The Science of Climate Change

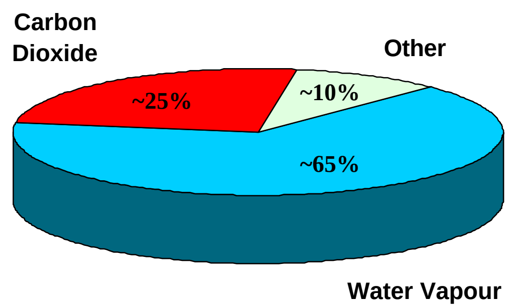
Part 1: Introduction/GHG/Radiative Forcing

Updated April 2001

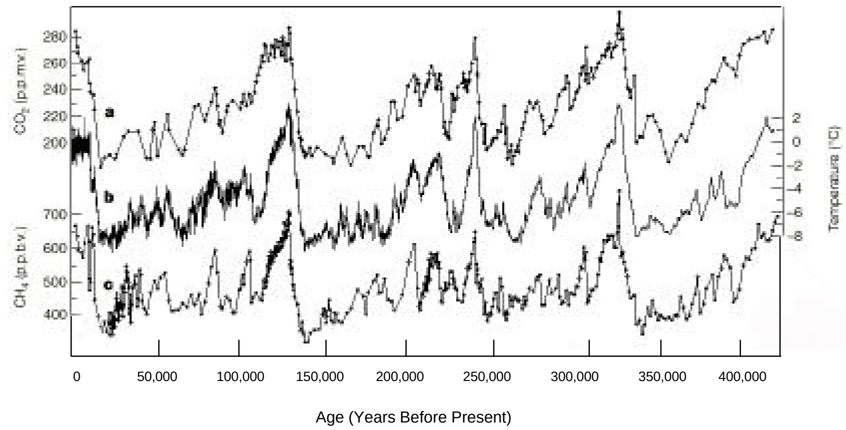
Environment Canada Environnement Canada

Canada

Primary Contributors To The Natural Greenhouse Effect



Past Trends in Temperature and Greenhouse Gas Concentrations in Antartica



Source: Petit *et al.* 1999.

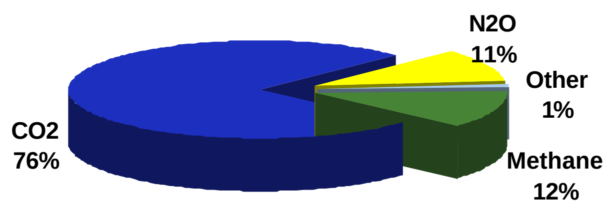
Ice cores are an excellent source of information on past global climates and atmospheric composition.

Antarctic ice cores indicate low concentrations of CO_2 and methane during glacial periods and high concentrations during interglacials.

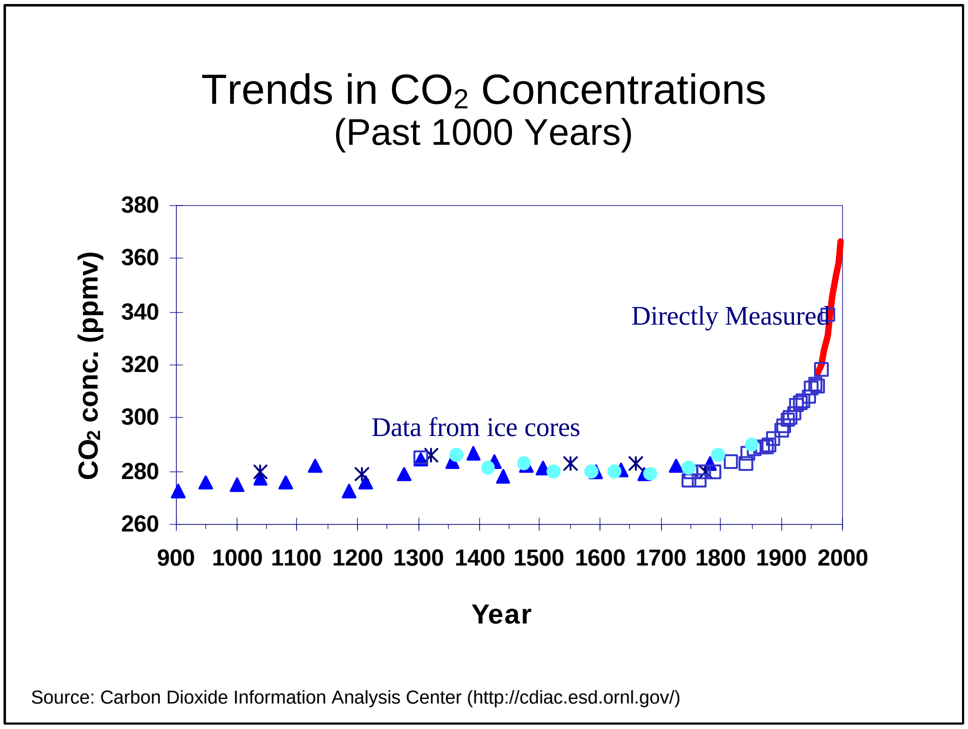
Greenhouse gas changes correlate closely with temperature changes.

