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A Canadian Contribution to the Paleoclimate Model Intercomparison Project (PMIP)
La contribution du Canada au projet Paleoclimate Model lntercomparison
Ein kanadischer Beitrag zum Projekt Paleoclimate Model lntercomparison (PMIP)

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La paléogéographie et la paléoécologie d’il y a 6000 ans BP au Canada
Paleogeography and Paleoecology of 6000 yr BP in Canada

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Article abstract

PMIP (Paleoclimate Model lntercomparison Project) is designed to compare and improve the ability of General Circulation Models (GCMs) to simulate a wide range of climatic conditions including known features of past climatic states that are significantly different from present conditions. One of the first simulations of past climate conducted under this project targets the 6000 yr BP period for the following reasons: 1) deglaciation was complete and the last remnants of the Laurentide Ice Sheet had essentially disappeared by this time, 2) sea surface temperatures approached modern values, 3) the orbital insolation regime was the only major boundary condition significantly different from present, and 4) a number of study sites can already be used to provide preliminary paleoenvironmental reconstructions for this period. Contributions from the Canadian scientific community towards this experiment are presented, following a brief overview of Canadian modern environmental conditions which places the regional contributions into a broader perspective.

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A CANADIAN CONTRIBUTION TO THE PALEOCLIMATE MODEL INTERCOMPARISON PROJECT (PMIP)*

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ABSTRACT PMIP (Paleoclimate Model Intercomparison Project) is designed to compare and improve the ability of General Circulation Models (GCMs) to simulate a wide range of climatic conditions including known features of past climatic states that are significantly different from present conditions. One of the first simulations of past climate conducted under this project targets the 6000 yr BP period for the following reasons: 1) deglaciation was complete and the last remnants of the Laurentide Ice Sheet had essentially disappeared by this time, 2) sea surface temperatures approached modern values, 3) the orbital insolation regime was the only major boundary condition significantly different from present, and 4) a number of study sites can already be used to provide preliminary paleoenvironmental reconstructions for this period. Contributions from the Canadian scientific community towards this experiment are presented, following a brief overview of Canadian modern environmental conditions which places the regional contributions into a broader perspective.

RÉSUMÉ *La contribution du Canada au projet Paleoclimate Model Intercomparison.* Le projet Paleoclimate Model Intercomparison (PMIP) a été conçu pour comparer les différents modèles de circulation générale et améliorer leur potentiel à simuler une grande gamme de conditions climatiques, y compris certaines caractéristiques connues de paléoclimats qui sont très différentes des conditions d'aujourd'hui. Une première expérience est prévue pour la période de 6000 ans BP pour les raisons suivantes : 1) la déglaciation est alors terminée et les derniers vestiges de l'Inlandsis laurentidien sont en grande partie disparus ; 2) les températures marines de surface sont près des valeurs actuelles ; 3) le régime d'insolation orbitale représente le seul paramètre substantiellement différent d'aujourd'hui et ; 4) un bon nombre de sites peuvent d'ores et déjà servir à effectuer des reconstitutions préliminaires de cette époque. Les premières contributions de la communauté scientifique canadienne à cette expérience sont ici présentées, en compagnie d'un bref aperçu des conditions environnementales actuelles afin de replacer les contributions régionales dans une plus large perspective.

ZUSAMMENFASSUNG *Ein kanadischer Beitrag zum Projekt Paleoclimate Model Intercomparison (PMIP).* Paleoclimate Model Intercomparison Project) wurde entworfen, um die allgemeinen Zirkulationsmodelle zu vergleichen und zu verbessern bezüglich ihrer Fähigkeit, eine weite Skala von klimatischen Bedingungen zu simulieren, einschließlich bekannter Charakteristika vergangener klimatischer Zustände, die sehr verschieden von den gegenwärtigen Bedingungen sind. Eine der ersten in diesem Projekt durchgeführten Simulationen des vergangenen Klimas zielt auf die Periode von 6000 Jahren v.u.Z. und zwar aus folgenden Gründen: 1) die Enteinsung war beendet und die letzten Überreste der laurentidischen Eisdecke waren zu diesem Zeitpunkt weitgehend verschwunden, 2) die Meeresoberflächentemperaturen waren nah bei den modernen Werten, 3) das Orbitalsonneneinstrahlungssystem war der einzige Parameter der sich von heute grundlegend unterschied und 4) eine Reihe von erforschten Plätzen kann schon gleich für vorläufige Rekonstruktionen der Paläoumwelt dieser Zeit genutzt werden. Es werden Beiträge der kanadischen Wissenschaft zu diesem Experiment vorgestellt, zusammen mit einer kurzen Übersicht über moderne kanadische Umweltbedingungen, welche die regionalen Beiträge in eine weitere Perspecktive rückt.

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INTRODUCTION

The International Panel on Climate Change (IPCC) (1990) recognized the need to develop accurate predictions of the consequences of anthropogenically-induced environmental stress, including global warming and global sea level rise. This concern has also attracted a growing international awareness of the necessity to reduce the uncertainties linked with ongoing environmental changes.

Increasing stress on the environment from human activities is anticipated for the near future. To cope with these expected changes, policy makers will have to rely on predictions from large-scale climate models, the General Circulation Models (GCMs), for reliable estimates of future environmental conditions to guide their decision-making processes. It is then of utmost importance that these models be accurately calibrated.

