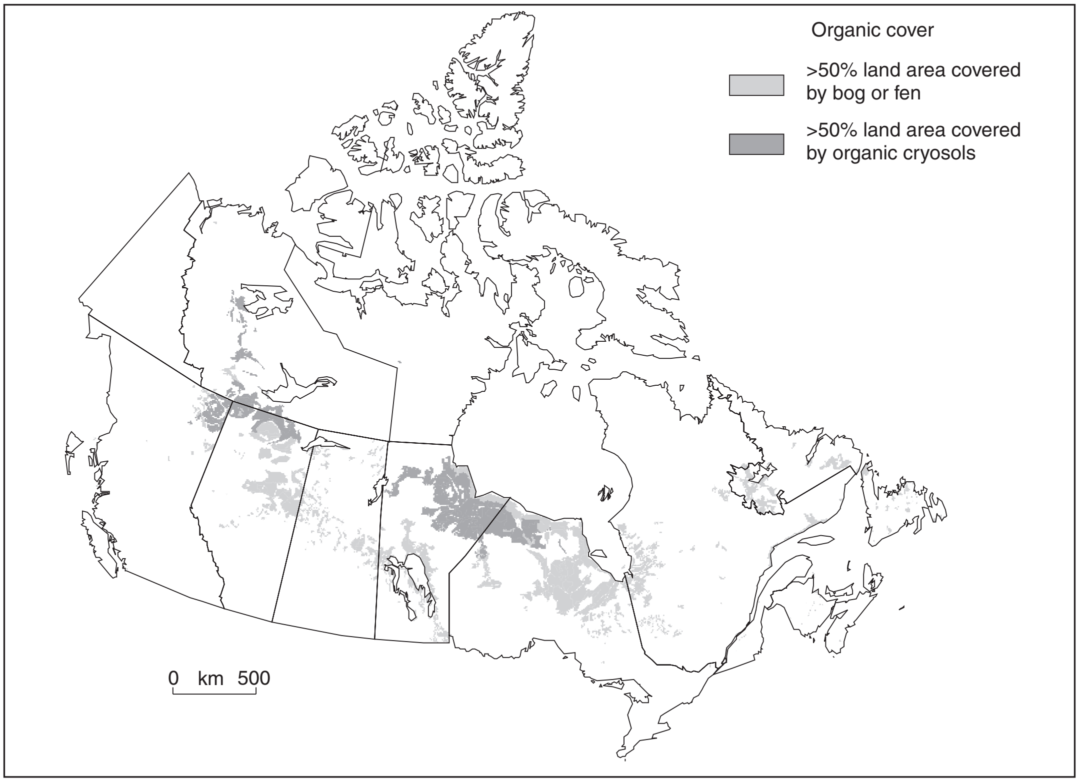

***Figure 15**. Regions having a significant organic cover. Information extracted from the peatlands map of Tarnocai et al. (1995) and C. Tarnocai and B. Lacelle (unpub. map, 1997).*

warming would therefore tend to be slower in organic soils and fine-grained mineral soils having high ice contents (Smith, 1988).

Information for this component was extracted from the surficial geology map of Fulton (1995). This map portrays broad genetic categories of surface materials that are further subdivided according to characteristics such as texture, thickness, and landform, giving a total of 23 categories. Units on the surficial geology map were combined into broad textural categories as shown in Figure 14. A lower rating was given to organic and fine-grained material (Fig. 10) because the ground-thermal regime should respond at a slower rate compared to areas where coarse-grained material or bedrock are present.

Map of thermal response to warming

The data layers representing the buffer layer and mineral soil components were combined to produce a map (Fig. 3a) that categorizes areas according to their relative (low, moderate, or high) thermal response to climate warming. A high thermal response is expected in terrain characterized by a minimal buffer layer and underlain by coarser grained sediments or bedrock, whereas a low thermal response is likely in areas with a substantial buffer layer overlying organic or fine-grained sediments. It is assumed that both the rate and magnitude of the response of the ground-temperature regime to warming will be lower in the latter case.

Potential for permafrost thaw

The likelihood of permafrost thaw and the rate at which this occurs also depends in part on the present ground-thermal regime. In general, permafrost that is currently at temperatures close to 0°C will have a greater potential for thaw (all else being equal) compared to colder permafrost (temperature less than -5°C, for example).