This suggests greenhouse gases have an important role in changes in global temperature.

Canada's Greenhouse Gas Emissions By Gas for 1996



Total Emissions ~ 671 Mt

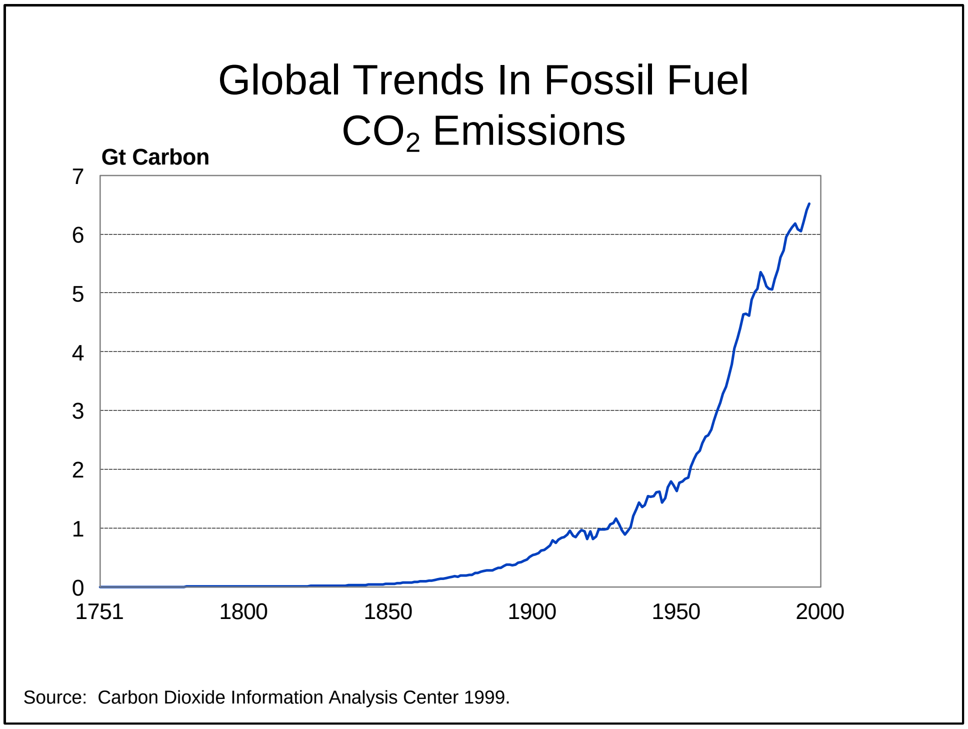


Data from Greenland and Antarctic ice cores show that atmospheric CO_2 concentrations have been remarkably stable during the past 10,000 years, varying within a narrow range around 280 parts per million by volume (ppmv).

The highest values of CO_2 during the past 400,000 years, until 200 years ago, appear to have been less than 300 ppmv.

Both ice cores and measured atmospheric data show a 30% increase above pre-industrial levels during the past two centuries.

Source: Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/)

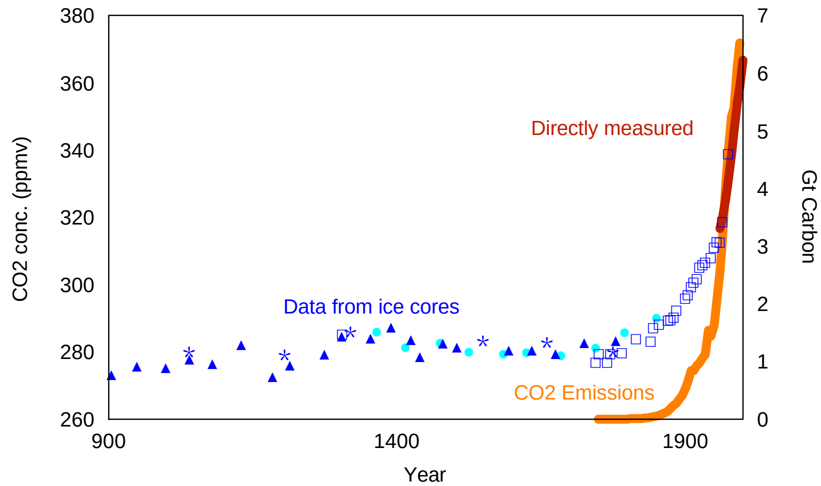


Carbon dioxide emissions from the burning of fossil fuels equalled less than one-tenth of a gigatonne of carbon in the late 1700s and early 1800s. By 1900 the annual emission of CO_2 was just under 1 Gt carbon and by the 1950s the annual emissions of CO_2 from the burning of fossil fuels was increasing very rapidly. In 1996, the global emission was 6.5 Gt of carbon.

