Climate Change and Variability: Implications at the Scale of the Watershed[1]

Ellsworth LeDrew

Department of Geography, University of Waterloo

Abstract

The evidence for climate change for many regions of the globe is now irrefutable. The temperature is rising at a rate that exceeds the statistical confidence limits for 'noise' over the past century of observations. The real debate is over the relative contributions of specific greenhouse gases, and the degree of the counter effect of cooling related to suspended particulate in the atmosphere. In this review, the implications of climate change at the scale of the watershed that are of interest to park managers in Canada are discussed. Issues include the difference between climate change and variability, regionalized evidence for each, the veracity of simulation model results at this scale, and the implications of uncertainty for management decisions.

Keywords: climate change, watershed scale, parks, protected areas

Introduction

With the exception of a cadre of die-hard geologists that confuses human-induced climate change with the normal climate change attributable to the long-term evolution of the planet, scientists from a variety of disciplines agree that the climate is changing and the implications are significant. The late F. Kenneth Hare, the preeminent climatologist of Canada, was the early bellringer for climate change and challenged the science community to anticipate the implications for the next 100 years and build them into decisions that affect the daily life of Canadians. We now have a variety of scenarios of climate change that are the foundations for political, economic and social strategic decisions. One notable example is *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems* by Hansen *et al*. (2003).

In this review we assess the limits of such scenarios for regional scale management decisions, such as those required of managers of Canada's national and provincial parks. This discussion is based upon a clear distinction between climate change and the natural variability of a complex system. The recent climate of selected regions of Canada is discussed within this context. The validity of global-scale scenario building at the regional scale of the park is evaluated, and some examples of inference to ecological implications at this scale are considered.

Canadian Evidence of Change and Variability

David Phillips of the Meteorological Service of Canada is pressed by the media each January for the top weather stories of the previous year. Amongst those for 2003 are:

- Four years of dry weather sparked raging wildfires. The summer's tally: $500 million in firefighting costs, $250 million in insured property losses, and 50,000 residents evacuated
- New Brunswick's worst ice storm
- Avalanches killed 28 skiers, including seven on a school trip (Environment Canada, 2003)

Each year appears to bring new extreme weather events. If we examine the departures of Canadian temperatures from the normal for each season, we find that, up to 2003, 25 of the last 26 seasons are above the climate normal. This unusual anomaly seems to validate notions of recent climate change and is consistent with similar evidence in other countries. There is the one contrary season of spring 2002, however, that is actually the fifth coldest since 1948 (Figure 1). If we examine the Canadian anomaly maps for the spring seasons of 2001, 2002, and 2003 (Figure 2), we see that cooling of spring 2002 was actually spread across much of Canada with a warming restricted to the far northwest. This was the consequence of a very extensive reconfiguration of the hemispheric Westerly winds. The question is how can this unusual situation arise alongside such clear long-term evidence of climate warming?

