1

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No 2)

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service

Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SAC 1970, c. C-30, et ses amendements subséquents.

**CLIMATE CHANGE AND PERMAFROST IN THE SOUTH MACKENZIE VALLEY: A
METHODOLOGICAL APPROACH**

by

Diane Bernadette Spivey

**A Thesis Submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for
Master of Arts**

**Geography Department
Carleton University
Ottawa, Ontario.**

**© copyright Diane B.Spivey
May 25th, 1990**

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Service Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

ISBN 0-315-60474-3

The undersigned recommend to the
Faculty of Graduate Studies and Research
acceptance of the thesis
"CLIMATE CHANGE AND PERMAFROST IN THE SOUTH MACKENZIE
VALLEY: A METHODOLOGICAL APPROACH"
submitted by Diane Spivey BA (Hons)
in partial fulfilment of the requirements for the degree of
Master of Arts

Thesis Supervisor

Chairman, Department of Geography

Carleton University

June 1990

ABSTRACT

The purpose of this thesis is to identify evidence for climate change in the south Mackenzie Valley and to consider the impacts of such a change on the permafrost terrain of the area. The impacts of climate change are discussed in terms of the energy exchange processes within the buffer layer which links the atmosphere to the ground. A map of vegetation susceptibility to climate change is presented based on the buffer layer structure and dynamics. The impacts of a 2°CO_2 climate change are considered for different vegetation types, and the relationship between climate and tree growth is assessed.

As a definitive answer to the question of climate change is still beyond the reach of science, the main aim of this thesis is to provide a methodological framework for assessing the implications of environmental change.

ACKNOWLEDGEMENTS.

Learning is not a process that can occur in isolation, and many people were instrumental in my learning process as I researched this thesis. My thanks go to my supervisor Prof. Peter Johnson for his guidance, calm philosophy, a ready supply of tea and his positive outlook in the face of cynicism. Prof Mike Smith provided much input and comment and thought provoking discussion. Dr. Alan Judge of the Geological Survey of Canada was instrumental in shaping the direction of this topic. Margo Burgess of the Geological Survey of Canada and Dr Kaye Macinnes of the Department of Indian and Northern Affairs provided me with data and an introduction to the field area.

I enjoyed the hospitality of the residents of Fort Simpson and felt part of their community and my special thanks go to Mr. Joe Mercredi of the Mackenzie Times. His kindness and generosity saved me from the horrors of the campground mosquitoes and supported me through the field season. Mr. Bernie Gauthier and the staff of the Northern Affairs Research Programme provided much technical support for the fieldwork and a wealth of knowledge about the area. The staff of the department of Renewable Resources provided information and technical assistance, and thanks go to Ralph Kermer and Ken Davidge. I would like to thank my brother, Barry Spivey, for spending his Canadian holiday in true Canadian style - communing with mosquitoes and bush bashing in search of

permafrost.

Much technical support was provided by the staff of the geography department, particularly Mr. Larry Boyle and Mr. Alan Pendlington. Mr. Steve Prashker translated the tree ring standardisation programme into basic and helped with many computer technicalities. Wolfgang Haider provided help with the statistics.

Writing a thesis seems like a good idea at the time but the novelty wears off occasionally; thanks to all the grad students in the class of '89-90 who were always ready to seek distractions from work. Special thanks to Sharon Smith for proof reading all of this. Thanks to Megan for the diagrams. Thanks to Susan and Doug Greenfield for being such easy going roommates.

Lastly, my special thanks go to Mr. Douglas Campbell for all his support, his sense of humour and culinary skills at the barbecue.

TABLE OF CONTENTS

	page
Acceptance Sheet.....	ii
Abstract.....	iii
Acknowledgements.....	iv
Table of Contents.....	vi
List of Figures.....	vii
List of Tables.....	viii

CHAPTER ONE: INTRODUCTION

1.1 Context.....	1
1.2 Aims.....	2
1.3 Scope.....	3
1.4 Methodology.....	3

CHAPTER TWO: CLIMATE, ENERGY EXCHANGE AND THE BUFFER LAYER

2.1 Introduction.....	8
2.2 Climate Change.....	9
2.3 The Concept of the Buffer	13
2.4 Permafrost.....	15
2.5 Energy Exchange Processes.....	17
2.6 Energy Exchange Processes in the Buffer Layer	
2.6.1 Organic Layer.....	21
2.6.2 Snow Cover.....	24
2.6.3 Vegetation Canopy.....	25
2.7 Summary.....	29

CHAPTER THREE: CLIMATE AND VEGETATION OF THE STUDY AREA

3.1 Introduction-the Concept of the Ecotope.....	30
3.2 Location of The Study Area.....	30
3.2.1 Climatic Patterns of the Study Area.....	30
3.2.2 Air Temperatures.....	33
3.2.3 Summary.....	33
3.3 Precipitation.....	38
3.3.1 Summary.....	38
3.4 Topography.....	38
3.5 Vegetation.....	42
3.5.1 Landscape Patterns.....	44
3.5.2 Peat Landforms and Permafrost Landscape	
Associations.....	49
3.5.3 Peat Palsa.....	49
3.5.4 Peat Plateaus.....	51
3.6 Buffer Layer and Susceptibility to Climate	
Change.....	51
3.7 Thermokarst Processes of landscape	
Change.....	54
3.8 Geomorphic Mechanisms of Landscape	
Change.....	56
3.9 Effects of Disturbance on	
Terrain.....	61

3.10 Summary.....	63
CHAPTER FOUR: THE IMPLICATIONS OF CLIMATE CHANGE FOR PERMAFROST AND VEGETATION	
4.1 Introduction.....	64
4.2 Surface Temperature - the N Factor.....	65
4.3 The Relationship Between Air and Surface Temperatures.....	66
4.4 Surface Temperature Calculations - the Regional Scenario.....	68
4.4.1Results.....	69
4.4.2 Methodological Considerations.....	74
4.5 Climate Change: The 2*CO ₂ Scenario.....	75
4.5.1Results.....	75
4.5.2 Precipitation Changes.....	77
4.5.3Summary.....	79
4.6 Dendroclimatology.....	80
4.6.1Methodology.....	81
4.6.2Results.....	83
4.6.3Discussion.....	85
4.7 Summary.....	88
CHAPTER FIVE: CONCLUSIONS	
5.1 Summary.....	90
5.2 Conclusions.....	90
5.3 Further Research.....	92
APPENDIX A: Climate data.....	95
APPENDIX B: Vegetation Type Characteristics.....	99
APPENDIX C: Field Site Data.....	101
APPENDIX D: Significance Levels for Climate - Tree Ring Regression.....	106
BIBLIOGRAPHY.....	107

LIST OF FIGURES.

1.1	Landscape as Ecosystem.....	5
2.1	Landscape patterns of the study area.....	8
2.2	Landscape prism.....	10
2.3	Global warming.....	12
2.4	Components of the buffer layer.....	14
2.5	Earth-atmosphere radiation budget.....	19
2.6	Thermal profile through a typical peat bog.....	22
2.7	Ground thermal regime beneath canopy.....	27
3.1	Two times CO ₂ vegetation.....	31
3.2	Location of the study area.....	32
3.3	Mean annual air temperatures.....	34
3.4a	Mean winter temperatures.....	35
3.4b	Mean summer temperatures.....	36
3.5	Mean annual precipitation.....	39
3.6a	Mean winter precipitation.....	40
3.6b	Mean summer precipitation.....	41
3.7	Physiography of the study area.....	43
3.8	Vegetation types of the study area.....	46
3.9	Canopy height.....	47
3.10	Canopy density.....	48
3.11	Raised edge of palsa.....	50
3.12	Buffer layer capability.....	52
3.13	Thermokarst processes of landscape change.....	55
3.14	Collapse edge of palsa.....	57
3.15	Processes acting on a palsa.....	58
3.16a	Leaning trees on palsa edge.....	60
3.16b	Surface cracking of palsa.....	60
3.17	Ground temperature changes on ROW.....	62

LIST OF TABLES.

2.1	Variation of thermal conductivity with snow density..	25
3.1	Percentage occurrence of vegetation types.....	54
4.1	Fort Simpson surface and air temperatures.....	70
4.2	Derivation of thawing and freezing N factors for Fort Simpson grass site.....	70
4.3	Summer and winter N factors for different vegetation types.....	70
4.4	Fort Simpson freezing and thawing air degree days for 1977-1987.....	71
4.5	Fairbanks N factors with Fort Simpson degree days, R values under current climate degree days.....	71
4.6	Maximum and minimum summer thawing degree days and winter freezing degree days.....	73
4.7	R values under maximum and minimum summer and winter degree days.....	73
4.8	Comparison of thawing to freezing degree day ratios for Fairbanks and Fort Simpson.....	74
4.9	2*CO ₂ air temperatures and degree days.....	76
4.10	R values under 2*CO ₂ climate degree days.....	76
4.11	Site eight index.....	84
4.12	Site nine index (long record).....	84
4.13	Site nine index (short record).....	84
4.14	Site eight average index values.....	86
4.15	Site nine average index values (long record).....	86
4.16	Site nine average index values (short record).....	86

CHAPTER ONE

INTRODUCTION

1.1 Context.

... the landscapes which we live in result from a long history of dynamic interplay between botanical, climatic and geological processes upon which human beings superimposed their imprint in the last 150 to 200 years.

(Anderson 1989, 39).

A change in the earth's climate will alter the balance between air and surface temperatures leading to disturbance of the physical environment. A change in the rates of processes which shape the landscape are likely to pose physical, social and economic problems for a world still learning to deal with its environment.

Climate change scenarios utilising two times CO₂ models suggest that climatic warming will occur under increased CO₂ emissions (Bolin, Doos, Jaeger and Warwick 1986). The specific impacts of such a climate change on the physical environment are open to much debate, but the permafrost regions are particularly vulnerable. Changes in mean annual air temperatures as a result of increased CO₂ concentrations will affect ground temperatures. Also increased CO₂ concentrations and increased temperatures may contribute to changes in vegetation growth rates and processes. This in turn may influence microclimate which could buffer the long term effects of macroclimatic changes.

The underlying theme of this thesis is the interlinked nature of environmental factors and processes acting on the

landscape. These factors and processes will be considered from the perspective of the buffer layer which is the biotic link between the atmosphere and the earth's surface (Luthin and Guymon 1974; Smith 1986). The concept of the buffer layer as a moderating influence on atmosphere - ground thermal interactions is fundamental to a discussion on the impacts of climate change. Climate and terrain can each buffer the effects of a change in the other, and it is an examination of these links which this thesis addresses.

The chosen study region lies within the discontinuous permafrost zone of Canada, an area where the impacts of climate change might be most easily detected due to the delicate thermal equilibrium which exists. Permafrost is a thermal condition but its presence contributes to the physical structure of the landscape.

1.2 Aims.

- 1 To assess evidence of climate change from the climate record of the Mackenzie valley over the past one hundred years.
- 2 To assess the mechanisms of landscape change.
- 3 To identify and characterise the buffer layer structure and dynamics of the study area in terms of sensitivity to climate change.
- 4 To model the impacts of a climate change on surface

temperatures for different vegetation types.

- 5 To utilise tree ring chronologies to make some observations on potential future changes in forest growth.

1.3 Scope.

Smith (1988) poses the question

"How can we assess the effects of a regional climatic change on permafrost conditions, given that local conditions exert a strong influence on the ground thermal regime?"

This thesis attempts to provide a broadly based approach to this question.

The basis of the study is drawn from wide but disparate data and literature sources relating to the Mackenzie Valley, including meteorological records, aerial photography, vegetation maps, tree ring chronologies and geothermal data. Field work over the course of two summers allowed for ground truthing of the various landscape associations of soils, permafrost and vegetation.

1.4 Methodology.

The philosophy of a methodology is rarely stated within the natural sciences, as the positivist approach is largely taken for granted. However, answers to research questions are only as good as the methodology they employ and this methodology should be stated to give context to the conclusions.

Climate change is a very complex question to address as

it concerns the global ecosystem. It is important to recognise factors such as the time frame within which climate change is viewed and the scale of observation of the impacts of a change. Both time and scale pose methodological problems for geographers.

This thesis is set in the framework of landscape ecology. The subject matter of landscape ecology is the form, function and genesis of environment in a three dimensional perspective. Firstly there is the visual element, 'landscape as scenery', secondly the chorologic or location in space 'conglomerate of land attribute units or map patterns', and thirdly, landscape as an ecosystem which incorporates the previous elements (See fig. 1.1). Time becomes the fourth dimension of landscape ecology (Zonneveld in Moss 1988). Evans (et al 1989) suggests that such an approach considers

... development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes and management of spatial heterogeneity.

Essentially, landscape ecology is a unifying, holistic approach which can accomodate the various methodologies of each of the separate disciplines which study the earth's surface. However, it is not the only methodological and philosophical approach which recognises the need for a holistic framework of study. Dansereau (1957) has emphasised the 'holocenotic' approach of biogeography - studying the environment as a whole. Rowe (1969) presented

Figure 1.1 Landscape as Ecosystem (Zonneveld in Moss 1988)

the notion of the plant community as a landscape feature and emphasised the combined role of ecological and geomorphological interpretation of the landscape in an early paper on the role of landscape ecology.

Wright (1981 in Riseborough 1986) suggests that two approaches to permafrost-climate studies have been adopted in North America, that of computer simulation modelling, and that of correlation between permafrost and terrain characteristics. Riseborough (1986, 3) has criticised the spatial correlation approach as follows,

The principal drawback of this approach is that it identifies whole systems (i.e. climate-vegetation-soil associations) without identifying the components of the system which are responsible for the association with permafrost.

