**MODELING CANADIAN PERMAFROST
UNDER PROJECTED CLIMATE
CHANGE SCENARIOS**

by

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in partial fulfillment of
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Abstract

Permafrost is a climatic condition of the ground and thus the permafrost environment is very vulnerable to changes in climate. Since a significant climate change has been projected throughout the next century, there is a need for a functional method of modeling the permafrost - climate relationship. In this thesis, the TTOP model presented by Smith and Riseborough (1996) is evaluated within a GIS with Canada wide data. It is established as a useful functional model for predicting permafrost conditions based on a limited number of climatic and geomorphic features. The model is used to determine current and projected future permafrost conditions in Canada based on actual and GCM projected climatic conditions. The results show that the TTOP model is able to map current permafrost conditions well considering input data limitations. The results also project that close to 60% of the Canadian permafrost environment will be subject to surface melting within the next 50 to 100 years.

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A nawr i'r dafarn. Lechyd da.

Kerri, 1999

Table of Contents

Title page.....	i
Acceptance form.....	ii
Abstract.....	iii
Acknowledgements.....	iv
Table of Contents.....	v
List of Tables.....	viii
List of Figures.....	ix
List of Appendices.....	x
List of acronyms and symbols used.....	xi
Accompanying Material: CD-ROM “Modeling Canadian Permafrost Under Projected Climate Warming Scenarios”	

CHAPTER 1

Overview and Objectives.....	1
------------------------------	---

CHAPTER 2

Climate Change and Permafrost.....	6
2.1. Climate / permafrost relationship.....	6
2.1.1. Regional Factors.....	7
2.1.2. Local Factors.....	9
2.1.2.1. Snow cover.....	13
2.1.2.2. Vegetation.....	14
2.1.2.3. Soil Conditions and Moisture Content.....	15

2.2.	Climate Change.....	17
2.2.1.	GCM's.....	20
2.2.1.1.	Limitations.....	21
2.2.1.2.	Results in the Arctic.....	23
2.2.1.3.	Evidence of Warming.....	24
2.2.2.	Response of the permafrost environment.....	27
2.2.2.1.	Geomorphological.....	27
2.2.2.2.	Hydrological.....	29
2.2.2.3.	Biological / chemical.....	30
2.2.3.	Committed Versus Realized Change.....	31
2.3.	A model of the climate-permafrost system.....	33
2.3.1.	The Nature / Role of Environmental Models.....	33
2.3.2.	Developing a model: The Climate-Permafrost System.....	35
2.3.2.1.	Examining the system.....	35
2.3.2.2.	Is a Model Needed?	37
2.3.2.3.	Creating the Model.....	37
2.3.3.	Using the Model.....	41

CHAPTER 3

Methodology.....	43
3.1. Acquiring data.....	43
3.1.1. N_T	44
3.1.2. N_F	44
3.1.3. I_F , I_T	46
3.1.4. R_k	48
3.1.5. Future Climate Data.....	48
3.2. Data Layers.....	53
3.3. Analysis.....	54
3.3.1. Current Conditions.....	54
3.3.2. Estimated Current Conditions.....	54
3.3.3. Future Values.....	55

Chapter 4

Results and Analysis.....	57
4.1. Mapping Current Permafrost Conditions.....	58
4.1.1. The Results of TTOP.....	58
4.1.2. Accuracy Analysis and Mapping Problems.....	64
4.1.3. Utility and Interpretation of TTOP.....	69
4.1.4. GCM Projections and TTOP.....	70

4.2.	Mapping Future Permafrost.....	74
4.2.1.	2 x CO ₂ TTOP.....	74
4.2.2.	Precipitation Projections.....	78
4.2.3.	Amount of Change.....	79

Chapter 5

Conclusions.....	86
References.....	105

List of Tables

Table 1:	Sample GCM projections.....	24
Table 2:	Depth of propagation of a temperature wave in frozen ground.....	32
Table 3:	Final permafrost stability categories.....	56
Table 4:	Categories used to classify future permafrost conditions.....	83
Table 5:	Percentages of areas from 2 x CO₂ projected permafrost maps.....	85

List of Figures

Figure 1:	Permafrost map of Canada.....	8
Figure 2:	Typical mean annual ground temperature profile.....	12
Figure 3:	Past climate change.....	18
Figure 4:	Limits of N_F formula.....	47
Figure 5:	The Surficial Geology of Canada.....	49
Figure 6:	Future CO₂ concentration projections.....	51
Figure 7:	Temperature at the top of permafrost (TTOP).....	59
Figure 8:	Nival Offset.....	61
Figure 9:	Thermal Offset.....	63
Figure 10:	Ground temperature map of Canada.....	66
Figure 11:	1 x CO₂ TTOP.....	72
Figure 12:	GCM Temperature and Precipitation Outputs: the relative accuracy.....	73
Figure 13:	2 x CO₂ TTOP.....	76
Figure 14:	Scaled TTOP: based on current conditions and projected change.....	77
Figure 15:	Current TTOP with snow at 50 and 200%.....	80
Figure 16:	Projected Change in Permafrost Temperature: based on GCM projections for current and future conditions.....	81
Figure 17:	Projected Change in Permafrost Temperature: based on current conditions and projected change.....	82

List of Appendices

Appendix A: Interpolation methods.....	90
Appendix B: Factor maps used for TTOP.....	93
Appendix C: Factor maps used for 1 x CO₂ TTOP.....	96
Appendix D: Factor maps used for 2 x CO₂ TTOP.....	98
Appendix E: Areas outside N_F parameters.....	100
Appendix F: Factor maps used for final TTOP.....	103

List of Acronyms and Symbols

TTOP:	Temperature at the top of permafrost
GIS:	Geographic information systems
MAAT:	Mean annual air temperature
MAGST:	Mean annual ground surface temperature
MAPT:	Mean annual permafrost temperature
IPCC:	Intergovernmental Panel on Climate Change
GCM:	General circulation model
BAU:	Business as usual
N_T:	Thawing n-factor
N_F:	Freezing n-factor
I_T:	Air thawing degree days (seasonal thawing index)
I_F:	Air freezing degree days (seasonal freezing index)
k_T:	Thawed ground thermal conductivity
k_F:	Frozen ground thermal conductivity
R_k:	Thermal conductivity ratio (k_T / k_F)
P:	Period (365 days)
T_A:	Air temperature
T_{GS}:	Ground surface temperature
T_P:	Permafrost temperature
FDD:	Freezing degree days
TDD:	Thawing degree days
CMCD:	Canadian monthly climate data
CCCMA:	Canadian Centre for Climate Modeling and Analysis

CHAPTER 1

Overview and Objectives

Permafrost (Harris *et al.* 1988) underlies over twenty-six percent of the world's land surfaces and about fifty percent of Canada. Since it is defined by temperature and not by the state of any water (or ice) in the soil, it can contain both states simultaneously. As the water can change its relative quantities of either state as its temperature changes, permafrost is a very dynamic substance. Permafrost is, in fact, the only substance on earth which exists naturally so near its melting point. Since permafrost is essentially a climate based phenomenon, it would seem valid to assume that any significant change in climate would have serious consequences for the state of permafrost. Numerous studies (e.g. Schlesinger and Mitchell 1985, Houghton *et al.* 1990) have projected a warming of climate in the foreseeable future, so an assessment of climate change impacts on permafrost would seem warranted, particularly since many climate change studies have indicated that global warming is expected to be most notable in polar regions (e.g. Cohen 1993, Houghton *et al.* 1996).

The existence of permafrost affects numerous properties of the ground, from its strength to its hydrology. Considering this, there are many reasons why the future state of Canadian permafrost is of interest. First of all, there is the intrinsic academic concern: permafrost forms a part of the lithosphere, and knowing how it works and reacts is worthy of attention in order to add to our knowledge of the Earth. There are also more practical considerations. The stability of the ground is of serious concern for building and maintaining roads, pipelines and other structures in permafrost regions. Frozen ground is stronger than thawed ground; moreover, freshly melted ground water further weakens the ground by leading to subsidence. As such, geotechnical issues regarding the strength of the ground and its effect on structures are significant. While buildings can be constructed in permafrost areas, certain features have to be incorporated into the design so structures will not affect the thermal stability of the ground and thereby jeopardize its integrity.

There are also ecological concerns related to the hydrology of the north and the global carbon cycle. Water flows much more easily through thawed ground compared to frozen ground. That fact, along with additions to the water flow from melted ground ice, both contribute to a significant change in the water system of an area as ice melts and water freezes. These changes will affect plant and animal life as the abundance of water fluctuates. Thawing of the ground could also affect, to a large degree, the global carbon cycle. If peatlands which are currently frozen were to melt, they would begin to decompose, releasing carbon, and the permafrost regions could change from a global

carbon sink to a source of carbon. This, in turn, would act as a positive feedback loop to global climate warming.

These ecological and geotechnical concerns also have social consequences. If buildings and other structures were faced with unexpected permafrost melting, costs to repair them could be high. In some cases, new construction may even be required. Changes in hydrology or other factors could alter the interaction of plants and animals. Both of these would affect the lives of those who depend on those constructions and resources.

Accepting the importance of permafrost to so many diverse factors of the Canadian landscape, it should be clear that permafrost is a significant factor in the northern environment. There are maps which show, with varying degrees of accuracy, the current delineation of permafrost in Canada. However, current climatological studies strongly suggest that Canada's climate will not remain constant in the near future. As these studies suggest a warmer climate, they would tend to indicate that in the future there will be less permafrost in Canada. The objective of this research is to predict where permafrost will occur under expected climate warming in Canada, and to produce new maps of permafrost distribution under projected future climate.

The first problem is to determine a method of linking air temperature to ground temperature. While the two are roughly similar, ground temperatures are typically warmer than air temperatures. This is largely due to the insulating effect of snow in the winter which keeps cold temperatures from penetrating into the ground and the fact that there is no similar effect in summer to keep the heat out of the ground. Another important factor is the seasonal change in thermal conductivity of the ground. Thermal conductivity is based on the ground type and the moisture content of the soil. Due to the high thermal conductivity of ice compared to water, the thermal conductivity can change drastically from thawed to frozen. The temperature of the ground depends on this ratio.

Once the important factors are known, it is necessary to determine a model which relates the two temperatures. The permafrost temperature model (TTOP) presented by Smith and Riseborough (1996), combines climate and surface factors together to determine the ground temperature. It accounts for the major factors of air temperature, surface conditions and soil thermal properties. Since the model uses only a few variables and requires limited types of data, it is particularly suited for application over a range of spatial scales. As such it is ideal for the national scale analysis to be attempted. Using current studies of projected climate warming and the relationship between air and ground temperatures, it should be possible to determine the future extent of permafrost.

The overall objective of the study is to determine the stability of permafrost in Canada in both time and space. If, under the climatic conditions postulated, permafrost conditions persist, then the permafrost environment could be considered more stable than if permafrost tends to disappear (or appear). This goal will be accomplished by mapping the results of several analyses representing different climate scenarios and their comparisons.

The maps will be produced using ArcView. The GIS (geographic information systems) approach is ideal as once the spatial extent of the various factors is known, they can be combined and examined within the GIS environment in order to determine the relative effects of a change in any of the factors.

CHAPTER 2

Climate Change and Permafrost

Before a study of this nature can be undertaken, several subjects must be known. Firstly, the relationship between climate variables and the existence of permafrost must be functionally determined. Secondly, the expected change in climate must be projected. Thirdly, the response of permafrost to climate changes must be determined in order to establish if this is a subject worth studying. Lastly, once the others have all been determined, some method of analysing the permafrost - climate system must be proposed.

2.1. Climate / permafrost relationship

Permafrost is essentially based on climate, but the overall effect of the atmospheric conditions on the ground temperature is mitigated by conditions at the ground surface. Various maps, using different criteria, have sought to delineate broad regions of permafrost (Ferrians 1965, Brown 1967, Kudryavtsev et al. 1980). However, until Brown's (1992) map, commissioned by the International Permafrost Association, discrepancies between methods of compilation and parameters used made direct

comparison difficult (e.g. Brown and Péwé 1973). The broad categories used were also a problem as 'continuity' of permafrost was dependent on map scale, minimum mapping unit, and the degree to which the assumptions of terrain and vegetative homogeneity were warranted. Comparisons of maps produced around the same time such as Nelson (1989) and Nelson and Anisimov (1993) show discrepancies of hundreds of kilometres in boundary placement.