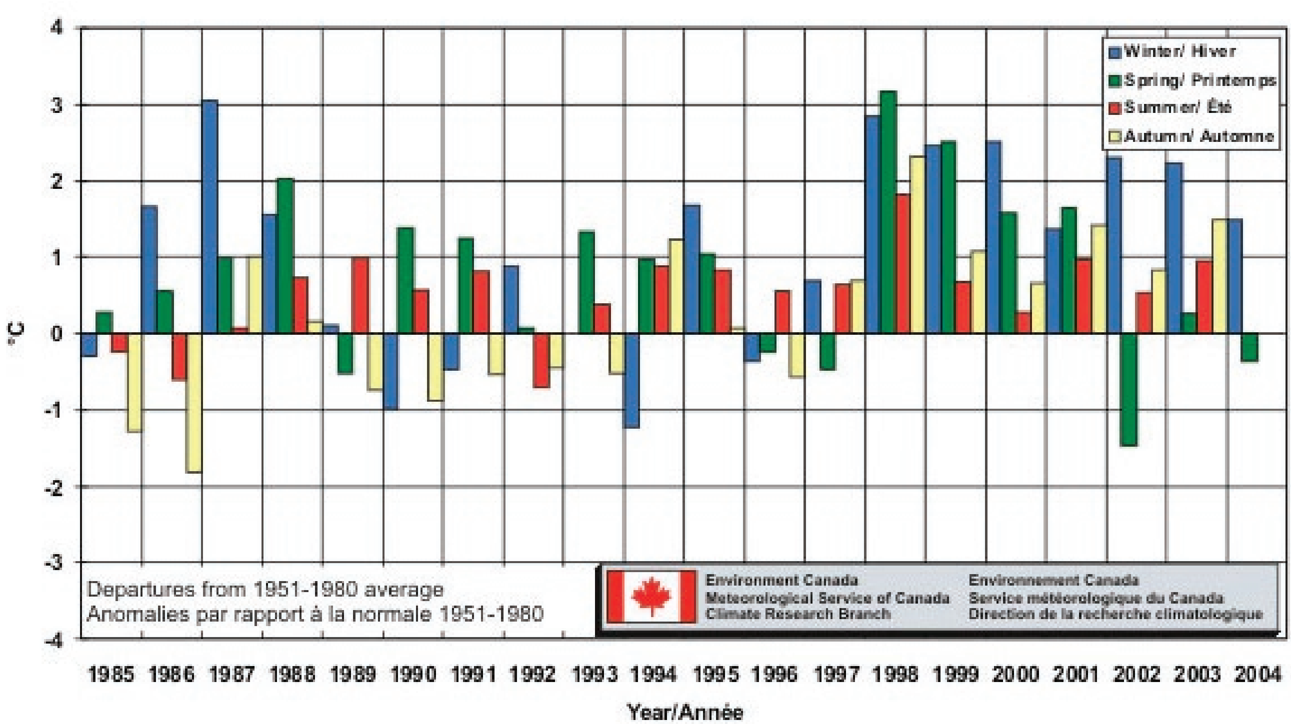
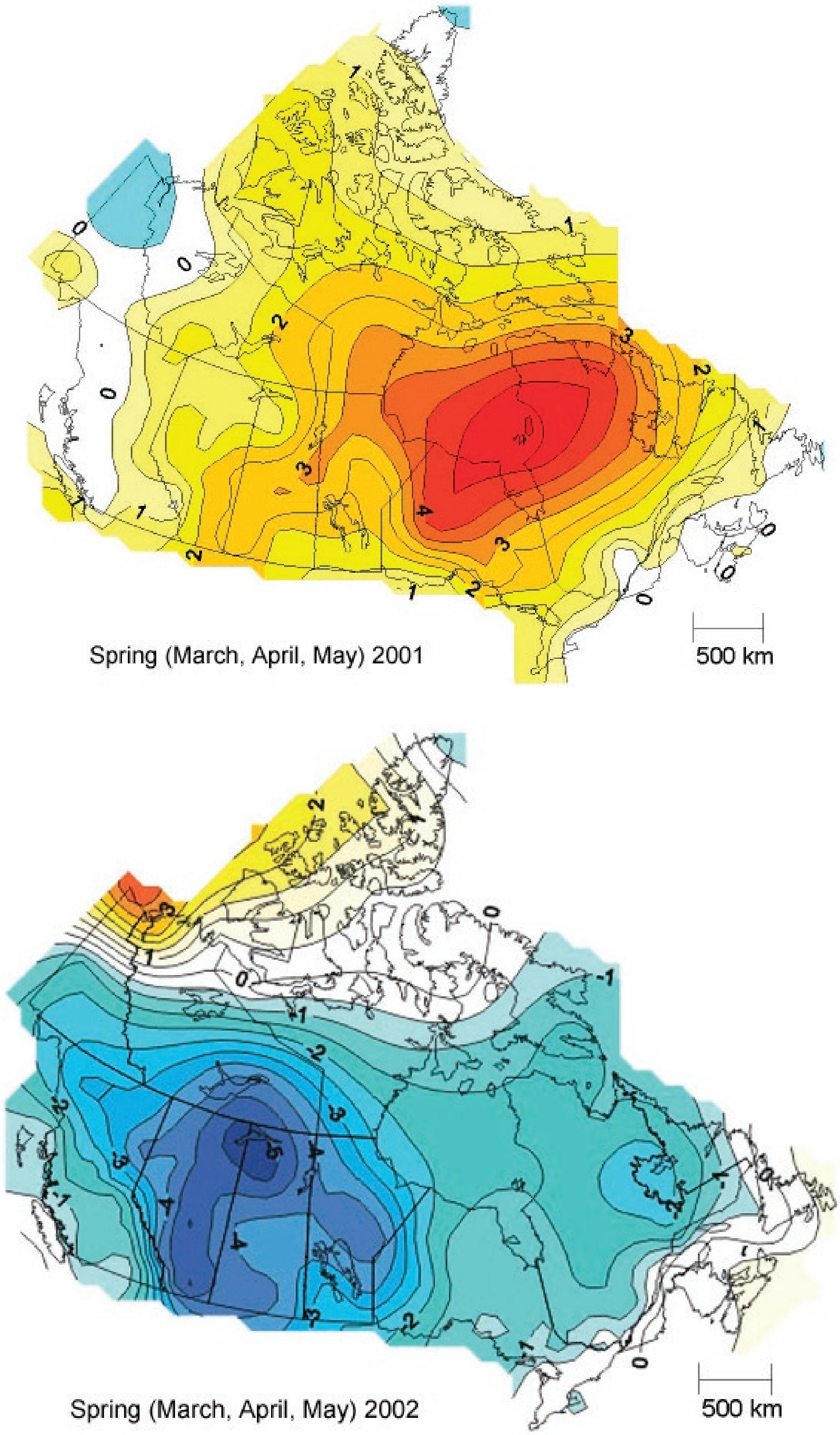
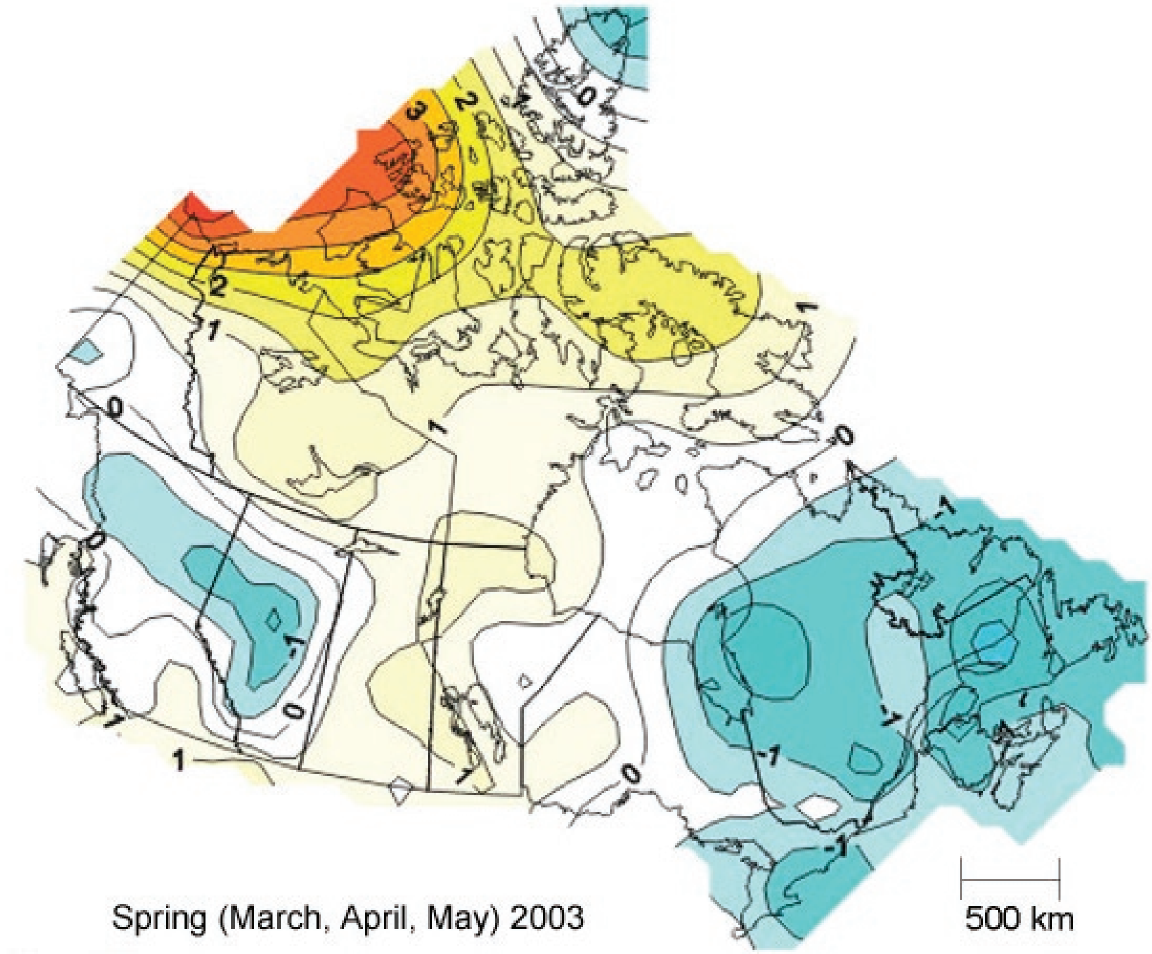


Figure 1. Seasonal anomalies for Canada from 1985–2004 (Environment Canada, 2004a).

Figure 2. Temperature anomaly maps of Canada for three spring seasons: 2001, 2002, and 2003, respectively (Environment Canada, 2004b).





The answer may be found in the distinction between climate change and variability and the effect of events as far away as the South Pacific. A schematic of the components of the climate system (Figure 3) illustrates a distinction between variables external to the climate system such as the solar output, gases ejected from the earth's interior via volcanoes, the arrangement of land and sea as a result of plate tectonics and internal variables such as the evaporation-cloud linkages and radiation balance-wind system linkages. Schneider and Dickinson (1974) proposed that climate change would be associated with changes in the external variables. These would induce a new state of the climate; whereas variability would be the result of the internal variables and associated feedback loops constantly adjusting to these new external states.

F. Kenneth Hare (1972) (Figure 4) illustrates various temporal routes that the change/variability distinction can take for an illustrative variable, such as temperature. In addition to long-term external changes in sinusoidal waves (A), such as may be attributed to the Milankovitch variations of orbital mechanics, there are abrupt changes with a variability superimposed upon the trend (B), a slow transition to a new external state (C)—again with variability superimposed upon this transition—or just a change in the degree of variability (D).

Changes can be identified in the change in sea ice extent (Figure 5). An extensive interannual variation occurs with seasonal cycles and is superimposed on the long-term trend towards reduced ice cover.

