CLIMATE CHANGE SCENARIOS FOR MACKENZIE RIVER VALLEY

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ABSTRACT
In Canada, the Environmental Impact Statement for a development project must consider the implications of climate change for project design, and the potential contributions of the project to greenhouse-gas emissions. The Mackenzie Gas Project is the largest development project yet proposed in Canada's North. Climate change is of direct relevance to this project because of the potential for terrain instability from melting permafrost. Air temperatures throughout Mackenzie valley have warmed significantly since 1970. In northwest Canada, baseline climate scenarios reproduce the observed temperature field reasonably well, but are less adept at simulating the magnitude and spatial variation of observed precipitation. Scenarios from seven Global Climate Models were ranked to provide an estimate of the range of climate change anticipated over the next half century for Mackenzie valley. The scenarios anticipate increases in mean annual air temperature of up to 2.5ºC over the 1961-90 baseline in 2010–39, and up to 5.7ºC by 2040-69.

RÉSUMÉ
Au Canada, le constat d'impact environnemental pour un projet industriel doit prendre en considération les implications du changement climatique sur la conception de projet et les contributions potentielles de ce projet sur les émissions de gaz à effet de serre. Le projet Mackenzie Gas est le plus grand projet industriel jamais proposé dans le Nord canadien. Le changement climatique est d'une pertinence directe à ce projet, parce qu'il est possible que la fonte du pergélisol cause une instabilité du terrain. Les températures de l'air à travers la vallée Mackenzie se sont réchauffées de façon significative depuis 1970. Dans le nord-ouest du Canada, les simulations de régimes climatiques reproduisent les champs de températures observés, mais celles-ci sont moins aptes à simuler la magnitude et la variation spatiale des régimes de précipitation. Des simulations de sept modèles ont été classées pour offrir une estimation de la portée du changement climatique prévu pour les cinquante prochaines années dans la vallée Mackenzie. Les simulations anticipaient des augmentations de la température annuelle moyenne, allant jusqu'à 2.5ºC au-dessus de la moyenne établie de 1961-90 en 2010-39, et jusqu'à 5.7ºC pour 2040-69.

1. INTRODUCTION

Climate change is probably the most discussed topic on the global environmental agenda (Weaver 2003). The global temperature has increased over the last 50 years, so that several of the warmest years on record have occurred in the last decade. Models of the general circulation (GCMs) are used to explore the effects on climate behaviour of changes in the composition of the atmosphere. A series of economically significant climate-related events in the 1980s prompted national governments to invest heavily in this branch of science. Acceptance of climate change as global in scale, unrestricted by national boundaries, led to establishment of the Intergovernmental Panel on Climate Change (IPCC). The IPCC's work has provided the scientific background and justification for the Kyoto Protocol on limiting emission of these gases.

The IPCC has issued three reports at five-year intervals, most recently in 2001 (IPCC 2001). These reports establish a clear case for the observed recent global climate warming to be caused by the increasing concentration of greenhouse gases.

Canada acknowledges that climate change is an issue of national significance and has signed the Kyoto Protocol. Environmental Impact Statements filed in connection with development projects are now required to address climate change issues. In particular, proponents are required to assess the impacts of climate change on a proposed project and the project's potential contribution to Canada's greenhouse-gas emissions.

The Mackenzie Gas Project is a proposal to develop three fields for production of natural gas in the Mackenzie delta area, and to build a 1200-km pipeline system to transport the gas and natural gas liquids to northern Alberta. The Mackenzie Gas Project is the largest development recently proposed in northern Canada. The project itself may be a precursor to development of further gas resources, e.g., in Cameron Hills and near Colville Lake, N.W.T. In order to consider the impact of climate change on project operations and infrastructure, climate change scenarios are required to represent the range of conditions of upper Mackenzie valley through to the delta and Tuktoyaktuk Coastlands. There are numerous scenarios available for prediction of climate change. The purpose of this paper is to select representative scenarios that may be used by this project and others in Mackenzie River valley.