In order to do so, one project, the Paleoclimate Model Intercomparison Project (PMIP) has been put forward at the international level to improve our understanding of past climates and to increase the ability of the GCMs to reproduce accurately past climatic patterns, through the refinement of their complex parameterization schemes and coupling procedures. The first experiment under PMIP targets on the 6000 years BP period for the following reasons: 1) deglaciation was complete and the last remnants of the Laurentide Ice Sheet had essentially disappeared by this time, 2) sea surface temperatures (SST) approached modern values, 3) the orbital insolation regime was the only major boundary condition significantly different from present and 4) a number of study sites can already be used to provide preliminary paleoenvironmental reconstructions for this period. Other experiments are planned for the following target periods: the Late Glacial Maximum (18,000 yr BP) and the last Interglacial (125,000 yr BP).

Two core components of the International Geosphere-Biosphere Program (IGBP) have been focused on the PMIP project: the PAst Global changES (PAGES) project and the Global Analysis Interpretation and Modelling (GAIM) project. The goal of PAGES is to compile high quality data sets suitable to document past climate. One of the goals of GAIM is to provide independent reconstructions, such as those generated by the biome model of Prentice *et al.* (1992), that will be used to test the ability of the GCMs to predict accurately past climatic conditions.

PMIP can already build upon a number of existing reconstructions including CLIMAP (global maps of sea surface temperature and continental ice cover from the last glacial maximum to the present, as inferred from data from deep sea sedimentary cores) (CLIMAP project members, 1981), SPECMAP (coupling of the Milankovitch cycle (variations of orbital insolation) with the glacial cycles of the late Cenozoic, as inferred from $\delta^{18}O$ data from deep sea sedimentary cores) (Peltier, 1993), and COHMAP (coupling of the atmospheric general circulation models with North American biome boundaries at a sequence of times from 18,000 yr BP to the present, as inferred from palynological data) (COHMAP members, 1988; Wright *et al.*, 1993).

The methodologies used to perform such comparative analyses have benefitted greatly from previous experiments. However, they also "have revealed serious flaws in the sets of paleodata utilized and in the general circulation models employed to simulate the past climate states represented by these data" (Peltier, 1993).

Recent syntheses presenting general trends in climatic regime (temperature and precipitation) during the Holocene have been compiled for eastern North America (Webb *et al.*, 1993) and western Canada (Ritchie and Harrison, 1993). However, some remote regions are still poorly documented and others are so complex that the existing information has to be interpreted with a regional perspective. High quality data and regional expertise are needed for the PMIP project.

A Canadian 6000 yr BP planning workshop was held in Ottawa in November 1992 under the joint sponsorship of the Royal Society of Canada, the Canadian Climate Centre and the Geological Survey of Canada (Telka, 1993). The participants (members of the Canadian climate modelling community, representatives of Canadian paleoenvironmentalists and other international scientists agreed that Canada should play an active role in the PMIP project on the following principles: 1) the main data sets that will be used for the PMIP project deal with climate variations through an ice age cycle (this cycle, global in scale, has had its most profound influence on the Canadian landmass); 2) the Canadian climate model, from the Canadian Climate Centre of Environment Canada, is one of the very best of the second generation of models (this group is already participating in the PMIP project and is strongly supportive of the concept of paleoenvironmentalists providing the very latest and best data for this period); 3) Canada can rely on the expertise of competent paleoenvironmentalists to cover every region of the country; and 4) Canadian sites can contribute significantly to the reconstruction of global past environments, including past climates. To illustrate this last point, a first Canadian vegetation map illustrating the information available for the 6000 yr BP period was presented at the planning workshop (Jetté, 1993, 1994).

At the workshop it was proposed to compile existing information on the 6000 years BP period and to prepare a multi-authored refereed publication on this period across Canada, as a first contribution to the PMIP project. The goals of this thematic volume are two fold: to collate the information available for the 6000 yr BP time slice and to link existing regional expertise with modelling activities.

Regional workshops were held across the country to invite participation of Canadian scientists to the project and a multidisciplinary approach was promoted in order to gather complementary information much needed to document past climatic conditions. Paleoenvironmentalists attending the workshops were invited to prepare regional syntheses and to compile climate-related information (vegetation, temperature, precipitation, water-level fluctuations, forest fires frequencies, etc.) that could be used to reconstruct the climatic history of their region. Their contributions are presented in this thematic volume, following an overview of modern Canadian environmental conditions, summarized in

TABLE I

Climate transect from southern Ontario to the Arctic

Location	1	2	3	4	5	6
Mean annual temperature (°C)	+7.3	+4.2	-0.6	-2.7	-9.8	-16.6
Length of period with temperatures above 0°C (months)	9	8	7	6	4	2
Mean frost-free period (days)	147	117	114	99	51	9
Mean daily maximum temperature of warmest month (°C)	26.4	25.1	23.2	21.0	19.4	6.8
Mean daily temperature of coldest month (°C)	-10.5	-18.8	-27.5	-30.2	-34.4	-36.8
Mean daily temperature of warmest month (°C)	20.3	18.7	17.7	15.6	13.6	4.1
Mean total annual precipitation (mm)	909	796	454	414	266	131
Latitude (°N)	43	45	54	57	68	74

1) London Airport, Ontario; 2) Combermere, Ontario; 3) The Pas Airport, Manitoba; 4) Cree Lake, Saskatchewan; 5) Inuvik Airport, Northwest Territory; 6) Resolute Airport, Northwest Territory;

See figure 2A for the location of the meteorological stations. Source: Environment Canada, 1989.