There are a variety of factors which must be considered in order to discover the exact nature of the relationship between the mean annual air temperature (MAAT) and the mean annual ground surface temperature (MAGST). These factors can be split into two groups, broad-scale, regional zonal factors and local factors.

2.1.1. Regional Factors

The dominant factor affecting the existence of permafrost is the air temperature regime. The colder the air temperature, whether due to increasing latitude or altitude, the more likely it is that permafrost will occur and the thicker it will tend to be. This can be seen quite clearly by looking at the permafrost map of Canada (fig. 1) where the change from no permafrost through the discontinuous zone to the continuous zone shows a clear south to north gradation, with a more confused progression in the mountains. The link between air temperature and permafrost is so strong that the best known maps of permafrost simply used particular air isotherms to delineate the various zones of

Permafrost Map of Canada

Fig. 1: Permafrost Map of Canada; Heginbottom et al. 1995.

permafrost occurrence (Ferrians 1965, Brown 1967, Kudryavtsev et al. 1980). The choices of which isotherms to use were based on empirical studies.

The pattern of permafrost distribution is not perfectly linear however. The main secondary factor affecting the overall pattern in Canada is the western mountains. These mountains force the western flow of air up, causing a wave in the jet stream which results in colder areas on the leeward side of the mountains at the same latitude as warmer areas farther east, where the air has returned to a normal flow. Large bodies of water such as rivers and lakes warm the ground, and if they are large enough, prevent permafrost from forming in the surrounding areas. Surface features between the air and the ground such as snowcover affect permafrost by increasing the differential between the air and ground temperatures. A clear example of this is glaciers which maintain the surface of the ground at 0°C, too warm for permafrost to occur. In the northernmost Arctic Islands, glaciated and recently glaciated areas could be expected to have less permafrost than the climate would otherwise dictate.

2.1.2. Local Factors

While broad climatic factors affect the regime at any place, local factors are also important to the ground thermal conditions (e.g. Lindsay and Odynsky 1965, Nicholson and Granberg 1973, Smith 1975, Mackay 1978, Vitt et al. 1994) with wide variations in ground thermal conditions occurring within a small area of uniform climate (e.g. Smith

1975, Brown 1978). These local differences can reflect significant variation in the extent and thickness of permafrost and its susceptibility to thawing (Smith and Riseborough 1983, Williams and Burn 1996). Consideration of the variations caused by site characteristics are important in modeling as variations in site characteristics can produce larger changes to the rate of permafrost degradation than variations in the details of the climatic trend (Smith and Riseborough 1983).

There are numerous factors which affect heat and mass exchange at the ground surface and thereby the local variations in permafrost. Since the number of processes is large, the interrelation between processes is extremely complex (e.g. Goodrich 1982). Radiation, through its effect on temperature, is the most important and differentiating ecological factor controlling the development of (and interactions between) vegetation, permafrost and geomorphology in the Arctic. It is affected by factors such as latitude, albedo, slope, aspect and relief. Ground temperature is also affected by hydrologic factors, such as snow cover, site wetness, proximity to water bodies, drainage and water/ice content of the active layer; lithologic factors such as ground composition, wind exposure and organic horizon thickness; and surface cover effects such as vegetation and peat cover, aerodynamic roughness and fire effects (e.g. Brown 1969, Luthin and Guymon 1974, Kudryavtsev et al. 1974, 1978, Brown 1978, French 1996).

The mean annual ground temperature profile in the surface layer is not linear. Rather, it is offset to progressively lower values of up to 3°C or 4°C (fig. 2) (Goodrich 1982) at depth within the active layer. This is due to the difference in thermal conductivity between thawed and frozen ground, the “negative thermal offset”, defined as the difference between the mean annual permafrost temperature (MAPT) and the MAGST (Kudryavtsev et al. 1974, Goodrich 1978, Burn and Smith 1988, Romanovsky and Osterkamp 1995). The higher winter conductivity, due to the larger conductivity of ice over water, can contribute to maintaining permafrost in areas where the mean annual surface temperature is above 0°C. It is possible that with climate warming, summers will become drier, resulting in a decline in the summer thermal conductivity which would reduce the effect of the overall warming.

Since it would be entirely too cumbersome to attempt to model permafrost taking into account every single factor, it is of particular interest to determine which factors are, relatively, the most important. Several studies have compared some of the various factors. Most, however, have investigated individual factors in isolation, without any determination of interrelated effects. Furthermore, various studies have considered different factors, making it difficult to compare results directly. Overall, the factors which consistently appear as important are variations in snow accumulation (e.g. Judge 1973, Mackay and MacKay 1974, Smith 1975), surface wetness and vegetation (e.g.

Smith and Riseborough 1983) soil moisture content and the organic-layer thickness (Williams and Burn 1996).

2.1.2.1. Snow cover

Mean annual ground temperatures are strongly dependent on snow cover (Brown 1978, Harris and Brown 1978). The time of year that snow falls, its density, thickness and duration all have significant effects (Mackay and MacKay 1974, Smith 1975, Goodrich 1982). Snow is an insulator by comparison with most natural ground surface materials and since it is present only during the cold part of the annual temperature cycle, the net effect over a year is to raise mean annual ground temperature, often by several degrees. Snow interposes a layer with low thermal conductivity between the air and the ground, thus insulating the latter from atmospheric changes and restricting the amount of heat loss in the coldest part of the year. Its insulating effect is greatest for lowest densities (Gold 1963). The duration of snow cover is important because it affects the length of time that the ground is subject to freezing temperatures. A heavy snowfall in the autumn or early winter will inhibit frost penetration, while a winter of low snowfall will do the reverse. If snow persists late into the spring, ground thawing will be delayed (French 1996). The local and regional spatial variability of snow cover, due to topography, vegetation and drift patterns, is the largest single factor accounting for variations in the ground surface temperature during the winter (Desrochers and Granberg 1988).

Since snow cover has such a profound effect on the permafrost regime, a change in the amount would cause a reactive change in the permafrost environment. A decrease in snowcover would lead to a decrease in permafrost temperatures, possibly offsetting the effect of climate warming. A change in the timing of precipitation changes could also have an effect as was shown by Smith and Riseborough (1983).

2.1.2.2. Vegetation

The effects of the vegetation canopy are to reduce the amount of solar radiation reaching the ground surface (French 1996) and to affect the accumulation and persistence of snowcover (Luthin and Guymon 1974, Rouse 1984). The canopy also has an effect by intercepting incoming precipitation. Although vegetation does affect the distribution of snow cover (Smith 1975, Rouse 1984, Sturm and Holmgren 1994), most of the effect due to vegetation occurs during the summer (Kudryavtsev et al. 1978) when it acts as an insulator (Rouse 1984). Since vegetation affects the microclimate, disturbance of it usually causes degradation of the underlying permafrost. A particularly good example of this is the effect of forest fires (Burn 1998). In Siberia (but not in North America) the transition from discontinuous to continuous permafrost coincides with the northern boundary of the boreal forest (taiga) and is accompanied by a sharp increase in the thickness of permafrost (French 1996). Differences in snow cover due to the change in vegetation probably contribute to these variations in permafrost thickness due to the

importance of snow as a thermal insulator of the ground and the effect of vegetation on the accumulation of snow.

One of the most important surface features which concerns the existence of permafrost is a layer of peat. Peat offers less resistance to the cooling of the underlying soil in winter than to the warming of it in summer (French 1996). In summer, it dries out and is an excellent insulator. In fall, precipitation wets the peat which then freezes producing a layer with high thermal conductivity. The result of this is that in areas with sporadic permafrost, it is closely associated with peat. The depth of seasonal thawing in peatlands is considerably less than in other types of terrain (French 1996).

2.1.2.3. Soil Thermal Properties and Moisture Content

The depth of frost or thaw is influenced strongly by the thermal properties and moisture content of the soil (Harlan and Nixon 1978). Water influences permafrost formation and distribution because of the high specific heat of water. In the discontinuous zone, drainage is usually linked to vegetation, snow cover and other terrain factors, and is of secondary importance. In areas on the southern fringe of the discontinuous zone, soil thermal properties can be the deciding factor in determining the presence or absence of permafrost (French 1996). The thickest permafrost will occur with a combination of low surface temperature, low heat flow and high thermal conductivity (Judge 1973).

The thermal offset depends on soil thermal properties (French 1996). and is usually largest within a peat layer. It also increases with active layer depth (Goodrich 1982) which is thinnest beneath poorly drained and vegetated areas and thickest beneath well-drained bare soil or rock (French 1996). The thermal offset tends to maintain permafrost in warmer areas with thicker active layers and tends to reduce permafrost in colder areas. With warming, sites with ice-poor lithology would experience rapid degradation due to the lower heat required for melting in the ground materials (Smith and Riseborough 1983). Other sites would be more susceptible to other effects such as subsidence due to the higher levels of ice content.

Since the occurrence of permafrost is based on all of factors mentioned, any change in one or all of them has the potential to affect the state of the permafrost system. Unfortunately, studies have not progressed far enough to account for all variations in ground temperature. Exceptions (in ground variations which affect its temperature) and anomalies occur which defy explanation. Difficulties arise in determining the quantitative influence of individual climatic and terrain factors (Brown 1978). As such, it is often difficult to predict permafrost conditions without detailed and costly site investigations. The main factors involved have been determined however, and it is changes in these factors which are most likely to have substantial effects on the integrity of permafrost regions. One of the more studied factors is the change in vegetation such as the removal of forests after a forest fire (Burn 1998) or other human activities. However,

perhaps the most serious factor, due to the extent of its effect and the degree to which it is expected to change in a short time period, is climate.

2.2. Climate Change

Climate change is a shift in the “average weather” that a given region experiences. This is measured by changes in all the features we associate with weather, such as temperature, wind patterns, precipitation, and storms. Recent years have seen significant discussion about the possibility that the actions of human beings have been affecting the environment in such a way that they may have caused the climate to change. There are numerous studies indicating that global temperatures will rise within the next 50 or so years (Houghton et al. 1990, Hulme 1996) most of which indicate amplified warming in Arctic regions. Some projections range up to an estimated increase of 17°C during the Arctic winter (e.g. Mitchell et al. 1990)

Climate fluctuates over all time scales. Fluctuations of global or hemispheric temperatures of a few tenths of a degree are common over periods as short as a few years (Houghton et al. 1990). On a longer scale, the global temperature difference between the last major Ice Age, which reached its peak about 18 000 years ago, and now is about 3 to 4°C (fig. 3) (Barron 1995). The causes of climate variations are based on solar, astronomical, geological and geographical factors. While humans can alter aspects of climate, such as the composition of the atmosphere and the nature of the Earth’s surface,

Fig. 3: Generalized temperature and precipitation history of the Earth. The curves indicate relative departures from present global means with periods colder than today shaded and dashed lines indicating periods of sparse data. The time scale is progressively expanded from bottom to top (Frakes 1979).

our effects are constrained within these geographical limits. Furthermore, while we can influence the composition of the atmosphere, we cannot control, or even accurately predict, some aspects such as volcanic eruptions, which can have a cooling effect on climate (Joussaume 1993).

Predicting the future state of climate is extremely difficult. It is possible that the interplay amongst the various forces will result in an overall cooling of climate, which is often given less consideration than it might deserve. A more thorough comprehension of future climate requires a broader study, where possible anthropogenic warming is just one of several potential climate mechanisms operating concurrently on various time scales (Bradley 1991, Nesje and Johannessen 1992). Such analysis is rarely performed, mainly because of the inadequacy of most climate models in that respect. In order to determine whether human induced climate changes are discernible in the present era, there is a need to find a method to factor out natural background variations. Unfortunately, current climate records are insufficient in duration to determine longterm climate cycles (Mann and Lees 1996, Hurrell and Trenberth 1997). Longterm climate simulations still provide the only method for establishing the natural low-frequency variability of the climate system (von Storch 1994, Manabe and Stouffer 1996). Superimposed on natural change however, are possible anthropogenic effects. The increase in CO₂ and other greenhouse gases is widely believed to be poised to contribute to an increase in overall global temperatures.

