

CLIMATE CHANGE AND VARIABILITY: IMPLICATIONS AT THE SCALE OF THE WATERSHED

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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.

Introduction

With the exception of a cadre of die-hard geologists that confuse 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 Canadian 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.

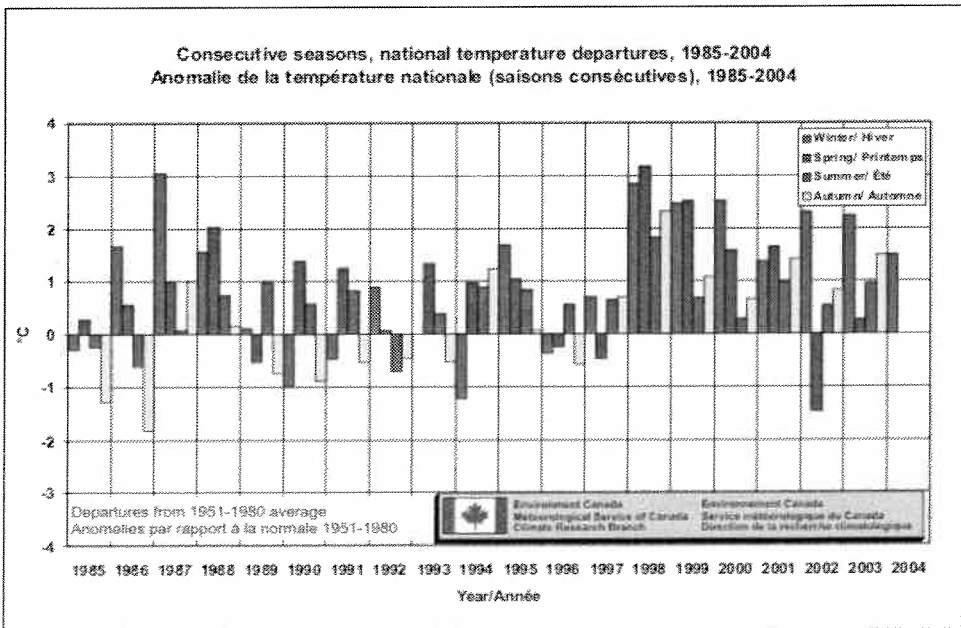
Canadian Evidence of Change and Variability

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; and,
- Avalanches killed 28 skiers, including seven on a school trip (www.msc.ec.gc.ca/media/top10/2003_e.html).

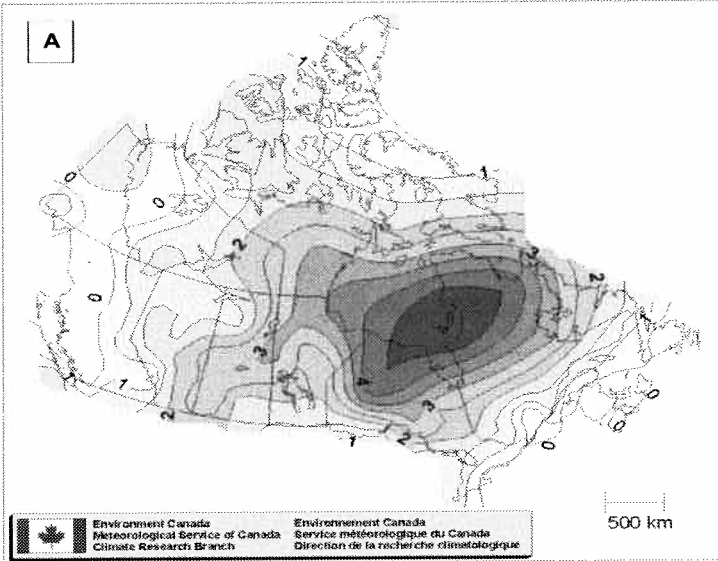
Each year appears to bring new extreme weather events. If we examine the departures of Canadian temperatures from the normal for each season, we find that 25 of the last 26 seasons are above the climate normal. This unusual anomaly seems to validate notions of recent climate change and is consistent 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 (Figures 2a, 2b and 2c), we see that cooling of this spring 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 reside along side such clear long-term evidence of climate warming.