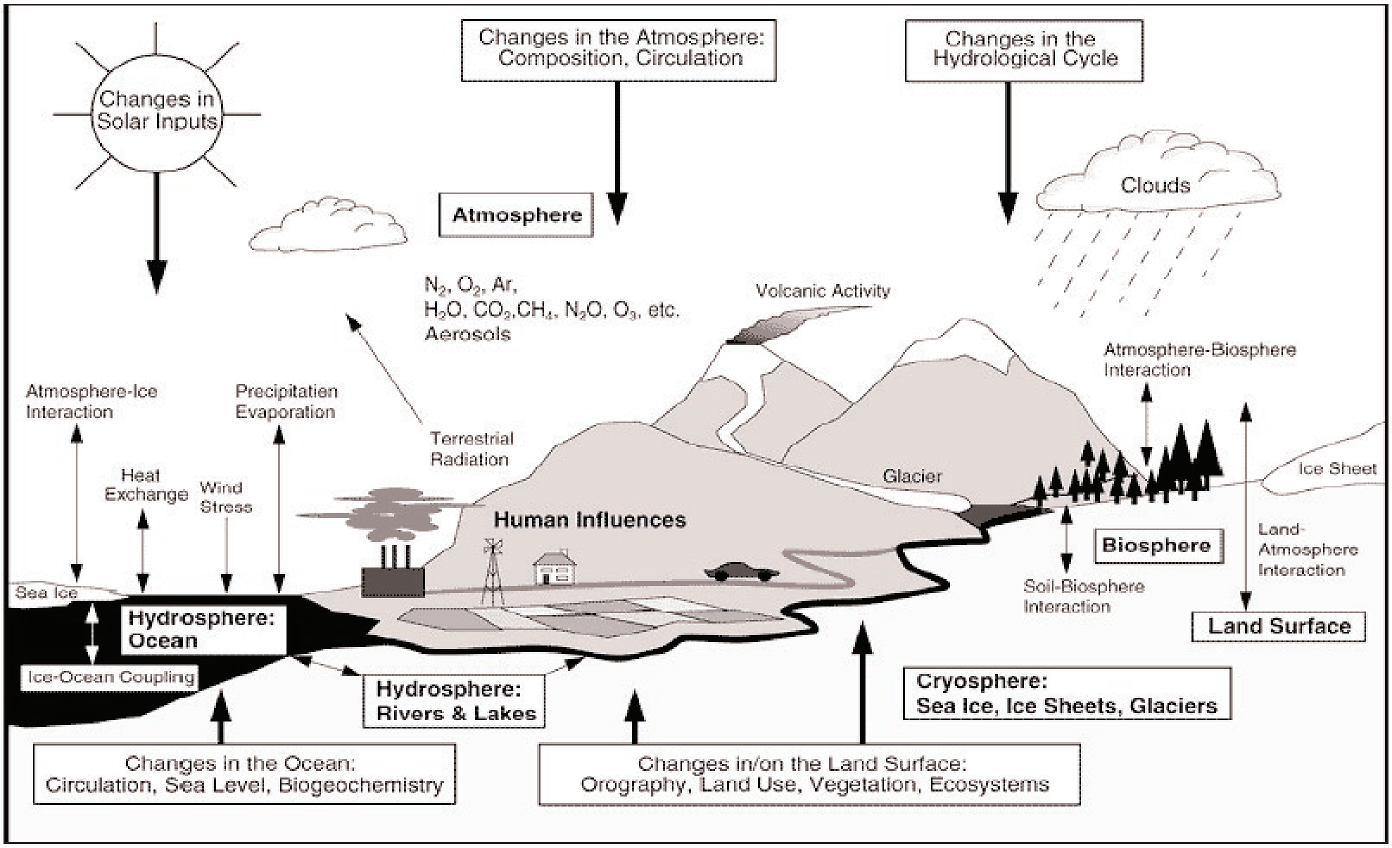


Figure 3. A schematic of the external variables (heavy arrows) and internal variables (light arrows) of the climate system (IPCC, 2001).

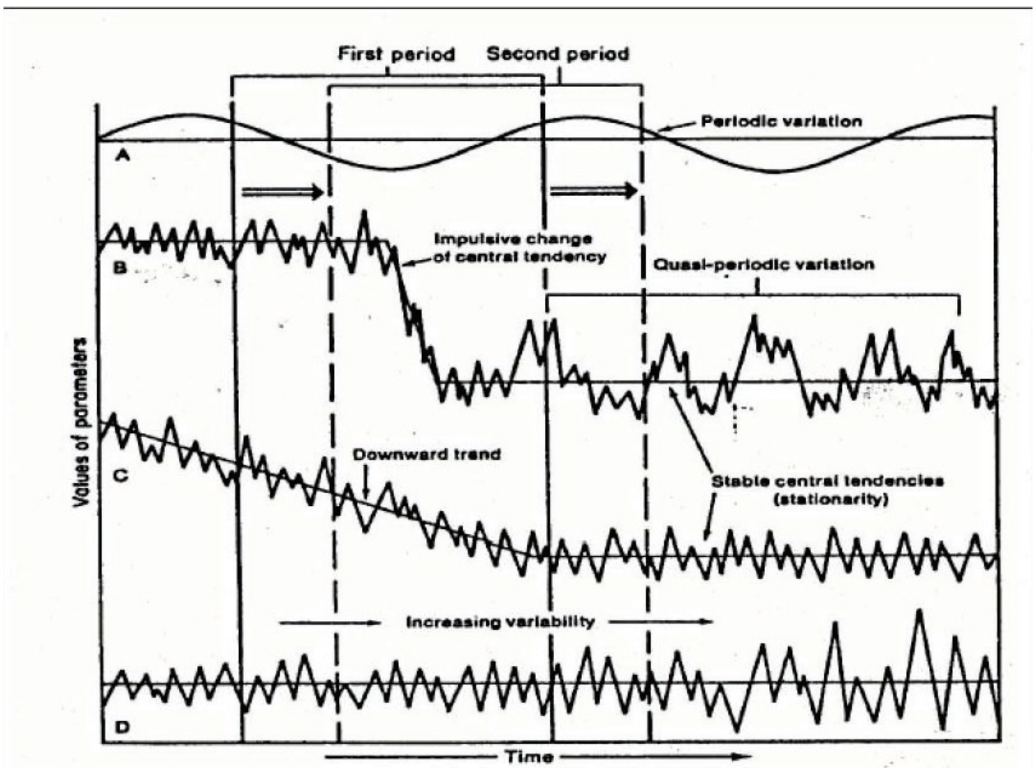


Figure 4. Schematic of types of climate change and variability for a climate variable, such as temperature (Hare, 1972).

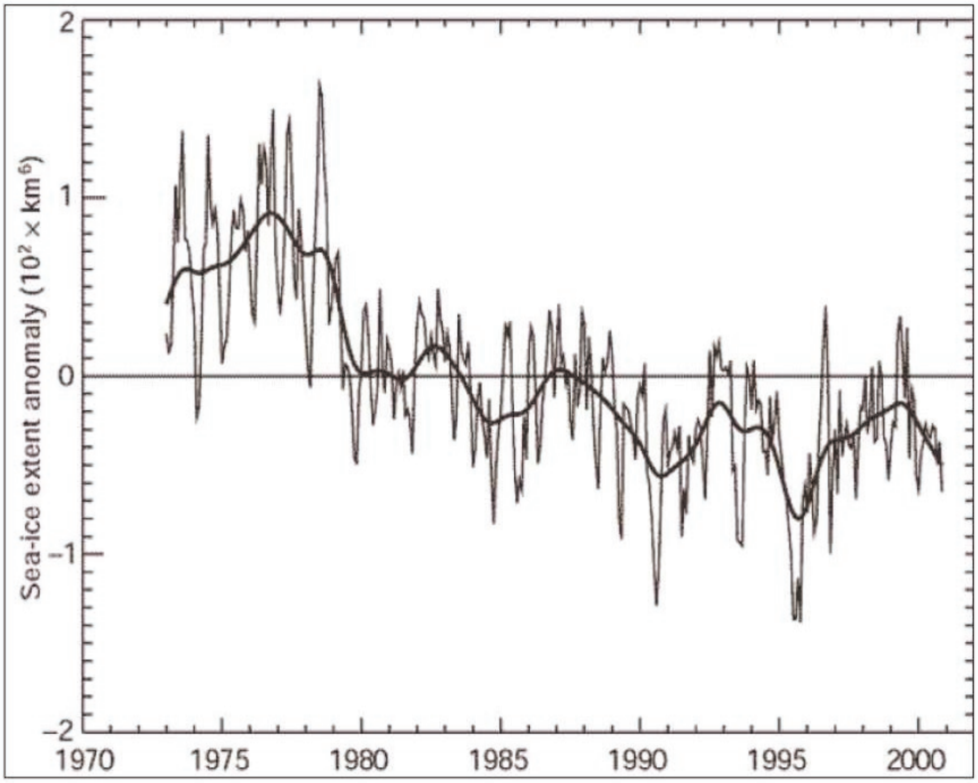


Figure 5. Temporal anomalies of sea ice extent (Parkinson, 2000).