2. REGIONAL CLIMATE

Mackenzie River valley has a subarctic continental climate, but north of tree line, between Inuvik and Tuktoyaktuk, conditions are characteristic of a low arctic maritime environment. There is a latitudinal gradient in temperature and precipitation along the valley, which trends SE-NW (Fig. 1). The gradient steepens north of Inuvik, particularly in terms of precipitation and summer temperature, which decline with proximity to the coast and the pack ice of Beaufort Sea (Fig. 2; Burn 1997). Ground temperatures vary with the atmospheric conditions, such that the valley contains a large portion of the range of permafrost conditions found in Canada (Heginbottom et al. 1995).

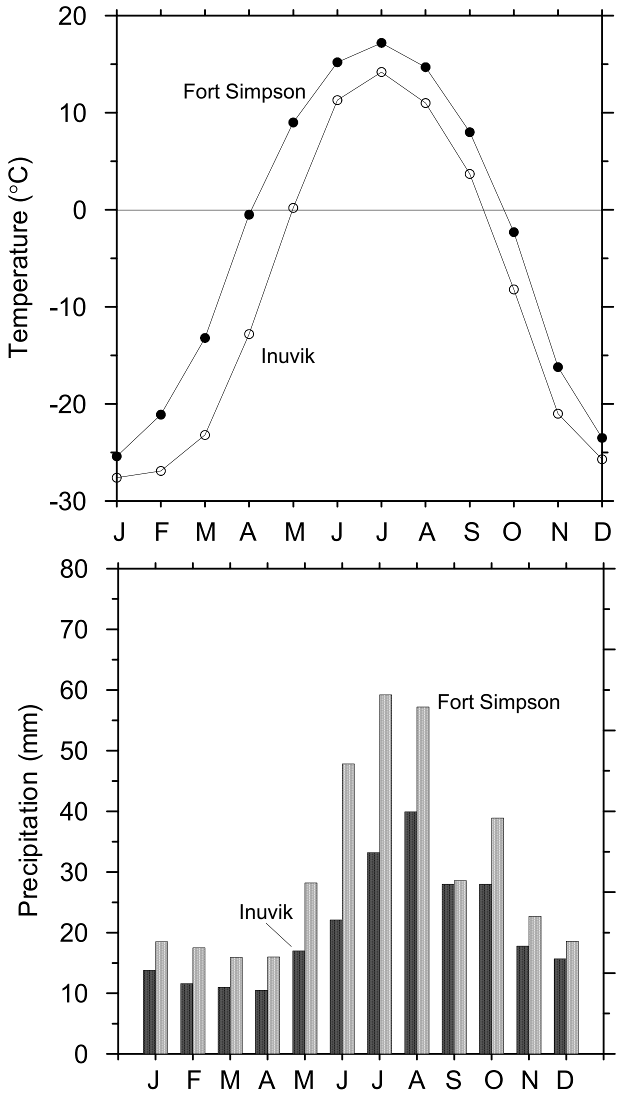

Figure 1. Monthly mean temperature and precipitation at Fort Simpson (61º 46'N 121º 14'W) and Inuvik (68º 18'N 133º 28'W), N.W.T. Fort Simpson and Inuvik are 920 km apart. Data from Environment Canada (2002a).

Comparison of climate normals for 1951-1980 to 1971-2000 indicates that all stations in Mackenzie valley have experienced an increase in mean annual temperature since 1970 (Table 1). The rate of increase in temperature is one of the highest in the polar regions (Serreze et al. 2000). The warming has been greatest in winter. Regional precipitation has not increased during this period (Table 2).