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

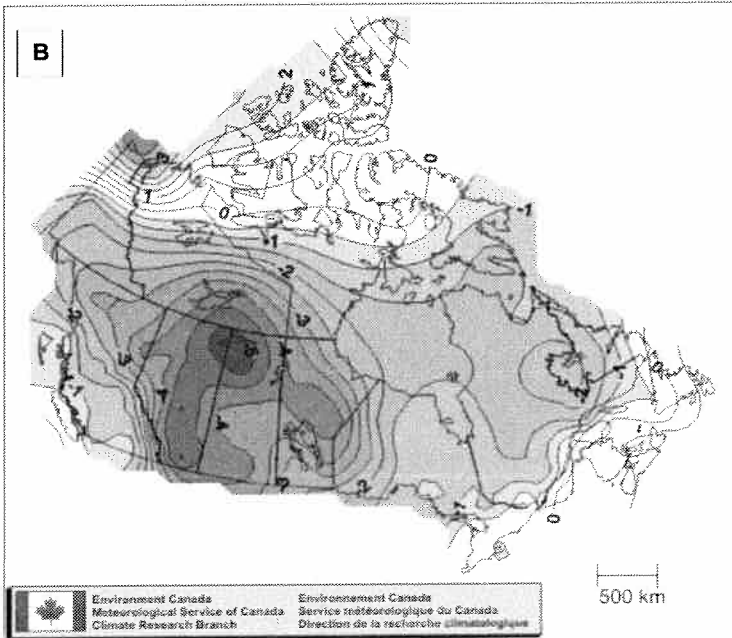


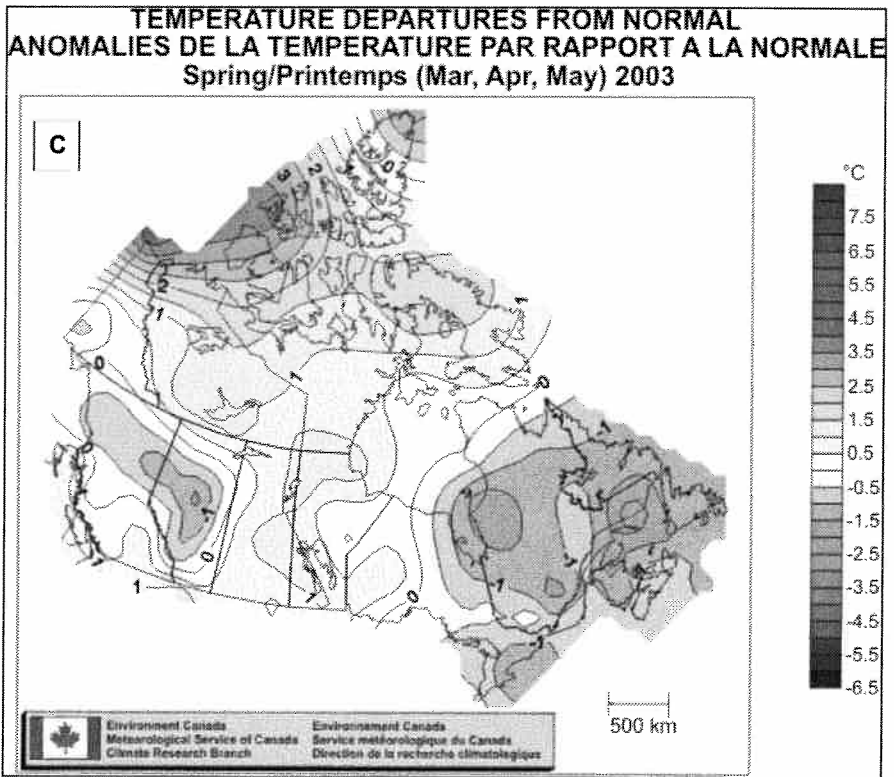
Figures 2a, 2b and 2c. Temperature anomaly maps for Canada for three spring seasons (Environment Canada, 2004b).

**TEMPERATURE DEPARTURES FROM NORMAL
ANOMALIES DE LA TEMPERATURE PAR RAPPORT A LA NORMALE
Spring/Printemps (Mar, Apr, May) 2001**



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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) illustrate 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 variable groups such as the evaporation-cloud linkages, and radiation balance – wind system linkages. Schneider and Dickinson (1974) has proposed that climate change would be associated with changes in the external variables that would induce a new state of the climate, whereas variability was result of the internal variables and associated feedback loops constantly adjusting to these new external states. The effect could be likened to a fine Swiss watch movement with internal gears of various sizes and rates of rotation keeping time and responding to an external adjustment of the entire mechanism to compensate for errors.

F. Kenneth Hare (1972) (Figure 4) illustrates various temporal routes that the change/variability distinction can take for an example variable, such as temperature. In addition to long-term sinusoidal waves, such as may be attributed to the Milankovitch variations of orbital mechanics, there are abrupt shifts with a variability superimposed upon the trend, a slow transition to a new external state – again with variability superimposed upon this transition, or just a change in the degree of variability. All represent a change in the climate and include the variability superimposed upon that trend. This can be identified in the change in sea ice extent (Figure 5) with an extensive interannual variation that changes from seasonal one cycle to the next and is superimposed upon a longer-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).

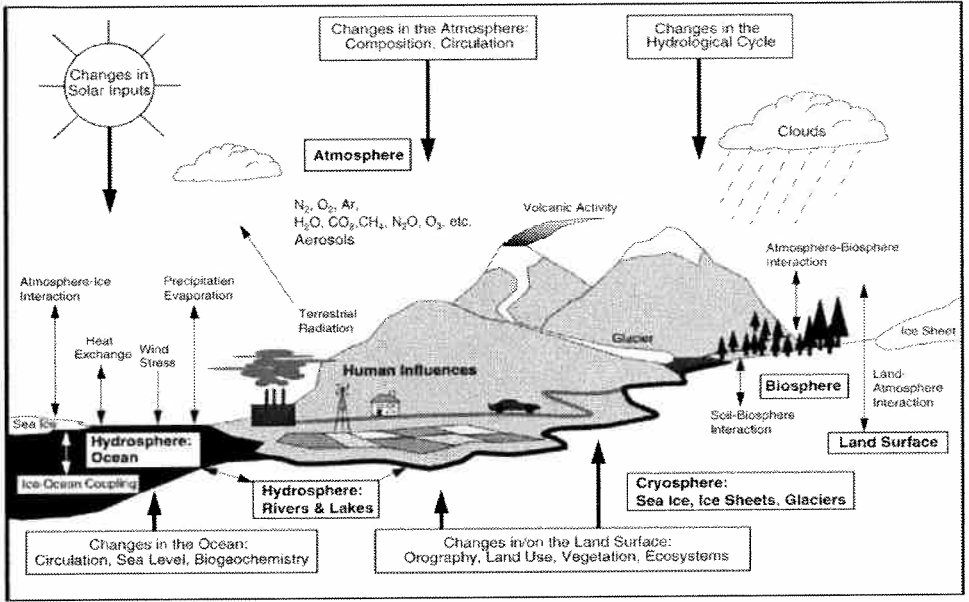


Figure 4. Schematic of types of climate change and variability for a climate variable, such as temperature.