Most current climate models estimate future conditions based upon some level of atmospheric greenhouse gases. In truth, the term climate “prediction” is misleading. Future climate “predictions” should properly be called scenarios. Climate simulations of anthropogenic climate change are, after all, heavily dependent on the emissions scenario with which the model is forced. These emissions are not generally “predicted” in the commonly used sense of the world. The IPCC (Intergovernmental Panel on Climate Change) (Houghton et al. 1996) replaced the term prediction with “projection” to remove the impression that climates of future decades could be predicted in the sense that day-to-day weather events might be.

2.2.1. GCM's

Currently, the principal tool for projecting the response of climate to changes in the level of greenhouse gases are computer-run, mathematical simulations or models of the atmosphere and ocean. The most sophisticated of these, called General Circulation Models (GCMs) express in mathematical form what is known of the processes that dictate the behaviour of the atmosphere and ocean. GCMs allow us to examine, by mathematical simulation, what should happen to climate in response to a variety of changes (Barron 1995). Typically, the main driving force for climatic change in GCM's is the atmospheric CO₂ concentration. This provides the radiative forcing mechanism which is then further affected by feedback mechanisms. GCM's which are capable of providing projections of future climate for parameters such as air temperature and

precipitation, are of two types. The first treats changes in climate parameters as step changes while more recent versions are able to accommodate the transient nature of change.

2.2.1.1. Limitations

While GCMs are widely recognized as the preferred method of projecting future climate, they do have some serious limitations. There are limits to the complexity which can be handled by modern computers. They cannot include physical processes whose horizontal dimensions are less than hundreds of kilometres. This constraint imposes simplifications on how well GCMs can model what is known and restricts the level of regional detail. (Barron 1995). The model grid is often 5° by 5° with 350 miles on one side. For example, the Canadian Climate Centre's model possesses a relatively fine resolution, with cells of dimension 3.75°, but this coarse spatial resolution is only good for broad storm and circulation patterns. Even if the computing power was available, there is insufficient data and understanding for processes at a finer grid. Because of the uncertainty associated with global circulation models, it has become commonplace to publish side by side climate predictions from several GCMs (e.g. Mitchell et al. 1990) despite the acknowledged tendency for them to agree.

Currently, the spatial resolution of GCMs is insufficient to permit more than a generalized representation of topography (Barron 1995). Recent works (Stuart and Judge

1991, Walsh and Crane 1992, Burn 1994, Bromwich et al. 1994, McGinnis and Crane 1994) have revealed substantial shortcomings in the ability of existing GCMs to replicate several features of the Arctic climate and further refinements are only likely to appear through high-resolution modeling with a specifically Arctic focus (Lynch et al. 1995). Adaptations of results from GCM runs to regional scales is highly problematic and is currently the focus of much study (e.g. Hewitson and Crane 1992, Garratt et al. 1993, Hewitson 1994). While the coarseness of GCM's is a significant problem there is no other method used for predicting future climate other than paleo methods. Some climate models are now capable of providing estimates for areas as small as 50 km by 50 km. Calibration and validation of GCMs are difficult because it is inappropriate to compare output for any specific grid point in the GCM with observations at an individual weather station. Therefore it may not be appropriate to compare the current climate archive with simulations of the present climate, in an area such as the Yukon where there are few weather stations, particularly since they are preferentially in valley bottoms (Burn 1994).

In addition to the GCM work, there is an increasing amount of meteorological, oceanic, tree-ring and sediment deposit data against which to check model projections. (Barron 1995). The record suggests a global average warming of 0.45°C - 1.5°C since the late nineteenth century, with an estimated small exaggeration (less than 0.05°C) due to urbanization in the land component (IPCC 1996). The magnitude of this warming is broadly consistent with the theoretical predictions of climate models. There has been

some criticism (e.g. Kullman 1994) that measured warming and the related response seen in biological and physical systems is insufficient to validate projections of global warming. However, corroboration by short-term data is neither sufficient nor necessary to justify confidence in long-term projections made with models.

2.2.1.2. Results in the Arctic

Most general circulation models suggest that future climatic changes may be most pronounced in the polar continental regions and of a magnitude that may affect the permafrost environment profoundly (IPCC 1990). While the models do not all give the same results (Table 1), they generally agree that warming will be greater in Arctic regions (e.g. Hansen and Lebedeff 1987), and that continents will warm more than oceans (IPCC 1990). The IPCC conclusions are typically referred to as the benchmark of projections. As a northern country, Canada could expect to warm more than many other countries. Furthermore, it is projected that land areas in the Arctic will experience amplified wintertime warming (Manabe and Stouffer 1980, Washington and Meehl 1984, Schlesinger and Mitchell 1985, Hansen et al. 1988, Houghton et al. 1990). Although the projected changes in temperature are relatively consistent between models and studies, which lends them credibility, since they are all based on the same principles, it would be surprising if their results were not all similar. Although the various projections vary widely, the average rate of warming is typically indicated to be greater than any seen in the last 10 000 years (Bolin et al. 1986).

Table 1: Sample GCM projections

Temperature Change	By when	Change in CO ₂	Area / Season	Source
4 - 5°C	2050	2 x	northwestern Canada	Cohen (1993)
1.5 - 4.5°C	2050	2 x	global	Houghton et al. (1996)
1.0 - 3.5°C	2100	2 x	global	Houghton et al. (1990)
8 - 12°C	2100	2 x	Dec-Jan-Feb	Houghton et al. (1990)
2 - 4°C		2 x	July	Schlesinger and Mitchell (1985)
8 - 14°C		2 x	January	Schlesinger and Mitchell (1985)
0.2 - 0.5°C	per decade	BAU*	global	Houghton et al. (1990)

*business as usual

2.2.1.3. Evidence of Warming

With the possibility of serious consequences to a change in climate and since predicted temperature changes could be detectable by now, particularly in the Arctic, there has been much interest in studying possible changes in ground regime in order to validate projected climate warming expectations. In the short term the thermal response will be masked by other ground temperature changes due to microclimatic effects and to inter-annual variability of climate and weather. As depth increases however, the required duration of a climate perturbation for it to be measurable, increases accordingly. The time required for the temperature wave to propagate creates a lag and, for example, the temperature amplitude at a depth of 10-20 m is representative of the climate 30 years earlier. The temperature wave will eventually stabilize at depth. If this part of the curve is then extrapolated to the surface, the surface temperature at which it is in equilibrium can be determined (Wilimovsky and Wolfe 1966).

It then becomes possible, via near surface ground temperature monitoring, to determine if there is a systematic change in ground temperatures. Monitoring at exposed bedrock sites will produce the most direct signal of climate change on the ground thermal regime (Brown 1978, Smith and Riseborough 1996). Warm, ice-rich sites, where surface stability is most vulnerable to climate warming, may also provide a temperature signal, albeit a weaker one as these sites are often in fine-grained soils (Riseborough 1990). Since monitoring only the active layer depth does not provide a reliable indicator of changes in permafrost temperature conditions (Smith and Riseborough 1996), permafrost temperature monitoring should focus on the permafrost table.

Studies of this nature have been carried out by numerous researchers. Increases in ground temperature have been observed in north-eastern Europe, Iceland, Russia and Alaska (Lachenbruch et al. 1966, Lachenbruch and Marshall 1969, Priesnitz and Schunke 1978, Zhang and Osterkamp 1993, Pavlov 1994, Wang and French 1994). Depending on the analysis, these changes have been attributed to recent climate changes, including a short-term cooling period (Osterkamp and Lachenbruch 1990), to changes in air temperature being modified by changes in snow cover or to the fact that the permafrost may have been cooler than originally assumed. Studies have also shown a shifting of permafrost northwards (Vitt et al. 1994, Halsey et al. 1995). While the predominance is for studies to focus on warming ground and degrading permafrost, this is not always the case. Osterkamp and Gosink's (1991) study of a longer time scale suggests that the

permafrost thickness at Prudoe Bay Alaska has varied no more than ± 60 m since the last glacial period and is likely near its long-term equilibrium thickness. Taylor (1991) showed that permafrost in the Queen Elizabeth Islands is still aggrading in response to the change in surface thermal regime prompted by emergence from the sea during the Holocene epoch. Furthermore, substantial contemporary cooling in the subpolar North Atlantic and fringing land areas (Jones 1990, Read and Gould 1992, Kahl et al. 1993) raises questions about the predictive power of climate models, particularly for polar regions (Adams and Woodward 1992).

These studies suggest that the current extent of permafrost is expected to contract due to projected global warming or expand locally due to other considerations. Most recent studies concentrate on the effects of warming in particular locations (e.g. Smith and Riseborough 1983, Lachenbruch and Marshall 1986, Osterkamp and Lachenbruch 1990, Smith 1990, Woo 1990) with relatively few looking at continental effects (Stuart 1986, Anisimov 1989, Nelson and Anisimov 1993). The purpose of this study is to determine the amount of forcing on the permafrost environment in Canada due to a change in atmospheric composition. Instead of extrapolating values from specific sites already studied, the approach will be on a continental scale using a model of the permafrost climate system.

2.2.2. *Response of the permafrost environment*

The reason for a study of this kind is not just academic. Beyond the intrinsic interest of the permafrost environment, changes to it could have a significant effect on Canada as a nation. Since the definition of permafrost is purely thermal, thinning or disappearance of it is not necessarily of incredible significance. This is particularly true since, considering the rate of change, disappearance would only occur at geological time scales (e.g. Lachenbruch et al. 1982, Osterkamp and Gosink 1991, Williams 1995) except where the permafrost is thin and even then it could still take hundreds of years to thaw (e.g. IPCC 1990, Burn 1992, Gavrilovna 1993, Ershov 1996). Since it takes so long for thick permafrost to melt, the most likely contemporary effect of thaw is surface cryogenic features such as ground subsidence, heaving, thermokarst and mass wasting, changes in hydraulic regime and in carbon storage (e.g. Jorgenson and Kreig 1988, Kane et al. 1991, Gorham 1991, Woo et al. 1992, Nakayama et al. 1993, Cohen 1997). It is these changes which are the main cause for concern particularly in areas where the soil contains a substantial amount of water or ice. In areas with little or no ground water, there may be very little effect of ground thaw. It is the possible magnitude and variety of these geomorphological, hydrological and biological changes that makes the determination of the susceptibility of the permafrost environment to thaw so important.

2.2.2.1. Geomorphological

Engineering in cold climates has to deal with well recognized and geotechnically

very demanding, problems of cold climates in general (Williams 1995). Ground warming on a global scale would move the zone of unstable permafrost, where the engineering problems are the greatest, into areas where previously there had been stable permafrost. Even a modest climatic warming could have significant effects for terrain conditions and northern engineering, since thousands of square kilometres would be affected even though the complete thaw of permafrost within the time scale of GCM projections is only possible where there is warm, thin permafrost (e.g. Riseborough and Smith 1993, Lunardini 1996).

The concerns include the consequences of melting such as subsidence (thermokarst topography) and instability of slopes (landslides, mudflows), water levels and changing ice conditions, as well as the thermodynamic and mechanical effects of freezing, especially frost heave. Subsidence is one of the more serious possible consequences of ground thaw as it would result in extensive flooding and coastal erosion. In some regions, 50 to 80% of the upper 20-30 m of the ground is ice (Williams 1995). Of this, perhaps a third is excess ice which would be released as water with corresponding subsidence of the ground when thaw is complete. This could cause widespread development of thermokarst lakes (e.g. Rampton 1974, Burn and Smith 1990). As the greatest amounts of ground ice are usually found near the permafrost table, it is expected that thermokarst features could occur at the beginning of climatic warming within a few decades (Pissart 1990). However, the climate change would need to be great

enough to melt the ice as increasing temperatures through the “warm frozen” range requires the exchange of far more energy per degree than the warming of unfrozen material (or very cold permafrost) (Riseborough 1990). As permafrost warms, its ability to carry a load weakens. If the permafrost melts completely, there can be complete failure of structural support and subsequent subsidence (Woo et al. 1992). There is therefore concern for the effect of widespread permafrost degradation on terrain stability (Burn and Smith 1993), particularly for areas without stable bedrock which is less susceptible to subsidence. Warming causes renewed heaving of the frozen soil at temperatures of -2 to -1°C because of the higher content of unfrozen water and greater permeability (Cheng 1983, Mackay 1988, Williams 1995, Ershov 1996). The warming of frozen ground reduces its creep resistance, thereby reducing the bearing capacity of piles or other footings in permafrost.