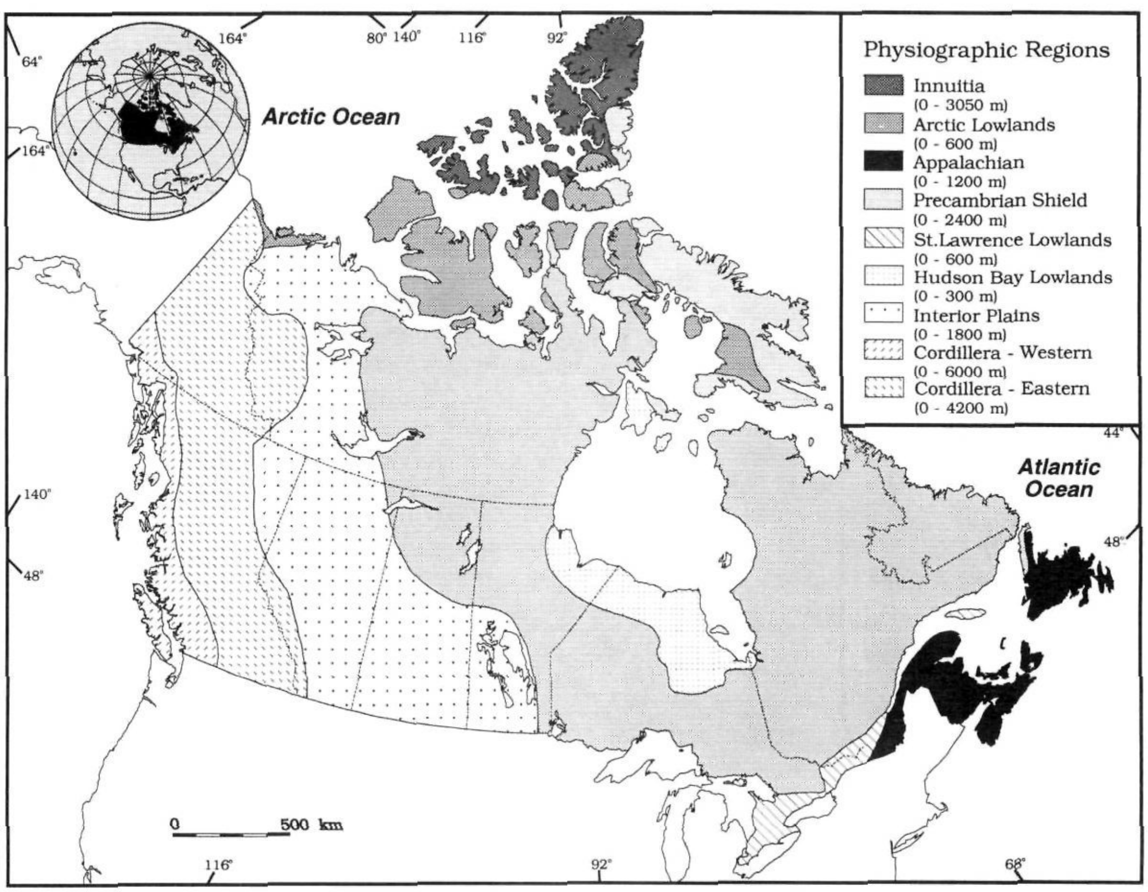

FIGURE 1. Main physiographic regions of Canada (modified from Bostock, 1970; Slaymaker, 1989.

Principales régions physiographiques du Canada (modifiée de Bostock, 1970 ; Slaymaker, 1989.

a table and figures (Table I; Figs. 1 to 4), in order to set the regional syntheses into a broader perspective.

MODERN ENVIRONMENTAL CONDITIONS

Physiography and relief (Fig. 1), especially the high, north-south alignment of the Cordillera in the west combined with the openness of the vast plains to the east, control the flow of the circumpolar westerly winds. These have an important impact on the Canadian climate (Table I; Fig. 2A and 2B). Canadian summers (Fig. 2A) are relatively warm but the winters (Fig. 2B) are long and cold, as compared with the climate of European countries located at the same latitude. Total precipitation is greater along the coasts (Fig. 2C). Permafrost (Fig. 3) underlies some 50% of the country and ten main ecoclimatic provinces, defined as "gradients of ecologically effective macroclimate (as expressed by vegetation)" (Environment Canada, 1989), characterize the vegetation of Canada (Fig. 4).

REGIONAL RECONSTRUCTIONS FOR THE 6000 YR BP PERIOD

Williams *et al.* (1995), using several proxy indicators such as pollen, diatoms, foraminifera and molluscs, present a Holocene paleoenvironmental reconstruction for the eastern Canadian Arctic. Their findings highlight a marine surface water maximum at 8 ka, a terrestrial thermal maximum during the middle Holocene (6-4 ka), and major water changes around 6 ka, driven by glacio-isostatic uplift of the Arctic channels.