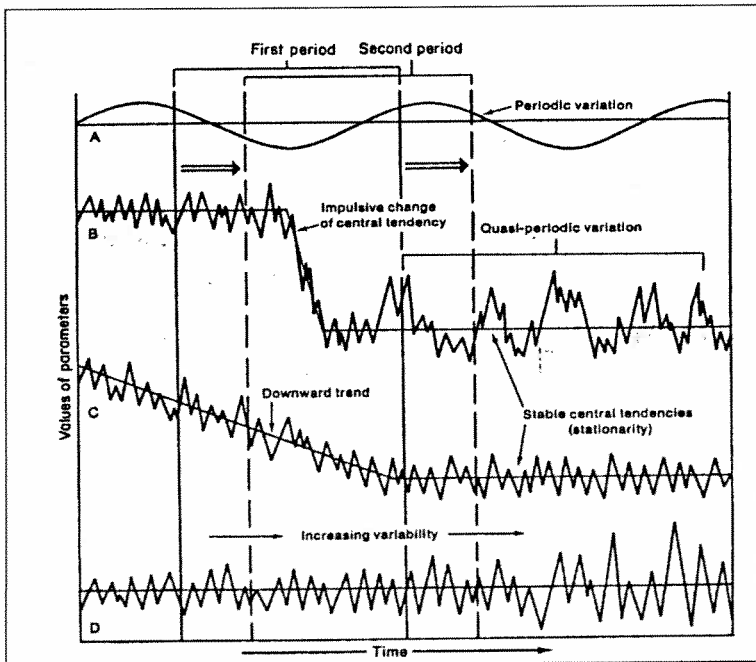
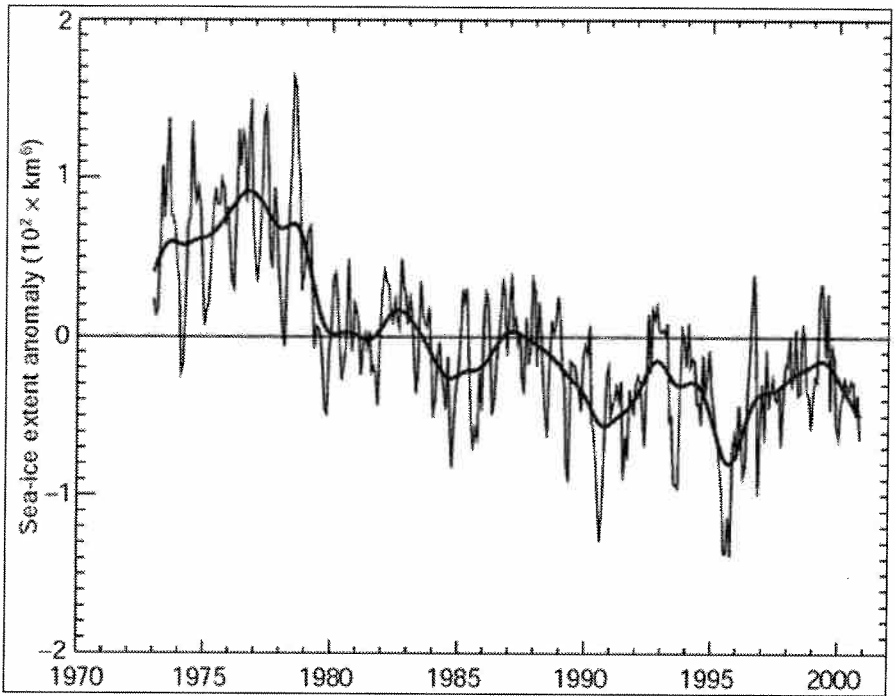


Figure 5. Temporal anomalies of sea ice extent (Parkinson, 2000).



While such a concept can help rationalize 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 possibility is the cyclic recurrence of the El Niño – 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 through teleconnections, 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 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 (Figure 9) 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.