2.2.2.2. Hydrological

The presence of permafrost and a seasonally frozen active layer usually restricts the infiltration of water and its recharge to groundwater systems which weakens the soil (Williams 1995). This restriction causes a very high percentage of rainfall and snowmelt in permafrost regions to contribute to surface runoff. This condition in turn leads to extreme differences between seasonal maximum and minimum streamflow rates (French 1996). Climate warming could lead to the thickening of the active layer which would then cause melting of excess ground ice, and the discharged water would affect

surrounding hydrological environments (Nakayama et al. 1993). Lakes and ponds, which have permafrost hydrologic divides, are more likely to drain laterally on to the groundwater system, dramatically altering hydrology and dependent ecosystems (Environment Canada, 1998). The released ground water would give rise to an increase in river discharge and an increase in landslides, erosion generally and flooding, together with increased sediment loads in the rivers.

2.2.2.3. Biological / chemical

Increased water volume would lead to changes in vegetation and, additionally, changes in albedo and evapotranspiration from plants in that area. The effects of damaging or removing vegetation in permafrost regions, are usually to allow the arrival of more heat to the surface and deeper summer thawing (Williams 1995). If there is as a result sufficient subsidence that standing water occurs, then the thaw process is accelerated further by the heat-absorbing properties of the water and the increased thermal conductivity of the more saturated materials (Williams 1995). In areas where the climate becomes drier, vegetation may possibly disappear and hence heighten annual soil temperature fluctuations. In other areas, vegetation may increase and eventually provide more insulation decreasing annual soil temperature fluctuations.

A change in vegetation could also affect carbon and methane storage. Arctic tundra has been a net sink for carbon dioxide during historic and recent geological times

(e.g. Gorham 1991, Oechel et al. 1993) and large amounts of carbon are stored in the soils of northern ecosystems (Billings 1987, Gorham 1991, Kolchugina and Vinson 1993, Botch et al. 1995), particularly in the near-surface layer of permafrost. As such, arctic warming may cause the soil to change from a carbon dioxide sink to a source by lowering the water table (Post 1990, Wigley 1991) thereby accelerating the rate of soil decomposition (CO₂ source) (Gorham 1991, Billings et al. 1982) so that this dominates over CO₂ sink (from photosynthesis). Increased temperatures may also increase the productivity of vegetation which may counteract the effect of increased decomposition (Kolchugina and Vinson 1993). There is still a lot of uncertainty regarding which of these factors will be the most important. The possibility exists that a lag between increased carbon efflux and uptake by vegetation may occur. The equilibrium of the carbon cycle may be re-established, but at a higher rate of carbon turnover.

2.2.3. Committed Versus Realized Change

Due to the possible changes in the permafrost environment, it is therefore of great interest to determine what the possible future extent of permafrost will be for Canada. One problem which has already been alluded to is that there is a time lag between a change at the surface and at depth. This is similar to the time lag between a change in atmospheric content and a change in climate. Human actions have been affecting the composition of the atmosphere for some time. While not much change in the climate has been realized currently, the roots of change have already been set and we are committed

to much more. Since the industrial revolution, the atmospheric composition of greenhouse gases has increased (IPCC 1996). While this change in the atmosphere has not yet increased the global temperature significantly, it is projected that, even if no further change in atmospheric composition were to occur, the global temperature would still rise. A similar delayed reaction can be expected from the permafrost environment since it takes a considerable amount of time, roughly proportional to the square root of time from onset (Williams 1995), for a temperature wave at the surface to propagate into the ground (table 2).

Table 2: Depth of propagation of a temperature wave in frozen ground (Nauka 1974)

Depth (m)	Time (years)
12.5-14.5	1
40-47	10
125-145	100
400-500	1000
1250-1450	10 000
4000-4700	100 000

Since the disappearance of permafrost in areas with thick permafrost will take a considerable amount of time, without knowing the current state of permafrost it is not possible to map future permafrost on a short-term time scale as the ground will not yet have adjusted to the new climate. It is possible to map transient surface and near surface conditions since the surface of permafrost reacts quite quickly to change. It is the consequences of surface changes which are of primary importance, and therefore, this

should be sufficient for most purposes. All that is needed then is a model which relates the surface conditions of permafrost to projected climate.

2.3. A model of the climate-permafrost system

2.3.1. The Nature / Role of Environmental Models

The earth is made up of a myriad number of systems, linked to each other by untold numbers of pathways. Unlike laboratory sciences, when dealing with the natural world it is not possible to account for every single factor and element having an effect on the environment. Many of the earth's processes are not known as well as those which can be studied in isolation. Often it is only possible to study the major factors or the effect of several factors in interconnection. Since it is not possible to recreate the world in the laboratory, the solution is either to find the best representation of a system which exemplifies what is to be studied or to attempt to model the environment in order to be able to manipulate the variables and estimate what the effects would be.

Models are simplified representations of earth systems. The purpose of modeling is to permit manipulation of representative earth systems in a manner which is not possible with the actual earth systems. Models can take many forms one of which is mathematical or functional modeling. These types of models use mathematical functions to represent the relationship between various factors in an earth system. An excellent example of mathematical modeling is the GCM which attempts to account for the

important factors affecting global atmospheric conditions. In order to develop a mathematical model, first the important factors must be determined, then the relationships among them must be studied. Each relationship between various factors is then replaced by a representative function. Once the factors are all accounted for and the model is capable of replicating the actual environment with reasonable accuracy and precision, elements in the model can be varied in order to examine what the effect of a change in the system would be. One significant problem when modeling more complex systems is the difficulty in determining what the starting conditions are since the model will usually be extremely sensitive to errors in the input values (e.g. Zhang and Osterkamp 1993).

Modeling natural systems is quite difficult due to the number of processes operating in the natural environment and the complications involved in determining them all. As more is learnt about a system, the model tends to become more and more complex in order to accommodate all the elements. The hope then is that the model becomes more precise and accurate in predicting the behavior of the environment. The problem with this however is that the more complex a model becomes, the more cumbersome it becomes to use and the increasing likelihood that required information will not be available (e.g. weather data from the Arctic Islands). While those modeling strive to represent the earth systems as accurately as possible, they are plagued by the fact that, except on very rare occasions, much data is not available. Researchers attempt to

represent the major factors assuming that the increasing error caused by using faulty data will nullify any improvements in the model made by including more minor factors. Therefore, the ideal model represents all the major factors affecting a system and includes only the more minor ones if there is an abundance of quality data.

2.3.2. Developing a model: The climate-permafrost system

2.3.2.1. Examining the system

Permafrost is indelibly linked to climate and there has been much work expended in resolving the climate-permafrost problem with varying degrees of success. A substantial amount of effort has been expended on the cartographic delineation of permafrost zones at small geographical scales (e.g., 1:5,000,000) for various parts of the earth. Data was compiled from field observations in regions of interest. Maps were then prepared based on these inventories of field data by creating broad categories of permafrost such as 'widespread' or 'discontinuous' based on correlations to air temperature (Brown 1967, Ferrians 1965, Kudryavtsev et al. 1980). Typically, the approach had been to assume that the relationship between the air and surface temperatures is a fixed difference with ground temperatures typically -6°C to -8°C degrees lower (e.g. Brown 1967). This method ignores variations in soil thermal properties, snow, ground cover and topography.

There is a better relationship between freezing and thawing indices and permafrost existence rather than directly from MAAT (Harris 1986) and the accuracy of a surface indicator will be increased further by including surface and soil conditions. Nelson (1986) and Nelson and Outcalt (1987) presented models which use minimal climatic, soil and snowcover information to delineate the broad equilibrium features of permafrost distribution. They predicted permafrost boundaries using the 'frost number', a 'dimensionless ratio defined by manipulation of either freezing and thawing degree-day sums or frost and thaw penetration depths'. The number took into consideration mean temperatures of the warmest and coldest months as well as the snow-cover regime. The frost index has been successfully used with 30-year normals to produce broad patterns of the observed distribution of permafrost under contemporary climatic conditions in central Canada (Nelson 1986) and the Former Soviet Union (Anisimov and Nelson 1990).

It is also possible to model the air temperature effects separately and account for surface factors with another variable. N-factors represent such a method of parameterizing surface conditions. 'The n-factor is the ratio of surface temperature to air temperature (both integrated over time) for any period - usually for winter and summer' (Shur and Slavin-Borovski 1993). Based on Lunardini (1978) and Jorgenson and Kreig (1988), n-factors can be applied as transfer functions between the air temperature and the temperature at the ground surface, to account for the local influence of vegetation and snow cover. The summer n-factor typically takes into account microclimatic effects such

as radiation, convection, evapotranspiration etc. due to vegetation. The freezing n-factor accounts for winter factors, particularly snow cover. N-factors can also take into account soil characteristics (Shur and Slavin-Borovski 1993).

While such studies do result in fair evaluations of permafrost extent on a national scale they are not appropriate for studying future conditions since they do not relate the factors in a functional manner. Since n-factors are based on actual measurable conditions, they can be used, as part of a model in climate change impact prediction.

2.3.2.2. Is a model needed?

In order to analyze the impact of climate change on permafrost there is a need to develop a functional model which accounts for all the important factors affecting the climate-permafrost relationship. Only a model of this kind would allow the input factors to be varied in order to determine how a change in one or more of them would affect the system.

2.3.2.3. Creating the Model

The climate-permafrost relationship can be represented by the temperature regime at three levels. The first, the temperature at a standard screen height, a Stevenson Screen, represents the linkage between regional climate and the local microclimate; the second, the temperature at the ground surface, is affected by variables on the surface, and the

third, the temperature at the top of permafrost is differentiated from the second by soil variables.

The temperature differences between the three levels can be modeled through two essential relationships, the air to surface differential and the surface to permafrost differential. The first would need to account for surface factors such as vegetation and snow cover while the second would have to account for ground conditions such as soil type, water content and soil density. Therefore, after starting with a factor representing air temperature, there needs to be another representing surface factors and a third representing soil conditions. Since it has been shown that seasonal indexes fit better than those based on yearly averages, it would seem prudent to separate the factors into winter and summer versions.

The next step is to combine the factors into a model representing the permafrost environment. The temperature at the top of permafrost (TTOP) model (equation 1) by Smith and Riseborough (1996) provides a method for determining the temperature at the base of the active layer using these variables. It expresses the mean annual temperature at the top of permafrost in terms of the annual regime of atmospheric temperatures, freezing and thawing n-factors (surface conditions) and the ratio of thawed and frozen soil conductivities (soil conditions).

$$(1) \text{ TTOP} = (k_T/k_F \cdot N_T I_T - N_F I_F) + P$$

Where:

N_T = Thawing N-factor (sensitive to vegetation)

N_F = Freezing N-factor (sensitive to snow cover and MAAT)

I_T = air thawing degree days (seasonal thawing index)

I_F = air freezing degree days (seasonal freezing index)

k_T = thawed ground thermal conductivity

k_F = frozen ground thermal conductivity

P = period (365 days)

The model accounts for each of the most important variables without cluttering the analysis with more minor details which might increase the precision of the output but not the accuracy due to an increase in the amount of error in the data. The two N-factors account for surface conditions in the summer and the winter. Changes in N_F have a larger and more direct influence on TTOP than equivalent changes in N_T since the influence of N_F is moderated by the ratio k_T / k_F which is less than unity. I_T and I_F account for air conditions. The effect of having both a winter and a summer factor allows the model to react to changes in the seasonal variations even in the absence of annual changes, the same as the permafrost environment. Finally, k_T / k_F accounts for soil conditions and is sensitive primarily to volumetric moisture content, and, while also based on mineralogy, is relatively insensitive to it.