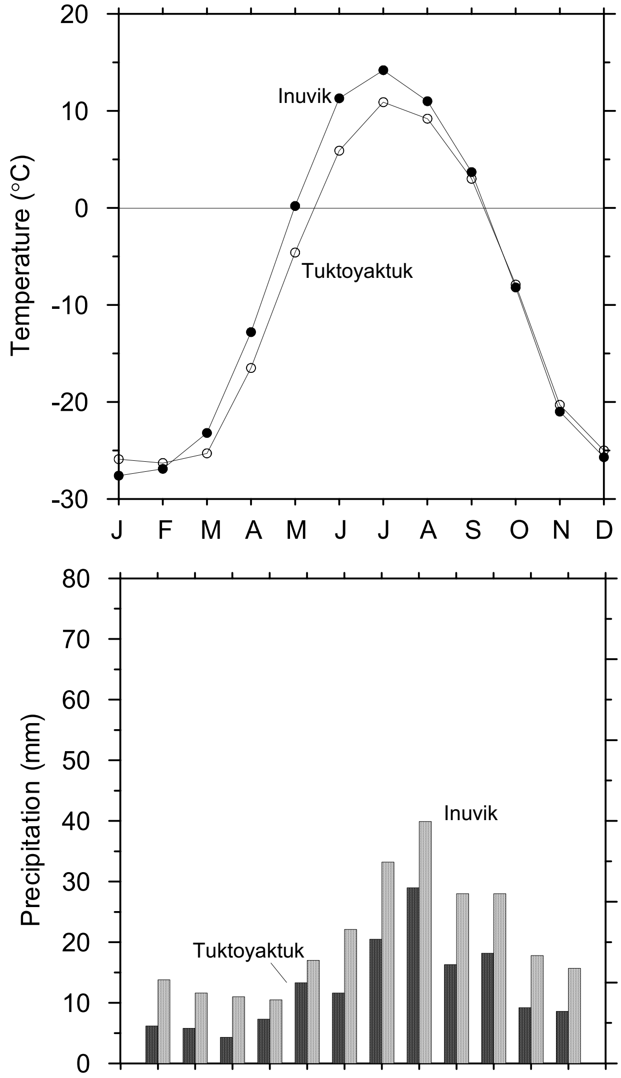

Figure 2. Monthly mean temperature and precipitation at Inuvik (68º 18'N 133º 28'W) and Tuktoyaktuk (69º 27'N 133º 00'W), N.W.T. Inuvik and Tuktoyaktuk are 130 km apart. Data from Environment Canada (2002a).

Table 1. Annual mean temperatures (ºC) for periods of climatic normals, Mackenzie valley, 1951-2000.

Station	1951-1980	1961-1990	1971-2000
Hay River	-3.6	-3.4	-2.9
Fort Simpson	-4.0	-3.7	-3.2
Norman Wells	-6.4	-6.0	-5.5
Inuvik	-9.8	-9.5	-8.8
Tuktoyaktuk	-10.9	-10.5	-10.2

Data from Environment Canada (1982, 2002a,b)

Table 2. Annual total precipitation (mm) for periods of climatic normals, Mackenzie valley, 1951-2000.

Station	1951-1980	1961-1990	1971-2000
Hay River	340	342	320
Fort Simpson	350	360	369
Norman Wells	328	317	291
Inuvik	266	257	248
Tuktoyaktuk	138	142	139

Data from Environment Canada (1982, 2002a,b)

3. CLIMATE CHANGE SCENARIOS

The IPCC's working groups use several GCMs, but there are seven models that are highly regarded and well reported. The GCMs are Australian (CSIROMk2B), British (HADCM3), Canadian (CGCM2), German (ECHAM4), Japanese (CCSR98), and American (NCARPCM, GFDLR30) (Table 3). These models characterize the climate in slightly different ways. Among the important differences between the models is the spatial resolution of the grid cells used to map the Earth's surface (Table 3).

Table 3. Grid cell size for various GCMs

Model	Width (ºLat)	Width (ºLong.)	Area (km^2)
CSIROMk2B	3.2	5.6	95,000
HADCM3	2.5	3.75	50,000
GFDLR30	2.2	3.75	44,000
NCARPCM	2.8	2.8	41,000
CCSR98	5.6	5.6	168,000
ESCHAM4	2.8	2.8	41,000
CGCM2	3.75	3.75	74,000

The IPCC has examined simulations from these GCMs, and suggests that output from the models may be used to derive estimates of potential regional climate change. Data from GCMs for Canada are available from the web site of the Canadian Climate Impacts Scenarios (CCIS) Project of Environment Canada: www.cics.uvic.ca/scenarios