An interpolation of point data depicting the mean annual near-surface ground temperature for over 300 sites (extracted from Smith and Burgess (2000)) was performed to create the map in Figure 3f. Ground temperatures can exhibit significant local variation due to variation in local environmental factors such as those (buffer factors) discussed above. The map presented, therefore, only shows regional trends in near-surface ground temperature. Within the zone shown to have a ground temperature greater than -2°C, permafrost is discontinuous and there are significant areas where the ground temperature is above 0°C. This is especially true towards the southern margins of the discontinuous zone where permafrost is localized (Fig. 1).

Ground temperature has been classified into three zones and these have been added to the thermal-response map (Fig. 3a). The potential for permafrost thaw would be greatest in areas underlain by permafrost that currently have a temperature close to 0°C and that also would exhibit a high thermal

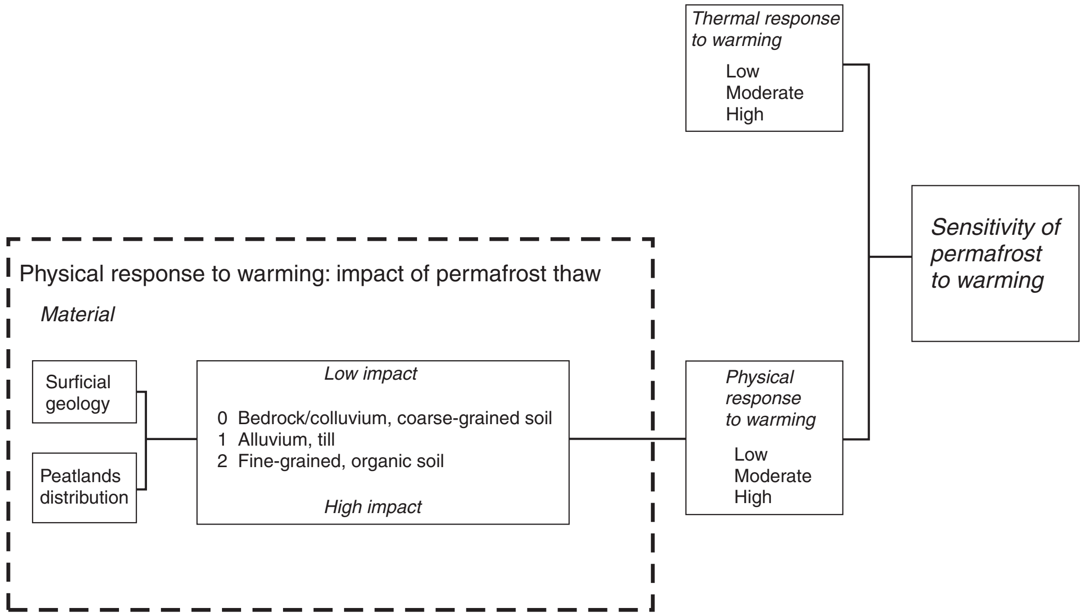

Figure 16. *Approach used to characterize the physical response to warming and the sensitivity of permafrost to warming.*

response to warming. Permafrost thaw and the disappearance of permafrost would be expected to occur first in these regions.

Physical response: impact of permafrost thaw

The consequences of a general climate warming on the permafrost regions are many and varied. In this study, however, only the effect of warming on ground stability, in particular thaw settlement, is considered. It is assumed that the main geological factor influencing ground stability is the ice content of the frozen earth material. The structural ice component (Heginbottom et al., 1995), which consists of pore ice and segregated ice lenses, will be greatest in organic and fine-grained materials and lowest in coarse-grained sediments and bedrock. In addition to structural ice, ground ice may be in the form of ice wedges or other massive bodies of pure ice, referred to as 'massive ice' in this study.