This equation can be manipulated into a nival and thermal offset representing the two differentials in the relationship. The nival offset (equation 2) accounts for the difference between the air temperature and the temperature at the ground surface. A winter factor, it is based on snow depth and air temperature. The thermal offset (equation 3) accounts for the difference between the ground surface and the top of permafrost. It is based on the relative difference between the winter and summer thermal conductivities. In summer, the thermal offset would also account for the differences between air temperature and the surface due to the inclusion of the thawing N-factor (N_T).

(2) Nival Offset

$$T_A - T_{GS} = I_F \cdot (1 - N_F) + P$$

(3) Thermal Offset

$$T_{GS} - T_P = N_T \cdot I_T \cdot (1 - R_k) + P$$

Where:

T_A = Air temperature

T_{GS} = Ground surface temperature

T_P = Permafrost temperature

R_k = Thermal conductivity ratio (k_T / k_F)

Between the ground surface and the temperature at the top of permafrost the most predominant factor is the conductive heat flow (Lachenbruch and Marshall 1986, Smith and Riseborough 1996) in addition to the effects of phase changes and the associated

latent heat releases and fluid migration (Beltrami 1996). Convective heat transfer will become progressively more important as the soils warm and remain unfrozen longer (Kane et al. 1991). The ramifications of neglecting it will be negligible when the soil is frozen. When the soil is thawed, models making this assumption will slightly under-predict the soil temperature and consequently under-predict soil thaw depths. The amount of under-prediction of temperature is relatively small and of short duration, so the estimate of thaw depths will not be significantly in error.

2.3.3. Using the Model

Once a model has been developed, the next step is to apply it to the environment to determine if it accurately reflects the reality being modeled. Since TTOP results in a temperature, it could be authenticated in the field for any area where the parameters are known. Furthermore, since it contains relatively few variables, it is ideal for use at a variety of scales. While the TTOP model can easily be used at specific locations, in order to determine any useful changes or projections of widespread changes, it is essential that there be a technique with which to show the spatial extent of the permafrost environment. One such method is the use GIS.

GIS will be used as a tool to aid in demonstrating the results of this model. For the purpose of this study, GIS software can be seen as a method to map out the spatial variability of the relevant factors. Once the factors have been mapped, the GIS program,

specifically ArcView in this case, allows them to be combined functionally. This allows the model to be constructed from the individual map layers. It also allows for other, related, interrogation of the model's factors.

Now that the various elements have all been determined, a method is available with which to model the current permafrost conditions. Furthermore, since TTOP does not depend on specific data, the climate variables can be altered to represent future, enhanced CO₂ conditions. This allows the model to be used for both current and future conditions in order to determine what changes can be expected in the Canadian permafrost environment in response to CO₂ forced warming.

CHAPTER 3

Methodology

3.1. Acquiring data

In ideal circumstances, all data required would be available for the area of study over a long period and in the format required. Unfortunately, as is often the case, not all of the data required to apply the TTOP equation at a national scale was available. As a result, decisions had to be made as to what data could be used and converted into the form necessary for each term in the equation. Luckily, the TTOP model needs very few different types of data:

N_T = based on vegetation

N_F = based on snow depth and mean annual temperature

I_t = air thawing degree days

I_f = air freezing degree days

R_k = thermal conductivity ratio (k_T / k_F)

In order to estimate the response of the permafrost environment to a change in climate, data is also required which details expected climate change.

3.1.1. N_T

The vegetation factor was the most problematic. While there are a variety of national scale datasets on the subject of vegetation cover, none of them offered the possibility of calculating the N_T factor. As a result, in the analysis, it was assumed to be unity. While this assumption will necessarily affect the veracity of the analysis, it is evident that the N_T factor has the least variation of the TTOP factors (Smith and Riseborough 1996). Thus the loss of accuracy was not considered to render the overall analysis useless.

3.1.2. N_F

The value of N_F is based on climate variables (MAAT) and snow depth according to a relationship developed by Riseborough and Smith (1998). It is similar in concept to one developed by Nelson and Outcalt (1987), although their version apparently underestimates the effect of snowcover (Riseborough and Smith 1998). The climate variable required is the MAAT. Since this can be calculated from FDD (freezing degree days) and TDD (thawing degree days) ($MAAT = [TDD - FDD] / 365$), both of which are also required, no additional data is required for MAAT. The snow depth data was obtained from two sources. The first was the *Updated Canadian Daily Snow Depth*

Dataset from Environment Canada. This database provided the average monthly snow depth for various weather stations in Canada. The main drawback was the lack of coverage in the Arctic. While southern Canada is well represented, in the high Arctic most of the stations are along the coast which may result in skewed overall values of snow depth when the estimates are extrapolated to the rest of the Arctic. This database was supplemented by a second set of data, Environment Canada's *Canadian Monthly Climate Data (CMCD)* (1994). This database provided the average snow depth at month end for more stations. Again, there was a problem with low representation in northern regions but by combining the two datasets, this concern was reduced. A further complication was the difference in the type of data available. The first dataset provided the average monthly snow depth, while the second dataset provided the monthly snow depth at month end. A comparison of identical stations in the two databases revealed that they were quite similar with most months showing a difference of less than a few cm. The increase in coverage of the area of interest outweighed the error due to the discrepancy in data type. Many areas were covered by both datasets and these points were averaged.

The snow and climate data were in point location form. In order to determine values for those areas of Canada not covered by weather stations, the values of known points were interpolated to the rest of the country using *interpolation method 1* (Appendix A). Interpolating relatively few values over an area as vast as Canada creates

some problems, most of which have been mentioned. For example, local variations in relief which affect snow depth are ignored. In areas with very few data points, which is typical of far northern regions, the loss of detail can become quite severe. Furthermore there is the problem that weather reporting stations are preferentially located in more assessible locations, such as coastal areas and valley bottoms. Since proximity to water and elevation both affect snowfall, averages based on non-representative values will necessarily contain some error. Unfortunately, there is no better way currently available to determine more accurate values for northern Canada.

The climate data was manipulated, using a relationship developed by Riseborough and Smith (1998), to values for N_F . It was developed using empirical data from various data sites. As a result, while it models central values quite well since it was these values from which it was developed, it has difficulty modeling more extreme values. The range of values which can be accurately modelled is shown in fig. 4.

3.1.3. I_F, I_T

Data for the FDD and TDD were obtained from CMCD in point form. They were also interpolated using *interpolation method 1*. For all of the information acquired from this source, the number of years or months for which the data are available was given and any station with less than five years of data was ignored. It would have been preferable to be able to use data from longer time spans, such as climate normals. However this

Limits of Nf Formula

Fig. 4: The Nf function was developed by Smith and Riseborough (1996) based on available data and can only model values which fall within its scope. Geographical areas which fall outside of the limits are shown in Appendix E.

would have resulted in even less data from the arctic which would have been more problematic.

3.1.4. R_k

There are various available methods to determine the conductivity ratio. The method of Johansen (1975) requires: (i) type of soil (mineral vs organic), (ii) soil texture (coarse vs fine), (iii) bulk density, (iv) quartz content, (v) water content and (vi) particle density. The values for the first three were estimated from the soil categories in the surficial geology map of Canada (fig. 5) obtained from the digital version of the National Atlas of Canada (Fulton 1995) provided by the Geological Survey of Canada. Except at extremely low moisture contents or extremely high bulk densities, the effect of quartz on the conductivity ratio is negligible (Riseborough and Smith 1998). Thus an arbitrary value of 40% quartz was used for all mineral soils. Since there was insufficient information to determine actual water contents, an estimated middle value of 50% was used for all areas. The particle density used was 2650 kg m^{-3} .

3.1.5. *Future Climate*

To complete the analysis, it was necessary to obtain values for future climate. These were taken from the output of GCM's. Results from climate models should not be interpreted as indicating how much the climate will have changed by a certain time. Instead they should be understood to be denoting the condition towards which climate

The Surficial Geology of Canada

Fig. 5: Surficial Geology Map of Canada; Fulton 1995.

change is tending, albeit at a pace which may not be known. In other words, climate models express the committed and not the realized change.

The second generation GCM currently available projects climate data for 1 x and 2 x CO₂ concentrations. The data from this model, based on MacFarlane et al (1992), was obtained from the Canadian Centre for Climate Modeling and Analysis(CCCMA). For the 1 x CO₂ model, the CO₂ concentration was set to 330 ppm and for the 2 x CO₂ version, the CO₂ concentration was set to 660 ppm. The models were run for a period of 20 years to eliminate transient effects in the system and the values used were those from the final, 20th year. The result from the 1 x CO₂ model were used to estimate current conditions. The value of 330 ppm occurred around 1970 - 1975 (Leggett 1990, Trivet et al. 1993). The estimates for future conditions vary widely depending on the emission scenario with a value of 660 ppm projected to occur as early as 2040 or 2050 (fig. 6) (Leggett 1990, IPCC 1991).

The GCM outputs provide montly temperature and total precipitation. The TTOP model requires FDD, TDD and total snowcover. The values for FDD and TDD were determined from the MAAT data by assuming that all the days in a month with below zero temperatures contributed to the FDD and that all the days in a month with above zero temperatures contributed to the TDD. While this is not true in actuality, the overestimation of FDD in winter and their underestimation in summer should

Fig. 6: Projected atmospheric CO₂ concentrations for various fossil fuel scenarios (IPCC 1991).

- (a) 2030 High Emissions Scenario
- (b) 2060 Low Emissions Scenario
- (c) Control Policies Scenario
- (d) Accelerated Policies Scenario
- (e) Alternative Accelerated Policies Scenario

complement each other with the opposite being true for TDD. The total snowcover was determined by using the precipitation data only for those months where the MAAT was below zero and converting that into a snow depth. Unfortunately, determining the values in this manner does not provide the actual projection since there can be snow during months with positive MAAT and rain throughout months with negative MAAT. Furthermore, the actual value desired is the ground snow cover and this may take some time to form during cold temperatures and persist long after the area warms. This method is the closest approximation however.

Since this data was obtained from a GCM, the output values are for large geographic blocks covering a rectangular region which includes Canada. In order to smooth the look of the map, the values of each block were assigned to the centre of the appropriate box and values for the remaining areas were interpolated, using *interpolation method 2* (Appendix A), from these central values. This action altered the overall look of the map but did not significantly increase the amount of error in the data. However, it is the inclusion of this data which severely limits the resolution of the final data. While there is a necessary limit to resolution when smaller scale maps are used, the CO₂ climate maps are particularly bad. This was due to the fact that they were developed from GCM data which is of extremely low resolution. This lack of resolution severely restricts how the end figures can be used. The results cannot be interpreted as indicating how the

permafrost at any particular site will react. Instead they should be viewed as a sign of the general trends which can be expected.

3.2. Data Layers

Once the various types of data were obtained, it was necessary to convert them into the map layers required for TTOP. The final model, as run, had four different data layers. The first, ' R_k ' represents the conductivity ratio (k_T / k_F). It was based on the categories provided in the surficial geology map, the saturation ratio and Johansen (1975). The second, ' N_F ', was the winter N factor based on the snow depth, MAAT maps and Riseborough and Smith (1998). The third, ' I_T ' and fourth, ' I_F ' used the TDD and FDD maps respectively, directly. The remaining parts of the equation are ' N_T ' and ' P '. Since both of these factors can be represented by a single value (1 and 365 respectively), it was not necessary to include them as map layers.

With these four map layers, it became possible, not only to produce the initial TTOP output map, but to manipulate the layers to display other information. After creating climate layers for 1 and 2 x CO₂ values it was possible to estimate the amount of change which could be expected.