However, the computer simulation approach, while identifying the significant controls on the ground thermal regime, also simplifies certain inputs to the system. An integration of the two approaches is necessary for land management and land use decision making at the regional scale.

The landscape ecology approach employed in this thesis allows for an holistic approach to the problem of climate change. By utilising the methodological and philosophical tools of landscape ecology it is possible to integrate the methodological constraints of time and scale and also incorporate spatially correlative and computer simulated data. This thesis utilises regional data within a conceptual

framework to examine key issues of climate change for the subarctic.

The data sources presented as evidence for climate change are applied at different levels within the ecosystem, both horizontally and vertically. The redistribution of energy within a system is an important characteristic of landscape ecology and a particular focus for this thesis. Meteorological information, ground thermal data, tree core chronologies and landscape attribute data all contribute to an examination of the impacts of climate change. Within the context of the landscape ecology approach, each of these sources of information can be woven into a methodological framework which builds upon each "piece". This may not provide immediate answers to the questions being addressed, but it does give some indication of the relationships between the different areas where one might look for answers.

CHAPTER TWO

CLIMATE, ENERGY EXCHANGE AND THE BUFFER LAYER

2.1 Introduction.

The environment is a function of the landscape and the atmosphere.

Environment can be conceived [of] not only as factors (such as radiant energy, moisture and chemical compounds) but also as the form and structure of the landscape ecosystem at any particular geographic place. (Lavkulich 1972).

Landscape, also referred to as terrain, is the totality of the earth surface form and its geological basis. Landform is the structure of the landscape of which both soils and vegetation are a function (ibid).

"... at all scales, landform controls climatic regime-the fluxes of energy and materials at the earth's surface where [the] atmospheric layer meets [the] earth..." (Rowe in Moss 1988, 39).

Figure 2.1 Landscape patterns of the study area

To understand the impacts of climate change upon terrain one must first understand the characteristics of the earth layer - geology, surficial deposits and vegetation, and its interactions with the atmosphere (fig. 2.1). Terrain has a spatial pattern and a vertical structure, and within a landscape ecology approach one can view the vertical links between each of the spatial patterns of these layers (Fig 2.2). If this approach is to be of some use it must be able to characterise the topographic expression of the surface in quantitative and qualitative terms based on a few key principles. This chapter will explore the concept of landscape as an ecosystem by examining some of the fundamental links between climate and terrain. The presence of frozen ground is of obvious concern if climate warming occurs, and a knowledge of where such ground will be affected is vital to current and future land use.

2.2 Climate Change.

The earth's climate, as a dynamic system, is always changing. However, the concern for climate change has been increasing over the last decade as studies suggest that air temperatures are rising globally (Thompson 1989). Such concern stems from the increasing amounts of what have been popularly termed "greenhouse gases" being emitted into the atmosphere. These gases are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons and

Figure 2.2 Landscape prism to show relationships between the geosphere and landscape components (after Fortescue, 1980 in Moss, 1988).

tropospheric ozone (O_3). While they are produced through natural processes, their concentration in the atmosphere appears to be increasing at an accelerated pace due to the activities of humankind (Bolin, Doos, Jager and Warrick 1986). Water vapour is also a "greenhouse" gas and the most abundant. The greenhouse effect is so called as these gases are transparent to incoming solar radiation but they absorb the outgoing longwave radiation and serve to warm the lower atmosphere (Bolin et al 1986, 2; Harvey 1988, 2). Although these gases only account for a miniscule fraction of the atmosphere their absence would result in a 30-40°C reduction in the earth's surface temperature (Thompson 1989, 326). The rate at which these trace gases are increasing in the atmosphere is still uncertain. However, Thompson's paper suggests that CO_2 concentrations have increased from 316 ppm in 1958 to 345 ppm in 1985. Figures for pre-industrial levels vary from 270-290 ppm.

Climate, on a global scale, is also influenced by changes in solar output, variations in planetary alignment and the strength of the earth's magnetic field (Thompson 1989). However, short term climatic change is most likely influenced by changes in trace gas and dust particle concentrations, the latter being the result of variations in volcanic activity and increased dust loading due to the impact of human activities on deforestation and land degradation (Thompson 1989). Available data indicates that globally we have experienced a

Figure 2.3 Annual average global temperatures (in Thompson 1989, after Gribbin 1988)

warming trend since the end of the last century up to 1940, with a cooling period to the mid- 1960s and a steady warming trend to the present (Bolin et al 1986, 17; see fig 2.3). Dickinson (in Bolin et al 1986, 263) suggests that higher latitudes will experience greater warming and increased precipitation than lower latitudes. Lachenbruch et al (1988) find evidence for a rapid warming having occurred over a large area of the Alaskan arctic (10^5 km^2), based on the temperature profiles of surface permafrost.

2.3 The Concept of the Buffer.

The relationship between air temperatures and ground temperatures is not straightforward. Ground temperatures can vary greatly within the same climatic region even over very short distances, due to differences in vegetation, soil type, geology, slope, aspect, drainage and snow cover which influence the local radiation-heat balance (Kudryatsev et al 1973).

Luthin and Guymon (1974) conceptualised these factors as part of a buffer zone which links the atmosphere to the mineral soil through a series of complex energy exchange mechanisms. The components of their buffer layer model are the vegetation canopy and the organic layer, with snow cover as an important seasonal variable (See figure 2.4, and refer also to fig 2.1). Other variables such as latitude, slope angle and aspect are also important controls on the ground

Figure 24 Components of the Buffer Layer

(after Luthin and Guymon, 1974)

thermal regime as they determine the net solar radiation recieved by a site. Geology, soil type and drainage conditions all have a bearing on the thermal conductivity of soils. There is an important interrelationship between soil moisture regime, vegetation canopy and the organic layer.

Riseborough and Burn (1988) identify "three soil interfaces across which exchanges of energy and moisture occur"

- A Between atmosphere and organic horizon.
- B Between organic horizon and mineral soil.
- C Between frozen and unfrozen mineral layers.

With reference to the presence of permafrost in the discontinuous zone the key interface is the organic horizon. The concept of the buffer as a link between atmosphere and ground illustrates the interdependency between the different components within this transition layer. Due to this intrinsic overlap some degree of repetition is unavoidable in the following discussion.

2.4 Permafrost.

Permafrost is a thermal condition and is defined as ground remaining frozen, i.e., below 0°C, for two years or more (Muller in French 1983). A portion of the ground immediately beneath the surface will thaw seasonally and this is referred to as the active layer (ibid). The depth to which the soil is permanently frozen, and seasonally thawed, depends on the surface temperature and the thermal conductivity of the ground. The base of permafrost occurs at a depth where the

geothermal heat flux, the heat emitted by the interior of the earth, just offsets "the amount by which the freezing point exceeds the mean surface temperature" (Williams and Smith 1989). Characteristics of the soil thermal regime which contribute to the presence of permafrost are beyond the realms of this discussion; further details can be found in Lunardini (1977), Farouki (1986), Williams (1982) and Williams and Smith (1989).

Permafrost is commonly divided into continuous and discontinuous zones on the basis of mean annual air temperatures (Brown 1973). Continuous or widespread permafrost occurs in areas where the mean annual air temperature is below -5°C . The boundary of the discontinuous or sporadic zone lies between -5°C and -1°C . Here areas of frozen and unfrozen ground coexist due to the difference between the air and ground temperatures resulting from variations in surface microclimate.

Provided that permafrost is maintained in thermal equilibrium with its environment, then the physical presence of frozen ground is of no major concern. However, a change in the regime of the energy exchange processes which lead to surface warming can lead to permafrost degradation. Thermokarst subsidence refers to the settlement of the ground surface due to the melting of ground ice (French 1983). The depression caused by the melting of ice then establishes its own thermal effects on the environment (Burn and Smith 1988).

Thermokarst can lead to ground subsidence, erosion and landslides.

Climate change predictions suggest that the earth is likely to experience atmospheric warming which will alter the surface energy balance, particularly in northern regions. If this scenario is true then it is important to identify those landscapes associated with permafrost and the energy exchange regimes in effect.

2.5 Energy Exchange Processes.

Solar radiation is the only energy input to the earth-atmosphere system, if one ignores the minor contribution from geothermal heat flowing from the earth's core (Oke 1978). Under equilibrium, over the period of a year exactly the same amount of energy which entered the system must be lost from it; if an imbalance occurs, climate will change (Oke 1978; Lunardini 1981). To understand how, one has to consider the energy exchange processes that partition the solar input.

Both the sun and the earth emit radiation, but they differ in their radiative characteristics, the sun emitting short wave (K) radiation and the ground emitting long wave (L) radiation in the simplest analysis (Williams 1982). The amount of radiation which reaches the ground, assuming a dry surface with no atmosphere, is given by the following equation (Williams and Smith 1989, 66)

$$Q^* = K\downarrow (1-\epsilon) - L\uparrow + L\downarrow , \text{ where}$$

Q^* = net all wave radiation
 K = short wave radiation
 ϵ = albedo of the surface
 $L\uparrow$ = outgoing long wave radiation
 $L\downarrow$ = incoming long wave radiation

The long wave radiation components of the equation are determined from the Stefan-Boltzmann equation (in Williams 1982, 109):

$$L = e \sigma T^4 , \text{ where}$$

e = emissivity of the surface
 σ = Stefan-Boltzmann constant
 T = absolute temperature of the surface in kelvin

These two factors determine the temperature of the earth's surface but the atmosphere will affect the incoming and outgoing radiation (Fig 2.5).

Cloud cover can intercept incoming short wave radiation and scatter or absorb it; so, too, can dust particles, water vapour and gases, which limits the amount of radiation which reaches the buffer layer (Lunardini 1981; Oke 1978; Rosenberg, Blad and Verma 1983). However, clouds, dust and "greenhouse" gases can also intercept outgoing shortwave radiation, absorbing it and reflecting it back to the surface. The amount of radiation which reaches the earth's surface will also depend on the zenith angle, which is the angle of the sun to the normal of the earth's surface. This depends on the

THE EARTH—ATMOSPHERIC RADIATION AND HEAT BALANCE MODEL

Figure 2.5 The earth-atmosphere radiation balance.
(after Lutgens and Tarbuck 1986)

time of day or year and the latitude of the surface, as well as topography and slope (Lunardini 1981, 214).

Surface temperature response to changing air temperature is complicated by a set of energy exchange processes. Through these processes the energy from radiation (Q^*) is partitioned into the following components

$$Q^* = Q_{LE} + Q_H + Q_G \quad , \text{ where}$$

Q^* = the net radiation,
 Q_{LE} = latent heat transfer into atmosphere
 Q_H = turbulent transfer of sensible heat into atmosphere
 Q_G = energy conduction to ground

Latent heat is the release or absorption of heat energy associated with a phase change (Williams 1982) and is determined by the available moisture and radiation (Williams and Smith 1989). The transfer of sensible heat Q_H , is the energy exchange involved in the 'warming or cooling of air' and is dependent on the temperature gradient between the air and the surface, windspeed and surface roughness. Heat conduction to the ground is driven by the temperature gradient and governed by the conductivity of the ground surface materials and the presence of moisture. For a fuller discussion of the processes and concepts involved in the energy exchange process see Lunardini (1981), Oke (1985), and Williams and Smith (1989).

While the balance between these energy exchange processes can vary from minute to minute, from day to night and day to

day, it is the year to year variations which are of interest in considering the impacts of climate change on permafrost.

Kudryatsev et al (1973) refer to the net interactions of these energy exchange processes as the radiation-heat balance. Knowledge of the surface radiation-heat balance is of vital importance in making accurate predictions about the impacts of climate change. The following sections will highlight some of the characteristics of the buffer layer which determine this.

2.6 Energy Exchange Processes in the Buffer Layer.

2.6.1 Organic Layer.

The presence of permafrost within the discontinuous zone is largely determined by an overlying peat layer (Brown 1968, Figure 2.6). The changing thermal properties of peat through the seasons help to maintain the thermal conditions necessary for preserving permafrost. These thermal properties are influenced by the nature of the surface vegetation, moisture status of the site, edaphic properties of the organic layer and macro-climate (Zoltai 1971; French 1983). Riseborough (1986) found that the hydrological properties of the organic layer regulate ground thermal conditions.

During the summer, the transfer of energy in terms of incoming shortwave radiation, is largely taken up in the evaporation of water in moist peat. Peaty materials tend to have high volumetric heat capacities due to their ability to

Figure 2.6 Profile through a typical peat bog in the southern fringe of the discontinuous permafrost zone (after Brown 1965 in Lunardini 1981)

retain large amounts of water within the mossy material of which they are largely composed. When dry, peat has a very low thermal diffusivity; in dry sphagnum it is an order of magnitude less than the lowest value for mineral soil (Brown and Williams 1972,20). Riseborough and Burn (1988) suggest that the thermal diffusivity (K) of the top 5cm of the organic layer can be inversely related to a drying index. This limits the amount of subsurface warming which can occur as the organic material buffers the ground from surface temperature effects and results in a relatively shallow active layer in comparison to other terrain types.

The moisture-dependent thermal diffusivity of the upper part of the organic layer, combined with consistently low thermal diffusivity of the lower part, is primarily responsible for the maintenance of cool conditions in the mineral horizon of the active layer. When the organic material is moist and has a high K value, evaporation lowers the ground surface temperature. As the organic material dries and the surface temperature rises, K declines, inhibiting propagation of the surface temperature wave. (Riseborough and Burn 1988).