The magnitude of climate change projected by GCMs depends on the amount of change in concentration of atmospheric gases, which depends, in turn, on the emissions of radiatively-active gases into the atmosphere, from both natural and anthropogenic sources. As a result, the IPCC has recommended a series of emissions scenarios, which describe plausible future changes in atmospheric composition. These are known as the SRES emissions scenarios after the IPCC's Special Report on Emissions Scenarios (IPCC 2000). The SRES scenarios are divided into four "families", A1, A2, B1 and B2. The A1 and A2 families have a more economic focus than the B1 and B2 families, which are more environmentally based. The A1 and B1 families are based on "storylines" that assume a high degree of global coordination and uniformity, whereas A2 and B2 maintain considerable regional diversity. There are three A1 scenarios which have been selected based on alternative energy-use pathways (A1B- balanced; A1FI – fossil fuel intensive; A1T – non-fossil fuel intensive) but all "describe a world with rapid economic growth, a rising global population until about 2050, and the rapid introduction of new and more efficient technologies" (CCIS web site). The IPCC has also suggested that estimates of regional climate change be derived from composite data using various GCMs and emissions scenarios, and with output for several grid cells near the region of interest. Commonly, GCM simulations are run several times with the same atmospheric forcing. These may be labelled, e.g., HADCM3 A12, to represent the second simulation of the UK's Hadley Centre third generation climate model using greenhouse-gas scenario A1.

Climate change scenarios for specific regions are commonly constructed by averaging several aspects of GCM output. (1) The differences between mean outputs for a future 30-year period and a baseline period, usually 1961-90, are regarded as the best estimates of change anticipated for that time interval. (2) Data for several grid cells are averaged to characterize a regional response, rather than relying on output for a specific grid cell. A minimum spatial average utilizes the grid cell containing a location of interest and the eight surrounding grid cells. The approach then applies the mean change in climatic variable temperature for each future time interval, derived from the simulations, to observed climate records from the baseline period.

The ability of GCMs to reproduce the magnitude and variability of baseline climate is an explicit factor influencing the confidence associated with model projections. For the western Cordillera of Canada, Bonsal et al. (2003) have shown that the GCMs in the generation previous to those listed in Table 3 reproduce the magnitude and spatial distribution of temperature observed between 1961 and 1990 reasonably well, but overestimate baseline precipitation. Burn (1994) attributed the poor representation of precipitation in northwest Canada by GCMs to the coarse resolution of topography in the region, which leads to underestimation of the rain shadow in the lee of Coast and St. Elias mountains. A similar result is obtained when the baseline simulation is compared with climate observed in Mackenzie valley for 1961-90. Therefore greatest confidence in the climate scenarios is associated with projections for changes in temperature.

4. SELECTION METHODOLOGY

The CCIS web site provides GCM output for a baseline period and three future intervals, 2010-39, 2040-69, and 2070-99. In this paper we present results for 2010-39 and 2040-69 only, because we regard data for 2070-99 as distant from the time scale of current interest in development considerations, which is, at most, half a century. Over the next few years the trends evident in Table 1 may continue, and future projects will be in an improved position to assess the nature and extent of climate change. There is already a record of temperature change, but Serreze et al. (2000) point out that the length of record is insufficient to determine whether the excursion is part of long-term natural variation, or stimulated by an enhanced greenhouse effect.

The CCIS Project's assemblage of scenarios contains 29 simulations using the SRES "storylines", which have been generated with seven GCMs.

Mackenzie River valley occupies three or four grid cells in the output from GCMs. The northern portion of the region has a climatic change distinct from the upper and middle valley in most simulations. On this basis, the region has been divided in two, into northern and southern sectors, with the boundary approximately at the latitude of Fort Good Hope. This line corresponds with the southern limit of continuous permafrost (Heginbottom et al. 1995). For the two sectors, a representation of potential change has been obtained from a weighted average of a cell and its eight surrounding neighbours in each sector, with weighting on an areal basis, using the cosine of each cell's latitude. Data for the northern sector, or lower Mackenzie River valley, have been compiled from grid cells over and adjacent to 67ºN 130ºW, approximately the location of Little Chicago. Data for the southern sector, or upper valley, have been compiled from grid cells over and adjacent to 63ºN 123ºW, approximately the location of Wrigley.

A primary consideration in the design of the Mackenzie Gas Project, and potentially for any future connector pipelines to the trunk route, is the impact of climate change on permafrost. Since this is primarily a thermal issue, the 29 simulations have been ranked according to the change in annual and winter temperatures. Changes in winter conditions have been selected for attention because, in general, GCMs predict the greatest warming in this season (Maxwell 1997), and because, at present, warming is concentrated in this season. The upper and lower estimates have been selected at the 86th percentiles of the distribution, at ranks 4 and 26, while the median is at rank 15. For each selection, the seasonal changes compose the annual change indicated for the appropriate time interval. These seasonal changes may be added to observed baseline climate records (Table 4) to produce scenarios of future climate for the project's sectors.