While the foregoing discussion can help explain the variation from one year to the next that the public recalls when an unusually warm and/or dry summer prevails, it does not help explain the triggers for unusual events. This is an area of active research with many unknowns, but one possible trigger is the cyclic recurrence of El Niño—the Southern Oscillation (ENSO) of the South Pacific approximately every seven years (Trenberth, 1997). Recent studies have indicated that this event may have significant consequences for Canadian weather, with real impact on grain yields in the prairie provinces (Garnett, 2002). The mechanism is not clear, but temperature anomalies for the surface of the South Pacific can affect surface temperature in the North Pacific which may have a bearing on the wave structure of the Jet Stream (Figure 6) and thus on downstream weather patterns over North America. 'Signature' temperature anomalies for winter and spring (Figure 7) have been derived from weather statistics when El Niño was dominant and indicate extensive warm anomalies over Canada. Reality often is something different. The winter of 2002–2003 was anticipated as an El Niño winter but the actual anomaly pattern was rotated about southern Hudson Bay by 90 degrees (Figure 8) to have a dramatically different effect. There is a great deal to learn. Further food for thought is provided in the La Niña phase of the South Pacific oscillation when cold water and high pressures predominate because of the retreat of warmer water to more southerly latitudes.

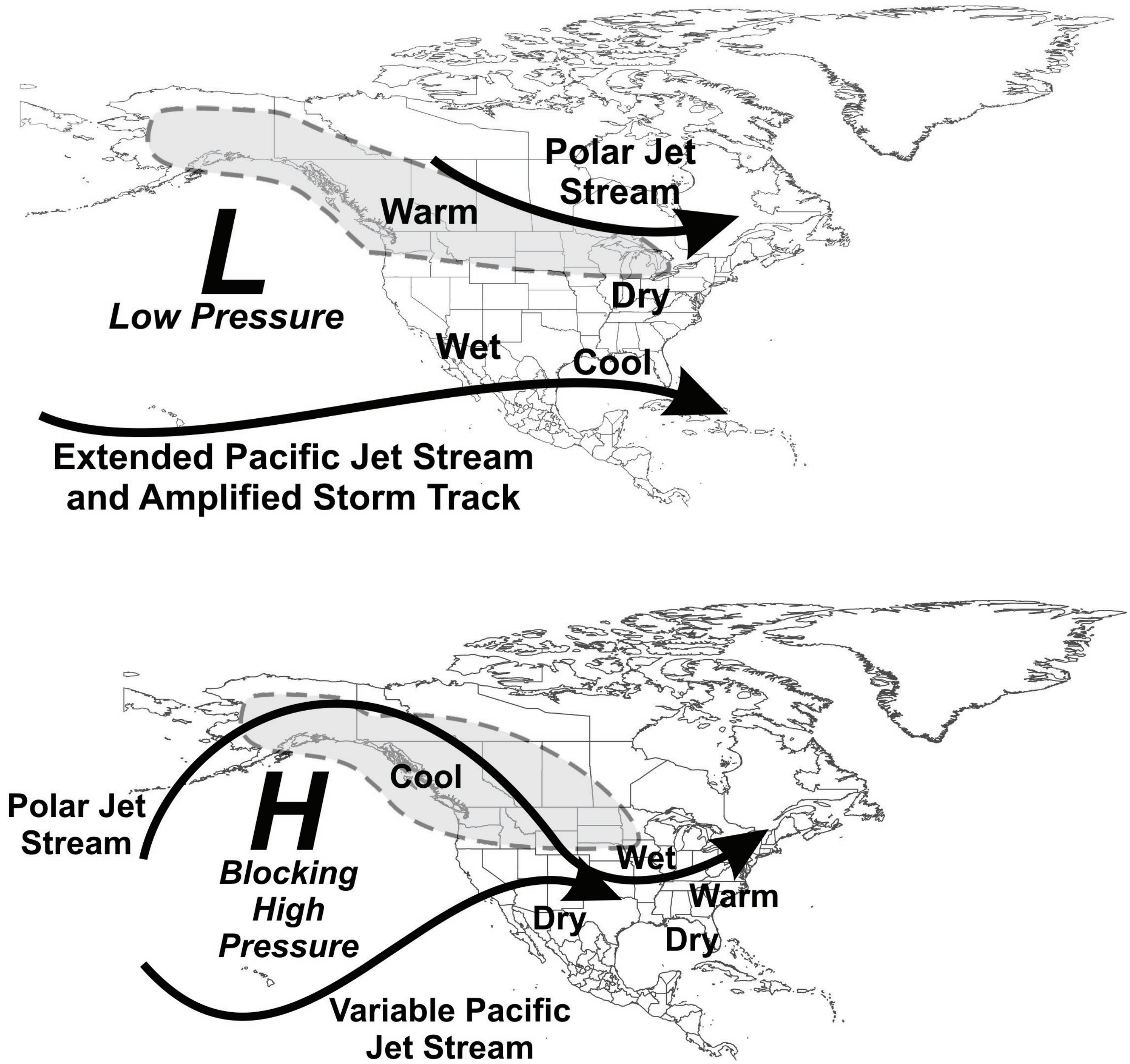


Figure 6. Jet stream configuration for an El Niño (top) and La Niña (bottom) episode (adapted from NOAA, 2004).

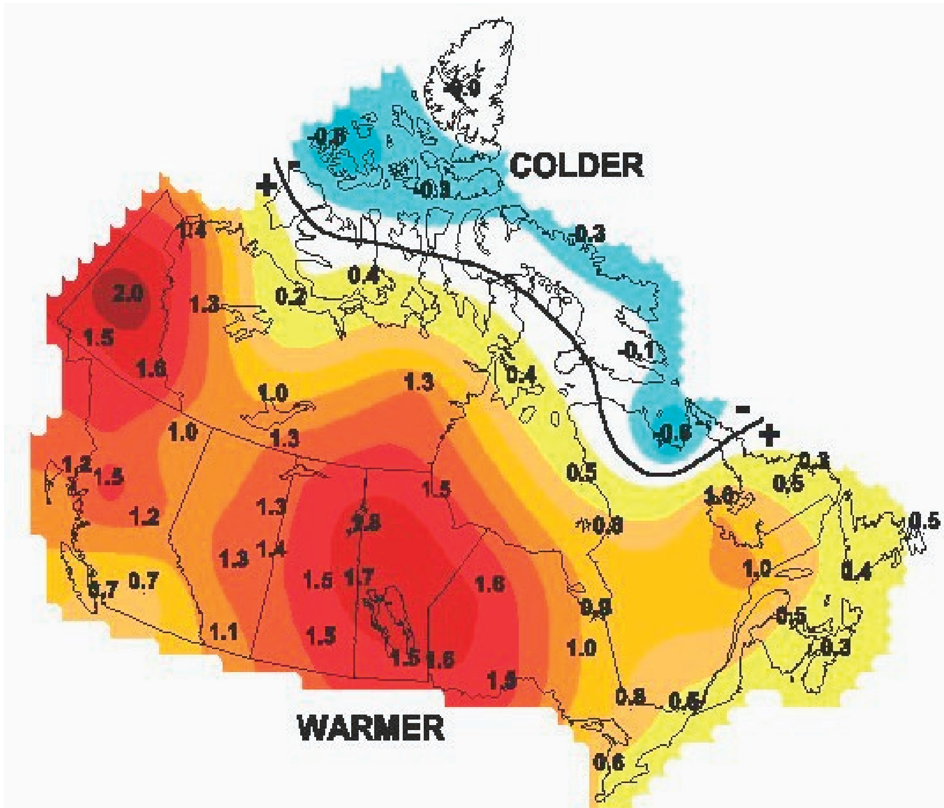


Figure 7. Expected Canadian temperature anomalies for an El Niño year (Environment Canada, 2004c).