Cwynar and Spear's (1995) synthesis of palynological investigations in the Yukon Territory indicates a vegetational composition different than today until *ca.* 6000 yr BP. They conclude that since all the species were present in this region well before 6 ka, the vegetation change since that date cannot be ascribed to migration lags but to cooler and, at least in the south, wetter growing seasons than previously.

From the Northwest Territories, Zoltai (1995) illustrates the extent and distribution of permafrost in peatlands 6000 years ago, with a discussion on the paleoclimatic significance of this distribution. Macdonald (1995) puts forward a reconstruction of tree-line at 6000 yr BP. Evidences indicate that the northern limit of the forest just prior to 6000 yr BP, was 25 km north of its modern location in the Mackenzie River and Delta region but at the same location as present in central Canada.

Hebda (1995) presents an extensive postglacial vegetation history for British Columbia. He reports that conditions were, 6000 yr BP, warmer with precipitation close to modern or possibly wetter than today.

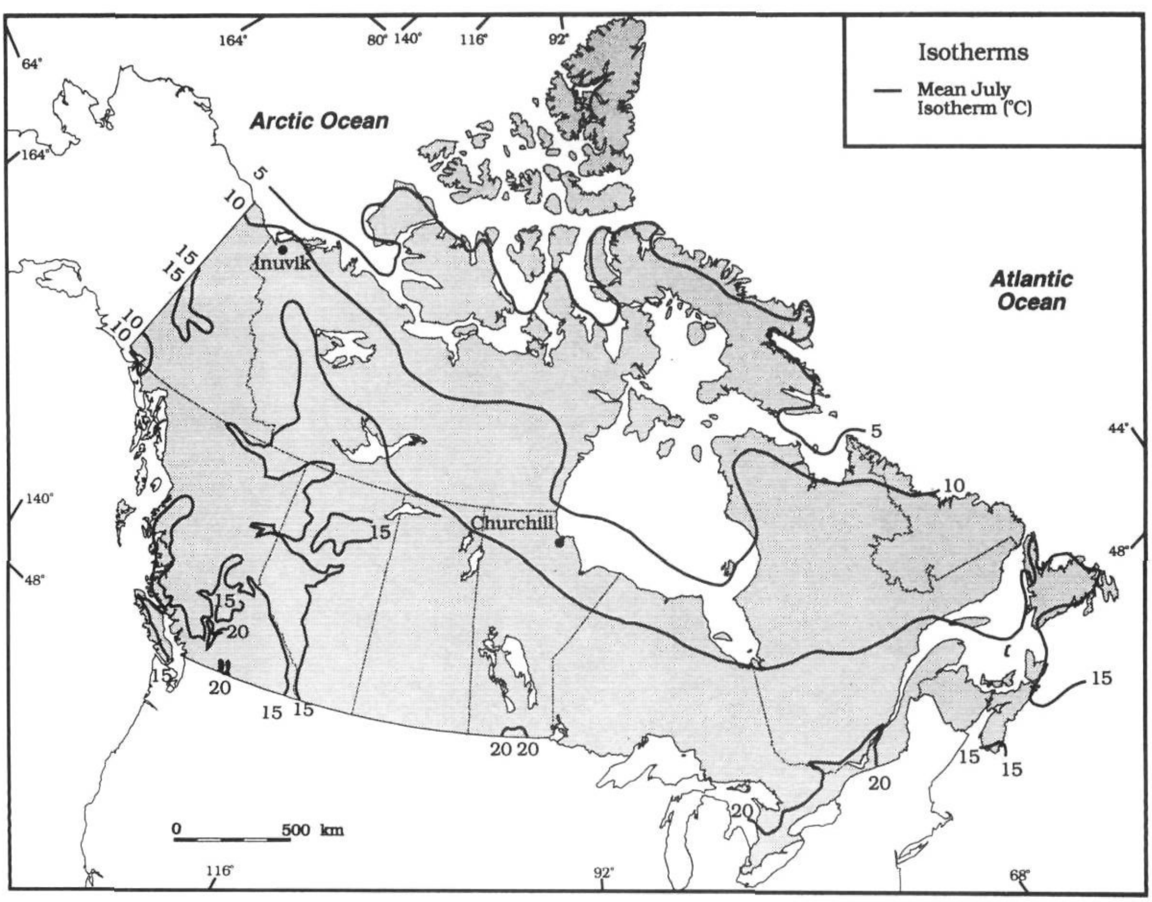

FIGURE 2A. Mean July temperatures (Environment Canada, 1987).

Températures moyennes de juillet (Environnement Canada, 1987).