3.3. Analysis

3.3.1. Current Conditions

The first step was an analysis of current conditions using the best available data. The standard (R_k , N_F , I_T , I_F) inputs were used to create a map of current permafrost temperature using TTOP (equation 4).

$$(4) \text{ TTOP} = (R_k \cdot I_T - N_F \cdot I_F) + 365$$

This map was compared to contemporary maps of permafrost extent and ground temperatures to determine the level of similarity between them. An analysis was then performed to determine the importance of two of the map layers, R_k and N_F .

3.3.2. Estimated Current Conditions

Before proceeding to project future conditions based on climate models, an analysis was performed to determine how well the climate models predict current conditions. The TTOP equation was used with the N_F , TDD and FDD values calculated from the 1 x CO₂ data and the same R_k value as previously. The output map was then compared to the original TTOP map to determine the agreement between the two. Subsequently the map was redone using different input values for precipitation to see if they better approximated the original TTOP map. The precipitation estimates used were the actual snow cover values calculated from the combination of the Environment

Canada snow depth data explained earlier and the total value from the projected climate model. The first of the two, the actual values, were used, in conjunction with the projected temperature values, to determine if the errors were originating essentially from falsities in the temperature or precipitation estimates. The purpose of the second set, using the total value of projected precipitation rather than just from the winter months, was to determine if the error in snowdepth estimated, originated from an error in the climate model or from the method used to separate frozen from thawed precipitation.

3.3.3. Future Values

Finally, the TTOP analysis was redone using the N_F , TDD and FDD values calculated from the 2 x CO₂ data, with the same R_k value as previously. This map was compared to the 1 x CO₂ map to ascertain the degree and geographical extent of any changes. Further TTOP output maps were completed using the 2 x CO₂ temperature data and various different precipitation data. The current actual values and total projected values were used, as before. Furthermore, others were done using arbitrary precipitation values to illustrate the effect of a doubling or halving of precipitation.

Since the only difference between the 1 and 2 x CO₂ maps should be the projected change in climate, it should be possible to determine the amount of change expected and then apply those values of change to the original TTOP map. This was done in order to have the most accurate final map as possible. Although the precision

cannot be improved as the climate model values are still being used and they are particularly imprecise, the level of accuracy can be improved by eliminating the errors due to an inadequate projection of current conditions.

In order to make the areas where a change in conditions is to be expected more obvious, the output maps based on the current TTOP and the 2 x CO₂ scaled TTOP output maps were compared to form one map showing three categories of permafrost (table 3). The size of the relative areas was calculated to further aid the descriptive analysis.

Table 3: Final permafrost stability categories

Category name	description
Unstable	starting temperature below 0°C ending temperature 0°C or higher
Moderate - 1°C	starting temperature below 0°C ending temperature -1°C or higher
- 2°C	starting temperature below 0°C ending temperature -2°C or higher
Warming - 0 - 5C	starting temperature below 0°C ending temperature lower than -2°C increase in temperature by less than 5°C
- 5-10°C	starting temperature below 0°C ending temperature lower than -2°C increase in temperature from 5°C to 10°C
- 10 + °C	starting temperature below 0°C ending temperature lower than -2°C increase in temperature by more than 10°C
No permafrost	starting temperature above 0°C

CHAPTER 4

Results and Analysis

The central purpose of the study was to predict the extent and stability of permafrost in Canada under future climate change. In the process of accomplishing that goal, the current distribution of permafrost was mapped with the TTOP model using both actual and GCM projected current climate parameters. This was to determine how well the TTOP model and GCM projections reproduce actual conditions. Future permafrost conditions were determined using GCM projections of future conditions. The result was three maps: TTOP, which estimates current permafrost conditions with the current climate data available; 1 x CO₂ TTOP, which estimates current permafrost conditions using GCM output; and 2 x CO₂ TTOP, which estimates future permafrost conditions based on GCM climate projections. The input maps used to make the three maps are shown in Appendices B, C and D respectively.

4.1 Mapping Current Permafrost Conditions

4.1.1. The Results of TTOP

The TTOP output map (fig. 7) can be analyzed to reveal the relative importance of the various factors which determine ground temperature and permafrost. The most clear influence is climate, resulting in the broad north / south progression of ground temperature zones which matches the overall climatic regime. The importance of surficial materials is seen in the small areas of cooler temperatures within the broad bands of warmer temperatures, due to the presence of organic soil. Organic soils often have a low value of R_k resulting in a low value of TTOP. This is why permafrost at the most southern boundaries is confined to this material (Smith and Riseborough 1996).

Snowcover (Appendix B) reveals its imprint in the larger warmer areas in west central Canada (northern Alberta, northwestern British Columbia, southern Yukon). These areas are warmer due to their high amount of snow. Many of the less extensive anomalies, particularly in the south, are the result of very high or low snowcover values. Due to the nature of the snow cover map, that the majority of the values were interpolated and that two non-equivalent datasets were combined, there is a high probability the map contains some errors. While it is quite possible that the various anomalous areas do have much more or less snow than neighbouring ones, particularly in the mountains, the values should be viewed with caution. It is also important to

Temperature at the Top of Permafrost (TTOP)

Fig. 7: TTOP; The output of the TTOP model showing temperature at the top of permafrost using current climate data. The factor maps used to produce this map are shown in Appendix B.

remember the limitations of the function used to calculate N_F . The areas outside the limits of the model are indicated in Appendix E.

One significant problem region on the map is northern Ontario. The climate data archive received did not include data for this region. Therefore the values for northern Ontario were derived from a direct interpolation between the Manitoba border and northern Ontario at the approximate longitude of White River. This eliminated the possibility of climate variations within the area. The output variations seen are based on the varying soil conditions and the amount of snow. However, there are only half the number of snow stations as well, since one of the two snow databases was obtained from the same source as the climate data, and did not include stations in northern Ontario.

The TTOP equation establishes the difference between the temperature of the air and at the top of permafrost in terms of two offsets. The nival offset (equation 2, fig. 8) accounts for the difference in mean annual temperature between the atmosphere (T_A) and the surface of the ground (T_{GS}) when snow is present.

$$(2) T_A - T_{GS} = I_F \cdot (1 - N_F) + P$$

In the summer, the nival offset is replaced by some other value which represents the effect of vegetation on the surface. Since the summer offset was deemed to be unity in

Nival Offset

Fig. 8: Nival Offset; Shows the effect of an intervening snow layer on ground temperatures.
 Calculated by the formula: $T_a - T_g = \frac{I_f \phi (1 - Nf)}{P}$

the present study, there is not a summer surface offset in this case. The second offset, the thermal offset (equation 3, fig. 9), represents the temperature difference between the ground surface and the top of permafrost (T_p) on an annual basis. It accounts for the seasonal change in the thermal properties of the soil in the active layer.

$$(3) T_{GS} - T_p = N_T \cdot I_T \cdot (1 - R_k) + P$$

The nival offset map (fig. 8) shows that the effect of snow cover increases northward up to a point. The reasons for the overall appearance of the map are easily explained with reference to the equation (2) and its two variables, I_F and N_F . The effect of I_F is to increase the nival offset as freezing degree days accumulate. This can be seen in the overall northward increase in the offset. N_F increases with depth and duration of snow cover and as the offset increases, its effect offsetting cooling temperatures increases. For this reason, the offset is largest where there are cold temperatures with substantial snow but drops off farther north due to lower amounts of snow. Specific areas with extreme values such as the Mackenzie Valley, northeastern Manitoba, Baffin Island, central Quebec, and north central Alberta are due to the extreme snow values.

Converse to the nival offset which tended to increase northward, the effect of the thermal conductivity ratio decreases northward with decreasing temperature. Overall, the northward gradation is more consistent in this case since, of the two variables involved, I_t

Thermal Offset

Fig. 9: Thermal Offset; The effect of the difference between winter and summer soil conductivities on ground temperature calculated by: $T_g - T_p = N_t \cdot I_t \cdot (1 - R_k) / P$

and R_k , only I_t has a broad spatial pattern. As temperatures decrease, so do thawing degree days and the value of I_t . R_k varies with soil conditions throughout Canada with no inherent broad pattern. When the thermal conductivity ratio is larger, (i.e. there is less difference between the frozen and thawed conductivities), there is less of a difference between the surface and subsurface temperatures. If there were no difference between the thawed and frozen conductivities (i.e. $R_k=1$) then the thermal offset would be zero. As such, areas which are either always frozen or always thawed will not be affected by the thermal offset.

4.1.2. Accuracy Analysis and Mapping Problems

The only true way to test the veracity of the TTOP model would be through numerous site studies. Unfortunately, considering the small generalized scale at which the model was run, an inconceivable number of study sites would be required in this case. Furthermore, due to the large minimum mapping unit ($10\,000\text{m}^2$), any particular site would not be represented by the map value for that area. Therefore, validation of the TTOP map must be accomplished through comparison to other, published, permafrost maps.

A comparison to the permafrost map of Canada (fig. 1) shows that the two maps portray similar bands of permafrost conditions, except that the TTOP map indicates permafrost as being less extensive. The permafrost map shows isolated or sporadic

permafrost conditions extending to the approximate latitude of the current 0°C isotherm in most of Canada (except Québec and British Columbia). The TTOP version predicts permafrost conditions beginning around the -2°C isotherm in most of Canada (except Québec). This reduction in permafrost extent might be expected since the climate has tended to warm since the end of the little ice age about 150 years ago. The TTOP model does not distinguish permafrost which has begun to degrade due to changing surface conditions but which persists. In this respect, the maps of future permafrost conditions are actually maps of committed change. They represent permafrost conditions if they reacted instantaneously to surface changes. At depth, it would take up to hundreds of years for the permafrost to reach equilibrium. In the near-surface, the permafrost would equilibrate quite quickly so these maps can be seen as representations of what could soon be expected at the surface and what would eventually occur at depth.

Another map which can be compared with the TTOP map is the published ground temperature map of Canada (fig. 10) since both show the geographical distribution of ground temperature. Since both maps (figs 7,10) have the same isolines, a direct comparison is possible. Due to its methodology, in which measurements at a few sites were interpolated to the rest of the country, the published ground temperature map is very generalized and is made up of broad bands of equal temperature. The same can be seen in the far north regions in the TTOP map where very little climate data is available. The -15°C isotherm passes through the Arctic Islands at about the same latitude in both maps.

Ground Temperature

Fig. 10: Ground Temperature; Measured at a depth of 10m. Source: Heginbottom et al. (1995).

It cuts through Devon Island in both, dips a little farther south to encompass Prince of Wales Island in the TTOP map and moves back north to include Melville Island in both versions. The -10°C isotherm is similar in both maps, dipping farther south in the centre of the country particularly in the TTOP map. The isotherm passes through the northern portion of Baffin Island, dips south onto the mainland, and moves north to cut through Victoria Island and encompass Banks Island. The -5°C isotherm is very similar in both as well, particularly in mainland Canada. Farther south, the TTOP map has more detail due to an increase in the number of measurement locations. There is still some similarity between the two maps but it is less evident. The 0°C isotherm passes through almost the identical region in Labrador and northern Québec on both. Moving west, it diverges in the two maps. In the published map, it continues in a northwest pattern, cutting through the very northern tip of Saskatchewan before dipping south again in the mountains and then returning to the northwest pattern. In the TTOP version, the 0°C isotherm passes farther south in the prairies and then continues northwest in a similar pattern to the cooler isotherms, effectively ignoring the effect of the mountains. In fact, the area where the two maps diverge the most is in the vicinity of the western mountains. This is due to the insufficient detail in measurement locations to accurately model the mountains. Northern Ontario was also a problem due to the lack of data. Overall, the warmer isotherms have similar general patterns in both maps although they tend to show cooler temperatures for most of southern Canada in the TTOP version. The overall similarity between the two versions lends credibiliy to the accuracy of the TTOP map.