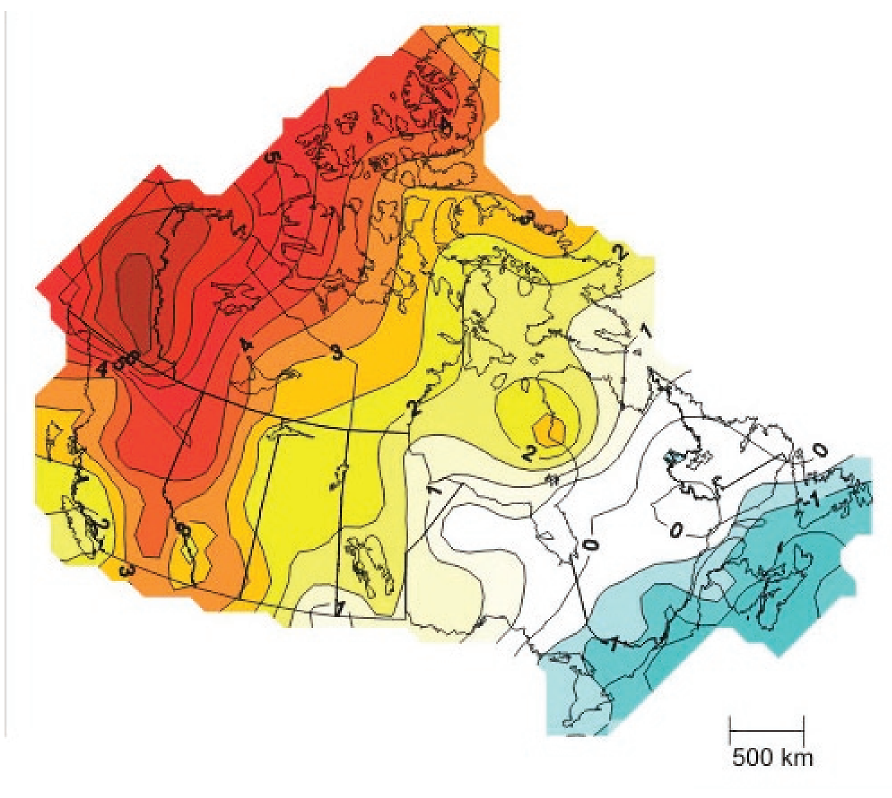


Figure 8. Actual temperature anomaly for winter 2003 (Environment Canada, 2004d).

The Long View of Canadian Climate

From 1993 to 2001 we have had the nine warmest winters since the start of instrumental record in Canada, and this is consistent with global temperature trends (Figure 9). The prediction for 2050 based upon Canadian Global Climate Models (Figure 11) is for warming over all of Canada with the exception of the Labrador Sea. Highest temperatures are found in the continental interior—the wheat belt and the Arctic Basin. If we anticipate the future climate for Southern Ontario from such simulations (Hayhoe and Shuter, 2003) we can determine that:

- The climate will feel as if Ontario has been translocated south to Virginia
- Temperature will rise 3–6 °C in summer and 4–8 °C in winter by 2100—extreme heat being more common
- Winter precipitation will increase by 15–40% and summer by -5% to +20%—water balance will decrease with more heat for evaporation and less precipitation
- Frequency of extreme storms will increase
- Great Lakes ice cover will decline—reducing protection from winter storms and having an impact on oxygenation

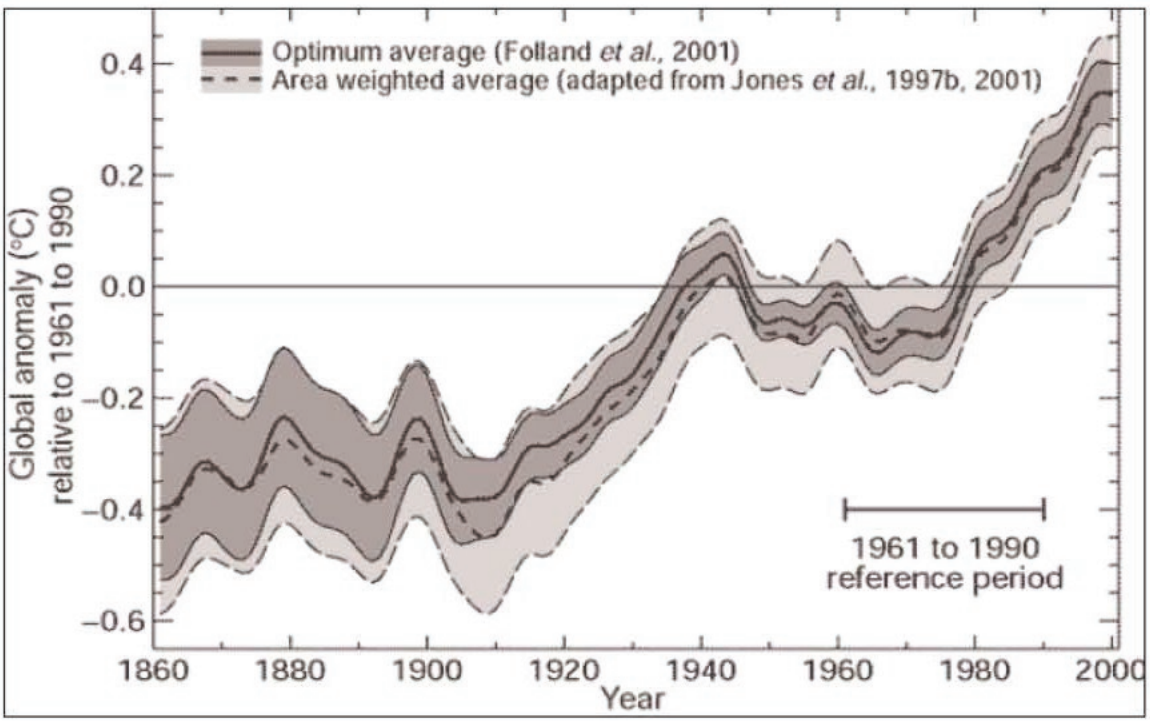


Figure 9. Global temperature anomalies from 1860 to 2000 (IPCC, 2001).

One clear lesson for future climate scenarios is that the implications will have to be assessed on a region-by-region basis. There is not an even warming in all regions as seems to be suggested in public media. In Figure 10, the temperature trends between 1950 and 1998 are shown for much of the western northern hemisphere. The reality is that over Canada the trend varies from -1.4 to +2.0 °C over that interval. This is a natural consequence of the shift in the standing waves of the westerly winds with climate change and the persistent influence of a trough of cold air in one region and a ridge of warm air in another.

