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Introduction

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Abstract : There is an increasing acceptance in the scientific community that the present trend of global warming is at least partially driven by rising concentrations of greenhouse gases (particularly CO_2) in the atmosphere because of anthropogenic activities over the past few centuries. Modelling of the future effects of increasing levels of greenhouse gases indicates that warming will be greatest in polar areas and that the Mackenzie valley, Northwest Territories, may experience the highest rise in mean annual temperature for any region in Canada. Because of the widespread presence of permafrost and accompanying ice-rich Quaternary sediments, the Mackenzie valley is particularly sensitive to climate warming. This Bulletin is the report of the Mackenzie Integrated Research and Monitoring Area project which was initiated to assess the sensitivity of landscape-altering processes in the Mackenzie valley to climate warming and to produce regional maps of permafrost and ground-ice distribution.

Résumé : Les membres de la communauté scientifique s'accordent de plus en plus pour dire que le réchauffement planétaire est, du moins en partie, causé par la libération croissante de gaz à effet de serre (en particulier de CO_2) dans l'atmosphère par les activités anthropiques et ce, depuis plusieurs siècles. La modélisation des effets résultant d'une hausse des concentrations des gaz à effet de serre indique que le réchauffement sera plus marqué dans les régions polaires et que la vallée du Mackenzie (Territoires du Nord-Ouest) sera la région du pays qui pourrait connaître le plus fort accroissement de la température annuelle moyenne. Étant donné la présence répandue de pergélisol dans la vallée du Mackenzie, et celle concomitante de sédiments quaternaires riches en glace, cette région est particulièrement sensible au réchauffement climatique. Le présent bulletin est en fait le rapport du projet de recherche et de surveillance intégrées du Mackenzie, lequel visait à évaluer les effets du réchauffement climatique sur les processus géomorphologiques actifs dans la vallée de ce fleuve et à dresser des cartes régionales de la répartition du pergélisol et de la glace de sol.

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DESCRIPTION AND PURPOSE

The Mackenzie valley is the lowland paralleling the Mackenzie River along its course from Great Slave Lake northwest to the Mackenzie Delta on the Beaufort Sea (Fig. 1). The distinctiveness of the Mackenzie valley as a physiographic feature varies, but is most pronounced where the river flows between the Mackenzie and Franklin mountains. Elsewhere it is a broad, undulating valley which rises gradually away from the Mackenzie River. Economically, the Mackenzie valley is a vital water, land, and air transportation corridor for communities along the Mackenzie River and Beaufort Sea coast, as well as for the hinterland on both sides of the river. Large hydrocarbon deposits that represent important national energy reserves are present at Norman Wells and in the Mackenzie Delta–Beaufort Sea area. Although the natural-resource potential of the region is incompletely known, it, combined with developing tourism and an increasingly independent aboriginal population, will maintain the economic importance of the region for the foreseeable future. It is imperative that the attributes of the region that make it particularly sensitive to development be understood and considered, as demands continue for construction and maintenance of transportation, industrial, and domestic facilities.

Permafrost is an important characteristic of the Mackenzie valley. It is patchy in the south, no more than a few metres thick, and closely associated with peat accumulations in wetlands. Along the Beaufort Sea coast, permafrost is virtually continuous and in many areas more than 500 m thick. Because of the widespread presence of permafrost and accompanying ice-rich Quaternary sediments, the Mackenzie valley is a region that is sensitive to climate change. Permafrost in the southern Mackenzie valley is especially susceptible to climate warming because of the large area in which it is thin and at temperatures close to 0°C. Predicted increases in air temperature will result in thawing and land subsidence.

In response to concerns about the effects of global climate change, the Mackenzie valley is one of three regions selected for the Geological Survey of Canada's 'Integrated Research and Monitoring Area' (IRMA) program. The objective of this program is to identify regions of Canada with geological