The insulating role of the organic layer in summer is due to its low thermal diffusivity, and helps maintain permafrost. In winter the reverse occurs. Frozen wet peat has a much higher thermal conductivity due to the freezing of the moisture which was replenished in the autumn. Once frozen, cooling can occur to a much greater depth than warming in the summer. However, two factors contribute to restrict the rate of heat loss from the ground during winter. Initially peat has a higher apparent heat capacity due to the latent heat released from it as the water within freezes. The second

influence on heat retention is due to snow cover as it provides a natural barrier between atmosphere and ground but frozen peatlands tend to be elevated above the surrounding terrain and consequently are more exposed and less likely to retain a deep snow cover (French 1983). Vegetation cover above the peat layer also plays an important role but this will be discussed seperately in section 2.6.3.

2.6.2 Snow Cover.

Snow acts as a buffer between the air and the ground modifying the amplitude of the ground surface temperature variation by increasing the temperature gradient between the two. The key factors are its depth and density, and its albedo. The albedo of the snow limits the amount of radiant energy which is absorbed at the surface. The snow surface reflects radiation depending upon the nature of the incident radiation and the structure of the surface snow (Yen 1969).

Snow depth determines the extent to which the ground freezes in winter and subsequently thaws in summer. A study by Taylor et al (1982) at Alert found that mean annual ground temperatures were several degrees higher beneath a snow cover than mean annual air temperatures. Goodrich (1982) suggests that the presence of a snow cover can raise the mean annual ground temperature as it acts as an insulating material. The insulating ability of the snow varies with depth and density. The density of the snow pack influences the thermal

conductivity, the denser the snow the greater the conductivity, due to decreasing air spaces (Nicholson and Granberg 1973). Crawford (1951) presents data to illustrate the increasing thermal conductivity of snow with increasing density (Table 2.1)

Beyond a critical depth there is little change in the thermal conductivity and years of shallow snow cover are critical in maintaining permafrost within the discontinuous zone (Nicholson and Granberg 1973). Granberg (1973) found a strong relationship between snow depth and terrain roughness, as terrain roughness affects wind velocity, and sharp breaks in relief cause boundary layer separation. This aspect of snow cover is described in section 2.6.3.

Month	Average Density	Thermal Conductivity
November	0.139	.00029
December	0.182	.00033
January	0.193	.00037
February	0.189	.00035
March	0.233	.00045
April	0.279	.00057

Table 2.1 Variation of the average density and thermal conductivity of snow cover (After Crawford 1951).

2.6.3 Vegetation Canopy.

The vegetation canopy is an important part of the buffer layer system as it affects the amount of incoming radiation and precipitation which can reach the snow and surface organic layer (Riseborough 1986). It also affects snow accumulation.

The size, structure and composition of the canopy will all affect inputs to the system, and stand "architectures" should be recognised as they influence heat, mass and momentum exchanges (Oke 1978).

"Much of the climatic influence of a forest can be explained in simple terms of the geometry of the forest," (Barry and Chorley 1976, 342).

Such factors as canopy height and density affect aerodynamic roughness and surface shading, and albedo and evaporative regime affect the energy exchange processes at the ground surface (Dickinson and Hanson, in Hansen and Takahashi 1984). Climatic change due to a doubling of atmospheric carbon dioxide might change the amount of radiation available for canopy processes such as transpiration and photosynthesis, which may affect rates of succession (Monteny et al in Hutchinson and Hicks 1985). Over the long term, successional changes can alter the albedo of the surface vegetation, which has feedback implications for climate (Dickinson and Hanson 1984).

The role of the canopy in controlling the ground thermal regime by attenuating radiation and intercepting precipitation has been summarised in a flow diagram by Riseborough (1986, see fig 2.7).

The composition of the canopy affects the nature of the radiation reaching the floor. Tree canopies diffuse the wavelength of the radiation, reducing the blue spectrum and concentrating red and near infra-red which creates reduced

Figure 2.7

Detailed Conceptual Model of the Ground Thermal Regime

(After Riseborough, 1986)

photosynthetic conditions near the ground (Oke 1978, 124). Individual leaves also attenuate radiation through their ability to absorb, transmit and reflect this energy. This varies with the nature of the internal cell structure and the pigmentation of the leaf. However, leaves also lose energy through sensible heat and latent heat transfer due to the evaporation of water from the leaf surface (Oke 1978).

Canopy structure will influence energy losses as wind speed increases evaporation from leaf surfaces and affects turbulent heat exchange processes. The stomata of the leaf also exerts control on the release of water vapour to the surface and this is influenced by the surrounding microclimate (Oke 1978). Both height and density play a role in determining turbulent exchange within a stand and snow accumulation.

Forest albedos are much lower than for other vegetation units, which would suggest that forests absorb more energy than other vegetation types. This is due to the internal reflection and absorption which occurs within and beneath the canopy. A single leaf is likely to have a higher albedo than the canopy as a whole due to the above factors. It is suggested that canopy density will play an important role in determining albedo, the greater the density of the canopy, the higher its albedo. Oke suggests that evergreens have high absorptivity which makes them sinks or sources of longwave radiation which can then be utilised by snow and other lower albedo materials to speed up rates of decay, essentially

creating a local "greenhouse" effect.

Dense or closed canopy forests would seem to reduce the amount of energy which can reach or leave the ground surface. The corollary of this is that the surface beneath open canopy vegetation, in non-organic terrain, is far more susceptible to the vagaries of climate. This will be illustrated in chapter four.

2.7 Summary.

Williams and Smith (1989) have summarised the role of the buffer layer in partitioning the initial solar inputs to the system, Q^* , into Q_H , Q_{LE} and Q_G . This partitioning is dependent on the nature of the surface in terms of its albedo, roughness and moisture status. It is also influenced by the combined effects of atmosphere with respect to turbulence and ground with respect to its thermal conductivity. Each component of the buffer layer plays a role in determining the surface temperature. The seasonal thermal properties of the organic layer determine the net radiation balance of the surface, but this in turn is a function of the energy exchange processes in the vegetation canopy and snow layer.

In a $2*CO_2$ world, the shift in seasonal conditions of temperature and precipitation will affect the stability of permafrost and the growth rates of vegetation. The following chapters will explore where, why and how this may occur.

CHAPTER THREE

CLIMATE AND VEGETATION OF THE STUDY AREA.

3.1 Introduction - the Concept of the Ecotope.

Processes contributing to climate change act at the level of the Ecosphere, this being 'the largest global landscape', but the impacts will vary at all levels. This chapter considers the impacts of climate change at the level of the ecotope. This is the 'smallest concrete ecosystem' which possesses at least one homogeneous characteristic, such as vegetation, soil or atmospheric conditions (Naveh and Lieberman 1984).

Figure 3.1 presents the 2*CO₂ scenario for changes in vegetation for the ecoclimatic provinces of Canada. To appreciate the significance of the changing climate and landscape patterns it is necessary to consider current vegetation and climate.

3.2 Location of the Study Area.

The south Mackenzie Valley was chosen as a regional study area due to the presence of discontinuous permafrost. The study area lies between 60° and 65° N, and between 118° and 125° W but the main area of concentration was around the settlement of Fort Simpson (Fig 3.2).

3.2.1 Climatic Patterns of the Study Area.

Figure 3.1 Predicted ecoclimate provinces of Canada based upon climatic changes resulting from a doubling of CO₂ (Canada Committee on Land Classification 1988)

Figure 3.2 Location of the Study Area Figure

The climate of the Fort Simpson area is subarctic, with long cold winters and short cool summers (Brandon 1965 in Lavkulich 1972). Mean annual temperature is -1°C , with a mean summer temperature of 12.4°C , and a mean winter temperature of -14.4°C .

3.2.2 Air Temperatures.

Graphs of mean annual, mean summer (May to September) and mean winter temperatures (October to April), have been produced for available climate station data along the Mackenzie valley based on a ten year running mean (See Appendix A for full list of stations and methodology employed). A brief discussion of the regional climate will help to summarise the patterns and place them within the broader perspective of climate change.

Evidence from climate station data suggests that temperatures have been rising steadily over the last century. The yearly (Fig 3.3), winter (Fig 3.4a), and summer (Fig 3.4b) figures all display a similar pattern of temperature change based on ten year running means. Rapid warming took place at the beginning of the century and continued through to the 1950s, with individual peaks occurring around 1915, 1932 and 1948. The latter half of the century saw a steady decline in temperatures through to the late 1970's. The evidence suggests that the 1970's and 80's experienced a renewed warming in winter but summer temperatures appear to have

FOPT SIMPSON YEARLY TEMPERATURE

Ten Year Moving Average

Temperature in Degrees Centigrade
 Figure 3.3 Mean annual air temperatures

FORT SIMPSON WINTER TEMPERATURES

Ten Year Moving Average

Temperature in Degrees Centigrade

Figure 3.4a Mean winter temperature
(note scale is not set to zero).

FORT SIMPSON SUMMER TEMPERATURES

Ten Year Moving Average

Figure 3.4b Mean summer temperatures
(note scale is not set to zero).

declined in the 1980's. Data from stations at Norman Wells, Ft Norman and Hay River follow a similar pattern to that of Fort Simpson with some discrepancies (see appendix). These stations indicate that temperatures have risen over the past century, albeit with some fluctuations. However, the air temperature has not declined to the 1905 level at any point over the period of record.

3.2.3 Summary.

The discrepancy between summer and winter temperature increases is quite significant; winter temperatures have increased over a wider range than summer temperatures, although the pattern of the changes is very similar. However, winter temperature increases are expected to be three or four times higher than summer increases according to Hansen et al. (1984 in Smith 1988) for a predicted 2°CO_2 climate change in northwest N. America.

The difficulty is in assessing whether this data set exemplifies normal climatic variability or significant climatic change. The climatic record for this part of Canada does not extend much beyond one hundred years for any station, and for three of the stations only forty years of data exist. The danger of extrapolating a warming trend on the basis of such limited data is obvious. However, Judge (1975) has found evidence to suggest that a 2°K warming has occurred in the Mackenzie Valley over the period of record.

3.3 Precipitation.

The precipitation patterns of the region have experienced a lot of change with a series of marked increases and decreases. The yearly pattern is similar to that of summer and winter (Fig 3.5). From the beginning of the century precipitation amounts declined in both summer (Fig 3.6a) and winter (Fig 3.6b), reaching their lowest point of the century in 1928. Since then two peaks have occurred, one in 1940, and one in 1964; during the 1980s winter precipitation amounts have continued to climb but summer precipitation has fluctuated and appears to be in decline.

3.3.1 Summary.

In summary, precipitation amounts have not increased significantly from the 1905 values, but there has been a steady increase from the lowest point in the period of record. If climate change is occurring due to increasing carbon dioxide concentrations, one would expect to see a link between warmer air temperatures and higher precipitation. Although some coincidence between peaks in air temperatures and peaks in precipitation amounts can be perceived, particularly in the latter half of the century, the link is tenuous and no conclusions can be drawn on this evidence.

3.4 Topography.

The field area includes the physiographic divisions of

FORT SIMPSON YEARLY PRECIPITATION

Ten Year Moving Average

Figure 3.5 Mean annual precipitation

FORT SIMPSON WINTER PRECIPITATION

Ten Year Moving Average

Figure 3.6a Mean winter precipitation

FORT SIMPSON SUMMER PRECIPITATION

Ten Year Moving Average

Figure .3.6b Mean summer precipitation

the Great Slave Plain and the Alberta Plateau (Bostock 1969 in Rutter, Boydell Savigny and Everingden 1974) (Fig 3.7). Most of the area lies below 330 m asl except for the Redknife hills in the south central area and the Martin hills in the northwest, which rise to an elevation of 867 m. The general relief of the area is undulating, with well drained ridges of relatively coarse grained materials separated by poorly drained organic, largely peaty areas (1974 Task Force on Northern Oil Development Canada).

3.5 Vegetation

In terms of vegetation and climate the study area is part of the sub-Boreal Forest climatic zone with two climatological distinctions, the subhumid High Boreal (HBs), and the subhumid Mid Boreal (MBs) (Environment Canada 1989). Fort Simpson is located in the HBs region. The vegetation of HBs areas is characterised by black spruce and jackpine forests, with some paper birch. White spruce, trembling aspen and balsam fir occur on warm, moist sites. Ground cover is feathermoss, lichen, cloudberry, labrador tea, bog cranberry and blueberry. Poorly drained areas of bog and fenland are colonised by black spruce, labrador tea, bog rosemary and cloudberry.

Vegetation classification is a very static and somewhat arbitrary method of data collation. However, it provides the basis of the 'chorologic dimension' of landscape ecology which

3.7 Physiography of Yukon Territory and western District of Mackenzie
(after Bostock, 1969 in Rutter, 1973)

focuses on the relationships between ecotopes. This in turn is a building block for the 'geospheric dimension' which analyses relationships on a continental and global scale (Zonneveld in Moss 1988). Classification assists in describing the patterning of the landscape; from this one can investigate the relationships between patterns, and the processes contributing to them.

"Each landscape unit has form and structure, anatomy and composition, a precise position in space and a history through time; it is the seat of past and present processes, influenced by an external milieu;" (Rowe 1969)

A knowledge of some of these current structures and processes will allow us to look at some of the future implications of climate change, based on a vegetation classification scheme designed by the Forest Management Institute (Task Force on Northern Oil Development, Canada 1974).