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

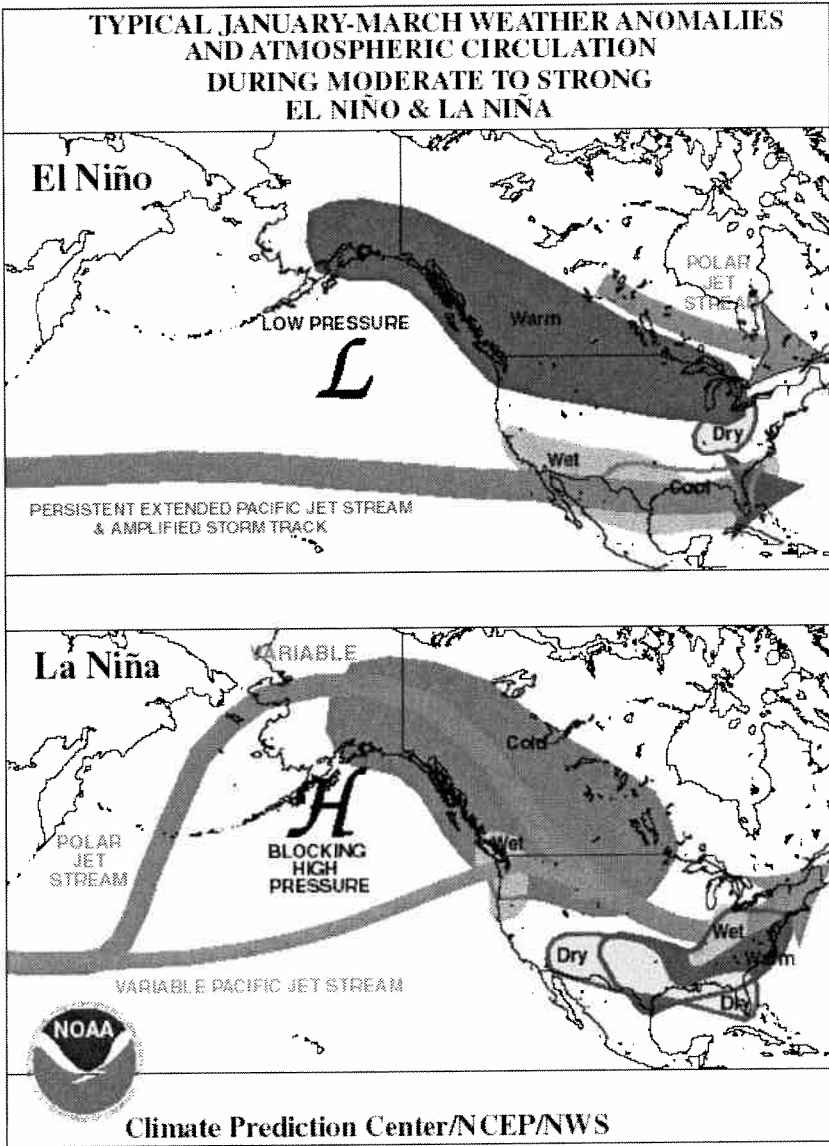


Figure 7. Expected Canadian temperature anomalies for an El Niño year (Environment Canada, 2004c).

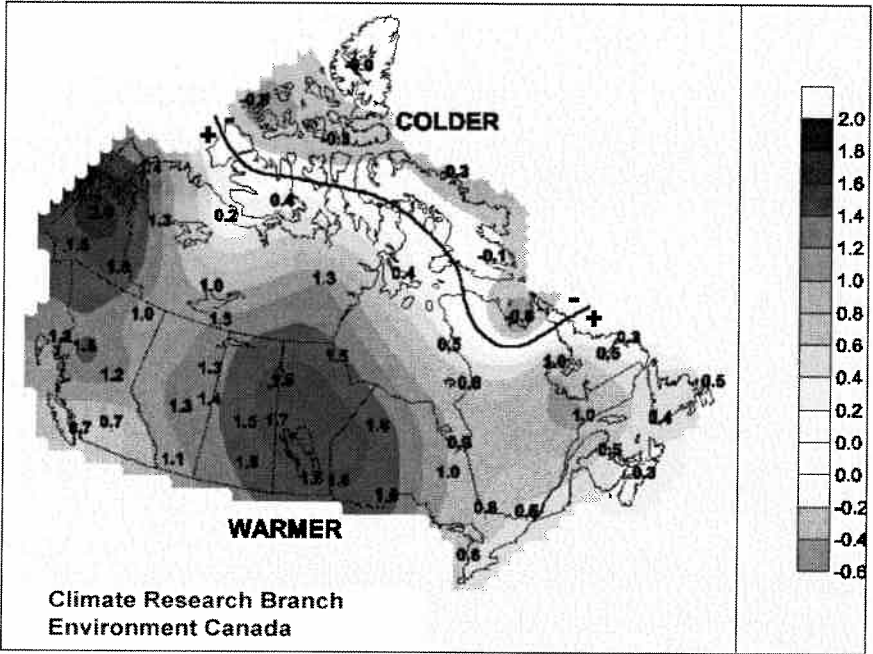


Figure 8. Actual temperature anomaly for winter, 2003 (Environment Canada, 2004d).

TEMPERATURE DEPARTURES FROM NORMAL
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Winter/Hiver (Dec, Jan, Feb) 2002/2003