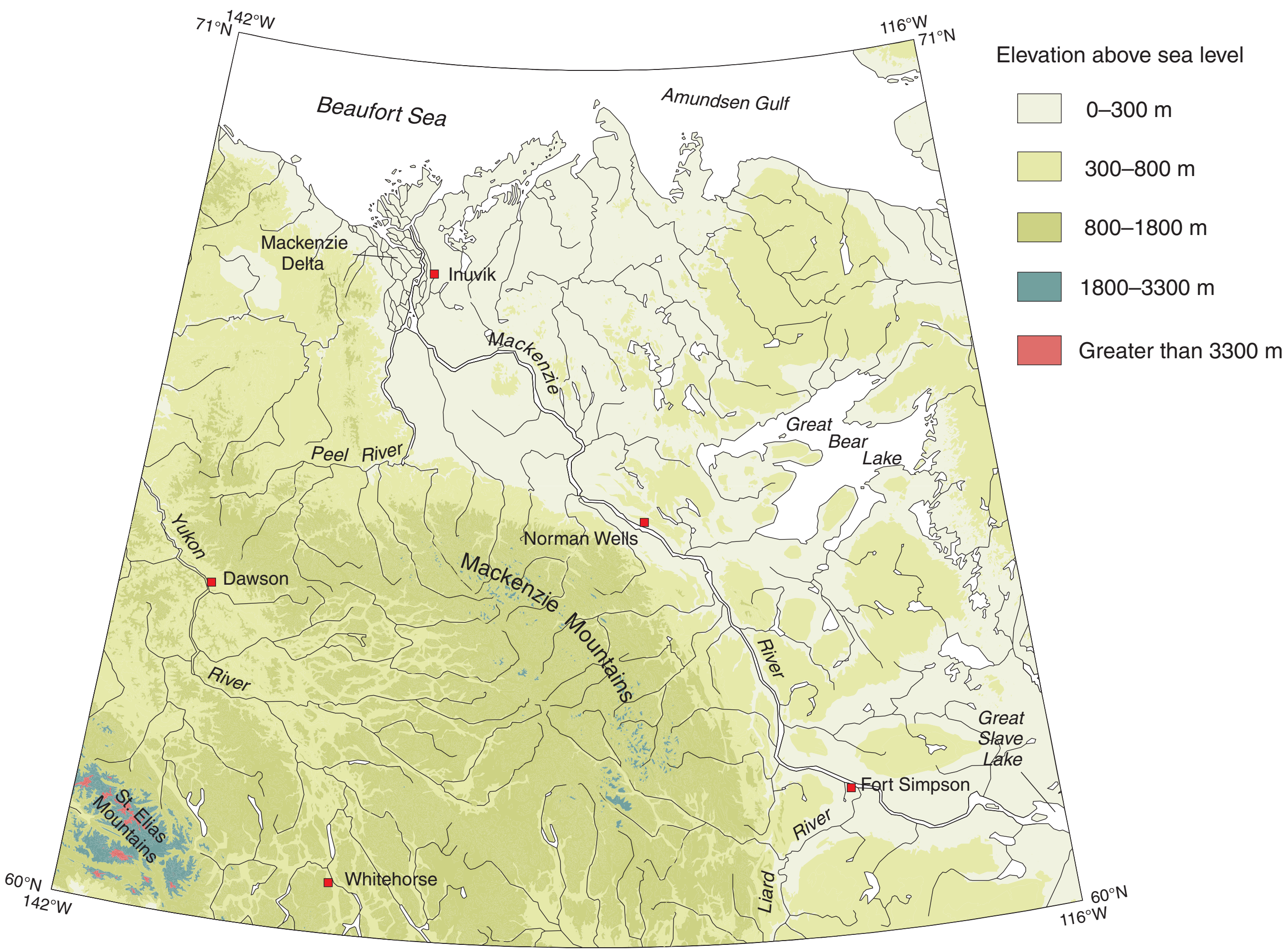

Figure 1. Physiographic map of the Mackenzie valley area. Topographic features and rivers are labelled in more detail in Figure 1 of Dyke (2000).

conditions or processes especially sensitive to climate change, and to determine the response of these conditions and processes to this change. Results from the Mackenzie IRMA contributed to the *Mackenzie Basin Impact Study* (Cohen, 1997), a comprehensive investigation by Environment Canada into the implications of climate change for a wide variety of social, economic, biological, as well as geological aspects of the entire Mackenzie River drainage basin. Southern Saskatchewan–southern Alberta (Palliser Triangle) and the Fosheim Peninsula in northwestern Ellsemere Island (High Arctic) were the other areas selected for the IRMA program. Specifically, the purpose of the Mackenzie IRMA was to reconstruct the climate since the end of the Laurentide Ice Age (about 13 ka BP) based on the relationship between climate and vegetation, to produce maps of permafrost and ground-ice distribution, and to determine the sensitivity of landscape-altering processes to climate warming.

The Geological Survey of Canada has been collecting data on permafrost, the character of frozen ground, and geomorphic processes in the Mackenzie valley since the early 1970s. These studies were initiated in response to engineering and environmental concerns arising from hydrocarbon exploration, pipeline proposals, and highway construction. Later, activities focused on monitoring of the Inter-Provincial pipeline built between Norman Wells, Northwest Territories and Zama, Alberta. The Mackenzie Valley IRMA represents a convenient umbrella under which this geoscience information can be assembled to provide a comprehensive summary of permafrost character, past climate change, and response of processes controlled by ground-ice thaw to climate warming. The Mackenzie valley IRMA report, then, is partly a synthesis of information about permafrost in the Mackenzie valley. The report is written for a more general rather than specialized scientific audience, with the purpose of presenting each topic in a manner useful for general knowledge, educational purposes, early stages of project planning, and as background for continued scientific research. The report also serves as a reference for use in engineering design and land-use planning in areas where information about geology and permafrost is required.

CLIMATE WARMING

During the last few decades, anticipation has been growing internationally that increasing concentrations of greenhouse gases in the atmosphere will change the climate in ways detrimental to social and economic patterns. Considering that this bulletin is a response to this concern, it is appropriate to compare predictions of climate change with known climate variation over similar or longer intervals of time in the past.