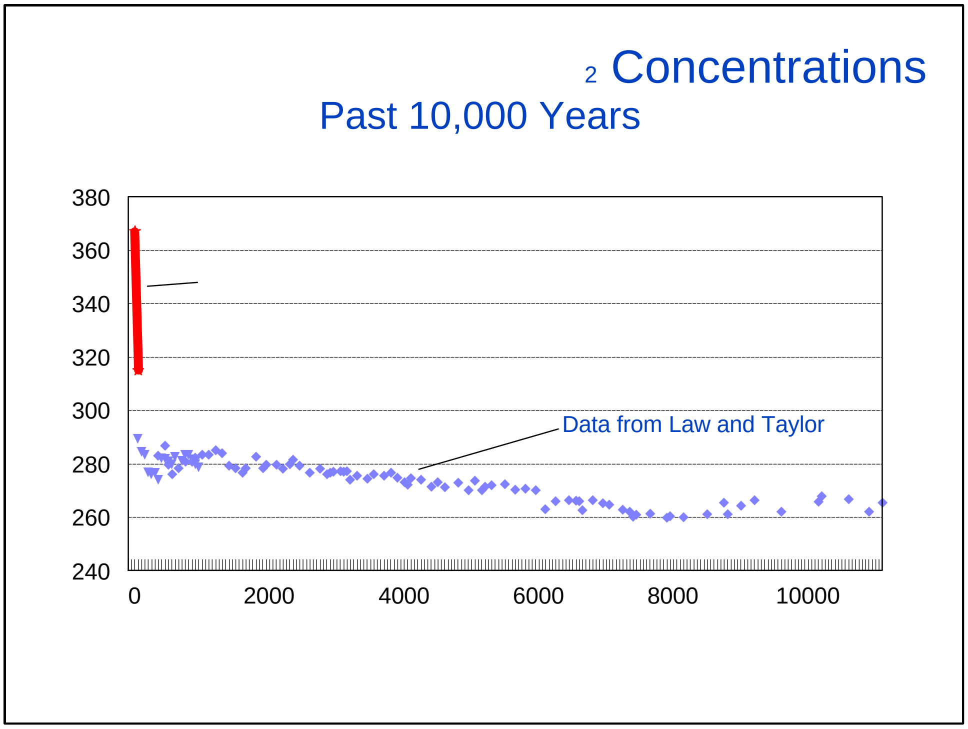
Source: Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/)

Trends in CO_2 Concentrations

2



Source: Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/)



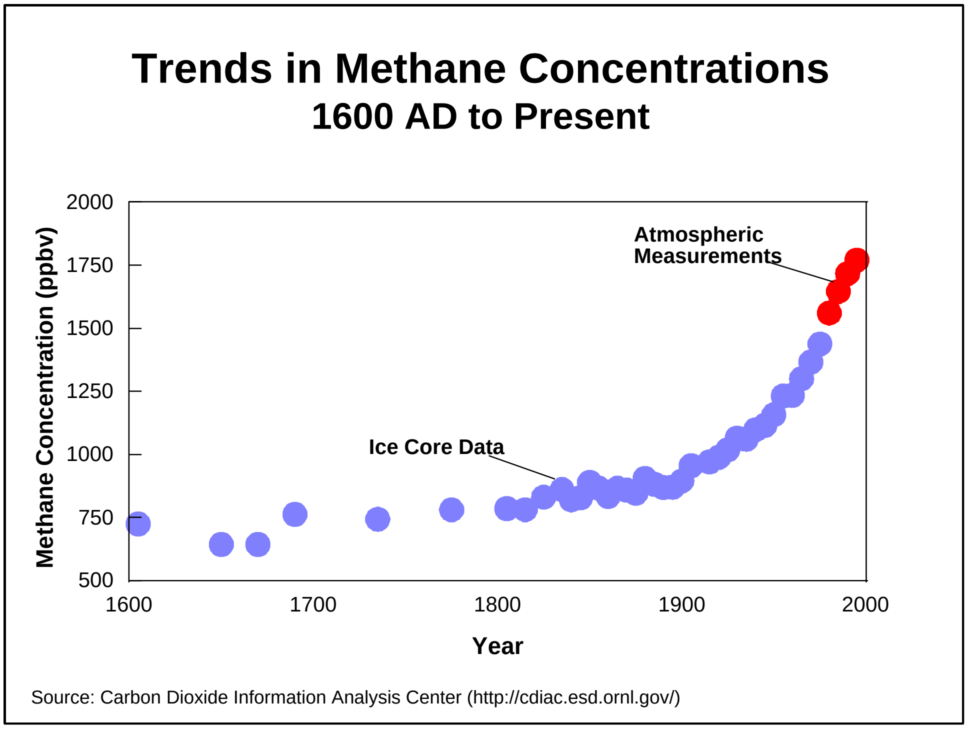
•Ice core data is from high resolution Antarctic ice cores as reported by Indermuhle et al. in Nature 398:121-126.