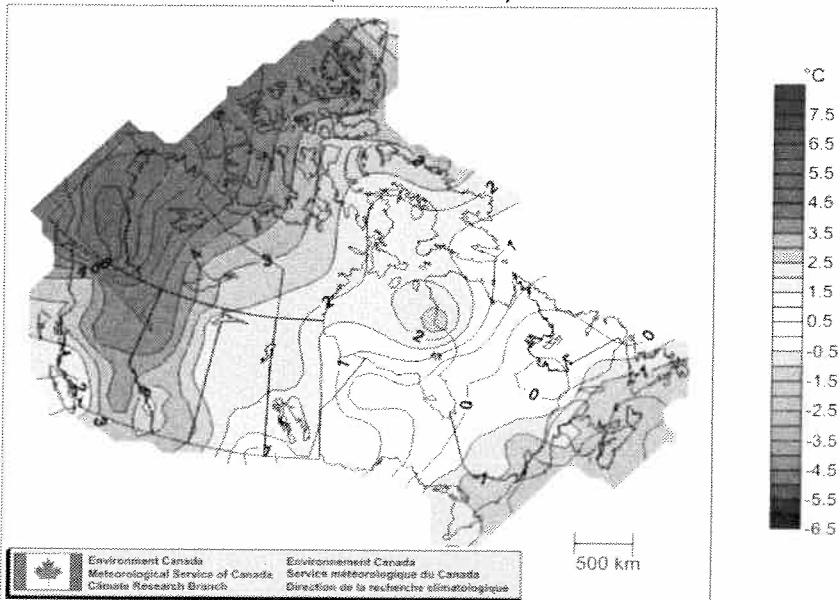
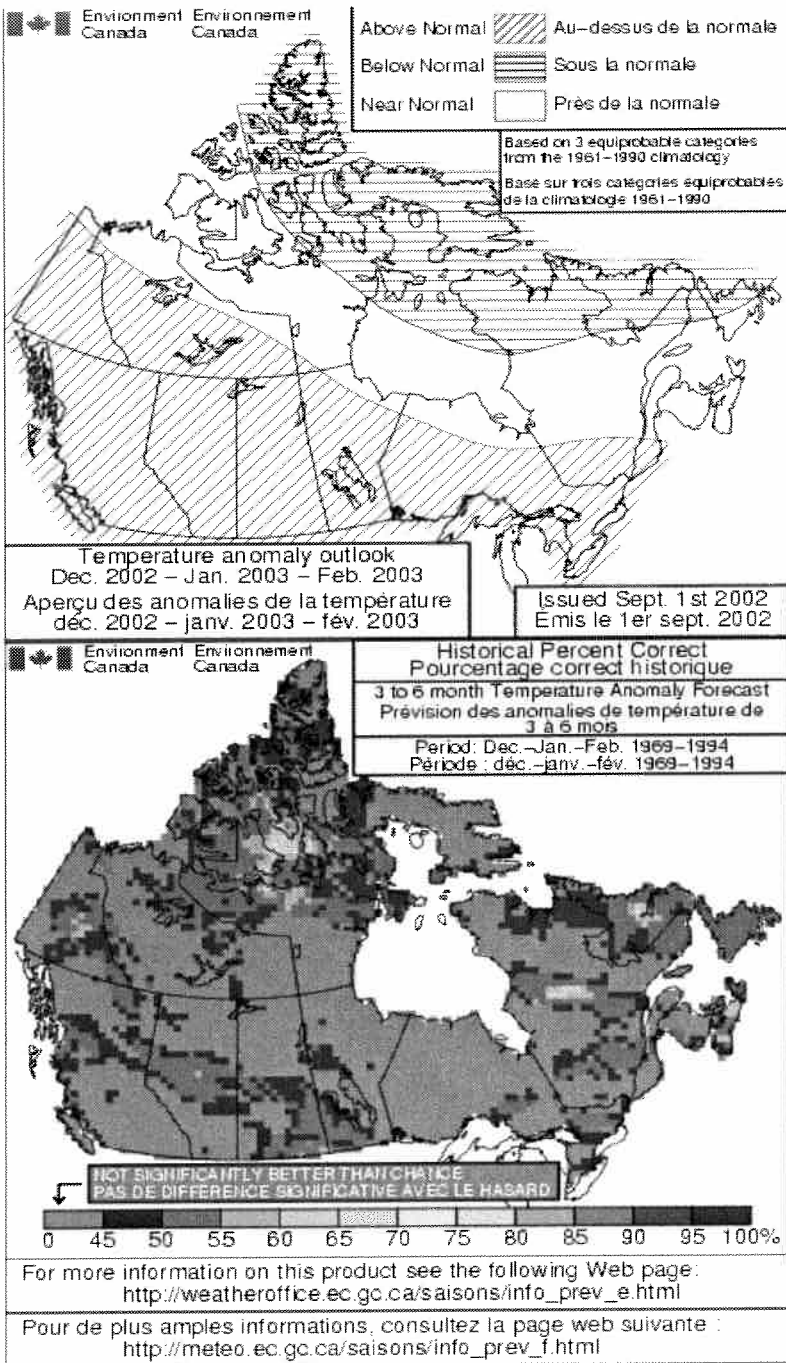


Figure 9. Forecast temperature anomaly (and level of confidence) for an expected El Niño winter, 2003 (Environment Canada, 2004e).



For more information on this product see the following Web page:
http://weatheroffice.ec.gc.ca/saisons/info_prev_e.html

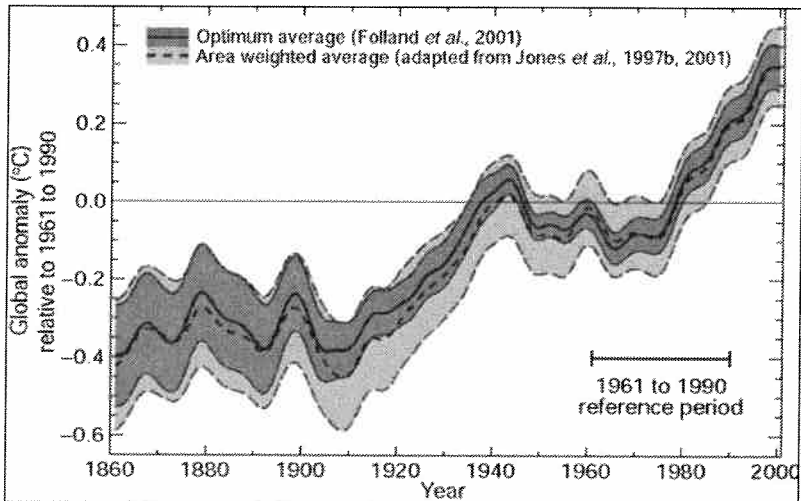
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The Long View of Canadian Climate

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 10). 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 we can determine that (Hayhoe and Shuter, 2003):

- The climate will feel as if Ontario has been translocated south to Virginia;
- Temperature 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; and,
- Great Lakes Ice Cover will decline – protection from winter storms and impact on oxygenation.