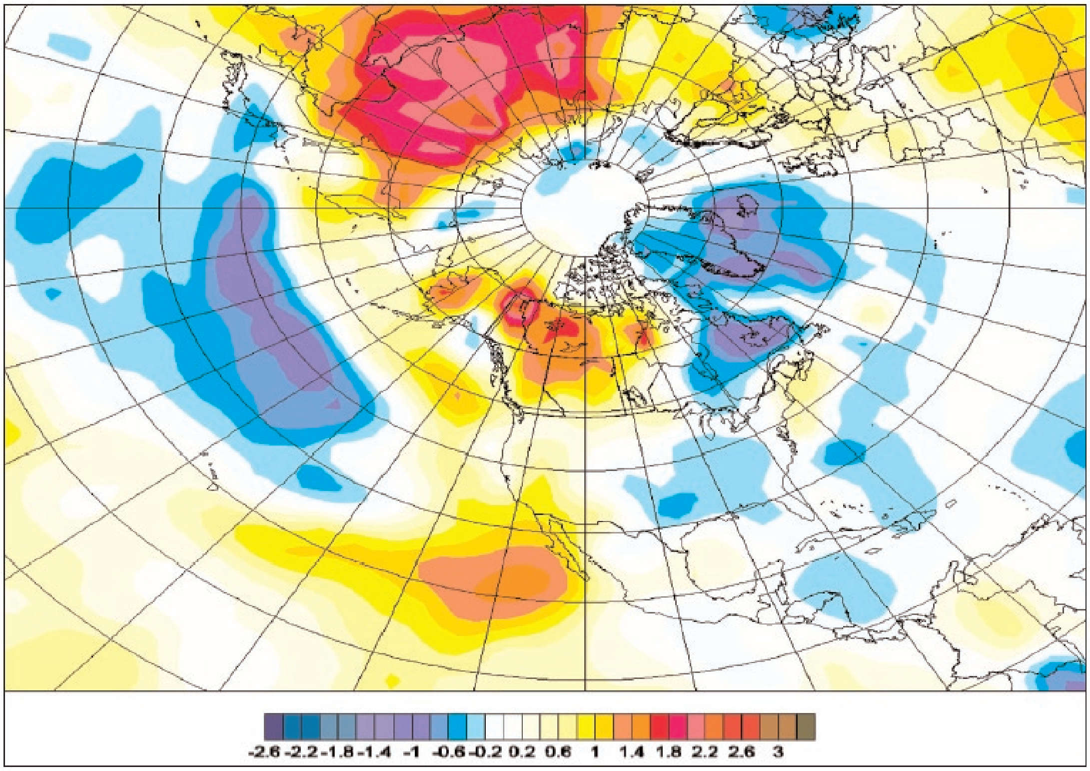


Figure 10. Observed temperature trends for Canada from 1950 to 1998 (Environment Canada, 2004f).

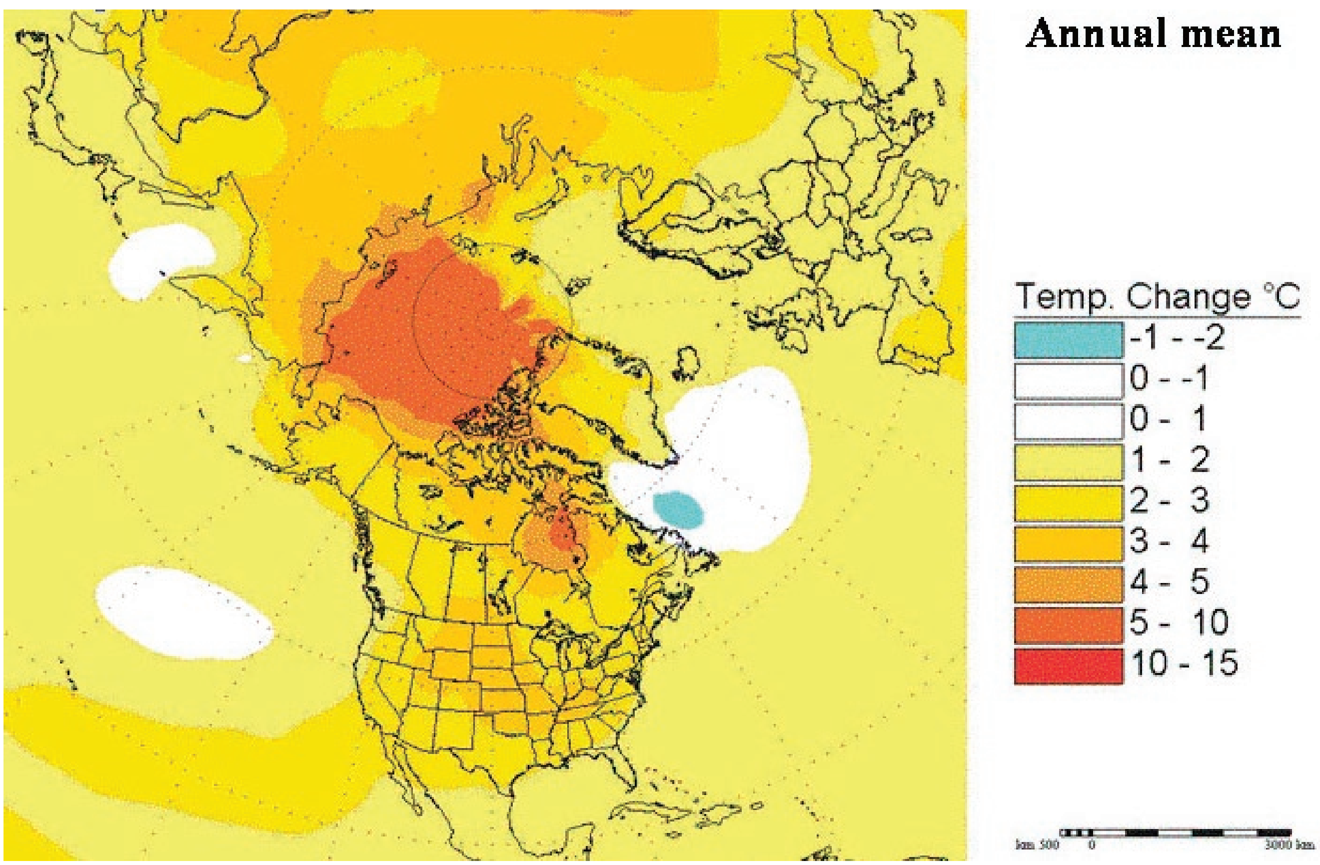


Figure 11. Projected temperature anomalies for 2050 (Environment Canada, 2004e).

Inferences at the Scale of the Watershed

Most scientists will agree that the Global Climate Models (GCM) are most valuable when considering differences in temperature over broad regions, such as the difference between a continental interior and a maritime region. We have confidence that the wheat fields of central North America will have much warmer temperatures and increased instances of drought. The scenarios for a complex environment such as Southern Ontario are more suspect. The modellers would be the first to point out the deficiencies and warn the users about the limitations.

Normally, the grid point system used for the calculations of fluid flow of the atmosphere has a spacing of a few hundred kilometers. Consequently, there are very few grid points to represent the complexities of the Southern Ontario geography. Subtle features such as the Dundalk uplands, which are so critical for the topographic uplift that releases snow from the lake-effect storms, are not included at all. Indeed, the several ranges of the Western Cordillera typically show as one sinusoidal wave in the lower topography of the model. Recent experiments with higher spatial resolution regional climate models (RCM) nested within the GCM include more detailed topography with approximately 50 km spatial resolution. They produce much more realistic simulation fields (Figures 12a and 12b).

The Great Lakes are not built into any but the most recent simulations. As a result the simulations do not include the heat or moisture sources which affect snowfall (Lake Effect Snows), nor the freeze over of the lakes which curtails the heat and moisture supply in mid-winter, further modulating the Lake Effect.