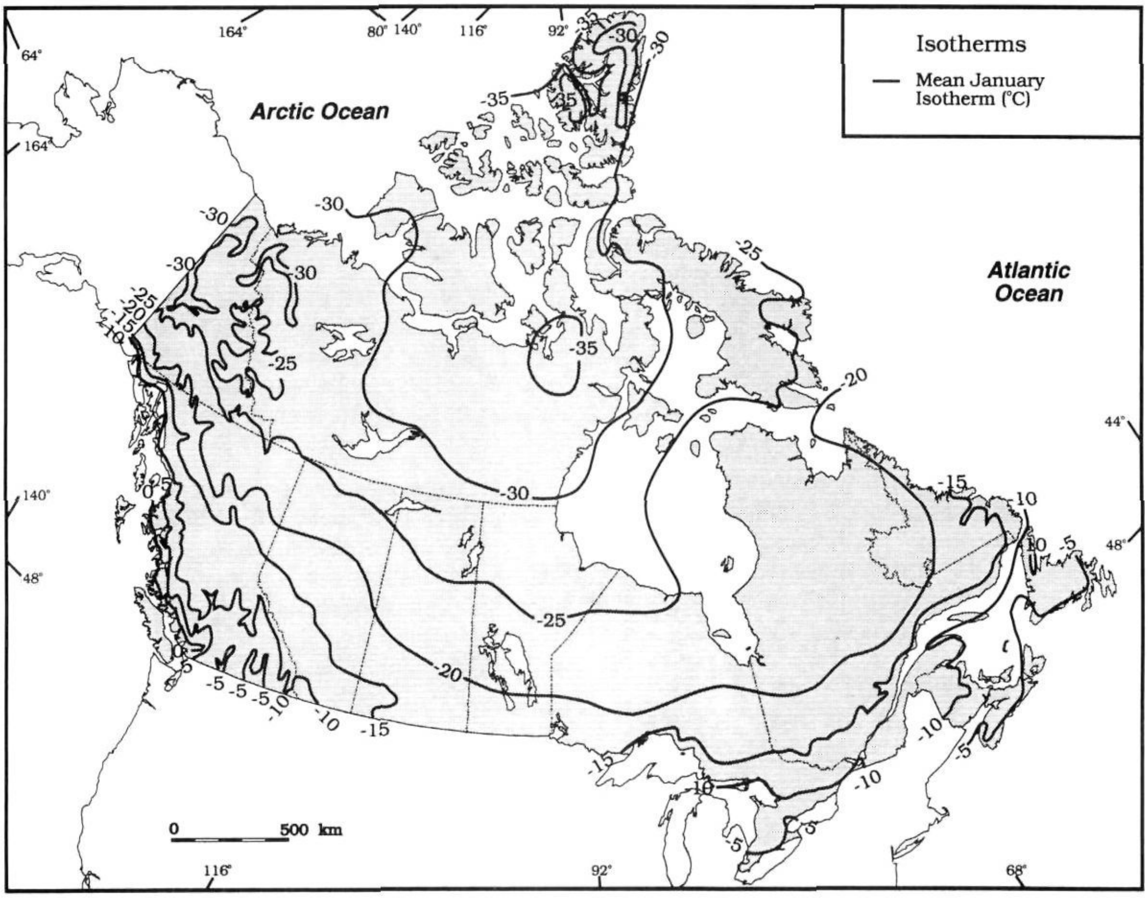

FIGURE 2B. Mean January temperatures (Environment Canada, 1987). *Températures moyennes de janvier (Environnement Canada, 1987).*