Table 4. Baseline (1961-90) seasonal mean temperature and total precipitation for stations in Mackenzie valley.

Station	DJF	MAM	JJA	SON	Annual
Temperature (ºC)					
Hay River	-22.2	-4.5	14.2	-1.1	-3.4
Fort Simpson	-24.2	-2.3	15.3	-3.8	-3.7
Norman Wells	-26.1	-6.6	14.9	-6.1	-6.0
Inuvik	-27.8	-13.0	11.6	-8.8	-9.5
Tuktoyaktuk	-26.5	-15.7	8.5	-8.3	-10.5
Precipitation (mm)					
Hay River	61	53	124	104	342
Fort Simpson	56	64	148	92	360
Norman Wells	51	46	143	77	317
Inuvik	44	42	100	71	257
Tuktoyaktuk	20	17	61	44	142

Data from Environment Canada (2002b)

5. RESULTS

5.1 Scenarios for 2010-39

Tables 5 and 6 list the scenarios composed from the raw data available on the CCIS Project web site for the projected changes in seasonal and annual temperature in upper and lower Mackenzie River valley for 2010-39. The data have been rounded to one decimal place. Table 5 indicates that results from individual models are sensitive to the greenhouse-gas scenario applied because of the differences between the simulations with the Canadian global climate model. However, Table 6 shows that there may be substantial differences in output from the same model under the same greenhouse-gas scenario, as with the Hadley Centre's model and the A1 simulations. This is a function of the complex system represented in the model, and indicates the importance of considering a full range of scenarios for future climate.

Table 5. Climate change scenarios for lower (N) Mackenzie Valley, 2010-2039, ranked by change in annual mean and in winter (DJF) mean temperature. Data are for the projected increase in mean temperature (ºC) over baseline conditions during the months indicated.

Rank	GCM	DJF	MAM	JJA	SON	Annual
Ranked by annual mean						
4th	CSIRO2B A21	2.1	1.5	2.6	3.6	2.5
15th	CCSR-98 A1T	1.4	1.8	1.1	2.0	1.6
26th	ECHAM4 A21	1.3	1.9	0.4	1.6	1.3
Ranked by winter mean						
4th	CGCM2 B23	3.1	2.1	1.5	2.2	2.2
15th	CGCM2 A21	1.9	2.2	2.0	2.3	2.1
26th	HADCM3 B21	1.1	1.5	1.3	1.3	1.3

Table 6. Climate change scenarios for upper (S) Mackenzie Valley, 2010-2039, ranked by change in annual mean and in winter (DJF) mean temperature. Data are for the projected increase in mean temperature (ºC) over baseline conditions during the months indicated.

Rank	GCM	DJF	MAM	JJA	SON	Annual
Ranked by annual mean						
4th	CCSR-98 B23	1.8	2.5	1.4	2.7	2.1
15th	HADCM3 A23	1.9	0.7	1.0	1.4	1.3
26th	HADCM3 A21	1.1	0.6	1.1	1.3	1.0
Ranked by winter mean						
4th	CSIRO2B A11	2.5	1.9	2.1	2.5	2.2
15th	CCSR-98 A21	1.5	0.6	0.6	1.4	1.0
26th	GFDLR30 A21	0.6	0.9	1.6	0.8	1.0

Table 1 documents an increase in mean annual air temperature for Mackenzie valley of about 1ºC between 1951-80 and 1971-2000. Tables 5 and 6 suggest an increase in this index of between 1.0 and 2.5ºC between 1961-90 and 2010-39. Therefore, in terms of temperature, the projections are consistent with the rate of change in the present regime. Warming is forecast to be greatest in the northern sector.

Figures 3 and 4 present the change in mean annual temperature (ºC) and total annual precipitation (%) in the 29 scenarios. All scenarios project increases in air temperature, but a few forecast a decrease in precipitation.