Figure 10. 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 stated in public media. In Figure 12, the temperature trends between 1950 and 1998 are colour coded 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 regions and a ridge of warm air in another. At the scale of the watershed, a warming scenario may not necessarily be appropriate. This caveat is complicated by the fact that while we are reasonably comfort-

able with temperature simulations for a greenhouse gas enhanced atmosphere, other climate variables, such as temperature, are very difficult to simulate with confidence and so a complete picture of the future climate state for a region is elusive.

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

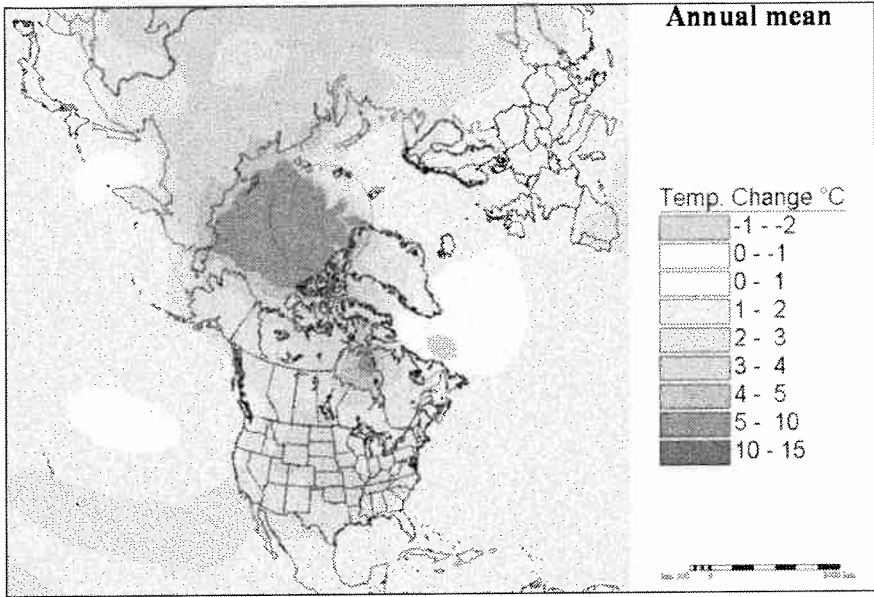
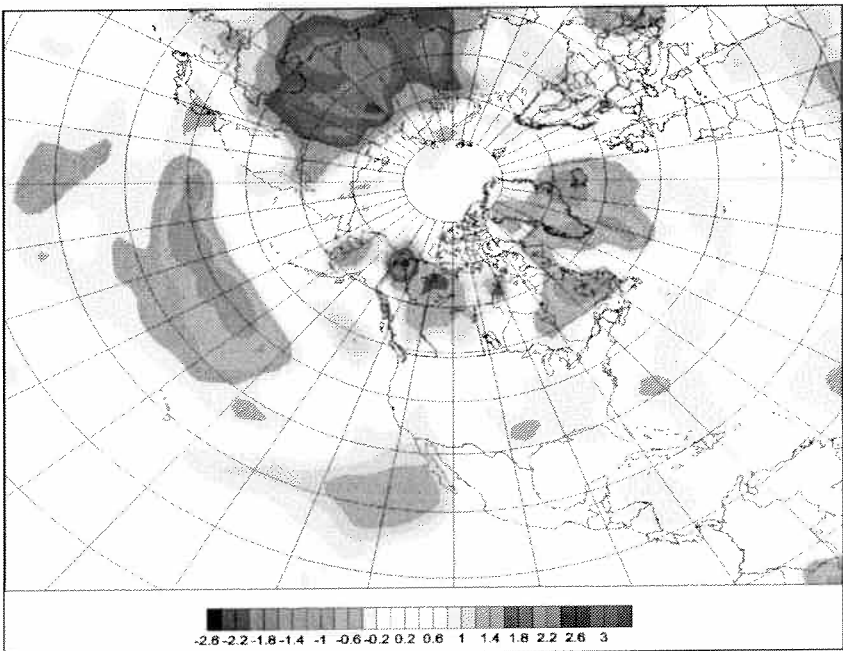


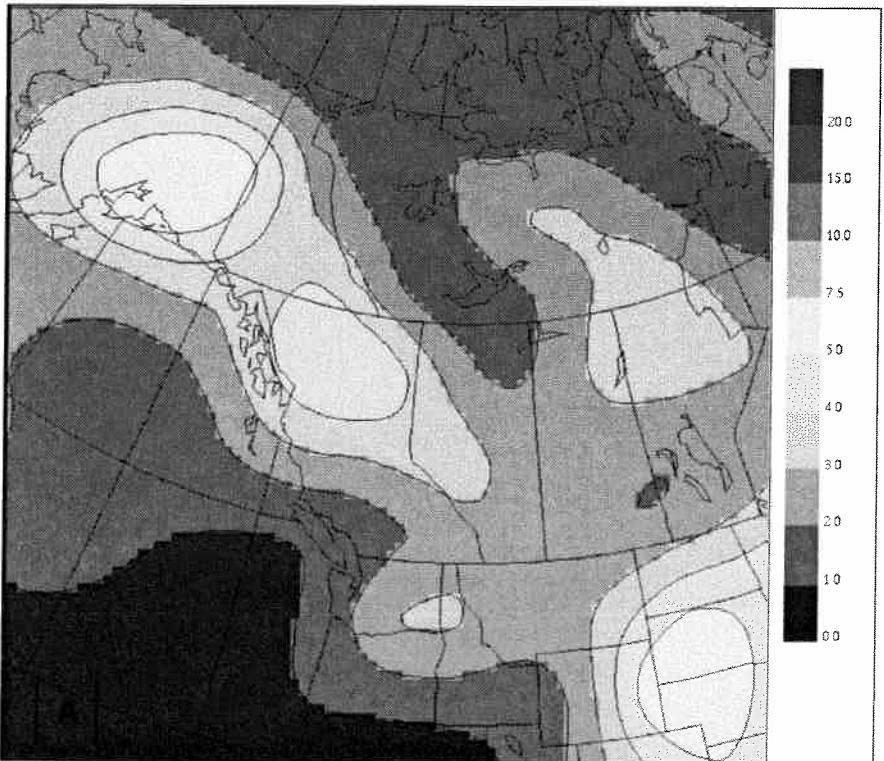
Figure 12. Observed temperature trends for Canada from 1950 to 1998 (Environment Canada, 2004f).