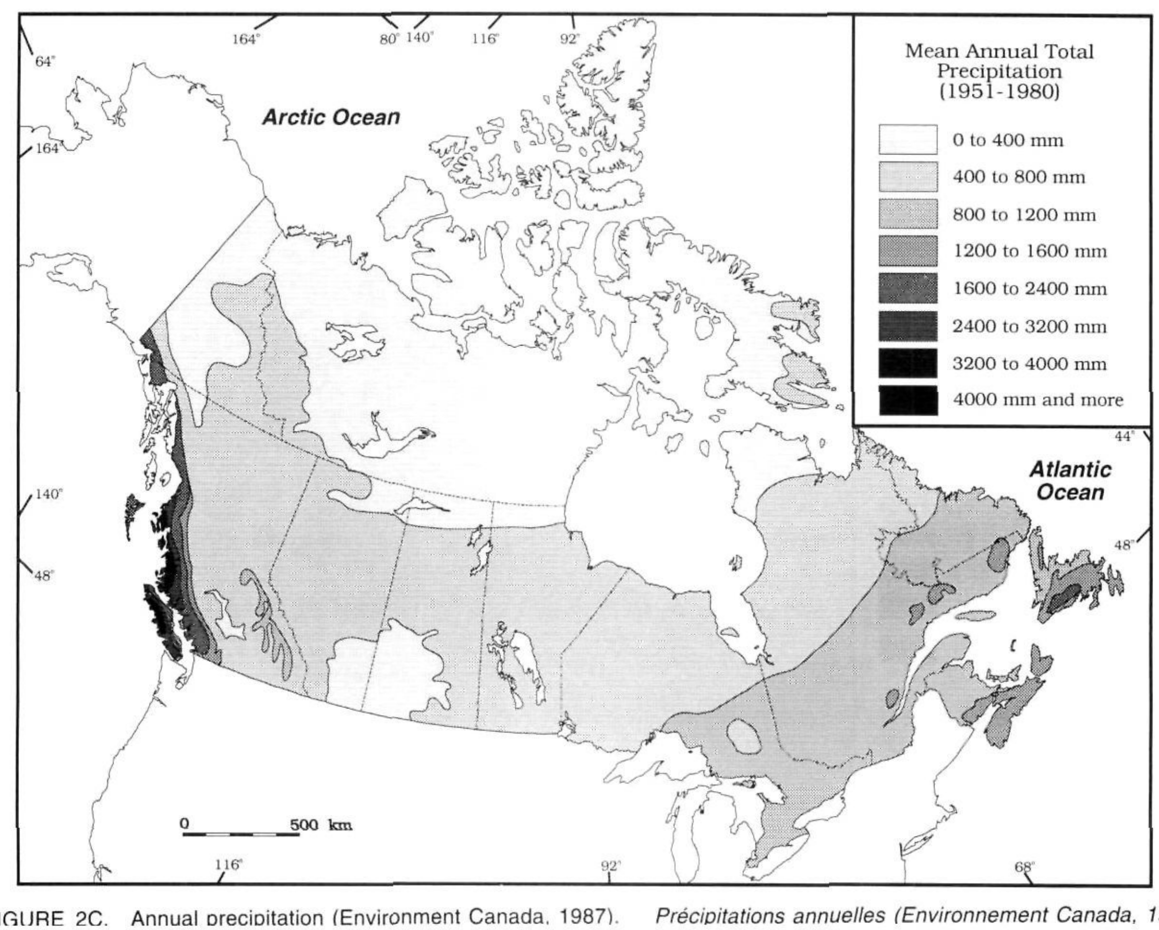

FIGURE 2C. Annual precipitation (Environment Canada, 1987). *Précipitations annuelles (Environnement Canada, 1987).*

The multidisciplinary study by Vance *et al.* (1995) for the Canadian prairies shows that, although the peak in postglacial aridity had passed, conditions remained warmer and drier than present in the western foothills and the plains *ca.* 6000 yr BP.

Anderson (1995) depicts a forest composition different than today *ca.* 6000 yr BP in the Great Lakes region. The boreal-mixed forest ecotone was displaced some 140 km northward (Liu, 1990) and the mixed-deciduous forest ecotone some 65 km northward, suggesting that regional climatic conditions were warmer than today 6000 yr BP. A new hypothesis is presented to explain the local distribution of vegetation and climate at 7000 to 5000 BP, at the lee of the Great Lakes.

Richard (1995) presents a detailed reconstruction of the vegetation at *ca.* 6000 yr BP from Québec and Labrador, and suggests some hypotheses concerning the evolution of climate between 7000 and 5000 yr BP.

Jetté and Mott (1995) report conditions slightly warmer than today in the Maritime Provinces (New Brunswick, Nova Scotia and Prince Edward Island), and demonstrate the effect, on the vegetation, of a drought that lasted from *ca.* 6500 to 6000 yr BP.

From Newfoundland, Macpherson (1995) reconstructs conditions no more than 1.5°C warmer than today and higher forest fire frequencies 6000 yr BP. She also observes a lag in the oceanic warming, as compared with the terrestrial warming.

These regional reconstructions provide a first synthesis of the Canadian climate at 6000 yr BP. However, this period is a static point in time. Climate is better characterized by trends, for examples, combinations of cool, warm, wet or dry conditions. During the Wisconsin Glaciation, most of Canada was covered by ice (Dyke and Prest, 1987). This huge mass of ice depressed the land surface, caused the lowering of sea level, was a permanent source of Arctic air in middle latitudes, changed global atmospheric circulation patterns and the distribution of precipitation, and was the cause of southward migration and compression of biozones. From its inception to its disappearance, the presence of the ice influenced global, regional and local climate. Time series and regional expertise are necessary to understand the evolution of the Canadian climate through time.

Remnants of the Laurentide Ice Sheet subsisted until *ca.* 6500 yr BP in northern Québec, according to Dyke and Prest (1987) and Vincent (1989), and until 5000 BP, according to Payette (1993). At the first target period of the PMIP project (6000 yr BP), sea level and isostatic rebound of the land were still adjusting following the recent ice retreat and biozones were still in disequilibrium. Therefore, understanding the history and dynamics of the ice sheet is extremely important in predicting sea level change and modelling global climatic change.

PREDICTIONS FOR THE FUTURE

Assuming a global warming of 4°C, which is within the range of the warming scenarios (2 × CO_2 climate scenario) predicted by the atmospheric general circulation models, permafrost in the sporadic distribution zone (Fig. 3) would thaw quickly. For example, a geothermal model tested in the Fort Simpson area (Burgess and Desrochers, 1993;