Even if the water bodies are not included in the models, the impacts, such as the length of the ice season, can be calculated. It is such a derived product that can be of most value for management decisions at the watershed scale. Table 1 provides the ice cover change expected for the Great Lakes and includes an uncertainty range. Change in lake levels due to the change in the water balance components are calculated for several lakes in Table 2. Some ecological implications are summarized in Tables 3 and 4. These data represent a considered effort to take into account the climate change scenarios as shifts in the boundary conditions for ecological assessments. As Regional Climate Models begin to include more geographical detail and replication of sub-synoptic scale processes, such as Lake Effect Storms and the implications for flooding, the uncertainty in these analyses will be reduced.

Table 1. Projected ice cover change for the Great Lakes (Kling *et al.*, 2003).

Lake	**Current Situation**	**Future Scenarios**	
		By 2030	**By 2090**
Lake Superior and Erie (6 basins)	77 to 111 days of ice cover	Decrease ice cover from 11 to 58 days	Decrease ice cover from 33 to 88 days
Lake Superior (3 basins)	No ice-free winters	Increase ice-free winters from 0 to 4%	Increase ice-free winters from 4 to 45%
Lake Erie (3 basins)	2% of winters are ice free	0 to 61% of winters are ice-free	4 to 96% of winters are ice-free
Small inland lakes	~90 to 100 days of ice cover	Decrease ice cover by 45 to 60 days with doubling of atmospheric CO_2	

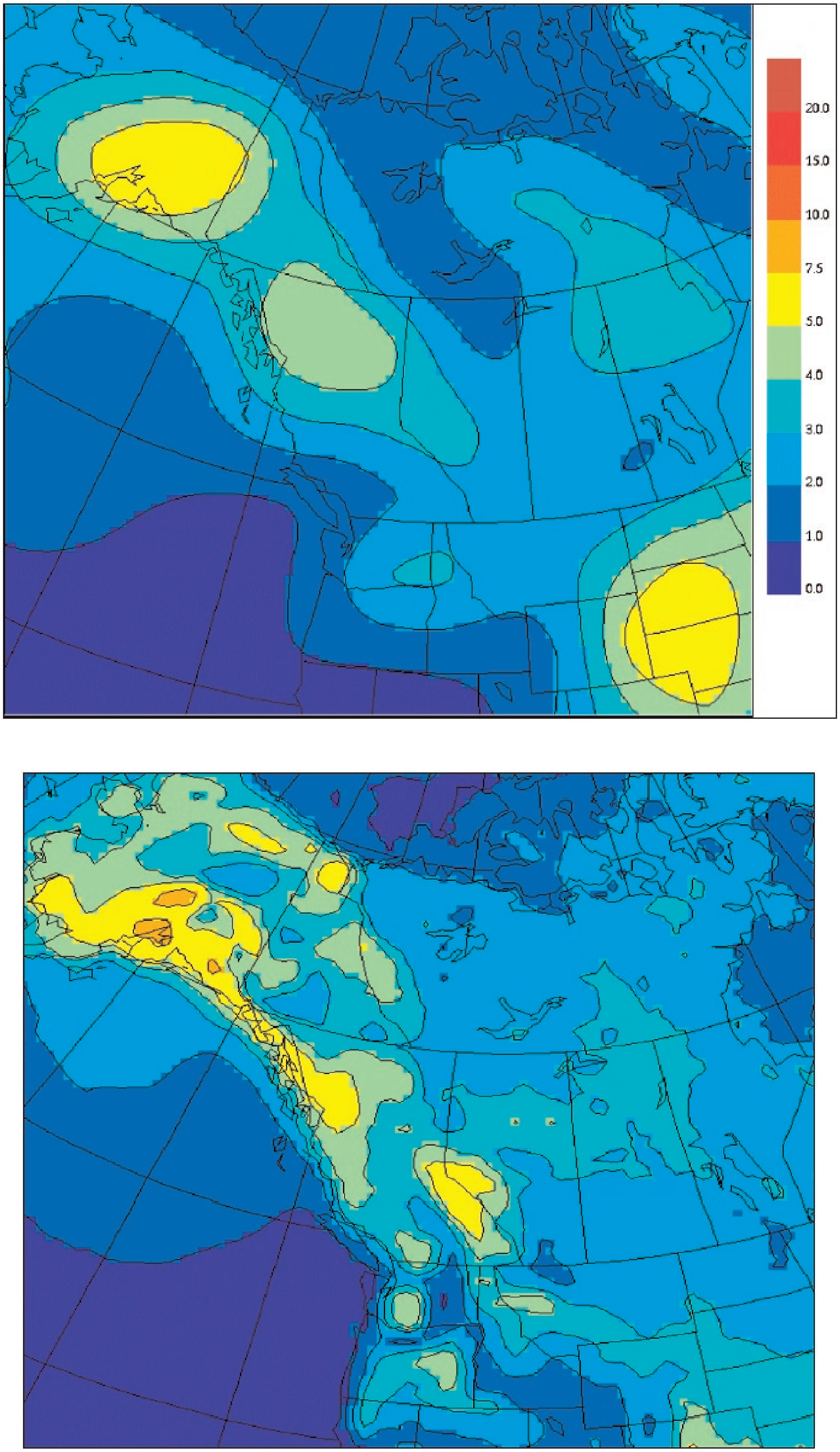


Figure 12a and 12b. Comparison of GCM temperature output with simplified topography for the Western Cordillera with that of regional climate models at 50 km spatial resolutions (Environment Canada, 2004g).

Table 2. Water levels most likely to decrease in the future (Kling *et al.*, 2003).

Lake	$2xCO_2$ (range of 4 simulations)	2030 (range of 4 simulations)	2090 (range of 4 simulations)
Lake Superior	-0.8 m to -2.5 m	-0.3 m to -0.6 m	-1.4 m to +0.4 m
Lake Huron	-3.2 m to -8.1 m	-1.3 m to -4.6 m	-4.5 m to +0.2 m
Crystal lake, Wisconsin	-1.0 m to -1.9 m (2 simulations)		
Groundwater near Lansing, Michigan		-0.6 m to +0.1 m	

Table 3. Expected effects of warmer and drier summer climate on lakes and subsequent impacts on algal productivity (Kling *et al.*, 2003).

Climate-Driven Change	Impact on Production	Most Sensitive Lake Type
Increases in both ice-free period and maximum summer water temperature	Increase in production	Moderate in area, depth, and nutrient concentration
Increase in duration of summer stratification and loss of fall top-to-bottom mixing period	Decrease in production caused by decrease in nutrient regeneration rates	Deep and oligotrophic (nutrient-poor; e.g., Lake Ontario)
Drought-induced decrease in lake water volume	Initial increase in production, followed by progressive decrease as the lake level declines	Small and shallow
Drought-induced decrease in annual input of nutrients (phosphorous) and dissolved organic carbon	Decrease in production resulting from nutrient limitation	Small and oligotrophic

Table 4. Impacts of climate change on stream ecosystems (Kling *et al.*, 2003).