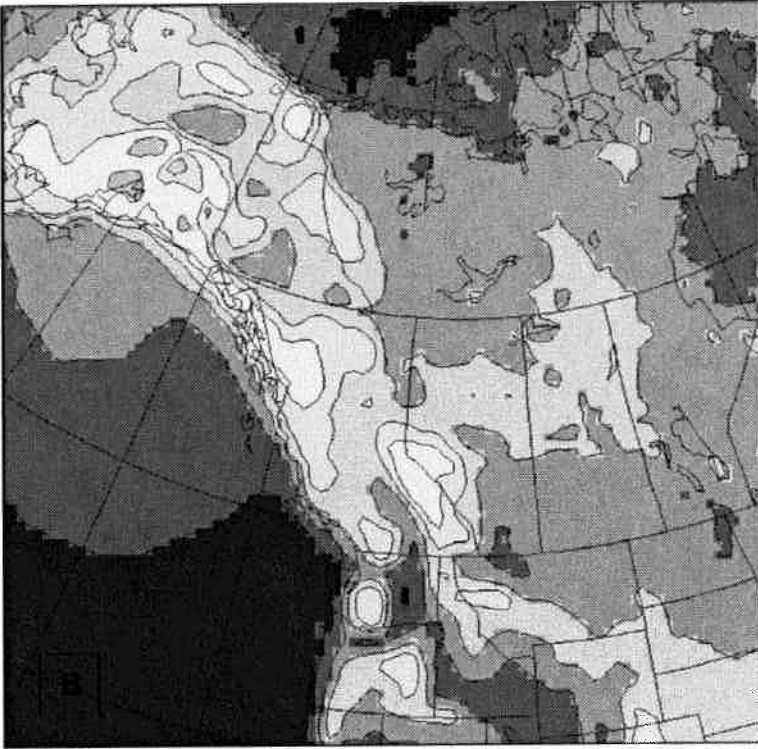


Inferences at the Scale of the Watershed

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 devastatingly warmer temperatures and increased instances of drought. The scenarios for a complex environment such as Southern Ontario are more suspect. The modelers would be the first to point out the deficiencies and warn the users about the limitations. Normally, the grid point distribution for the calculations of fluid flow representing 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 geograph. 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 are typically 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 13a and 13b).

Figures 13a and 13b. Comparison of GCM temperature output with simplified topography for the Western Cordillera with that of regional climate models at 50 km spatial resolution (Environment Canada, 2004g).





There are no Great Lakes in all but the most recent simulations and so there is no heat nor moisture sources for the Lake Effect Snows, and no freeze over of the lakes to shut off the heat and moisture supply in mid-winter, which further modulates the Lake Effect.

Nevertheless, the scenarios can provide important insight if viewed with these restrictions in mind and used to determine change compared to an internally consistent benchmark. An example for the Southern Lake Huron region is illustrated in Figure 14. A baseline is developed on a monthly basis for a model run without Greenhouse Gas Enhancement; a simulation of the present given the restrictions noted above. Then model scenarios for 2050 and 2090 are presented (these are actual temperatures, not change from the baseline as implied in the title). One real value of such data is in the analysis of the temperature distributions. In Figure 15 the temperature probability density function is calculated for the present (which could be the baseline if internal model anomalies are desired) and for the future climate. A seemingly innocuous 2°C net warming is associated with a marked increase in probability of extremely warm temperatures. These are the temperatures associated with mortality of at-risk segments of the population, such as seniors. The high mortality rates of the extremely warm summer of 2003 in Europe is one unfortunate consequence.

Even if the water bodies are not include in the models, the impacts, such as 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. The ecological implications are summarized in Tables 3 and 4. These data represent a considered effort to consider the climate change scenarios as shifts in the boundary conditions for ecological assessments. As Regional Climate Models 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 analysis will be reduced.

Figure 14. GCM temperature simulations by month for the southern Lake Huron region (Lake Huron, 1999).