3.5.1 Landscape Patterns.

The vegetation types of the Fort Simpson area have been mapped at the ecodistrict level at a scale of 1:125,000, based on aerial photo interpretation (Task Force on Northern Oil Development, Canada 1974). The utility of the map is that it offers baseline data on forest type and transition, tree height and species, canopy density and percentage cover of vegetation type (see appendix B for vegetation characteristics). Each of these factors have unique characteristics which will influence the degree or rate at

which they are affected by climate change and each stand on the map can be viewed as a separate ecotope. Utilising this data, maps of vegetation type (Fig 3.8), canopy height (fig 3.9), and canopy density (fig 3.10) were produced using the EPPL7 GIS package. A total of nine vegetation types were identified (table 3.1) and each was drawn as a separate polygon. Closed canopy vegetation was delimited based on a density of $>61\%$, open canopy was anything $<60\%$. High shade providing trees were delimited as $>61\text{ft}$, with low shade trees being $<60\text{ft}$. Classes were assigned based on the contents of the polygon and the maps were then overlain and a new class was assigned to produce the final map of buffer layer resistance to climate change. Offsite values refer to sites with incomplete data or vegetation types with unique occurrence which were not included on the maps. Some vegetation types occur as pure stands on the map, others as complexes. For the purposes of this map the dominant vegetation type in terms of areal percentage determined the class of the polygon. (The "lines" which appear around the edge of some of the polygons are due to the printer).

It is assumed that certain landscape associations are underlain by permafrost, namely black spruce and peat (Lavkulich 1972). Black spruce sphagnum and black spruce lichen stands often occur in combination with sphagnum bogs and pond fields. These are thermokarst features so these particular aggregates were given a separate class due to their

VEGETATION TYPES

- ☐ Riparian Spruce/Hardwoods
- ☐ Riparian Spruce/Feathermoss
- ☐ Upland Spruce (pine)/Hardwoods
- ☐ Upland Spruce/Feathermoss
- ☐ Black Spruce/Sphagnum
- ☐ Black Spruce/Lichen
- ☐ Sedge Fen
- ☐ Sphagnum Bog/Pond Field/Thermokarst
- ☐ Pioneer Steep Slope
- ☐ Water
- ☐ Offsite

FIGURE 3.8 VEGETATION TYPES OF THE FORT SIMPSON AREA

FIGURE 3.10 VEGETATION DENSITY IN THE FORT SIMPSON AREA

known association with permafrost (see section 3.7).

3.5.2 Peat Landforms and Permafrost Landscape Associations.

In the Fort Simpson area, permafrost underlies 35% of the terrain; of this, more than 90% is attributed to the presence of an organic peat insulation layer (Rennie, Reid and Henderson 1978). The other 10% is attributed to north facing slopes or black spruce (*picea mariana*) tree cover. Borehole data from the Mackenzie valley suggest that organic soils are far more likely to be frozen than other soil types in the Fort Simpson region (Heginbottom, Kurfurst and Lau 1978). There are several different peat forming materials but permafrost is most readily associated with forest peat and is associated to a lesser extent with sphagnum peat in the study area (Zoltai and Tarnocai 1975). Lavkulich suggests that all elevated/convex organic terrain contains permafrost and in this region two main types of feature can be identified, namely peat plateaus and peat palsa. Brown (1968) suggests that palsas and peat plateaux

"... are morphological variations of the same process ... which pass through a life cycle of growth and degradation."

3.5.3 Palsa.

Peat palsa are small elongate hills up to 50m in length and elevated 2 to 5 m above the surrounding terrain. Brown (1968) suggests that these features initially develop when ponds are frozen to the bottom in winter. The saturated peat

beneath is 'domed up' by frost action as ice lenses form, which accounts for their elevation (Zoltai and Tarnocai 1971), and once formed they provide conditions conducive to continued permafrost aggradation. Their raised surface means that they often have a thinner snow cover in winter due to their greater exposure to the wind (Brown 1968).

This reduces the insulating effect of snow. Also the raised edges are more exposed to the wind, which helps to maintain cooler temperatures (See Chapter Two for detailed discussion of energy exchange processes).

The vegetation of these mature landforms tends to be sphagnum mosses, lichens, black spruce trees and shrubs such as cloudberry, leather leaf and labrador tea.

Figure 3.11 Raised edge of palsa.3.5.4

3.5.4 Peat Plateaus.

Plateaus are elevated 1 to 2 m above the surrounding fen bog terrain and are far more extensive than palsa. The lower peat plateau may be limited in height due to less water availability and to denser tree growth, which reduces wind exposure and promotes snow accumulation (Brown 1968). They are characterised by similar vegetation to palsa, black spruce trees, lichens and mosses and labrador tea.

Climate, snow cover and water supply are critical factors in palsa and plateau formation (Brown 1968). A change in one or all of these factors can lead to permafrost degradation. These landforms can be picked out relatively easily on aerial photos and they always indicate the presence of permafrost within the discontinuous zone (Reid and Janz 1974). In this respect they would seem to be useful objects of study in addressing the question of climate change. Within the landscape ecology approach their ease of identification and characterisation allows for regional assumptions to be made. However, there is some debate as to whether these features pass through a cycle of growth and degradation and if this is related to climate change or edaphic change (Chatwin 1981).

3.6 Buffer Layer and Susceptibility to Climate Change.

The map of buffer layer resistance to climate change illustrates that thirty one percent of the map sheet area is underlain by permafrost (Figure 3.12). The low buffer

capability permafrost areas of the map indicate the presence of permafrost under low density and low shade providing vegetation (refer to legend). The areas associated with thermokarst are currently areas of low density vegetation and low height. These areas have already experienced thermal disruption and are the areas most likely to feel the immediate impacts of climate change due to their instability. These areas are identified as speckled bog by Rennie (et al 1978) and occur over 32% of the Simpson area. Table 3.1 illustrates the percentage cover of each vegetation type in the study area.

The resulting map is essentially a map of potential microclimates for different buffer layer structures based on differences in canopy composition, density and height. However, the significance of the map is of limited value if climatic data are not integrated into the analysis. Ideally data to describe wind speed and direction, sunshine hours-daily incident solar radiation, precipitation and temperature would need to be integrated with the data on the map. A number of studies have attempted to quantify these processes in detail, but if we are to try and work at the regional scale a more general appraisal of the energy exchange processes in the buffer layer is required and this problem will be addressed in the next chapter.

PERCENT	VEGETATION TYPE
0.05	Riparian Spruce/Hardwoods
0.20	Riparian Spruce/Feathermoss
19.65	Upland Spruce (pine)/Hardwoods
25.96	Upland Spruce/Feathermoss
13.16	Black Spruce/Sphagnum
1.06	Black Spruce/Lichen
15.45	Sedge Fen
16.73	Sphagnum Bog/Pond Field/Thermokarst
0.71	Pioneer Steep Slope
6.15	Water Bodies
0.87	Offsite

Table 3.1 Percentage Occurrence of Vegetation Types.

3.7 Thermokarst Processes of Landscape Change.

Climate change has significant implications for terrain in the discontinuous permafrost zone. Thie (1974), in a study of the distribution and thawing of permafrost in Manitoba, has linked the increase in the rate of thermokarst subsidence, as evidenced from collapse scars, to a period of climatic amelioration since 1850. French (1983) suggests that thermokarst subsidence is not only the result of regional or global climatic changes but can be due to a variety of natural and human disturbances (Figure 3.13).

A study by Chatwin (1981) suggests that considerable ground ice degradation has occurred in the Fort Simpson area, based on air photo interpretation of characteristic features indicative of permafrost such as palsas and peat plateaus (Reid and Janz 1974). Evidence for climate change was deduced from isotope ratios in peat producing plants which suggest

Figure 3.13

Thermokarst Processes of Landscape Change

(After French, 1983)

that current mean annual temperatures are the warmest in 10,000 years. A warming trend over the last 400 years was also indicated by the isotope values.

Thermokarst topography is much in evidence from aerial photos of the Fort Simpson area. However, there are insufficient aerial records for the field site to establish rates of permafrost degradation. Some of the processes leading to thermokarst change in this area will now be reviewed based on Mackay's model (in French 1973, 107). Mackay outlines three primary mechanisms which contribute to thermokarsting, geomorphic, vegetational and climatic; but, while they would seem to be different in origin, they all ultimately involve a change in macro and microclimate.

3.8 Geomorphic Mechanisms of Landscape Change.

Disruption of the thermal regime of palsas and peat plateaus can be caused or exacerbated by changes in a range of processes which act upon these landscapes, such as surface cracking, block slides and edge collapse. Several of these processes were observed in the field. The site chosen for field investigation was a peat plateau/palsa complex, located approximately forty kilometres northwest of Fort Simpson, adjacent to the Mackenzie Highway (see appendix C). There are a number of palsa within this area, some of which exhibit collapse features on a large scale (Fig 3.14). However, others showed no major signs of active degradation. The peat

plateaus showed signs of steady erosion. Evidence for degradation was based on the collapse geometry of permafrost features, of which three basic types were found in the field area. These were

- 1 Edge collapse
- 2 Internal sinkholes
- 3 Surface cracking

Figure 3.14 Collapse edge of palsa in study area.

Chatwin (1981) identifies three mechanisms which may lead to cracks,

- 1 Surface rupture due to differential heaving
- 2 Thermal contraction of the surface layers and
- 3 Dessication cracking

Each of these mechanisms can contribute to block slides or edge collapse which can create thermal disturbance. These effects are summarised in Figure 3.15 and field observations of some of these mechanisms are recorded in appendix C.

Figure 3.15 Processes acting on a palsa

Surface cracks can be very extensive, but Chatwin found no evidence to suggest that the active layer beneath these features was any deeper than that on the rest of the palsa. The role of the cracks in palsa collapse is largely mechanical, as evidenced from the nature of their occurrence. The cracks eventually isolate blocks of material which slide downslope into the adjacent bog. Several detached blocks of material were observed at site two and observations made of the early stages of this phenomenon (Figure 3.16a and 3.16b). The presence of trees can also contribute to this process; the weight of a dislodged tree as it begins to lean over can hasten the process of block detachment and edge collapse. Edge collapse on palsas is visually obvious within the field area but the process of edge collapse along the margins of peat plateaus is much more subtle and difficult to discern. Often it is only the slight tilting of a tree which suggests that degradation may be occurring. Several of the plateaus within the area displayed characteristic leaning trees. Such 'passive' degradation leads to the formation of large sphagnum peat bogs and occasionally open ponds littered with dead, fallen trees. This type of thermokarst topography is much in evidence along sections of the Mackenzie highway, where changes in drainage pattern have led to thermal disruption of the peat plateaus.

Figure 3.16a Leaning trees on palisade edge

Figure 3.16b Surface cracking of palisade

3.9. Effects of Disturbance on Terrain.

Removal of surface vegetation in permafrost terrain can lead to rapid thermal disequilibrium, soil erosion and drainage changes. Human beings are perhaps the biggest cause of terrain disturbance in the more remote regions of the world due to the "necessity" of economic resource exploitation. The installation of a 'buried, ambient temperature gas pipeline' from Norman Wells, Northwest Territories to Zama Lake, Alberta necessitated the removal of surface vegetation from the right-of-way during the pipe's installation. The work was carried out in winter, on a snow mat, to minimise the damage to the surface cover.

Temperature records from the Manners Creek site (Kilometre 558) of the Norman Wells Interprovincial Pipe Line have been recorded by Energy Mines and Resources for the period 1985 to the present (Burgess and Riseborough 1990). Four bore holes were instrumented to measure temperature to a depth of 5m at some sites and 20m at others. The results indicate a warming of the temperature by an average of 1.2°C at 1m depth, for the on right-of-way (ROW) cable furthest from the pipe, over the period of record (Fig 3.17). By comparison, off ROW surface temperatures, where vegetation cover is still undisturbed, have risen by 0.6°C. The on right-of-way warming has been accompanied by active layer deepening at some sites and this has been attributed to the thermal disequilibrium created by the removal of the surface

Figure 3.17 Ground temperature changes on ROW.

vegetation (Burgess and Riseborough, 1990). A slight warming of the off-ROW temperatures at 1m depth is attributed to a short term air temperature increase. This illustrates the thermal importance of the buffer layer in moderating surface response to air temperature changes. Remedial measures can and have been used to control the thermal regime of the ground surface, but it is difficult to replicate original surface conditions over the short term.

3.10 Summary.

The evidence from the climate record illustrates a cyclical pattern of increasing and decreasing temperature and precipitation in the region but overall temperatures appear to be rising.

The buffer layer map of the study area illustrates the current extent of permafrost degradation, 16% of the area is characterised by thermokarst terrain. If this is indicative of the rising air temperatures during the century, then climate change predictions have significant implications for permafrost terrain. The role of vegetation plays a key role in determining the magnitude of surface temperature changes, as evidenced by the thermal data from the pipeline. The low buffer capability of the remaining vegetation underlain by permafrost in the study area suggests that the presence of frozen ground is tenuous at best.

CHAPTER FOUR

THE SURFACE ENERGY BALANCE AND THE IMPLICATIONS OF CLIMATE CHANGE FOR PERMAFROST AND VEGETATION DISTRIBUTION.

4.1 Introduction.

The chorologic dimension of landscape ecology was explored in the previous chapter and some of the horizontal links between landscape attributes and patterns were used to identify permafrost landscape associations which would be most immediately affected by climate change. This chapter returns to the concept of landscape as ecosystem discussed in chapter two and offers an approach which summarises the vertical links between atmosphere and surface. A time component is integrated into an analysis of surface temperatures in an attempt to predict some of the future impacts of climate change. The magnitude of change which is anticipated for most surface temperatures in the Fort Simpson area has implications for vegetation growth rates as well as permafrost degradation.