Abundant data demonstrate that global climate has warmed during the past century. Temperature records extending back to 1860 reveal that the global mean surface air temperature has increased by 0.5 to 0.7°C since that time (Houghton and Woodwell, 1989). The temporal pattern of increasing temperature is not constant, but rather consists of warming and cooling cycles at intervals of several decades. Nonetheless, the long-term trend is one of net global warming with the ten warmest years since 1880 all having occurred in the 1980s and 1990s (Hansen et al., 1996). Corresponding with this warming, alpine glaciers are generally retreating, sea levels are rising, and climatic zones are shifting (Houghton and Woodwell, 1989). All these changes exemplify the environmental impact of global warming.

Although recent global climatic warming is unmistakable, the mechanisms driving the change are poorly understood. Over the past millennium, global temperatures were warmer than present in the interval from roughly AD 1000 to 1300 (Medieval Warm Epoch) and cooler from roughly AD 1450 to 1890 (Little Ice Age). It can be argued that the present warming trend represents the natural transition from a cool to a warm period, a process that has occurred several times in the past; however, the present warming period also corresponds to a significant rise in some atmospheric 'greenhouse' gases (CO_2, CH_4, N_2O, and CFCs and other halocarbons) through human activities, primarily the burning of fossil fuels since the start of the industrial revolution, and from deforestation, animal husbandry, landfills, and rice agriculture (Houghton et al., 1996). Greenhouse gases have an important effect on the Earth's energy budget and contribute to the warming of the atmosphere by trapping infrared radiation emitted from the Earth's surface that would otherwise be transmitted to space. This absorbed radiation is later re-emitted, some of which is transmitted towards Earth and contributes to the warming of its surface. The entire process is commonly called the 'greenhouse effect'. Major increases in any one of the greenhouse gases result in a greater trapping and re-emittance of infrared radiation by the atmosphere, thus leading to higher surface temperatures.

Of the greenhouse gases influenced by the activities of man, CO_2 currently contributes more to the greenhouse effect than all of the other gases combined (excluding water vapour) (Houghton et al., 1996). Ice-core data from Antarctica reveals a close correlation between temperature and CO_2 levels extending over the past 160 000 years (Houghton and Woodwell, 1989); however, this is a coarse correspondence, with no indication of which of the two parameters causes the other to change. Furthermore, the correspondence does not appear to exist at smaller time scales, such as the last few centuries, during which the cool interval known as the Little Ice Age occurred. The Little Ice Age represents the coolest interval during the last 10 000 years. Although warming since the Little Ice Age is attributable to an increase in CO_2 which began about the same time, the onset of the Little Ice Age fails to correspond with any decrease in CO_2. This discrepancy weakens the argument that all subsequent warming is due to the increase in CO_2 concentration which started with the industrial revolution; however, it should be noted that an extensive analysis of climate data resulted in the Intergovernmental Panel on Climate Change (IPCC) reporting, "Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability... Nevertheless, the balance of evidence suggests that there is a discernable human influence on global climate." (p. 5, Houghton et al., 1996)

Another climate-controlling factor that corresponds more closely to climate reconstructions is the amount of incoming energy from the sun. This energy or solar radiation can be inferred from ^{14}C values in tree rings because ^{14}C is produced by the interaction of ^{14}N and radiation in the upper atmosphere. Changes in the amount of solar radiation seem to correlate better with our records of past climate (Lean et al., 1995). There appears to be a return to what has been the 'normal' climate throughout much of the last 10 000 years. Recent increases in CO_2 have probably contributed to this warming, but a more thorough understanding of factors that initiated events like the Little Ice Age is required before the role of CO_2 can be fully understood.

Over the past several decades, considerable effort has been devoted to modelling the future effects of increasing levels of CO_2. Models suggest that the concentration of atmospheric CO_2 will increase 35 to 170% by 2100, depending on economic, demographic, and policy factors, as well as assumptions about processes that transform and remove gases from the atmosphere (Houghton et al., 1996). Predictions from climate models indicate that warming will be greatest in the polar regions. Estimates from different models vary, but all agree that a rise of 3–5°C will occur in the Mackenzie valley if the atmospheric CO_2 content doubles by 2050 (Smith and Cohen, 1993). Although predictions of future warming produced by general circulation models may be considered extreme, a continuation of the net warming trend established since the end of the nineteenth century is reasonable to expect.

Recent climate change in the Mackenzie valley is evident from instrumental records that, for a few locations, extend back to the 1890s. These data indicate that mean annual air temperatures have increased 1.7°C over the last century, the highest increase for any climatic region in Canada (Environment Canada, 1995); however, this change may not be representative of the entire Mackenzie valley because of the scarcity of data for such a large area. If it is representative, this warming amounts to a 100–200 km northward shift of isotherms that represent mean annual air temperature. The southern limit of permafrost in the northern prairie provinces has also moved north; however, this response has lagged behind increases in air temperature because of the insulating effect of the vegetation cover (Halsey et al., 1995). Also, recent climate warming is not ubiquitous in the Canadian north, for example, a decrease in average annual air temperature over the same time interval has occurred in the eastern Arctic and permafrost is thickening in northern Quebec due to this local cooling.

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