The most significant problems with the TTOP analysis are due to the quality of the input data. Particularly, the lack of data on soil moisture content and the lack of sufficient snowfall and temperature data in northern Canada and Ontario. These forced the need for several assumptions. First it was assumed that the moisture content of all the soil conditions was 50%. Then it was assumed that the snow cover and temperature data points could be linearly interpolated to cover areas with no data. While the breadth of these assumptions casts some doubt on the validity of the results, it is important to remember that the TTOP model does not rely on these assumptions. The input data may be limited in quality but the results show that the approach is valid and they demonstrate that permafrost distribution and conditions can be mapped using an analytical model. This approach also allows the input factors to be manipulated which then permits future conditions to be estimated under changed conditions. This could not be done with published maps as it would require an arbitrary extrapolation of current conditions. Furthermore, the precise relationship between climate and permafrost was not explicit. With data improvements there should be fewer impediments to modelling current and future permafrost conditions sufficiently using the TTOP model.

A further problem with the study is that, like earlier attempts at mapping permafrost, the continuity of permafrost is still dependant on map scale, cell size and the degree to which the assumptions of terrain and vegetative homogeneity are warranted. Again, this is not a problem with the model itself but rather the spatial precision of the

data used. It is possible to use the TTOP model at a variety of scales depending on the particular needs.

4.1.3. Utility and Interpretation of TTOP

Previous permafrost maps (e.g. Brown 1967, Ferrians 1965) delimited areas of permafrost as 'continuous' and 'sporadic'. However, in an area of 'continuous' permafrost it was still possible to find locations without permafrost, due to local factors. This is due to the variability of factors which cause permafrost, which make it very difficult to say that a large area is 100% permafrost. Instead, researchers would choose an arbitrary percentage, such as 80%, and say that areas with more than 80% were continuous permafrost. The results of the TTOP map can be viewed in a similar manner. The colder the temperatures are, the more extensive permafrost is likely to be in a particular area. Areas with TTOP values close to zero could be viewed in a similar manner as the areas on previous maps which were classed as 'sporadic' permafrost. Permafrost in both areas is likely to appear in locales most susceptible to permafrost, such as organic soils, and absent in less prone areas, such as those near water bodies.

Another element of the TTOP map to remember is that the temperature value is those at the top of permafrost and not at depth. Since climate has not been stable for the past few thousand years, permafrost at depth will not necessarily be in thermal equilibrium with current surface conditions. Areas where the climate was formerly too

warm for permafrost may since have cooled. Since these areas will contain permafrost at the surface, and the TTOP output value will be below zero, they will be correctly predicted. Conversely, areas where permafrost was well established in the past and where surface conditions are no longer able to maintain it, will still have permafrost while the TTOP value given will indicate an absence. The only way to predict the occurrence of these relict (Harris *et al.* 1988) areas would be to use past climate data to determine past conditions and then extrapolate those depths of permafrost in the past to the present using some rate of melting. Chances are, however, that areas which are currently in thermal disequilibrium will have been in that state for some time. They will have already completed a significant amount of near surface thawing and may already have thawed beyond the near surface areas where excess ice is typically found. As such, the inability to predict these areas is not seen as a serious problem.

4.1.4. GCM Projections and TTOP

In order to predict future permafrost conditions, it is necessary to have a projection of future climate. The GCM's available provide such projections; however, their output is very generalized and coarse grained. Before using them for future scenarios, it is important to assess their accuracy. To estimate how well they represent reality, the 1 x CO₂ projection, which should roughly model current conditions, was used with the TTOP model to estimate current permafrost conditions. This output map was

compared to the map produced with actual climate data and the published permafrost map to determine how well they match.

Overall, the 1 x CO₂ version (fig. 11) has many similarities with the other two permafrost maps. Like the published map, it consists of very broad bands of temperature which is due to the generalized nature of the GCM output. There are some small areas with increased detail, since the surficial materials data used was not from a GCM. The pattern of the isotherms resembles the original TTOP map, with cool temperatures dipping the lowest in central Canada around Hudson Bay and rising northward to the west and east. The point where the 1 x CO₂ version diverges from the other two permafrost maps is the actual temperatures; it consistently shows cooler temperatures throughout the whole country. The most likely cause of this is an error in the GCM output.

The relative effect of the precipitation and temperature aspects of the GCM output was compared, by producing TTOP maps with GCM precipitation and actual temperature data, and vice versa. The results show that the version with projected precipitation data (fig. 12a) is less like the original TTOP map (fig. 7) than the one with projected temperature data (fig. 12b). It (12a) tends to show more extensive permafrost with the reverse true of the projected temperature map. Both maps (fig. 12) match the distribution in Québec equally, with the projected precipitation map overestimating

1 X CO₂ TTOP

Fig. 11: 1 X CO₂ TTOP; The output of the TTOP model showing temperature at the top of permafrost using projected current climate data. The factor maps used to produce this map are shown in Appendix C.

GCM Temperature and Precipitation Outputs the relative accuracy

Map a: TTOP with actual temperature projected precipitation data.

Map b: TTOP with projected temperature and actual precipitation data.

Fig. 12: The output of the TTOP model showing temperature at the top of permafrost using (a) actual temperature and GCM precipitation data and (b) GCM temperature and actual precipitation data. The purpose of these two maps is to illustrate the relative strength of the two parts of the GCM output.

permafrost conditions and the projected temperature map underestimating them. Throughout the rest of the country, the 0°C isoline in the projected temperature map and the original TTOP version are quite similar, passing through northern portions of Ontario, Manitoba and Saskatchewan and passing to the north of Alberta and British Columbia, delimiting a region of non-permafrost conditions in the southern Yukon and Northwest Territories. The projected precipitation version shows cooler permafrost conditions throughout this area. Therefore, it seems the precipitation projections are the more flawed, resulting in an underestimate of the amount of snow or its duration. While all of the GCM output could benefit from improvements in precision and accuracy, only the precipitation projections need major corrections.

Therefore, even though the two TTOP maps are not identical, the analysis shows that the GCM output can be used to project future permafrost conditions. The only drawback being that the amount of precipitation is probably underestimated, likely resulting in cooler predicted permafrost temperatures.

4.2. Mapping Future Permafrost

4.2.1. $2 \times \text{CO}_2$ TTOP

If one accepts the validity of the GCM projections, it is possible to use the $2 \times \text{CO}_2$ output to project future permafrost conditions. There are two elements to the GCM projections. First, they attempt to project current conditions and second, based on

expected changes, they attempt to project future conditions. Both of these processes are open to errors. The amount of error involved in projections of current conditions has already been analyzed in the comparison between the 1 x CO₂ and other permafrost maps. To accomodate this error, a second 2 x CO₂ map was produced. The first 2 x CO₂ map was made using the actual 2 x CO₂ projected values. The second, a corrected 2 x CO₂ TTOP output map (called scaled TTOP), was produced using the current conditions TTOP map as a starting condition rather than the 1 x CO₂ TTOP map. The starting conditions were then forced with the amount of climate change predicted to occur between the 1 x and 2 x CO₂ GCM output. The factor maps used to produce the scaled TTOP map are in Appendix F.

Since the 2 x CO₂ TTOP (fig. 13) map was produced using GCM output, the spatial precision is low and the appearance is one of broad bands of similar temperatures, with some geographical small variation due to R_k . The same is not true of scaled TTOP (fig. 14). This map appears as if no GCM output was used, which is misleading as the amount of warming has been applied in broad bands. The reason for the less generalized apperance is that the starting temperature and precipitation values were based on actual and not GCM values. This map should give a more reliable projection of future conditions than the one based on 2 x CO₂ GCM output since the errors in projecting current conditions from GCM output have been removed.

2 X CO₂ TTOP

Fig. 13: 2 X CO₂ TTOP; The output of the TTOP model showing the temperature at the top of permafrost using projected future climate values. The map projects permafrost conditions for a CO₂ concentration of 660 ppm, projected to occur around 2050-2100 (DOE Climate Change Committee 1990, Leggett 1990). The factor maps used to produce this map are shown in Appendix D.

Scaled TTOP

based on current conditions and projected change

Fig. 14: Scaled TTOP; The output of the TTOP model showing the temperature at the top of permafrost using actual current climate data and the amount of change projected to occur between current and future GCM projections. The factor maps used to produce this map are shown in Appendix F.

The 2 x CO₂ TTOP map (fig. 13) shows permafrost present only in the central to northern portions of the Territories, the Arctic Islands and a small area at the very northern tip of Québec. The scaled TTOP map (fig. 14) shows even less extensive permafrost. In this map, only north and eastern Nunavut retain TTOP values of less than 0°C. Even some of the Arctic Islands, such as Baffin Island, no longer have complete extent of permafrost. However, most of the Arctic Islands fall in the range of values outside the limits of the N_F function (Appendix E) and, as such, the resulting temperatures should be viewed with some caution. The only other area which maintains permafrost is in the southwestern Yukon right on the Alaskan border. Considering the area in which the values occur, a northern region with few measurement locations, it is possible that those values are in error. However, it is in the mountains and in a region of permanent ice so the values are plausible. It is quite possible that permafrost would not actually occur immediately below permanent ice, but the surrounding regions would likely have deep permafrost provided that they had been glacier free for some time.

4.2.2. Precipitation Projections

In the 1 x CO₂ analysis, it was judged that the GCM precipitation amounts were underestimated. It is possible that the errors in the GCM output are either random or systematic. If the errors are systematic, it is probable that the amount of change between 1 and 2 x CO₂ is accurate but the starting point is not. If this is the case, the scaled TTOP map will give a more accurate projection of future permafrost. However, if the errors are

random, there is no way of knowing if they were only present in the 1 x CO₂ version. This presents a possible cause of error in the final map which could only be determined through an extensive analysis of GCM methods and outputs.

With no way to re-estimate the precipitation values, the analysis of precipitation was restricted to determining what effect various amounts of precipitation would have on permafrost temperature. Two maps were created, using current air temperature values: the first had the precipitation values doubled (fig. 15a) and the second had them halved (fig. 15b). A comparison between the two shows clearly how important precipitation is to the temperature and extent of permafrost. Less precipitation causes the area of sporadic permafrost to cover most of the prairies, with cold permafrost enveloping almost all of the Territories region and northern Québec. Conversely, an increase in precipitation eradicates most of the cool permafrost and maintains cold permafrost only on the northern Québec and Territorial borders, in northern and western Nunavut and the Arctic Islands.

4.2.3. Amount of Change

To better visualize how permafrost conditions can be expected to change, the future conditions maps were overlayed on the present conditions maps to show the amount of change. Both maps (figs 16, 17) used the scheme explained in Table 4, which separates areas of the country into three categories. In the first, in brown, permafrost is

Current TTOP with Snow at 50 and 200%

Map a: TTOP with projected temperature data and 50% precipitation.

Map b: TTOP with projected temperature data and 200% precipitation.

Fig. 15: The output of the TTOP model showing temperature at the top of permafrost using projected current temperature data and actual precipitation data with the precipitation data multiplied by 50 (map a) and 200% (map b).

Projected Change in Permafrost Temperature based on GCM projections for current and future conditions

Fig. 16: Change in TTOP: This map shows the amount of change projected to occur in permafrost conditions separated into several categories. Areas projected to remain permafrost free are classified as 'no permafrost', areas projected to lose permafrost are classified as 'unstable'. The remaining areas are separated into categories showing how close they will be to 0°C or, for areas more than 2°C below zero, how much they are expected to warm in °C. The categories are explained further in table 3. The results were determined based on GCM projections for current and future conditions.

Projected Change in Permafrost Temperature based on current conditions and projected change

Fig. 17: Corrected Change in TTOP: This map shows the amount of change projected to occur in permafrost conditions separated into several categories. Areas projected to remain permafrost free are classified as 'no permafrost', areas projected to lose permafrost are classified as 'unstable'. The remaining areas are separated into categories showing how close they will be to 0°C or, for areas more than 2°C below zero, how much they are expected to warm in °C. The categories are explained further in table 3. The results were determined based on current climate data and the amount of change projected to occur between current and future GCM projections.

not present under either current or future conditions. The second, in yellow, maintains permafrost under current conditions but not under projected future conditions. The third, in various shades of green and lighter blue, contains regions which maintain permafrost under both current and future conditions but with a changed temperature.