Climate-Driven Change	Likely Impacts on Physical and Chemical Properties	Likely Impacts on Ecosystem Properties	Intensifying or Confounding Factors
Earlier ice-out and snowmelt	Peak flows occur earlier. Ephemeral streams dry earlier in the season. Backwater pools experience anoxia earlier.	The timing of fish and insect life cycles could be disrupted.	Snowmelt occurs earlier and faster in urban areas and where coniferous forest harvest has occurred.
Lower summer water levels	More headwater streams dry; more perennial streams become intermittent. Concentration of dissolved organic carbon decrease, thereby reducing ultraviolet-B attenuation. Groundwater recharge is reduced.	Habitat decreases in extent. Hydrologic connections to the riparian zone are reduced. Groundwater recharge is reduced. Species with resting life stages or rapid colonizers dominate communities.	Impervious surfaces and impervious soils exacerbate stream drying due to reduction in infiltration and groundwater recharge.
More precipitation in winter and spring and increased water levels	Spring floods reach greater heights. Surface runoff increases. Nutrient and sediment retention decrease. Groundwater recharge potential increases.	Floodplain habitat for fish and invertebrates grows. Hydrologic connections with wetlands increase.	Precipitation occurring when soils are frozen results in higher runoff and increases flood height.
Warmer temperatures	Stream and groundwater temperatures increase.	The rates of decomposition and respiration increase. Insects emerge earlier. Primary and secondary production per unit of biomass increases when nutrients are not limited; however, total production could decrease if aquatic habitat shrinks under drought conditions.	Impervious surfaces and both natural and human-made retention basins increase water temperatures. Woody riparian vegetation can buffer stream temperatures. In areas with porous soils and active groundwater connections, temperature extremes are smaller.
More frequent heavy rainfall events	Large floods occur more frequently. Erosion and pollutant inputs from upland sources increase. Runoff increases relative to infiltration.	Fish and invertebrate production decreases. Fish and insect life histories and food webs are disrupted by changes in the intensity, duration, and frequency of flooding.	Impervious surfaces increase runoff and stream flow. Channelized streams increase peak flow.
Elevated atmospheric CO_2		Possible changes in leaf litter quality could impact aquatic food webs.	

Conclusions

Vulnerability and uncertainty are the keywords in application of climate change scenarios to regional management decisions. Because of the thermal inertia in the climate systems associated with the heat storage of vast water bodies, changes implemented today will have an effect only in the future. Climate change is 'in the pipeline'. Any potential adjustments that address the Kyoto Protocol will only reduce the eventual change by a small fraction of that expected. We need several protocols and immediate implementation to have any appreciable effect. This is why the scientific literature has moved from discussion of mitigation to that of adaptation. The difficulty is "What do we adapt to?" in a situation where significant features such as the Great Lakes and regional topography are not included. In some simulations we have very little confidence in the modelled precipitation change. In other simulations we have confidence in the simulated temperature only for ensemble averages over very large areas.

Recognizing such limitations, we can, however, make useful decisions for managing the effects of future climate change. The significant issues include:

- Lower lake levels mean dredging and rebuilding locks, but longer shipping seasons due to less ice
- Hydropower generation will be compromised
- Effects of more extreme storms exacerbated by channeling and paved surfaces
- Implications of more intense downpours for sewer and water delivery infrastructure
- Changes in timing and severity of flood pulses will have impacts on breeding sites and wildlife migration

The climate is changing and will continue to change. We need to understand the inherent limitations of simulation models at the regional level and bring understanding of these limitations into the management process. In effect, our confidence decreases as the spatial resolution increases. All the scenarios are climate driven, there is not yet any feedback from changes in the biosphere that are known to affect regional climate. Tremendous advances are being made in climate analysis, and we expect our assessments of future climates to improve demonstrably within a short period. The Regional Climate Model nested inside the Global Climate Model represents a significant advance that will jump-start many adaptation studies.

Acknowledgements

I wish to acknowledge the financial support of NSERC for the research that led up to this summary paper. I thank Gordon Nelson for urging me to look at this problem from outside the cave of the traditional scientist.

Notes

[1] *The paper has been amended from:* LeDrew, E. Climate Change and Variability: Implications at the Scale of the Watershed. pp. 505–523. In: Lemieux, C.J., J.G. Nelson, T.G. Beechey, and M.J. Troughton. 2004. *Protected Areas and Watershed Management: Proceedings of the Parks Research Forum of Ontario (PRFO) Annual General Meeting 2003*. Waterloo: PRFO.

References

Environment Canada, 2003. The top ten weather stories for 2003. [Online] http://www.msc.ec.gc.ca/media/top10/2003_e.html

Environment Canada. 2004a. Consecutive seasons, national departures, 1985–2004. [Online] http://www.msc-smc.ec.gc.ca/ccrm/bulletin/spring04/figseasont_e.html?season=Spring&date=2004

Environment Canada. 2004b. Climate trends and variations bulletin for Canada. [Online] http://www.msc-smc.ec.gc.ca/ccrm/bulletin/spring01/index_e.html

Temperature and precipitation in historical perspective, spring 2002. [Online] http://www.msc-smc.ec.gc.ca/ccrm/bulletin/spring02/national_e.cfm

Temperature and precipitation in historical perspective, spring 2003. [Online] http://www.msc-smc.ec.gc.ca/ccrm/bulletin/spring03/national_e.cfm

Environment Canada. 2004c. Climate change and research branch. [Online] http://www.mb.ec.gc.ca/air/nino/ah00s88.en.html

Environment Canada. 2004d. Long-range forecast user's guide. [Online] http://www.msc-smc.ec.gc.ca/ccrm/bulletin/winter03/national_e.cfm

Environment Canada. 2004e. Slide 25: Temperature patterns will change substantially by 2050. [Online] http://www.msc-smc.ec.gc.ca/education/scienceofclimatechange/understanding/presentation_resources/section4/slide25_e.html

Environment Canada. 2004f. Changes in temperature are unevenly distributed. [Online] http://www.msc-smc.ec.gc.ca/education/scienceofclimatechange/understanding/presentation_resources/section2/SICC2_e.PPT#11

Environment Canada. 2004g. Models: the Canadian regional climate model (CRCM). [Online] http://www.cccma.bc.ec.gc.ca/models/crcm.shtml

Environment Canada. 2004h. Science and impacts of climate change presentation graphics. [Online] http://www.msc-smc.ec.gc.ca/education/scienceofclimatechange/understanding/presentation_resources/index_e.html

Garnett, E. R. 2002. Rejoice Canadian prairie farmers, El Niño is on the way? *CMOS Bulletin*, 30(2):29.

Hayhoe, K. and B. Shuter. 2003. *Confronting Climate Change in the Great Lakes Region: Impact on Ontario Communities and Ecosystems*. [Online] http://www.ucsusa.org/greatlakes/

Hansen, L.J., J.L. Biringer, and J.R. Hoffman (eds.). 2003. *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems*. World Wildlife Fund (WWF), Climate Change Program: Berlin, Germany. 246 pp.

Hare, F. Kenneth. 1972. Lecture Notes. University of Toronto, Toronto.

Hengeveld, H., E. Bush, and P. Edwards. 2002. *Frequently Asked Questions About the Science of Climate Change*. Ottawa: Meteorological Service of Canada, Minister of the Environment, Minister of Supply and Services.

Hengeveld, H. 2000. *Climate Change Digest—Projections for Canada's Climate Future*. Ottawa: Meteorological Service of Canada, Minister of the Environment, Minister of Supply and Services. 27 pp.

IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001, the Scientific Basis*. UNEP. Cambridge: Cambridge University Press. 881 pp.

Lake Huron. 1999. *Lake Huron and Climate Change*. Blyth, Ontario: The Lake Huron Centre for Coastal Conservation. 4 pp.

Kling, G.W., K. Hayhoe, L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles, D.R. Zak, R.L. Lindroth, S.C. Moser, and M.L. Wilson. 2003. *Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems*. Union of Concerned Scientists, Cambridge. [Online] http://www.ucsusa.org/greatlakes/glchallengereport.html

NOAA (National Oceanic and Atmospheric Administration). 2004. El Niño and La Niña. [Online] http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/winter25%25.gif

Parkinson, C.L. 2000. Variability of arctic sea ice: the view from space, an 18-year record. *Arctic*, 53(4): 341–358.

Schneider, S. H. and R.E. Dickinson. 1974. Climate modeling. *Reviews of Geophysics and Space Physics*, 12(3): 447–493.

Trenberth, Kevin E. 1997. The definition of El Niño. *Bulletin of the American Meteorological Society*, 78: 2771–2777.