The nature of thermal disruption which leads to permafrost degradation can be modelled, but it requires detailed knowledge of the surface energy balance. The question remains then, how does one quantify the energy exchange processes in the buffer layer at a regional scale? A reliable measure of the sum of these processes is required to address the issue of climate change, and an approach to this problem will now be considered.

4.2 Surface Temperature - the N Factor.

The characteristics of the surface vegetation have a strong influence on the surface temperature. By recognising the energy exchange characteristics of different vegetation aggregates, one can gain some understanding of the spatial patterns of surface temperature variation. This much is obvious, but there is still the problem of how to identify and quantify all the energy exchange processes.

Lunardini (1981, 560) proposes the use of an N factor, which is essentially the surface temperature expressed as a function of the net transfers of energy at the surface. It is an empirical constant which must be calculated for each surface as it varies with terrain, vegetation type, latitude and season, for the reasons considered in detail in chapter two.

Calculations to determine the N factor for the freezing or thawing season can be derived from the freezing and thawing degree day sums at the surface: thus,

$$N = \frac{I_s}{I_a} = \frac{(T_f - T_s)dt}{(T_f - T_a)dt} ,$$

where

I_s/I_a = surface and air index of thawing or freezing and is the difference between freezing point, 0°C, and the observed temperature, multiplied by the length of the season

T_f = temperature frozen 0°C

T_s = surface temperature

T_a = air temperature

dt = length of freeze or thaw season

Freezing and thawing degree days represent the potential amount of energy available to the surface. They do not reflect the total solar radiation which finally reaches the surface (Linell 1973). This is due to the complex energy exchange processes which take place in the buffer layer, hence the wide variations between air and surface temperatures (see chapter two). The use of N factors surmounts this problem as they summarise the energy exchange processes as the difference between the air and surface temperature, expressed in terms of freezing and thawing degree days.

N factors vary seasonally, the variation of N being closely linked to changing net radiation according to Lunardini. In winter the presence of a snow cover moderates the influence of air temperatures on surface temperatures. Radiation, precipitation and canopy conditions will vary from summer to winter, all of which will influence the surface energy balance.

4.3 The Relationship Between Air and Surface Temperatures.

A study by Jorgensen and Krieg (1988, 178) using N factors, determined for a series of vegetation types during the freeze and thaw season, investigated the effects of changing air temperatures on the presence of permafrost beneath different vegetation units. The energy balance at the surface, R, was determined by the following equation:

$$R = \frac{((DDTa \ Nt \ P)/(DDFa \ Nf))}{(Kf/Kt)} ,$$

where

DDTa = thawing degree day values for the air

DDFa = freezing degree day values for the air

Nt = thawing N factor

Nf = freezing N factor

P = a value for potential insolation

Kf = frozen thermal conductivity of underlying soil

Kt = thawed thermal conductivity of underlying soil

When the depth of seasonal freezing exceeds the depth of seasonal thawing, permafrost will aggrade. If thawing degree days begin to exceed freezing degree days permafrost will degrade. An R value of less than one indicates the stability of permafrost, a value of more than one suggests that permafrost will be unstable, i.e., close to the melting point. However, the nature of the underlying soil is also a major control on the presence of permafrost. Carlson (in Linell 1973) suggests that the ratio of the ground's frozen to unfrozen conductivity K_f/K_u must be greater than the ratio of thawing to freezing degree days for permafrost to exist. Thermal conductivity is the rate of heat transfer through a substance, and this will vary with the nature of the material and seasonal changes in moisture; ice has a much greater thermal conductivity than water or air (Williams and Smith 1989). The ground beneath the surface vegetation is likely to be composed of different types of soil, characterised by different thermal properties which will influence the rate of heat transfer to or from the surface.

4.4 Surface Temperature Calculations - the Regional Scenario.

An attempt was made to use a simplified version of Jorgenson and Krieg's model to look at the effects of changing air temperatures on permafrost distribution in the Fort Simpson area. Surface temperature data for the area is somewhat limited in terms of amount and consistency of record, although some measurements are available. However, what is not available are consistent air and surface temperature measurements throughout the entire freeze and thaw seasons. Knowledge of this for contemporary landscape associations would aid predictions of future surface temperature changes, with obvious benefits. A data set for an unfrozen surface beneath grass was available and these results are incorporated into the following discussion. However, due to lack of suitable surface temperature records for permafrost terrain, the N factor data of Jorgenson and Krieg was utilised to determine the surface energy balance, R, from the following equation:

$$R = \frac{(DDTa \ Nt)}{(DDFa \ Nf)},$$

where

DDTa = air temperature thawing degree days
 DDFa = air temperature freezing degree days
 Nt = surface N factor for the thaw season
 Nf = surface N factor for the freezing season

In this instance the soil frozen and unfrozen thermal conductivity is assumed to be uniform. Also the field area

is assumed to be a uniform plane and latitudinal differences in insolation are ignored. These are simplifications to the model, but the approach is intended primarily to illustrate the influence of the buffer layer on ground temperature response to climate change.

4.4.1 Results.

Freezing and thawing degree day values for the average, highest and the lowest years over the period of record were determined from mean monthly air temperature data for Fort Simpson. Using these, and values for N factors obtained from different sources, current R values were determined for various vegetation types in the Fort Simpson area. N factors for Fort Simpson meteorological station surface temperature data were calculated for a grassland site using air temperature data from a comparable time period (Table 4.1 and 4.2). The N factor results for dense black and white spruce were obtained from Lunardini (1981, 563) for a site at Fairbanks and the rest were obtained from Jorgenson and Krieg (Table 4.3). Table 4.4 presents the air temperature and degree day data for Fort Simpson, based on the average temperature of the period 1977 to 1987.

As can be seen from Table 4.5, the surface energy balance varies widely within the same area due to variations in vegetation cover, as evidenced by the range of R values. An R value of less than 1 indicates the stability of permafrost,

Fort Simpson	Soil Temp	Degree Days	Air Temp	Degree Days
Jan	-8.6	267	-28.1	-871
Feb	-8.3	232	-22.1	-619
Mar	-7.0	217	-16.0	-496
April	-2.0	62	-3.2	-99
May	7.0	217	8.0	248
June	15.1	453	14.6	516
July	18.5	574	17.2	533
Aug	16.0	496	15.0	465
Sept	7.6	228	7.5	225
Oct	0.9	28	-1.6	-50
Nov	-4.2	126	-14.4	-432
Dec	-6.6	205	-24.7	-766

Table 4.1 Fort Simpson surface and air temperatures used in calculation of N factor for Table 4.2.

	Degree days Frozen	Degree Days Thawed
Soil	1137	1986
Air	3333	1987
N	0.34	0.99

Table 4.2 Derivation of thawing and freezing N factors for Fort Simpson grassland site.

Vegetation Type	Nt	Nf
1 Mixed birch-spruce forest	0.85	0.35
2 Closed white spruce forest	0.80	0.35
3 Open black spruce forest	0.60	0.30
4 Closed black spruce forest	0.50	0.30
5 Dense black/white spruce, moss	0.37	0.29
6 Grassland (Fort Simpson)	0.99	0.34

Table 4.3 Summer and winter N factors for different vegetation types.

Temperature 1978-1988 average	Degree Days
JAN -23.43	874
FEB -20.88	644
MAR -13.86	464
APR -1.53	125
MAY 8.45	251
JUN 14.81	432
JUL 16.91	516
AUG 13.84	447
SEP 7.88	222
OCT -1.75	118
NOV -15.50	471
DEC -23.47	757
Thawing Degree days	>0°C=1968
Freezing Degree days	<0°C=3464

Table 4.4 Fort Simpson freezing and thawing air degree days for 1977-1987 average monthly air temperatures.

Vegetation Type	R Value
1 Mixed birch-spruce forest	1.38
2 Closed white spruce forest	1.30
3 Open black spruce forest	1.14
4 Closed black spruce forest	0.95
5 Dense black/white spruce, moss	0.70
6 Grassland (Fort Simpson)	1.74

Table 4.5 Fairbanks N factors with Simpson degree days
R values under current climate degree days.

more than one suggests instability or degradation of permafrost, where present. Of the vegetation types associated with permafrost, two can be considered stable under current climatic conditions. Dense white and black spruce forest seems to offer the most stable conditions for permafrost

aggradation, with an R value of 0.70. Closed black spruce forest has a value of 0.95, a slight change in climate could result in thermal instability. The R factor for open black spruce, 1.14, suggests that permafrost is currently unstable under such vegetation. This is supported by limited ground truth observations in the study area (see appendix C). The proliferation of thermokarst terrain under low density black spruce vegetation identified on the buffer layer map of the area also supports this finding (refer to section 3.6).

These values represent the surface energy balance under average climatic conditions. However, the temperature of the ground is a function of past and present climate due to the lag between air and surface temperatures. Using maximum and minimum freezing and thawing degree days and freezing and thawing N factors, one can gain some indication of the damping effect of the buffer layer on temperature extremes (see table 4.6). Surface temperatures would be conducive to the aggradation and stability of permafrost under all vegetation types except grassland, using minimum summer thawing degree days. With maximum winter freezing degree days, permafrost would be stable under open and closed black spruce vegetation, and dense white and black spruce forest (Table 4.7).

Season	Freezing Degree days	Thawing Degree days
winter max	4078	1803
winter min	2491	2048
summer max	3048	2215
summer min	3991	1491

Table 4.6 Maximum and minimum summer thawing degree days and winter freezing degree days (with accompanying thawing and freezing degree days).

Type	Maximum Winter R	Minimum Winter R
1	1.07	2.00
2	1.01	1.89
3	0.88	1.64
4	0.73	1.38
5	0.56	1.05
6	1.29	2.39
Type	Maximum Summer R	Minimum Summer R
1	1.76	0.91
2	1.66	0.85
3	1.87	0.97
4	1.21	0.62
5	0.93	0.48
6	2.11	1.09

Table 4.7 R values under maximum and minimum summer and winter degree days (refer to Table 4.5 for vegetation types).

4.4.2 Methodological Considerations.

The danger of extrapolating information from a different area is outweighed by the need for some indication of surface temperature response to climate change. The use of this data set is also a test of the validity of the landscape ecology approach; if landform is a function of physical and atmospheric processes, then the vegetation units of an area with similar latitude and climate should be similar in character. If soil type is ignored then N factor data derived from a similar vegetation type should be transferrable to areas with similar freezing and thawing degree day ratios. Fairbanks has a similar thawing (T) to freezing (F) degree day ratio to Fort Simpson (table 4.8) although it is situated 4 degrees further north.

Location	Summer	Winter	T/F
Fort Simpson	1987	3333	0.60
Fairbanks	1700	2950	0.58

Table 4.8 Comparison of thawing to freezing degree day ratios for Fairbanks and Fort Simpson

Williams (1982, 122) suggests that it is almost impossible to fully describe the energy exchange processes of a site

"... it is clear that the role of complex surface cover, such as vegetation, is more problematic than that of heat and mass transfer within the ground itself."

Until sufficient data exists, then, this is the first

step in analysing the problem beyond a purely qualitative approach. Both qualitative and quantitative methods have a role to play within landscape ecology.

4.5 Climate Change: The 2*CO₂ Scenario.

To address the issue of climate change, R values for the same vegetation types were produced using the higher air temperatures anticipated under 2*CO₂ levels of the GISS model (Hansen, Lacis and Rind et al 1984) (Table 4.9). With 2*CO₂ climate warming, the greatest change of air temperatures is expected during the winter months. Summer monthly temperature changes would range between 2.5° and 3.8°C, whereas winter temperatures would range between 3.4° and 7.8°C.

4.5.1 Results.

The effect of a 2*CO₂ climate change would eventually result in the complete disappearance of permafrost (Table 4.10). The R values for each vegetation type have doubled under 2*CO₂ temperature changes and this can be expected to lead to fundamental changes in permafrost distribution and vegetation growth rates. The speed at which these changes will occur is debatable and very much depends on the nature of the step function in temperature change applied at the surface (Smith, 1990, personal communication). However, temperature will not be the only climatic variable to change. Precipitation patterns will change with variations in the

Month	Temp Inc (2*CO ₂) -(1*CO ₂)	AES Air Temps	2*CO ₂ Air Temps	2*CO ₂ Degree Days
January	7.3	-23.43	-16.13	500
February	5.8	-20.88	-15.08	-422
March	4.0	-13.86	-9.86	-306
April	3.4	-1.53	1.87	58
May	3.3	8.45	11.75	364
June	2.9	14.81	17.71	531
July	2.5	16.91	19.41	602
August	2.8	13.84	16.64	516
Sept.	3.8	7.88	11.68	350
October	5.5	-1.75	3.75	116
November	7.1	-15.5	-8.4	-252
December	7.8	-23.47	-15.67	-486
Thawing Degree Days >0°C				2518
Freezing Degree Days <0°C				2235

Table 4.9 2*CO₂ air temperatures and degree days.

Vegetation Type	R Value
1 Mixed birch-spruce forest	2.74
2 Closed white spruce forest	2.58
3 Open black spruce forest	2.25
4 Closed black spruce forest	1.88
5 Dense black /white spruce, moss	1.44
6 Grassland (Fort Simpson)	3.28

Table 4.10 R values under 2*CO₂ climate degree days.

length of the freeze and thaw season and this will play an important role in buffering the surface from the predicted temperature changes which have been presented in this section.

4.5.2 Precipitation Changes.

Expected changes in precipitation due to predicted climate change are a 10-50% increase in summer and 60% increase in winter (Hansen et al., 1984 in Smith, 1988) for northwestern north America.