The approach used to characterize the impact of permafrost thaw is outlined in Figure 16. Information obtained from the surficial geology map (Fulton, 1995) and the peatlands map (Tarnocai et al., 1995) were used to develop a map (Fig. 3b) that ranks materials according to their susceptibility to thaw instability. Organic and fine-grained materials, which generally have high structural ice contents, were given a higher rating than coarse-grained materials or bedrock that generally have low structural ice contents. For this component, a region was considered to have a significant organic cover (and therefore expected to exhibit a high physical response to warming) if: 1) the areal coverage of bogs was greater than 50% or 2) the mean annual near-surface ground temperature was less than -2°C and the areal coverage of fens was greater than 50%. In the discontinuous permafrost zone where ground temperatures are close to 0°C, fens are characterized by high water tables and are generally unfrozen (Dyke et al., 1997). The map produced (Fig. 3b) classifies areas according to their relative physical response to warming, that is, the impact of permafrost thaw in terms of thaw settlement.

Where massive ice is present, the impact of permafrost thaw will be high even though the surficial materials, and thus the structural ice content, may suggest less impact. Areas where massive ice is abundant (Heginbottom et al., 1995; Smith et al., 2001) are shown in Figure 3b; however, massive ice does occur (some of which has only more recently been reported) in areas where the national permafrost map indicates its distribution is sparse. For example, massive ice bodies up to 10 m thick have been found associated with hummocky till and glaciofluvial deposits of the Lac de Gras, Northwest Territories and eastern Contwoyto Lake, Nunavut regions (Wolfe, 1998; Dredge et al., 1999). Several natural exposures of massive ice on the Fosheim Peninsula of Ellesmere Island, Nunavut have also been recently reported (Pollard and Bell, 1998; Robinson and Pollard, 1998; Pollard, 2000). Larger scale surficial geology maps would need to be consulted for a more detailed evaluation of the massive ground-ice distribution at a regional or local scale, that is beyond the scope of this study.

SENSITIVITY OF PERMAFROST TO WARMING

Figures 3a and 3b show the spatial variation of the thermal response to warming (i.e. relative rate and magnitude of ground-temperature change) and the physical response to warming (i.e. relative impact of permafrost thaw) using three categories: low, moderate, and high. The proportion of the present permafrost region (excluding areas of water and glacial ice) within each category is also shown.

Our analysis indicates that about 90% of the terrain in the present permafrost region would exhibit a moderate to high thermal response to increases in air temperature. Most of this terrain is located in the northern portion in association with a limited buffer layer. A low to moderate thermal response is expected in the southern portion of the permafrost region, where the buffer layer is more substantial; however, most of the area that would exhibit a high thermal response to warming is underlain by permafrost at temperatures less than -5°C and therefore has a lower potential for permafrost thaw. For more than half the present permafrost zone, ground temperatures are greater than -2°C, suggesting a high potential for permafrost thaw.

The physical response to warming is high in about 13% of the present permafrost region (excluding areas of massive ice). Most of this is located within the southern portion of the permafrost zone where ground temperatures are warmer than -2°C and the potential for permafrost thaw is high. In areas where ground temperatures are considerably lower, the expected physical response is generally low to moderate; however, there are areas where massive ice may be present and the consequences of permafrost thaw in these areas could be more severe than indicated.

The sensitivity of permafrost to warming consists of two components, the thermal response to warming and the impact of thaw (physical response). The map of the sensitivity of permafrost to warming (Fig. 3c) was produced by combining these two components as shown in Figure 16. More weight has been given to the physical response to warming in the development of the sensitivity index because the physical response is considered to be more important than the thermal response (Smith and Burgess, 1999). The sensitivity index is low for example, in areas that may exhibit a high thermal response to warming, but where there is a minimal physical response due to the low ice content of the underlying materials. Areas classified as having a low thermal response, but a high physical response to warming are considered to be more sensitive to climate warming.

About 50% of the area within the zone containing warm permafrost (zone 3, Fig. 3c) has been classified as having a moderate to high sensitivity to warming. A significant portion of this area, however, is within the sporadic and localized permafrost zones where permafrost may underlie less than 50% of the landscape, often being limited to areas of organic terrain. Generally areas covered by organic cryosols (Fig. 15) are classified as moderately sensitive to climate warming because although they are thaw sensitive, the thermal response to warming is generally low. Much of the permafrost in the southern portion of the discontinuous zone is not in equilibrium with the present climate and has been preserved due to the insulating properties of the peat (Halsey et al., 1995). Mean annual air temperature for zone 3 (Fig. 3c) is predicted from the Canadian Centre for Climate Modelling and Analysis model to be greater than -3.5°C for the period 2040–2060 AD. Halsey et al. (1995) suggested that while permafrost should continue to persist in organic terrain where the mean annual air temperature is predicted to be below -3.5°C, it will degrade where the temperature is between 0.5°C and -3.5°C. Therefore, widespread degradation of permafrost may be expected within zone 3, and significant ground settlement and instability may occur within areas determined to have a moderate to high sensitivity to climate warming.