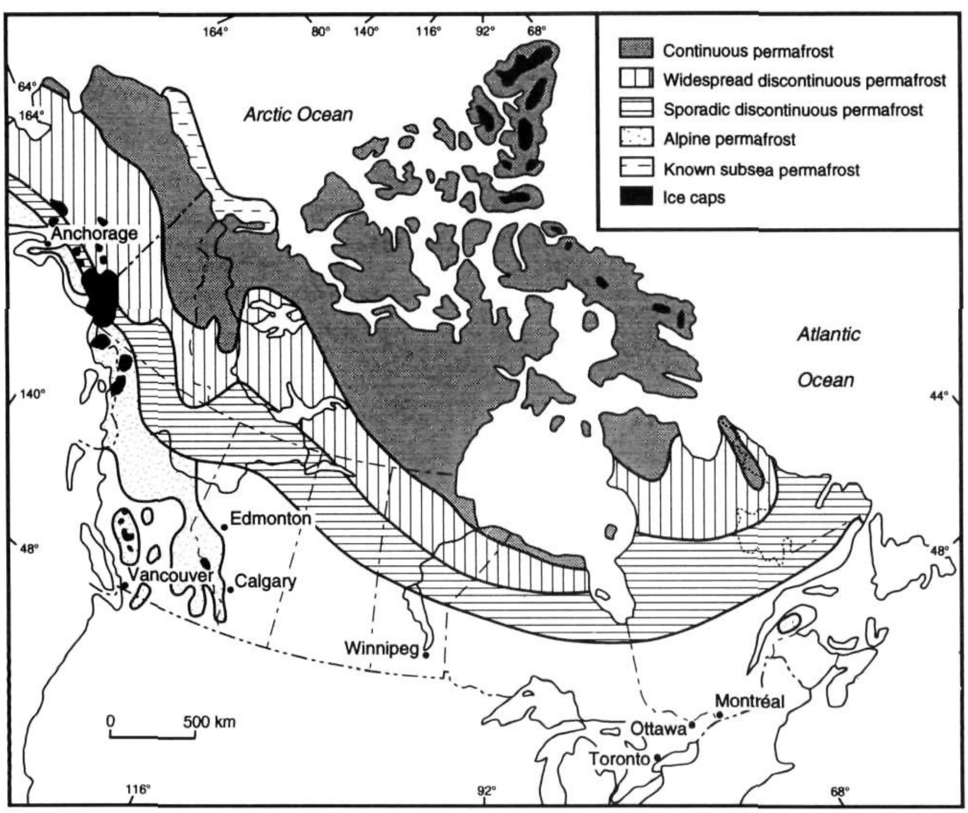

FIGURE 3. Permafrost distribution (J.A. Heginbottom, pers. comm.).

Répartition du pergélisol (J.A. Heginbottom, comm. pers.).

Riseborough and Smith, 1993) predicts a complete thawing of the permafrost in this area within a 60 year period under these conditions. This would have a strong impact on the landscape in northern Canada, thawing surficial sediments and triggering mass movements. Damage to existing infrastructures (roads, buildings, pipelines) would occur, the extent of which would depend upon the amplitude and duration of the warming period. In addition, CO_2, methane, and other greenhouse gases trapped in frozen peat bogs and sediments would be released, enhancing the global warming effect.

According to Rizzo and Wiken (1989), assuming the same extent of warming, tree-line position and vegetational zones would change, creating, in the process, a strong impact on agriculture (prairies), logging (extent of the boreal forest), fruit and vegetable growing (southern Ontario, southern Québec, southern British Columbia), fish, fauna, etc. The climate of the Prairies would likely remain under a dry continental regime. The water resources of this area might become scarce and today's drought-prone areas could well be transformed into useless deserts.

In addition, it is predicted that such warming would also cause sea level to rise, affecting coastal areas. Projections of future sea-level rise range from 0.3 (Meier, 1990) to 3.5 m (Hoffman *et al.*, 1983) by the year 2100. All these changes would strongly affect Canadian society and economy.