Precipitation changes will have a twofold effect on ground temperatures. Increased precipitation in winter in the form of snow will play a critical buffering role for the ground thermal regime due to its thermal characteristics. The albedo of snow directly affects the rate of heat transfer to the ground, and its insulative qualities slow down the rate of heat loss from the ground. Snow melt in spring also absorbs a considerable amount of heat energy. The presence of a snow cover may limit the impact of air temperature changes, but it could also raise the surface temperature by slowing down the rate of heat transfer from the ground during winter. Decreased precipitation in summer and winter is likely to lead to warmer drier conditions which will raise surface temperatures. Increased rainfall could affect processes in the discontinuous permafrost zone (Smith 1988), and perhaps exacerbate the rates of thermokarst degradation and erosion.

Smith and Riseborough (1983) found that when air temperature warming occurred in winter, snow cover buffered the surface from the effects. However, on a longer term basis of climate change, precipitation was increasingly in the form of rainfall during the winter months in their model. This reduced surface insulation and increased evaporation leading to lower surface temperatures. This may contribute to permafrost maintenance even under increased air temperatures.

The expected temperature increase using GISS predictions indicates that the length of the freezing and thawing season will change. Winter will only be five months in duration, compared to the current seven month period. If, as Hansen suggests, winter precipitation increases 60%, snowcover will be concentrated into a shorter time period. If this snowfall is concentrated early in the season before the surface has begun to cool then the surface temperature will remain warm and the surface temperature will rise over the long term (Smith 1988).

If most of this precipitation is rainfall, then evaporation will become the dominant control on surface temperatures. The role of moisture may change significantly with changes in the length of the thaw season. If thawing degree days increase, there could be greater evaporation in the fall. The significance of this for the organic layer could be a much lower thermal conductivity during the winter, thereby slowing heat exchange into or out of the ground. This

would help to maintain permafrost stability despite changing air temperatures. Smith and Riseborough (1983) suggest that variations in surface wetness can have a much larger impact on surface temperatures than changing air temperatures. In their sensitivity model increasing surface wetness led to decreasing surface temperatures. In this respect, surface roughness, site aspect and wind direction will all affect surface temperature.

4.5.3 Summary

The air temperature changes predicted using the GISS model suggest that the future climate will be quite different from the present. Air temperatures will increase in all months, changing the thaw season to seven months duration and winter to five months. Using Jorgenson and Krieg's model, surface temperatures will double under $2 \times \text{CO}_2$ leading to changes in permafrost stability, and ultimately leading to its disappearance. Precipitation patterns will undoubtedly change but the moderating effect this will have on surface temperatures is difficult to determine. There will be many feedback loops between surface temperature, precipitation and vegetation, with the changes which can be expected to accompany air temperature increases. While the results of surface energy balance changes considered in the last section do not take these feedbacks into account, they do help to illustrate which vegetation types will be most sensitive to

change.

Changes in surface moisture and temperature will be moderated by the vegetation of the buffer layer but these changes will, in turn, alter the character of the surface vegetation with obvious feedback implications for the whole ecosystem. The next section illustrates the link between climate and the buffer layer by establishing the principal controls on climate-tree growth relationships.

4.6 Dendroclimatology

Tree ring chronologies were obtained from two peat palsa sites in the field area to try to identify the climate growth relationship using dendroclimatological techniques.

The study of dendroclimatology utilises tree ring chronologies to establish the nature of past climate. Dendrochronology is based on two fundamental concepts, the principle of uniformitarianism which suggests that present day processes which affect tree growth must also have operated in the past, and the principle of limiting factors 'a biological process cannot proceed faster than is allowed by the most limiting factor.' (Fritts 1976). Tree ring widths can be influenced by a series of external or internal factors. External factors limiting to growth are water, temperature, light, CO_2 , O_2 and soil minerals. Internal factors are available food, growth regulators, enzymes and water. The external constraints to growth are responsible for the

internal conditions, but the links are complicated due to a time lag effect (Fritts 1976).

The annual growth ring is the basis of dendrochronology and is defined by LaMarche (in Hughes, Kelly, Pitcher and LaMarche 1982, 3) as

"...a growth band in the xylem of a tree or shrub which has anatomically definable boundaries and is formed during a single period of cambial activity that occurs only once per year."

Variations in the width of the annual ring can be used to indicate the influence of environmental factors on tree growth.

4.6.1 Methodology.

Standard sampling procedures were followed to obtain cores from healthy black spruce trees and prepare them for examination. However, cross dating to identify false or missing rings was not undertaken. A range of statistical analyses were applied to the data. Standardisation of the rings removes the growth trend of decreasing ring width with increasing age, obvious in the early stages of growth, and reduces all widths to a standard index value. This was carried out by fitting a negative exponential curve to the data using a computer programme by Fritts, Mossiman and Bortoff (1969). Chronologies are limited by the sample with the least number of years so trees with a short period of record were analysed separately.

It is customary to present a master site chronology by

averaging all the sample values, but it was decided to present individual sample results for each site to illustrate the degree of variability. Cores were obtained during June and early July before the seasonal growth, so all samples were lagged with the climate data. Many different processes combine to control tree growth, which often leads to a lag effect between climate and growth (Fritts 1978). 1988's growth was correlated with 1988 and 1987's temperature but 1987 provided the best results. These samples are the best matching ones for each site, poorly correlated samples were eliminated after running a cluster procedure in Statistical Package for the Social Sciences (SPSSPC). A correlation value of 0.91 was obtained for cross correlation of the mean chronologies for both sites, which suggests that they experience similar growing conditons.

The initial aims of the study were to establish a correlation between tree growth and climate to make some assumptions about the future growth of trees under climate change. Climate station data is from the same source as that used in section 3.2. The field site is approximately 40 km from the meteorological station, so the official data is expected to be representative of these sites. Lack of cores from trees in non-permafrost sites allows for only limited observations to be made. However, some interesting links between growth and climate were observed in the data and the results will now be presented.

4.6.2 Results.

Sensitivity is a statistical measure of the variability in ring width which reflects the trees' sensitivity to climate change (Hughes et al., 1982). Mean sensitivity analyses suggest that the tree specimens used for this study are relatively complacent, as they exhibit little variation in year to year ring width. Mean sensitivities are in the range of 0.11 to 0.27, with an average value of 0.23. This is not unusual for subarctic chronologies, and these samples display higher mean sensitivity values than other subarctic sites (Cropper and Fritts 1981). Although complacency might suggest that trees are not very responsive to climatic variation, this does not mean that they do not contain a climate signal (Hughes et al, 1982). The results of this study illustrate this.

Initially index ring width was correlated with mean summer air temperature, mean summer precipitation and June and July growing degree days to try and identify the main control on tree growth (Table 4.11, 4.12 and 4.13). Results of this procedure gave only very small values of R^2 when a multiple regression analysis was run. Five year moving averages of both ring width and climate data were then used to eliminate some of the noise which occurs in such growth limiting sites. Smith (1985) suggests that tree rings may be more indicative of lower frequency climate variations than year to year variations. The low sensitivity values of this site suggest

Sample	Multiple R	R2	R2a
1	0.21	0.04	0.01
2	0.31	0.09	0.06
3	0.16	0.02	-0.01
4	0.19	0.04	0.00
5	0.15	0.02	-0.01
6	0.12	0.01	-0.02
7	0.40	0.16	0.13
8	0.22	0.05	0.02
9	0.23	0.05	0.02
10	0.21	0.05	0.01

Table 4.11 Site Eight Index

Sample	Multiple R2	R2	R2a
1	0.13	0.02	-0.02
2	0.17	0.03	-0.01
3	0.41	0.17	0.13
4	0.34	0.12	0.08
5	0.14	0.02	-0.02
6	0.28	0.08	0.04
7	0.16	0.02	0.01
8	0.34	0.12	0.08

Table 4.12 Site Nine Index Values (long record)

Sample	Multiple R2	R2	R2a
1	0.27	0.08	0.00
2	0.28	0.08	0.00
3	0.11	0.01	0.07
4	0.15	0.02	-0.06
5	0.17	0.03	-0.05
6	0.44	0.20	0.13
7	0.26	0.07	-0.01
8	0.18	0.03	-0.05
9	0.44	0.19	0.12
10	0.11	0.01	-0.07
11	0.32	0.10	0.03
12	0.16	0.03	-0.05

Table 4.13 Site Nine Index Values (short record)

that this is the case.

The use of moving averages gave much better results for R^2 and suggests that precipitation and growing degree days would appear to be a better indicator of ring width variation than mean summer temperatures (Table 4.14, 4.15 and 4.16). This is based on the significance levels obtained from the multiple regression procedure (see Appendix D). These findings are in agreement with the results of a study by Jacoby, Cook and Ulan (1985). They found that linear regression of tree ring chronologies reflect variations in June and July degree days more than mean summer temperatures. In this study the strongest significance was found between June and July degree days greater than 0°C and mean summer precipitation. Temperature was significant for a few samples from site eight.

4.6.3 Discussion.

The implications of the chronology results are that moisture stress, and not temperature per se, will be the principal limiting factor to growth for trees on sites underlain by permafrost. From the previous discussion on temperature and precipitation changes (section 4.5.2), precipitation will increase. However, it is likely that higher temperatures will increase evaporation, leading to moisture stress.

Under a 2*CO₂ warming the boreal forest could be greatly

Sample	Multiple R	R2	R2a
1	0.29	0.05	0.01
2	0.49	0.24	0.21
3	0.47	0.22	0.19
4	0.23	0.05	0.02
5	0.53	0.28	0.25
6	0.26	0.07	0.03
7	0.78	0.61	0.60
8	0.60	0.36	0.33
9	0.42	0.18	0.15

Table 4.14 Site Eight Average Index Values

Sample	Multiple R	R2	R2a
1	0.21	0.04	0.00
2	0.46	0.21	0.18
3	0.77	0.60	0.58
4	0.61	0.37	0.34
5	0.11	0.01	-0.03
6	0.65	0.42	0.39
7	0.39	0.15	0.12
8	0.45	0.21	0.17

Table 4.15 Site Nine Average Index Values (long record)

Sample	Multiple R	R2	R2a
1	0.76	0.57	0.53
2	0.62	0.39	0.33
3	0.55	0.30	0.24
4	0.37	0.14	0.06
5	0.58	0.33	0.27
6	0.66	0.44	0.39
7	0.54	0.30	0.23
8	0.51	0.26	0.20
9	0.56	0.31	0.25
10	0.41	0.17	0.09
11	0.75	0.56	0.52
12	0.49	0.24	0.17

Table 4.16 Site Nine Average Index Values (short record)

2

of/de

2

reduced in areal extent but its boundaries may be expanded poleward (Bolin et al 1986, 501). Boreal forests cover a significant portion of the study area and represent a major factor in the buffer layer for many terrain units. Such a shift may well change the ground thermal regime over a large area, much of which is currently underlain by permafrost. Boreal forests also serve as a major sink for "the world's terrestrial organic carbon" (Bolin in Bonan 1988). Bonan suggests that boreal forests may actively contribute to global carbon dioxide dynamics. A change in distribution may affect their role in this cycle, perhaps adding to increased CO₂ levels.

As yet there are no conclusive studies to illustrate exactly how Boreal forest boundaries will change under conditions of climate change.

"... the forest system has great inertia but features short periods when relatively small outside perturbations can greatly alter the eventual path of the system." (Bolin et al 1986, p.481).

Webb et al (1989) suggest that increased decomposition of the moss layer of the boreal forest with increased warming will lead to major changes in the soil nutrient and thermal regime. Mosses thrive under moist shade conditions, but too much shade under a closed canopy results in the mosses eventually being shaded out. However, as the canopy opens, moss productivity also declines. Currently, permafrost in the study area is present under a moss layer of very open canopy.

A change in the surface albedo is the only direct influence on the net radiation absorbed by the earth-atmosphere system (Dickinson and Hanson 1984, 180). If vegetation patterns change, there could be a change in global albedos with significant implications for climate change.

4.7 Summary.

Calculations of the surface energy balance using the concept of N factors illustrates the role of vegetation in determining surface temperature. The results of this chapter show that certain vegetation types under present climatic conditions are likely to be underlain by permafrost in the study area, namely black spruce, and mixed black and white spruce. The range of air temperature extremes which occur are buffered by the vegetation, but if the length of the thaw season was to decrease, permafrost could be expected to aggrade under five of the six vegetation types considered.

The results of the expected $2 \times \text{CO}_2$ air temperature changes suggest that a concomitant doubling of surface temperatures will occur. This would result in widespread permafrost degradation and its eventual disappearance. However, the results cannot be taken at face value due to the complex interactions of climate and surface processes which will influence the rate at which these thermal changes will take place. Precipitation changes and variations in the length of the freeze and thaw season can all be expected to modify the

predicted surface temperature changes, perhaps giving lower values of R.

Changes in surface vegetation are likely to further complicate global air temperature changes. From the evidence of the climate growth relationship for trees in the study area, moisture availability and early growing season degree days are most important to tree growth. Summer degree days will increase significantly with increased carbon dioxide emissions, which could enhance the growth of trees in the area. However, the higher temperatures are also likely to lead to greater evaporation rates, and therefore increased moisture stress which may offset the effects of a temperature increase.

The complexity of the situation precludes firm conclusions, but the study does give some insight into the nature of expected surface temperature changes and the implications for permafrost and vegetation.