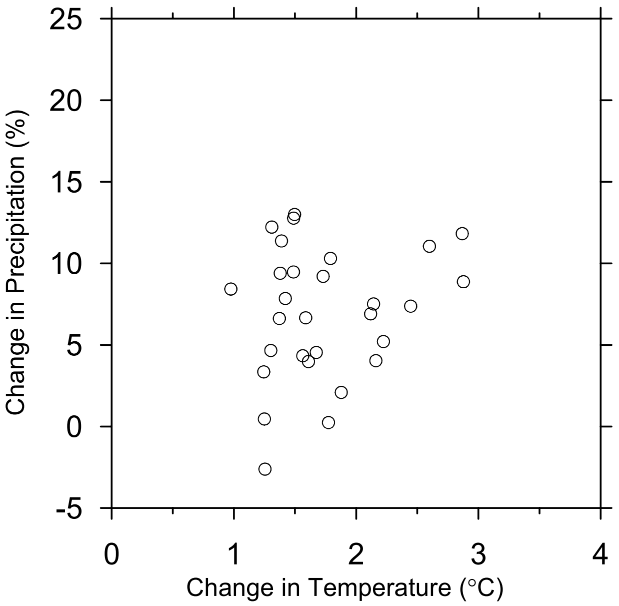

Figure 3. Change from baseline by 2010-39 in annual temperature and precipitation for 29 scenarios in lower Mackenzie valley.

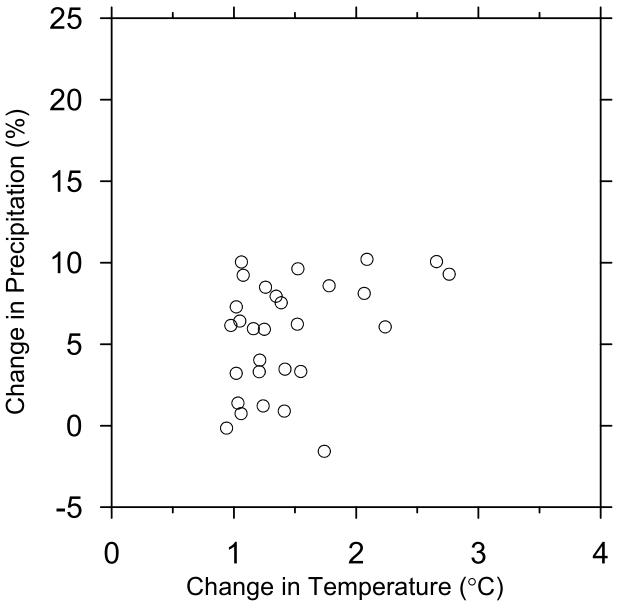

Figure 4. Change from baseline by 2010-39 in annual temperature and precipitation for 29 scenarios in upper Mackenzie valley.

These data are relatively well confined within each scatter plot. Figures 5 and 6 show that the changes expected in winter conditions are greater and less constrained than over the year as a whole.

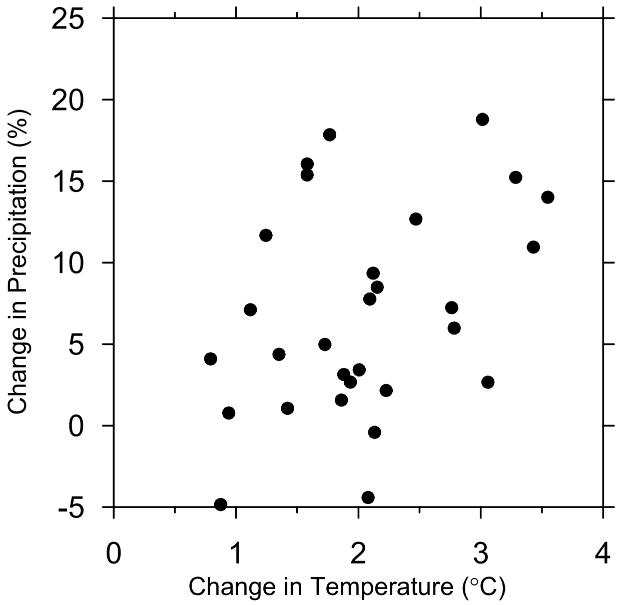

Figure 5. Change from baseline by 2010-39 in winter temperature and precipitation for 29 scenarios in lower Mackenzie valley.