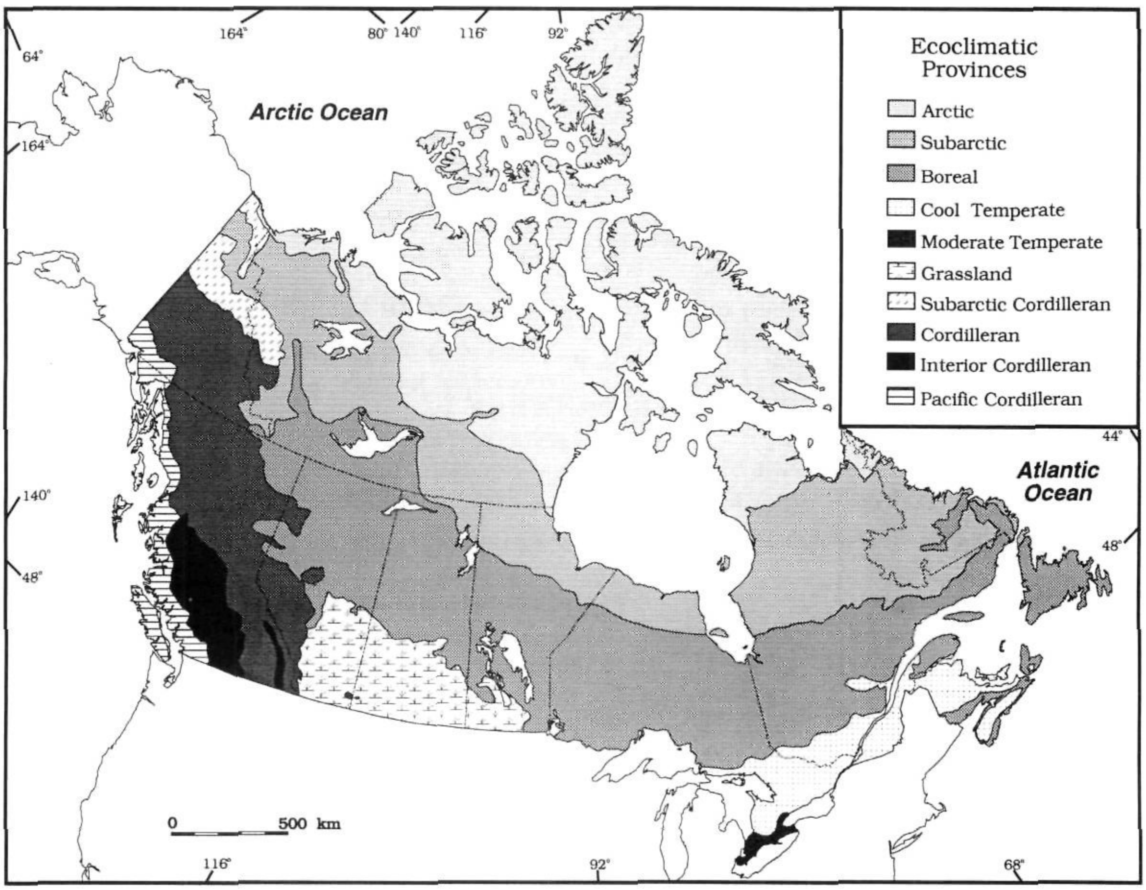

FIGURE 4. Canadian ecoclimatic provinces. Arctic: treeless, with tundra, polar semi-desert, or polar desert. Subarctic: open-canopied conifer woodlands, with tundra patches. Boreal: closed-canopied forests of conifer or mixed-conifer-hardwood. Cool Temperate: mixed forests of shade-tolerant hardwood-conifer. Moderate Temperate Province: deciduous forests. Grassland Province: with grassland with or without small groves of hardwood trees. Subarctic Cordilleran: open-canopied conifer woodland and alpine tundra in elevational zones. Cordilleran Province: closed-canopied conifer or mixedwood forests, open-canopied conifer woodland, and alpine tundra in elevational zones. Interior Cordilleran Province: grassland (with or without scattered trees), closed-canopied conifer or mixedwood forest, open-canopied conifer woodland, and alpine tundra in elevational and rain shadow zones. Pacific Cordilleran: closed-canopied conifer forest, open-canopied conifer woodland, and alpine tundra in elèvational zones. Source: Environment Canada, 1989.

Provinces écoclimatiques du Canada. Arctique : toundra, semi-désert ou désert polaire, sans arbres. Subarctique : forêts clairsemées de conifères, avec étendues de toundra. Boréale : forêts de conifères ou forêts mixtes de conifères et de feuillus. Tempérée froide : forêts mixtes de feuillus tolérants à l'ombre et de conifères. Tempérée modérée : forêts décidues. Prairies : prairies accompagnées ou non de petits groupements de feuillus. Cordillère subarctique : forêts clairsemées de conifères et toundra alpine en zones élevées. Cordillère intérieure: prairies (avec ou sans arbres épars), forêts de conifères ou mixtes, forêts clairemées de conifères et toundra alpine dans les zones élevées ou sèches. Cordillère: forêts de conifères, forêts clairsemées de conifères et toundra alpine en zones élevées. Source : Environnement Canada, 1989.

THE GEOLOGICAL RECORD AS THE LINK BETWEEN THE PAST AND THE FUTURE

The vegetation in northern Canada is very sensitive to climatic change and has been little disturbed by human activities. In these areas, the correspondence between modern climatic conditions and modern environments are tentatively used to reconstruct past environments and climates, using information extracted from the geological record. The resulting local and regional climatic history can then be linked with the evolution of the landscape (vegetation, permafrost development, drought frequency, water level fluctuation, etc.) through time. In these areas, studies of past environmental change are merged with impact studies to help predict the consequences of future environmental change, be it a warming or a cooling trend.

CONCLUSION

This thematic volume is the first contribution of the Canadian scientific community to the Paleoclimate Model Intercomparison Project. This first initiative has already strengthened collaboration between Canadian modellers and paleoenvironmentalists; hopefully it will create strong collaborative links between Canadian scientists and the International community and will orient future Canadian contributions to PMIP.

Canada has an important role to play in the PMIP experiment. Existing Canadian sites can already contribute vital information required for the reconstruction of past global environments and the experiment will benefit from the expertise of numerous regional experts from across the country. The last glacial cycle had a profound influence on the Canadian land mass. Understanding the history and dynamics of the Laurentide Ice Sheet and postglacial evolution of the landscape is extremely important in predicting sea level change and in modelling global climatic change.

A good understanding of the processes linked with environmental changes can provide the link between past conditions, when the climate was warmer than the present, and future conditions, when the climate will likely be warmer than the present. The 6000 yr BP period at high latitudes was, according to various sources (COHMAP Members, 1988; Diaz *et al.*, 1989; Zoltai, 1995), drier and some 3 to 5°C warmer than at present (summer temperatures). A good knowledge of environmental conditions for this period, in addition to providing paleoenvironmental data needed by the PMIP experiment, will be useful to plan and prepare for future environmental changes.

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