CHAPTER FIVE

CONCLUSION

5.1 Summary.

In the study of the complex problems associated with climate change there are lots of results at hand, but no easy answers. There are currently many studies of the impacts of climate change being undertaken in many different disciplines. If climate change is to become part of the political agenda in planning for the expected changes then a more holistic grasp of the problem is necessary. Due to its structural nature, landscape ecology is a framework which can be used to organise and integrate different methodologies, working within systems theory. However, landscape ecology cannot "solve" the problems implied by climate change. Detailed process studies cannot be replaced by best guesses but the idealistic holism of landscape ecology allows us to return our focus to the reasons and motivations behind scientific investigation.

Using this approach, evidence for climate change was considered within a regional context using a range of quantitative and qualitative data sources from which some conclusions can be drawn.

5.2 Conclusions.

On the basis of the evidence gathered in this thesis, there is some support for the notion that air temperatures are

rising along the Mackenzie Valley. This is coupled with evidence of widespread thermal erosion of permafrost landforms in the study area, which suggests there is a link between the two. Permafrost terrain occupies almost a third of the Fort Simpson area but more than half of this has been affected by thermokarst processes, based on evidence from aerial photos and vegetation maps of the area. The processes which lead to thermokarst would all appear to be climatically induced, but not necessarily in the sense of global climate warming having occurred. A changing microclimate due to disturbance by human and physical agents are among the contributory factors which are difficult to isolate from the effects of macroclimate.

The climate data for the region illustrates a slight rise in air temperatures over the century. The pattern of climatic variability is similar in nature to that of the northern hemisphere as a whole, which indicates that air and surface temperatures have increased over the past 150 years (see appendix A). This, coupled with the current extent of thermokarst permafrost terrain suggests that there is a real need to address the issues posed by climate change predictions.

The characterisation of the seasonal nature of energy exchange processes for different vegetation types presents a useful conceptual approach to examine spatial variations in surface temperature. The results of this for surface temperature changes using the predicted 2°CO_2 shift in air

temperatures indicate that surface temperatures will rise drastically, but the degree of change will vary with the characteristics of the buffer layer, if the complicating factors of changing precipitation are ignored. The effects of such a rise in temperature will be widespread degradation of permafrost under all vegetation types and changing environmental conditions for vegetation growth. Currently the biggest control on tree growth in permafrost areas is precipitation and growing degree days, both of which will be significantly altered under $2 \times \text{CO}_2$ conditions. However, this scenario does not take into account the climatic and surface changes which will accompany air temperature increases and complicate air and surface links. The length of the thawing season will increase and so too will precipitation amounts. Winter snow cover is perhaps the most critical factor in determining surface temperatures; winter precipitation is expected to increase by 60% and the timing of this will affect the degree of surface warming.

5.3 Further Research.

The areas of further research are almost boundless, but some of the specific areas which arose from this research are worth noting.

1. Methodology, it shapes everything we do but it is rarely stated or evaluated as a tool of research. To address the physical, social and economic impacts of climate change

it is important to be aware of the motivations for research. In the move towards the global village, the holistic approach to study employed in this thesis has the potential to integrate and synthesise a wide range of research findings which would assist in working towards common goals in dealing with climate change.

2. Knowledge of past and present air and surface temperatures is the only basis we have of determining if climate change is occurring. Some attempts are now being made to collect this data but there is a need for a standardised approach to the task. The highly variable nature of ground temperature records in the study area points to a gap in knowledge about the ground surface.

3. A series of monitoring sites could be established for different vegetation and terrain types (representing distinct ecotopes) to collect base level data on physical, ecological and climatic parameters. The current monitoring system in operation along the Norman Wells pipeline illustrates that such an approach is feasible.

4. The buffer layer is a concept which has widespread application in the study of processes which shape the earth's surface. Increasing technological sophistication in areas of remote sensing and the development of geographical information systems now allow for a much more complete assessment of landscape characteristics. Although limited use was made of GIS capabilities within this thesis, this could be much

expanded to integrate environmental data such as climate, topography and surface temperature.

5. Further investigation of the climatological controls on growth and the effects of enhanced carbon dioxide levels is needed. Most research in this area has been at the leaf level, due to the obvious difficulties of scaling up such an experiment.

6. There are currently several models attempting to investigate atmosphere - earth interactions and feedback mechanisms. Further refinement of these models will provide more insight into the key links between the climate and the ground, and what the effects of these feedback mechanisms will be.

Climate is definitely changing, but it is always in a state of flux. Carbon dioxide levels have risen quite significantly since the beginning of the industrial revolution. If this continues, some of the scenarios considered within this thesis may well cause problems for the planet and its people. But, while we may not be able to preserve the homeostasis of the system, by having a fuller understanding of the landscape ecosystem we can work towards dynamic homeorhesis, evolutionary stability, under conditions of climate change.

APPENDIX A**Climate Data.**

Climate data was obtained from Atmosphere Environment Service Canada for the following stations along the Mackenzie Valley Fort Simpson, Norman Wells, Fort Norman, Hay River and Wrigley.

Missing data were a problem for every station so a method of "reconstruction" was employed to fill the gaps in the data. This was achieved by taking the average of ten years of records on either side of the missing value. In some instances there was not five years before or after the missing record, so the average was taken from the nearest ten years of data. "Reconstructed" data points were used in subsequent calculations.

The use of five and ten year running mean annual temperature and precipitation allowed for interannual noise in the climatic signal to be smoothed out. Figures show the mean annual temperatures for some of the stations along the Mackenzie Valley.

The latitudinal surface air temperature trends are shown here for comparison to the regional climate data.

Surface air temperature trends (in Hansen and Takahashi 1984, 1984).

FUNDAMENTAL AVERAGE TEMPERATURE CHANGE TEN YEAR RUNNING MEAN

NORMAN WELLS AVERAGE YEARLY TEMPERATURE

WRIGLEY AVERAGE YEARLY TEMPERATURE

TEMPERATURE AND HUMIDITY RECORD

INCHES TO 100 METERS

TEMPERATURE AND HUMIDITY RECORD

INCHES TO 100 METERS

APPENDIX B

Vegetation Type Characteristics.

RIPARIAN SPRUCE/HARDWOODS:

TREE white spruce, balsam poplar and/or aspen in pure or mixed stands.
 SHRUB alder, willow, alpine bearberry, prickly rose, buffalo berry.
 HERB horsetail, wild strawberry, pyrola, bunchberry.
 MOSS feather mosses.

RIPARIAN SPRUCE/FEATHERMOSS:

TREE white and black spruce, larch, white birch, trembling aspen.
 SHRUB alder, willows, labrador tea, bilberry, bearberry, juniper, prickly rose.
 HERB horsetail, pyrola.
 MOSS feather mosses, sphagnum.

UPLAND SPRUCE (PINE)/HARDWOODS:

TREE white spruce, trembling aspen, jack pine, lodgepole pine, white birch
 SHRUB alder, willows, squashberry, red-osier dogwood.
 HERB horsetail, pyrola, twinflower.
 MOSS feather mosses
 LICHEN reindeer mosses

UPLAND SPRUCE/FEATHER MOSS:

TREE white and black spruce, trembling aspen, white birch.
 SHRUB alder, willows, dwarf birch.
 HERBS pyrola, horsetail, twinflower.
 MOSS feather, sphagnum.
 LICHEN reindeer.

BLACK SPRUCE/SPHAGNUM:

TREE black spruce, larch.
 SHRUB alder, willows, dwarf birch, labrador tea, bilberry, bearberry prickly rose, cloudberry, black crowberry.
 HERB horsetail, pyrola.
 MOSS feather, sphagnum.
 LICHEN reindeer, iceland.

BLACK SPRUCE/LICHEN:

TREES black spruce, larch.
SHRUB willow, alder, dwarf birch, labrador tea, bilberry,
cloudberry, black crowberry, bearberry.
HERB horsetail.
MOSS sphagnum and feather.
LICHEN reindeer, iceland.

SEDGE FENS:

TREE absent
SHRUB dwarf birch, willow, bilberry, labrador tea, shrubby
cinquefoil.
HERB horsetail.
MOSS sphagnum, feather

APPENDIX C

Field Site Data.

Three palsa were chosen for investigation and one peat plateau, all within close vicinity of each other, see map. Baseline observations were made on edge collapse, surface cracks and active layer depths and this data is presented in the following section, along with a brief description of each site. Cores were taken from trees on some of these sites and this data is summarised in chapter four.

Site One.

Site one is a palsa located approximately 2km from the highway and accessed along a seismic line. Vegetation consists of white and black spruce trees, dead white birch and young willow bushes, along with leatherleaf, labrador tea, cloudberry, sphagnum and feather mosses and lichens. Its shape is far from "classic" due to collapse of sections of the palsa which have left an arcuate shape. It is oriented parallel to seismic line, approximately 75m from it. Maximum elevation is 3.52m. Tree cores were taken from this site and results are recorded as site eight.

Crack Dimensions Site 1.

Length(m)	Depth(cm)
3.70	35 35 50 40
0.55	55 40 50 35 32
6.45	34 41 46 57 63 70 58
3.83	71 79 66 40 29 49
1.50	35
3.21	27 35 65 39

Active Layer across central palsa surface (1 m intervals).

49,48,36,42,48,46,38,44,45,47,45,45,43,38,32,48,40,45,29,37

Average=42.3 cm (23-07-89)

Active layer at 1m from collapse edge

thaw,53,53,54,48,48,thaw,50

Average=51cm (23-07-89)

Active layer 2m from collapse edge.

50,51,51,39,50,49,47,47

Average=48cm (23-07-89)

Tree Densities (10m₂)

>1m=36 <1m=31

Site Two.

Site two is a palsa located opposite to site four. The vegetation is similar to site four. However, the maximum elevation of site two is only 3.9m above the surrounding fen, the average height being 3.04m.

Crack Dimensions Site 2.

Length(m)	Depth(cm)	Width (cm)
0.70	15 27 10	
1.50	12 12 07	
0.70	18 30 17	
0.60	35 37 30	23 34 21
6.50	40 35 33	25 60 80
2.30	27 20 23	50 24 15
7.30	27 30 20 15 35 31	24 20 15 20 18 30 25

Tree Densities (10m₂)

>1m=63 <1m=73

Site Three Peat Plateau.

This site is adjacent to palsa site two. It is an area of low relief, the maximum elevation above the surrounding fen pond between 0.8 and 1m. It is densely treed and hummocky terrain, approximately 50m long characterised by black spruce trees and an understorey of sphagnum moss.

Site Three Active Layer Depths in middle of Plateau (1m intervals).

33,36,30,29,31,21,47,36,25,27,21,26,27,30,32,25,30,27,27,30

Average=29.5

Plateau Edge.

40,43,28,28,25,26,33,27

Average=27.5

Tree Densities

1m²=7,7,3,4,5,5,4,4,2,5

Average=4.6 trees per m²

Site Four.

Site four is a palsa located approximately 0.75km from highway and accessed along seismic line. Characteristic vegetation is black spruce, dead white birch, some white spruce, labrador tea, leatherleaf, cloudberry, sphagnum and feather moss, lichens. Maximum elevation of palsa is 5m above the water surface of the surrounding fen. The edge of the palsa is gradually collapsing into the pond, exposing a thick,

poorly decomposed, sphagnum peat. Permafrost underlies the whole palsa and ice lenses were in evidence at a depth of 114cm within the mineral soil layer which consisted of a silty clay. The palsa on site four displayed two sinkholes, these are circular depressions which lie below the general elevation of the surface vegetation and reflect internal mechanisms of ice degradation. The collapse edge of the palsa was elevated two metres above the surface vegetation of the sinkhole which suggests that differential heaving may be occurring. The difference in height between the surface vegetation of the sinkhole and the surface vegetation of the surrounding hummocks was 1.05m. The mosses in the sinkholes remained saturated throughout the summer period of observation, despite the fact that the sinkhole appeared to be frozen at a depth of 61cm on 9th of august 1989.

Tree cores were taken from this site and recorded as site nine.

Site Four Active Layer Depths 1m from Collapse Edge.

27,55,45,50,52,45,51,49,57,40,48,41,35,40,41

Average=45.1 (11-07-89)

Site Four Active Layer Depths 5m away from Collapse Edge.

40,45,45,40,28,43,30,30,25,28,40

Average=35.8 (11-07-89)

Sinkhole Two active layer on hummock

46,50,43,35,28,50,45,50

Average=43.3 (14-07-89)

Crack Dimensions Site 4.

Length(m)	Depth(cm)	Width (cm)
3.40	25 30 30	
2.00	35 13	
1.00	30	
2.10	43 33	
6.10	80 70 70 60	55 63 50 60
3.00	28 28 39	

Tree Densities (10m₂)

>1m=33 <1m=24

APPENDIX D.

Significance Levels for Tree Ring - Climate Regression.

Site Nine (long record)

	Degree days	Precipitation	Temperature
A	0.0901	0.8107	0.1300
B	0.0065	0.0759	0.5587
C	0.0000	0.0000	0.2637
D	0.9828	0.0000	0.9081
E	0.6580	0.4820	0.9618
F	0.0148	0.0000	0.9941
G	0.5369	0.0023	0.7394
H	0.4147	0.0001	0.3951

Site Nine (short record)

A	0.0004	0.0010	0.0000
B	0.2063	0.1648	0.0002
C	0.0044	0.4104	0.9068
D	0.9865	0.4246	0.0920
E	0.0084	0.3149	0.5325
F	0.0004	0.0421	0.3764
G	0.3578	0.2189	0.0025
H	0.2336	0.7254	0.0739

Site Eight

A	0.0498	0.9015	0.1678
B	0.0920	0.0224	0.0001
C	0.0010	0.0149	0.0750
D	0.1707	0.5788	0.0383
E	0.0001	0.0000	0.0001
F	0.8292	0.0957	0.4217
G	0.0000	0.0000	0.0152
H	0.0236	0.0000	0.5774
I	0.0388	0.2491	0.0005

BIBLIOGRAPHY.