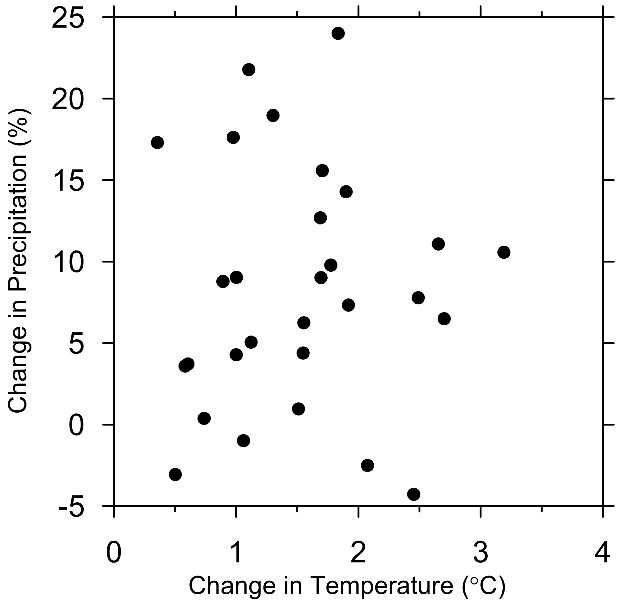

Figure 6. Change from baseline by 2010-39 in winter temperature and precipitation for 29 scenarios in upper Mackenzie valley.

5.2 Scenarios for 2040-69

Tables 7 and 8 present scenarios for 2040-69. Warming in winter is projected to be greater than the change to summer conditions. Warming of the northern sector is projected to be greater than in the upper valley. Combining the data in Table 4 with results in Tables 7 and 8 indicates that by 2040-69, the air temperature regime at Inuvik is projected to be similar to current conditions near Norman Wells, and the mean annual temperature at Fort Simpson may be above 0ºC (Fig. 7). Similarly, over the next half century, the winter regime at Inuvik may shift to conditions currently experienced near Fort Simpson. Such changes would have significant consequences for the thermal regime of permafrost terrain.

Figure 7 presents a combined record of the observed increase in mean annual temperature (Table 1) and the projected change in mean annual temperature for Fort Simpson and Inuvik. The present rate of change in the climatic regime is consistent with the higher projections for future increases in mean annual air temperature. We have not discussed specific changes in the precipitation regime for 2040-69 because these projections are not regarded with as much confidence as the projections for changes in temperature, however, almost all scenarios forecast an increase in this variable.

Table 7. Climate change scenarios for Lower (N) Mackenzie Valley, 2040-2069, on the basis of rank by change in annual mean and in winter (DJF) mean temperature. Data are for projected increase in mean temperature (ºC) over the months indicated.

Rank	GCM	DJF	MAM	JJA	SON	Annual
Ranked by annual mean						
4th	CCSR-98 A1FI	7.7	4.7	2.6	7.9	5.7
15th	CGCM2 A23	4.7	3.8	3.1	2.7	3.6
26th	GFDLR30 B21	4.1	2.2	2.2	2.5	1.7
Ranked by winter mean						
4th	CCSR-98 A1FI	7.7	4.7	2.6	7.9	5.7
15th	HADCM3 A22	4.7	2.0	2.4	4.5	3.4
26th	CCSR-98 B11	3.4	2.7	2.2	4.8	3.0

Table 8. Climate change scenarios for Upper (S) Mackenzie Valley, 2040-2069, on the basis of rank by change in annual mean and in winter (DJF) mean temperature. Data are for projected increase in mean temperature (ºC) over the months indicated.

Rank	GCM	DJF	MAM	JJA	SON	Annual
Ranked by annual mean						
4th	CCSR-98 A1FI	5.9	5.2	2.5	5.3	4.7
15th	GFDLR30 A21	3.2	2.4	2.2	3.9	2.9
26th	CGCM2 B21	2.1	2.3	2.0	1.7	2.0
Ranked by winter mean						
4th	CCSR-98 A1FI	5.9	5.2	2.5	5.3	4.7
15th	GFDLR30 B21	3.7	2.2	2.4	2.1	2.6
26th	CGCM2 B21	2.1	2.3	2.0	1.7	2.0