Throughout the Mackenzie valley, permafrost is considered to be moderately to highly sensitive to warming. The results of geothermal modelling (Burgess et al., 2000) for this region indicated that complete degradation of permafrost in response to warming may be possible within the next 50 years in the southern, discontinuous zone near Fort Simpson where permafrost is on the order of 5–10 m thick. Throughout a significant area of the northern Prairies (particularly northern Manitoba) and the Hudson Bay lowlands, the sensitivity of permafrost to warming is considered to be moderate to high. This is mainly due to the high ice-content soils associated with organic terrain within this region.

Although permafrost is warm and thermal response is high in the Cordilleran region, the overall sensitivity of permafrost to warming is generally low. Surficial material overlying bedrock is generally thin and 'thaw stable' in this region. The sensitivity of permafrost to warming within Quebec and Labrador is moderate to low except in a few patches of organic terrain or where moderate to high ice-content soils (silt, clay, or till) are present.

Where permafrost is colder and thicker (zones 2 and 3, Fig. 3a and 3c), such as in the Arctic Islands and Canadian Shield area of western Nunavut, the potential for permafrost thaw is low, but progressive increases in active-layer thickness and thinning of the permafrost would be expected in areas where the thermal response is considered to be high. The physical response is classified as moderate in a significant portion of the continuous permafrost zone due to the lower structural ice content of surficial materials, but there are extensive regions where massive ice may be present and where the impact of warming could be severe. A substantial portion of the continuous permafrost zone, therefore, is considered to be moderately to highly sensitive to warming.

This sensitivity should be considered when planning northern development. For example, the design of tailings dams to be built on permafrost foundations at existing or future mine sites should incorporate climate warming where the sensitivity of permafrost to warming has been classified as moderate to high and the life of the facility is planned to span an extended period of time. Increases in active-layer thickness and the associated thaw settlement can also make travel more difficult. Thus, climate warming may have significant consequences for those living or travelling on the land in permafrost regions with moderate to high sensitivity.

CONCLUSIONS

Warming and thawing of permafrost due to climate warming are expected to result in instabilities in the landscape and changes to the engineering behaviour of soils, with direct impacts on northern ecosystems, communities, lifestyles, and infrastructures. An understanding of the sensitivity of permafrost to climate warming will help to ensure that damage to existing northern infrastructures is minimized and that future developments are designed to withstand the impacts of warming. In addition, our capacity to evaluate and adapt to a variety of climate-change impacts on the natural environment will improve.

This study has characterized the potential response of permafrost in Canada to climate warming, based on an analysis of data sets readily available at a national level. The analysis considers the major factors influencing the thermal response and physical response to a general climate warming. Maps were produced to show the spatial distribution of the relative thermal response and the associated physical response of the terrain. A sensitivity index combining both the physical and thermal responses was developed and subsequently mapped.

A significant proportion of the zone containing warm permafrost (temperature >-2°C) is expected to be moderately to highly sensitive to climate warming. Significant developments and infrastructure currently exist within this region and remedial measures may be required to minimize damage to structures.

This study has provided a methodological approach and a national map product that should assist engineers, planners, and environmental scientists and regulators in design of new northern development and assessment of adaptation requirements for existing infrastructure and activities. Determination of the sensitivity of permafrost to warming at a regional or local scale requires a more detailed analysis and/or higher resolution data than that presented here; however, the results of this study can provide a foundation for future work by delineating areas where permafrost is considered to be sensitive to climate warming and where more detailed studies may be necessary.

There are many consequences of permafrost thaw and this study has only considered the effect of warming on ground stability, specifically in terms of thaw sensitivity (or settlement). The map characterizing the thermal response of permafrost to warming can also be used in studies to examine other aspects of permafrost sensitivity to warming, such as the impacts on hydrology. In addition, the map characterizing the physical response to warming may be used to examine the impact of changes in the ground-thermal regime due to other surface changes such as forest fires.

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