- Anderson, T.W. (1989). Vegetation changes over 12,000 years. Geog, vol 18, 3, summer. Energy Mines and Resources Canada. pp. 39-47.
- Barry, R.G. and R.J. Chorley (1976). Atmosphere Weather and Climate. Third edition. Richard Clay Ltd. (Chaucer Press).
- Bolin, B. Doos, B.R. Jager, J. and R.A. Warrick (Eds)(1986). The Greenhouse Effect, Climate Change and Ecosystems. Scientific Committee on Problems of the Environment of the International Council of Scientific Unions. Wiley and Sons. 541p.
- Bonan, G.B. (1988). International Institute for Applied Systems Analysis. A Simulation Model of Environmental Processes and Vegetation Patterns in Boreal Forests: Test Case Fairbanks, Alaska. WP-88-63.
- Brown, R.J.E. (1968). Occurrence of permafrost in Canadian peatlands. Proceedings of the Third International Peat Congress, EMR, NRC. pp. 174-181.
- Brown, R.J.E. (1973). Distribution of permafrost in north America and its relationship to the environment: A review. In Proceedings, Second International Conference on Permafrost, North American Contribution. National Academy of Sciences, Washington.
- Brown, R.J.E and G.P. Williams (1972). The Freezing of Peatlands. National Research council Division of Building Research Technical paper No.381, Ottawa.
- Burgess, M.M. and D.W. Riseborough (1990). Observations on the thermal response of discontinuous permafrost terrain to development and climate change - an 800km transect along the Norman Wells pipeline. Proceedings of the Fifth Canadian Conference on Permafrost, March 1990.
- Burn, B.M. (1973). The Climate of the Mackenzie Valley-Beaufort Sea. Environment Canada Climatological studies No. 24, vol. 1.
- Burn, C.R. and M.W. Smith (1988). Thermokarst Lakes at Mayo, Yukon Territories, Canada. In, Proceedings Fifth International Conference on Permafrost. Volume 1, Trondheim, Norway, Aug 2-5 1988. Tapir Publishers. pp. 700-705.
- Canada Committee on Ecological Land Classification (1988).

Newsletter, 17. Supply and Services Canada.

- Chatwin, S.C. (1981). Permafrost Aggradation and Degradation in a Sub-Arctic Peatland. Unpublished Msc Thesis, Department of Geology University of Alberta, Edmonton. 163p.
- Cropper, J.P. and H.C. Fritts (1981). Tree ring width chronologies from the north American arctic. Arctic and Alpine Research, vol 13, 3, pp. 245-260.
- Crawford, C.B. (1951) Soil temperature and thermal properties of soils. Frost Action in Soils, A Symposium Thirtieth Annual Meeting. Highway Research Board Special Report No. 2 Technical memo No.102. pp. 17-41.
- Dansereau, P.M. (1957). Biogeography; an Ecological Perspective. Ronald Press Co. New York. 394p.
- DeVries, D.A. and N.H. Afgan (1975). Heat and Mass Transfer in the Biosphere. Part 1 Transfer Processes in the Plant Environment. John Wiley and Sons.
- Dickinson, R.E. (1986). How will climate change? In Bolin et al op cit. pp. 206-270
- Edlund, S. (1989). Vegetation indicates potentially unstable arctic terrain. Geos, vol 18, 3, summer. Energy Mines and Resources Canada. pp. 9-13.
- Evans, B.M. D.A. Walker, C.S. Benson, E.A. Norstrand and G.W.Peterson (1989). Spatial interrelationships between terrain, snow distribution and vegetation patterns at an arctic foothills site in Alaska. Holarctic Ecology, 12, 3, pp. 270-278.
- Farouki, O. (1986). Thermal Properties of Soils. Clausthal-Zellerfeld. Trans Tech. 136p.
- French, H.M. (1983). The Periglacial Environment. Longman Ltd.
- Fritts, H.C. (1976). Tree Rings and Climate. Academic Press Inc.
- Fritts, H.C. J.E. Mossiman, and C.P. Bortorff (1969). A revised computer programme for standardising tree-ring series. Tree Ring Bulletin. 29, pp. 15-20.
- Goodrich, L.E. (1982) The influence of snow cover on the ground thermal regime. Canadian Geotechnical Journal 19, pp. 421-432.

- Granberg, H.B. (1973). Indirect Mapping of the Snowcover for Permafrost prediction at Schefferville, Quebec. In N. American Contribution Second International Conference on Permafrost. National Academy of Science, Washington, pp. 113-120.
- Hansen, J.E. and Takahashi, T. (Eds)(1984). Climate Processes and Climate Sensitivity. Geophysical Monograph 29, Maurice Ewing Series No.5 American Geophysical Union, Washington, D.C.
- Hansen, J.E. A.Lacis, D.Rind, G.Russell, P.Stone, I.Fiung, R.Ruedy and J.Lerner. (1984). Climate Sensitivity Analysis of Feedback Mechanisms. In Hansen and Takahashi Op cit. pp. 130-163.
- Harris, C. (1974). Autumn, Winter and spring soil temperatures in Okstindan, Norway. In Journal of Glaciology, 13, pp. 521-533.
- Harvey, R.C. (1982). The Climate of Arctic Canada in a 2*CO2 World. Atmosphere Environment Service Canada. Rep. no. 82-5, 21p.
- Heginbottom, J.A. P.J. Kurfurst and J.S.O. Lau (1978). Regional occurrence of permafrost, Mackenzie Valley. In Proceedings of the Third International Conference on Permafrost Volume One. National Research Council of Canada, Ottawa. pp. 400-405.
- Hughes, M.K. P.M. Kelly, J.R. Pilcher and V.C. LaMarche Jr. (1982). Climate from Tree Rings. Cambridge University Press. 223p.
- Hutchinson, B.A. and B.B. Hicks (1985). The Forest-Atmosphere Interaction. Proceedings of the Forest Environmental Measures Conference. D. Reidel Publishing Co. 684p.
- Jacoby, G.C. E.R. Cook and L.D. Ulan (1985). Reconstructed summer degree days in central Alaska and northwestern Canada since 1524. In Quaternary Research, 23, pp. 18-26.
- Jorgenson, M.T. and R.A. Krieg (1988). A model for mapping permafrost distribution based on landscape component maps and climatic variables. In Proceedings of the Fifth International Conference on Permafrost. Volume 1 (op cit). pp. 176-182.
- Judge, A.S. (1975). Geothermal Studies in the Mackenzie Valley by the Earth Physics Branch. Geothermal Series Number 2, Ottawa, Canada. 12p.

- Kudryatsev, V.A. B.N. Dostovalov and L.S. Garagulya (1973). Radiation heat balance of the soil surface as a factor in the formation and dynamics of seasonally frozen soils and permafrost. International Conference on Permafrost, USSR Contribution, National Academy of Science, Washington D.C. pp. 18-21.
- Kozlowski, T.T. (1962). Tree Growth. The Ronald Press Co. 442p.
- Lachenbruch, A.H., Cladouhos, T.T. and R.W. Saltus (1988). Permafrost Temperature and the Changing Climate. In, Proceedings Fifth International Conference on Permafrost. Volume 3, Trondheim, Norway, Aug 2-5 1988. Tapir Publishers.
- Lavkulich, L.M. (1972). Soils, Vegetation and Landforms of the Fort Simpson area, NWT. ALUR 71-72-51. Indian and Northern Affairs.
- Linell, K.A. (1973). Long term effects of vegetative cover on permafrost stability in an area of discontinuous permafrost. Second International Conference on Permafrost, North American Contribution. Yakutsk, Siberia. National Academy of Sciences, Washington D.C. pp. 668-93.
- Lunardini, V.J. (1981). Heat Transfer in Cold Climates. US Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Van Nostrand Reinhold Company. 731p.
- Luthin, J.N. and G.L. Guymon (1974). Soil moisture - vegetation -temperature relationships in Central Alaska. Journal of Hydrology 23, pp. 233-246.
- Lutgens, F.K. and E.J. Tarbuck (1986). Atmosphere An Introduction to Meteorology. Prentice Hall Inc. New Jersey. Third edition. 492p.
- Mackay, J.R. and D.K. Mackay (1974). Snow cover and ground temperatures, Garry Island, NWT. Arctic, 27, 4, pp. 287-296.
- Moss, M.R. (1988). Landscape Ecology and Management. Proceedings of the First Symposium of the Canadian Society for Landscape Ecology and Management; University of Guelph, May 1987. Polyscience Publications Inc., Montreal, Canada. 240p.
- Naveh, Z. and A.S. Lieberman (1984). Landscape Ecology Theory and Application. Springer-Verlag, New York Inc.

356p.

- Nicholson, F.H. and H.B. Granberg (1973). Permafrost and snow- cover relationships near Schefferville, Quebec: recent studies. In Proceedings, Second International Conference on Permafrost, Yakustk, USSR. U.S. National Academy of Sciences, Washington D.C., pp. 71-100.
- Oke, T.R (1978). Boundary Layer Climates. Methuen and Company, London, 372p.
- Reid, D.E. and A. Janz (1974). Biological Report Series Volume Three. Vegetation of the Mackenzie Valley - Part Two. Northern Engineering Services Company Limited. Canadian Arctic Gas Study Limited.
- Rennie, J.A. D.E. Reid and J.D. Henderson (1978). Permafrost distribution in the southern fringe of the discontinuous permafrost zone, Fort Simpson, N.W.T. In Proceedings of the Third International Conference on Permafrost Volume One. National Research Council of Canada, Ottawa. pp. 439-444.
- Riseborough, D.W. (1986). Modelling Climatic Influences at a Boreal Forest Site. Unpublished B.A. thesis, department of Geography, Carleton University, Ottawa.
- Riseborough, D.W. and C.R. Burn (1988). Influence of an organic mat on the active layer. In, Proceedings Fourth International Conference on Permafrost. pp. 633-638.
- Rosenberg, Blad and Verma (1983). Microclimate: the Biological Environment. John Wiley and sons. 495p.
- Rowe, J.S. (1969). Plant Community as a Landscape Feature. In Essays in Plant Ecology. Greenidge, K.N.H. editor. Nova Scotia Museum Halifax, N.S. pp. 63-81.
- Saunders, A. (1987) Editor. A question of Degrees. Northern Perspectives, vol 15, no.5 dec.87.
- Schneider, S.H. (1984). On the empirical verification of model predicted CO₂ - induced climatic effects. In Hansen and Takahashi (op cit). pp. 187-201.
- Smith, M.W. and D.W. Riseborough (1983). Permafrost Sensitivity to Climatic Change. Permafrost: Fourth International Conference Proceedings, National Academic Press, Washington D.C. p1178-1183.
- Smith, M.W. (1985). Obtaining Climatic Information from Tree Rings. Our Geographic Mosaic. Research essays in honour

of G.C. Merrill. Carleton University Press. D. Knight ed. pp.158-170.

Smith, M.W. (1988). The Significance of Climate Change for the Permafrost Environment. In, Proceedings Fifth International Conference on Permafrost. Volume 3, Trondheim, Norway, Aug 2-5 1988. Tapir Publishers. pp. 18-23.

Task Force on Northern Oil Development Canada (1974). Vegetation Types of the Mackenzie Corridor. Environmental Social Committee Northern Pipelines, Report No. 73-46.

Taylor, A.E. R.J.E. Brown, J.Pilon and A.S. Judge (1982). Permafrost and the shallow thermal regime at Alert, NWT. In Proceedings of the Fourth Canadian Permafrost Conference. Roger J.E. Brown Memorial Volume, NRCC, Ottawa. pp. 12-22.

Thie, J. (1974). Distribution and Thawing of Permafrost in the Southern part of the Discontinuous Permafrost Zone in Manitoba. Arctic, Vol.27, No.3. Journal of the Arctic Institute of North America.

Thompson, R.D. (1989). Short-term climatic change: evidence, causes, environmental consequences and strategies for action. Progress in Physical Geography. Vol 13, 3. Edward Arnold. pp. 315-347.

Webb, R.S. M.T. Ter-Mikhaelian, A.M. Solomon, T.M. Smith, S.E. Pitovranov, N.T. Nikolov, A.A. Minin, R. Leemans, S.Lavorel, M.D. Korzukhin, J.P. Hrabovsky, H.O. Helmisaan, S.P. Harrison, W.R. Emanuel, G.R. Bonan. (1989). Developing a Global Vegetation Dynamics Model: Results of an IIASA Summer Workshop. RR-89-7. I. Colin Prentice et al.

Williams, P.J. (1982). The Surface of the Earth Introduction to Geotechnical Science. Carleton University Press.

Williams, P.J. and M.W. Smith (1989). The Frozen Earth Fundamentals in Geocryology. Cambridge University Press.

Yen, Y.C. (1969) Recent studies on snow properties. Advances in Hydrosience, vol 5, Academic Press, New York.

Zoltai, S.C. (1971). Southern Limit of Permafrost Features in Peat Landforms, Manitoba and Saskatchewan. Geological Association of Canada Special Paper No.9. pp. 305-310.

Zoltai, S. C. and C. Tarnocai (1975). Perennially Frozen Peatland in the Western Arctic and Subarctic of Canada. Canadian Journal of Earth Science Vol.12, No.1 Jan. pp.28-43.

Zonneveld, I. S. (1988). Landscape Ecology and its Application. In Moss op cit 1988. pp.3-16.

END

1 2 0 4 9 1

FIN