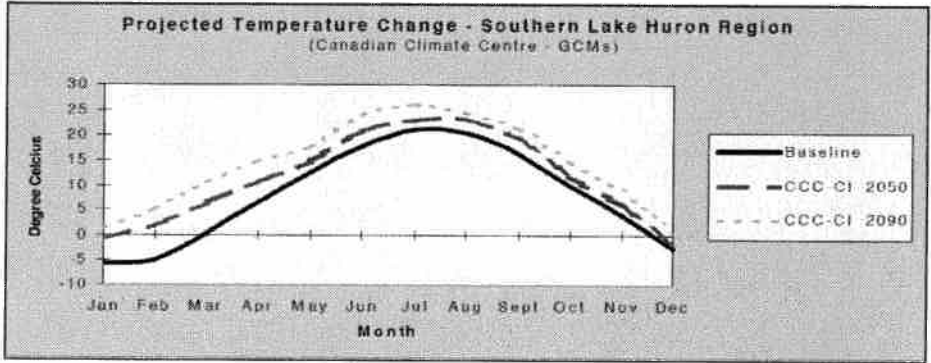


Figure 15. Temperature distribution for a 2.0°C temperature perturbation (Environment Canada, 2004h).

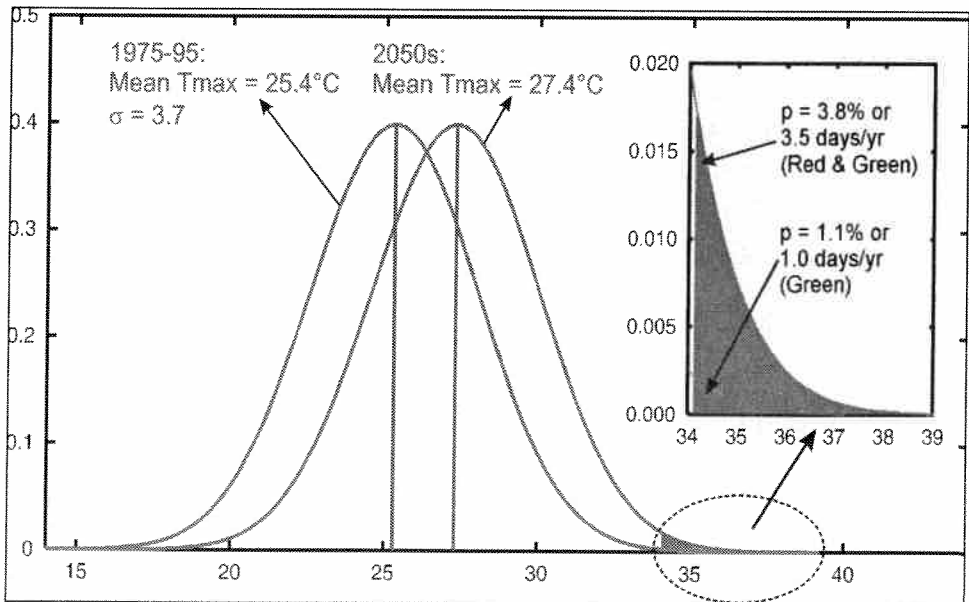


Table 1. Projected ice cover change for the Great Lakes (Kling et al., 2003).

LAKE	CURRENT SITUATION	FUTURE SCENARIOS	
		2030	2090
Lakes Superior and Erie (6 basins)	77 to 111 days of ice cover	Decrease ice cover from 11-58 days	Decrease ice cover from 33-88 days
Lake Superior (3 basins)	No ice-free winters	Increase ice-free winters from 0-4%	Increase ice-free winters from 4-45%
Lake Erie (3 basins)	2% of winters are ice free	0-61% of winters are ice free	4-96% of winters are ice free
Small inland lakes	-90-100 days of ice cover	Decrease ice cover by 45-60 days with a doubling of atmospheric CO ₂	

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

LAKE	2 x CO ₂ (RANGE OF 4 SIMULATIONS)	2030 (RANGE OF 4 SIMULATIONS)	2090 (RANGE OF 2 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 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; eg., 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 output 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 snow melt	Peak flows occur earlier. Ephemeral streams dry earlier in the season.	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	Backwater pools experience anoxia earlier. More headwater streams dry; more perennial streams become intermittent. Concentrations of dissolved organic carbon decrease, thereby reducing ultraviolet B attenuation.	Habitat decreases in extent. Hydrologic connections to the riparian zone are reduced. Groundwater recharge is reduced.	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	Groundwater recharge is reduced. Spring floods reach greater heights. Surface runoff increases. Nutrient and sediment retention decrease.	Species with resting life stages or rapid colonizers dominate communities. 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	Groundwater recharge potential increases. Stream and groundwater temperature increase.	The rate 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.
More frequent heavy rainfall events	Larger floods occur more frequently. Erosion and pollutant inputs from upland sources increase.	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.	In areas with porous soils and active groundwater connections, temperature extremes are smaller. Impervious surfaces increase runoff and stream flow.
Elevated Atmospheric CO ₂	Runoff increases relative to infiltration.	Possible changes in leaf litter quality could impact aquatic food webs.	Channelized streams increase peak flow.

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 Kyoto's and implementation soon 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?' when significant features such as the Great Lakes and regional topography are not included, when we have very little confidence in the change in precipitation, and confidence in temperature only for ensemble averages over very large areas.

We can, with considered assessment of the limitations, make useful decisions for managing the effects of future climate change. We expect that there will be more extreme storms and the effects will be exacerbated by channeling and paved surfaces. More intense downpours will have implications for sewer and water delivery infrastructure. Lower lake levels mean dredging and rebuilding locks, but there may also be a longer shipping season due to less ice. Changes in the timing and severity of flood pulses will have an impact on breeding sites and migration (Kling *et al.*, 2003). The significant issues include:

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

The climate is changing and will continue to change. We are in the pipeline. 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. There are tremendous advancements 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 may adaptation studies.

Acknowledgments

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