Table 4: Categories used to classify future permafrost conditions

Category	Description
no permafrost	Regions where the current conditions do not support permafrost
Regions where the current conditions support permafrost and future conditions:	
unstable	do not support permafrost
within 1°C	are within 1°C below zero
within 2°C	are within 2°C below zero
increase of 0-5°C	are more than 2°C below zero and have increased by 0 - 5°C
increase of 5-10°C	are more than 2°C below zero and have increased by 5 - 10°C
increase of >10°C	are more than 2°C below zero and have increased by at least 10°C

The map which is believed to be the most accurate projection of future permafrost conditions is the scaled TTOP map (fig. 17). In this map, the first area is of little interest as there is no change in permafrost conditions. The second category is much more important however. In these areas, permafrost should exist currently but sometime before 660ppm atmospheric CO₂ concentration is reached, the climate warming would begin to degrade it. This would cause numerous changes as described previously. The map shows that this region of probable unstable permafrost conditions is very widespread in Canada. It extends from the southern boundary north, encompassing all of northern Labrador, Québec, Manitoba and Saskatchewan, some of northern Ontario

and Alberta, most of the Yukon and Northwest Territories, the south and western portions of Nunavut and the southern portion of Baffin Island. Most of the rest of mainland Canada has a projected future TTOP within 2°C of zero which suggests that very little further warming would be required to thaw these regions as well. Even in the third group where surface temperatures are not projected to warm to the point of thaw there is still some concern where the ground has warmed considerably, since, even without thawing, a warming of the permafrost will cause changes in the properties and behaviour of the ground.

The third group has been subdivided into sections which indicate how close the final projected temperatures are to zero (within 1, 2 or more than 2°C) and, for areas which remain below -2°C, how much of a warming has occurred. This provides an indication of how much more warming would be needed to make areas near zero unstable or, where they are several degrees below zero, how much the TTOP temperature has increased.

The results of the above analyses show that the state of permafrost in Canada is, for the large part, precarious. Both versions of the 2 x CO₂ output map indicate that slightly less than 60% of Canada's permafrost covering 27-28% of its land area is seriously threatened with eradication (Table 5), should projected climate warming come to pass. The only area where permafrost appears consistently stable is in the Arctic

Islands with the exception of Baffin Island, the extreme northern border of the Territories and northeastern Nunavut. However, since most of this area is outside of the parameter range of the N_f function, no firm conclusions on these regions' stability can be drawn.

Table 5: percentages of areas from 2 x CO₂ projected permafrost maps

	Scaled 2 x CO₂	2 x CO₂
unstable	28 %	27.4 %
within 1°C	3 %	4.9 %
within 2°C	3.1 %	3.4 %
increase of 0-5°C	0.4 %	0.9 %
increase of 5-10°C	7.4 %	16.4 %
increase of 10+°C	6.8 %	6 %
no permafrost	51.3 %	41 %

CHAPTER 5

Conclusions

The main purpose of this study was to evaluate a method that would permit a functional analysis of specific aspects of the permafrost environment, in particular, the effect of climate conditions and surficial geology on the systematic distribution of permafrost in Canada. The TTOP model used is based on these main factors which it organizes into two offsets. The first offset accounts for the difference between the air temperature and the temperature at the ground surface while the second accounts for the difference between the ground surface and the top of permafrost. The model assumes that the existence of permafrost can be modeled based solely on these factors but is not restricted by any assumptions of the data itself. The results from the model were compared to the published ground temperature map by Heginbottom et al. (1995). That comparison showed that the two maps were very similar, especially in northern Canada, the Arctic Islands, Québec and Labrador. In the south, there is increased detail in the TTOP map which made the comparison less apparent but there was still general agreement between the two. This demonstrated that the TTOP model is capable of reproducing the current permafrost conditions as well as present published maps do, with

the benefit that it allows for the manipulation and analysis of its variables. This in turn permits the analysis of the effects of changes in input variables on the permafrost environment.

A second purpose of the study was to apply the TTOP model to estimate the future permafrost conditions of Canada under expected climate warming. This was accomplished by first testing the accuracy of projections of current conditions. A comparison of these results to the previous maps showed that the climate projections slightly overestimated current permafrost conditions. It was suggested that this was most likely due to problems in the projection of precipitation and not temperature conditions. Using the future climate projections and assuming that they are as accurate as current ones, the results showed that a significant portion of Canada's permafrost, approximately 28% of its land area, faces degradation within the next 50 to 100 years should climate change come to pass as expected. The areas most affected would be the majority of mainland Canada currently underlain by permafrost, including the northern portions of Labrador, Québec, Ontario, Manitoba, Saskatchewan and Alberta. The area of degradation would include almost all of the northern Territories except for the extreme north coast which could expect to find surface permafrost temperatures within a few degrees of melting. Even the Arctic Islands and the extreme northeastern portion of Nunavut, essentially the only areas which would remain stable, could expect a rapid warming of ground temperatures with the resultant effects.

These two findings establish a starting point for further studies. While this study looked at Canada as a whole, modeling at that scale cannot correctly estimate microscale conditions. The study has determined the extent of the problem for Canada but not the specific locales where change would occur. What is needed next is research at more detailed scales with more precise data to determine what exactly the effects would be at local scales.

The TTOP model could be used with localized data to precisely present permafrost conditions at that scale. These conditions could then be verified through site studies. Afterwards, by using projected climate warming projections, the future state of permafrost at specific places in Canada could be determined. By adding a rate of thaw, the lengths of time to eradication could also be resolved. At the site scale, consideration could also be made as to the makeup and ice content of the ground. For example, if the ground is made up of thin soil over bedrock then the effects of permafrost warming would be much reduced. The result of a study of this kind would elucidate how exactly the permafrost at that area would change and this type of study of future changes can only be completed with a method that does not rely on the assumptions of the original climate. In that regard, the TTOP model is perfect. A useful addition to an analysis with TTOP would be to add an element of past conditions to account for relict permafrost.

One goal in this study of the broad analysis of Canada was to indicate which regions of Canada would most likely be of interest for a more in depth study of permafrost conditions. As it is, according to the analysis, most of the permafrost underlain portions of Canada fall within areas of interest due to the serious concerns of degradation and warming. Therefore, although the study was not useful in eliminating areas from the realm of interest by establishing them as solidly within the region of stable permafrost conditions, it did demonstrate how widespread the problem could be. Considering the variety and seriousness of changes to the environment which would be caused by a change in the cryotic conditions of the ground and the large extent of areas to be affected, further studies are urgently needed. With the importance of the permafrost environment to Canada and the significant levels of thaw expected, it is an issue which can be ignored only at our peril

Appendix A: Interpolation Methods

Justification

When deciding what methods and values to use when interpolating, it was noted that the data available varied significantly from the north to the south. It was decided to use the same choices for the entire country to avoid the problem of how to join the areas with different values. Then, when choosing values, the needs of the northern regions of Canada were considered to be paramount to those of the south as it is in the northern regions where the effects of permafrost are expected to be most significant. After trying numerous combinations of interpolating criteria, the following were found to best reproduce Canadian values:

	Interpolation Method 1	Interpolation Method 2
Output grid cell size	10 000 m	10 000 m
Interpolation method	Inverse Distance Weighting (IDW)	IDW
neighbour / radius	nearest neighbour	nearest neighbour
number of neighbours	3	6
Power	2	2
Barriers	none	none

Output grid cell size:

The value was chosen as the smallest size which could be readily manipulated with the computing power available. A larger number would have caused the output maps to appear very generalized and would have decreased the overall precision.

IDW:

Inverse distance weighting was chosen as it treats each point as having a local influence that diminishes with distance. The alternative, spline, is ideally suited to gently curving surfaces which is not always the case here. For example, the representation of snow cover thickness as a smooth field is not particularly compatible with small geographical scales, as it causes topographic heterogeneity to be effectively ignored. Unfortunately, as there is no alternative to interpolating a surface, the only solution is to limit the smoothing algorithm used.

Nearest neighbour:

Nearest neighbour was chosen as the number of points varies so immensely from area to area, that using a fixed area would result in wide discrepancies in the number of points considered. If a fixed area was used, in order to ensure that all areas in the north contained at least a few points to determine an average within a given area, regions in the south would have been averaging huge numbers of points and eliminating any value received from the greater extent of measuring sites.

Number of neighbours:

A value of three was used when interpolating the original snow and climate data maps to reduce the importance of distant points. While in the south, a much higher number could have been used, in the north, the points are so distant that to include more points in the average would entail averaging over tremendous distances. A value of 6 was used when interpolating the CO₂ data layers as that was the smallest number that did not produce large unsightly blocks of like values.

Power:

This value was left low as the influence of distant points was considered to be of low importance. In the north, considering distant points would eliminate the benefit of the few local measuring sites available.

Barriers:

No barriers were used as, in the far north, any major barriers used such as elevation or coastlines would result in some areas having no measured values within the barriers. In the south, the measuring sites are in such close proximity that very few areas will be averaging values from across a major barrier such as mountains or coastlines.

Appendix B: Factor Maps for TTOP

The TTOP map was created using the formula:

$$\{(TDD \times Nt \times Rk) - (FDD \times Nf)\} / P = TTOP$$

Where:

TDD: determined from current data (Environment Canada 1994), final map shown here.

Nt: 1

Rk: determined using Johansen (1975) and based on the surficial geology map of Canada (Fulton 1995).

FDD: determined from current data, (Environment Canada 1994) final map shown here.

Nf: calculated from current TDD, FDD and snow data (shown here) (Environment Canada 1994, 1998), final map shown in Appendix E.

P: 365

Thawing Degree Days

Thermal Conductivity Ratio

Freezing Degree Days

Average Snow Depth

Appendix C: Factor Maps for 1 X CO₂ TTOP

The 1 X CO map was created using the TTOP formula:

$$\{(TDD \times Nt \times Rk) - (FDD \times Nf)\} / P = TTOP$$

Where:

TDD: determined from GCM data, final map shown here

Nt: 1

Rk: Unchanged from original TTOP calculation, shown in Appendix B

FDD: determined from GCM data, final map shown here

Nf: calculated from GCM TDD, FDD and snow data (shown here), final map shown in Appendix E

P: 365

Thawing Degree Days

Freezing Degree Days

Average Snow Depth

Appendix D: Factor Maps for 2 X CO₂ TTOP

The 2 X CO₂ map was created using the TTOP formula:

$$\{(TDD \times Nt \times Rk) - (FDD \times Nf)\} / P = TTOP$$

Where:

TDD: determined from GCM data, final map shown here

Nt: 1

Rk: unchanged from TTOP calculation, shown in Appendix B

FDD: determined from GCM data, final map shown here

Nf: calculated from GCM TDD, FDD and snow data (shown here), final map shown in Appendix E

P: 365

Thawing Degree Days

Freezing Degree Days

Average Snow Depth

Appendix E: Areas Outside Nf Parameters

The Nf model used was unable to accept extreme values. As such, it was not possible to model areas with very high snow cover or very low temperatures. Areas which fell outside of the boundaries are indicated here and final TTOP results for those areas should be discounted.

Nf values for original TTOP calculation

Nf values for 1 x CO₂ TTOP calculation

Nf values for 2 x CO₂ TTOP calculation

Nf values for final (scaled) TTOP calculation

Nf value for TTOP calculation with precipitation at 50%

Nf value for TTOP calculation with precipitation at 200%

Appendix F: Factor Maps for Scaled TTOP¹⁰³

The final TTOP map was created using the TTOP formula:

$$\{(TDD \times Nt \times Rk) - (FDD \times Nf)\} / P = TTOP$$

Where:

TDD: determined using actual current climate data and the amount of change projected to occur between current and future GCM projections, final map shown here

Nt: 1

Rk: Unchanged from original TTOP calculation, shown in Appendix B

FDD: determined using actual current climate data and the amount of change projected to occur between current and future GCM projections, final map shown here

Nf: calculated using current climate data and the amount of change projected to occur between current and future GCM projections for TDD, FDD and snow cover (shown here), final map shown in Appendix E

P: 365

Thawing Degree Days

Freezing Degree Days

Average Snow Depth

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