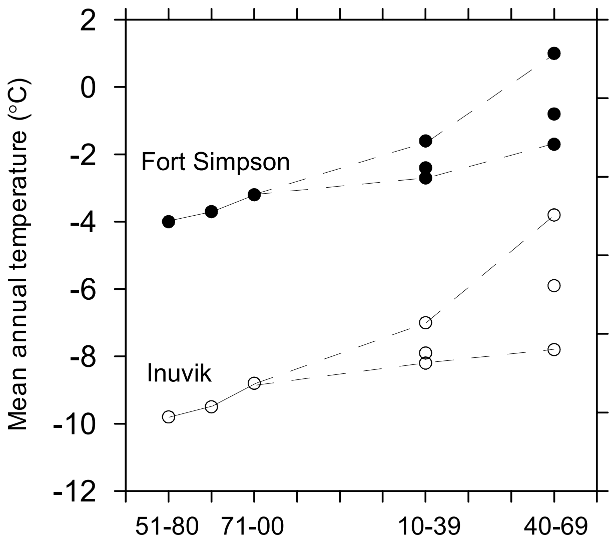

Figure 7. Mean annual air temperature at Fort Simpson and Inuvik, N.W.T. from climate normals for 1951-80 to 1971-2000 (Table 1) and with the ranges of scenarios presented in Tables 5 to 8. The dashed lines indicate bounding limits derived from 86th percentiles of the range from 29 GCM scenarios. Median estimates from the 29 scenarios are also presented.

6. CONCLUSIONS

In summary, we present the following:

a. Climatic normal statistics indicate that mean annual temperatures throughout Mackenzie valley have increased over the last three decades by up to 1ºC.

b. There has been no regionally consistent change in annual total precipitation.

c. Global climate models resolve Mackenzie valley into two sectors, with the boundary approximately at the latitude of Fort Good Hope.

d. For the Mackenzie valley region, global climate models reproduce the temperature field of the baseline 1961-90 climate reasonably well, but overestimate the amount of precipitation.

e. All scenarios considered for future regional climate change forecast increases in mean annual and seasonal temperatures, with the warming greatest in northern parts of the region, and in winter. The median projections are for increases of 1.6 and 3.6ºC in mean annual temperature in northern Mackenzie valley in 2010-39 and 2040-69, respectively, and of 1.3 and 2.9ºC in the upper valley.

f. The vast majority of the scenarios forecast increases in precipitation, but a few simulations have little change or a slight decrease in this variable.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Burn, C.R. 1994. Permafrost, tectonics, and past and future regional climate change, Yukon and adjacent Northwest Territories. Canadian Journal of Earth Sciences, Vol. 31, pp. 182-191.

Burn, C.R. 1997. Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada. Canadian Journal of Earth Sciences, Vol. 34, pp. 912-925.

Burn, C.R. 2003. Climate change scenarios for the Mackenzie Gas Project. Northern Water Resource Studies, Indian and Northern Affairs Canada, Yellowknife.

Bonsal, B.R., Prowse, T.D., and Pietroniro, A. 2003. An assessment of global climate model-simulated climate for the western cordillera of Canada (1961-90). Hydrological Processes, Vol. 17, pp. 3703-3716.

Environment Canada. 1982. Canadian climate normals, temperature and precipitation. 1951-80. Vol. 3. The North – Y.T. and N.W.T. Atmospheric Environment Service, Environment Canada, Ottawa, Ont.

Environment Canada. 2002a. Canadian climate normals, 1971-2000. http://www.msc.ec.gc.ca/climate/climate_normals/stnselect_e.cfm

Environment Canada. 2002b. Canadian climate normals, 1961-1990. http://www.msc.ec.gc.ca/climate/climate_normals_1990/show_stations_e.cfm

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.A. 1995a. Canada-Permafrost. In National Atlas of Canada, 5th ed. National Atlas Information Service, Natural Resources Canada, Ottawa. Plate 2.1. MCR 4177.

IPCC. 2000. Emissions Scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, England.

IPCC. 2001. Climate Change 2001, The Scientific Basis, Contribution of Working Group I to the Third Scientific Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, England.

Maxwell, B. 1997. Responding to global climate change in Canada's Arctic. The Canada country study: climate impacts and adaptation. Vol. 2. Atmospheric Environment Service, Environment Canada, Downsview, Ont.

Serreze, M.C., Walsh, J.E., Chapin, F.S., III, Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., and Barry, R.G. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change, Vol. 46, pp. 159-207.

Weaver, A.J. 2003. The science of climate change. Geoscience Canada, Vol. 30, pp. 91-109.