•Data suggest CO2 concentrations during the Holocene increased from a low of 260 ppmv about 7000 years ago to values of about 280 ppmv during the past several thousand years.

•Lower concentrations during the mid-Holocene appear to be linked to a period of enhanced carbon uptake by forests during post-glacial growth

•Concentrations dipped slightly during the Little Ice Age several centuries ago

•The rates of change in CO2 concentrations during these natural variations are two orders of magnitude less than that observed since the industrial revolution.

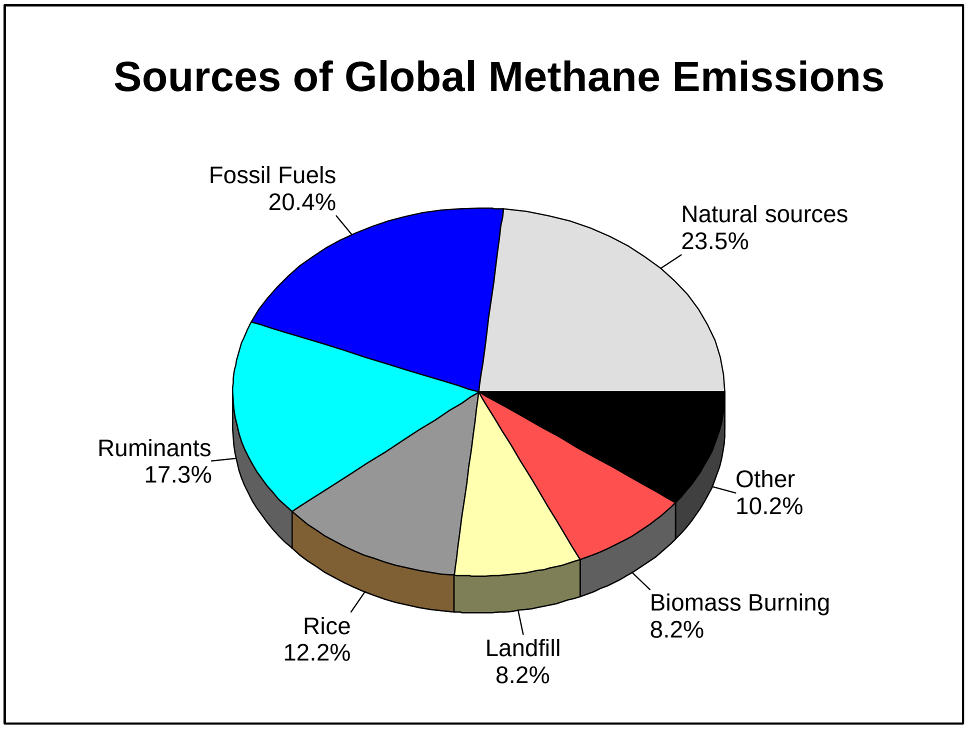


Date from Greenland and Antartic ice cores indicate that methane concentrations have varied slightly around a mean value of 750 parts per billion by volume (ppbv) during the pre-industrial period of the past 10,000 years.

Highest values detectable in ice cores during the past 400,000 years appear to be less than 800 ppbv.

Concentrations have increased above this level by 145% during the past two centuries.

Source: Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/)



More than 75% of current global methane emissions come from anthropogenic sources.

Primary human sources are fossil fuel production/consumption and agricultural activities. The primary natural methane source is emissions from wetlands.

KYOTO PROTOCOL
GREENHOUSE GASES

Gas	Atmospheric Lifetime (yrs)	GWP
CO_2	Variable	1
Methane	12	21
N_2O	120	310
HFCs	1 to 200+	140 to 11700
PFCs	3000 to 50000	6500 to 9200
SF_6	3200	23900

Source: Houghton *et al.* 1996.

The Global Warming Potential (GWP) is an attempt to provide policy makers with a means of comparing the relative climatic effects of the various greenhouse gases with that of an equivalent emission of CO_2.

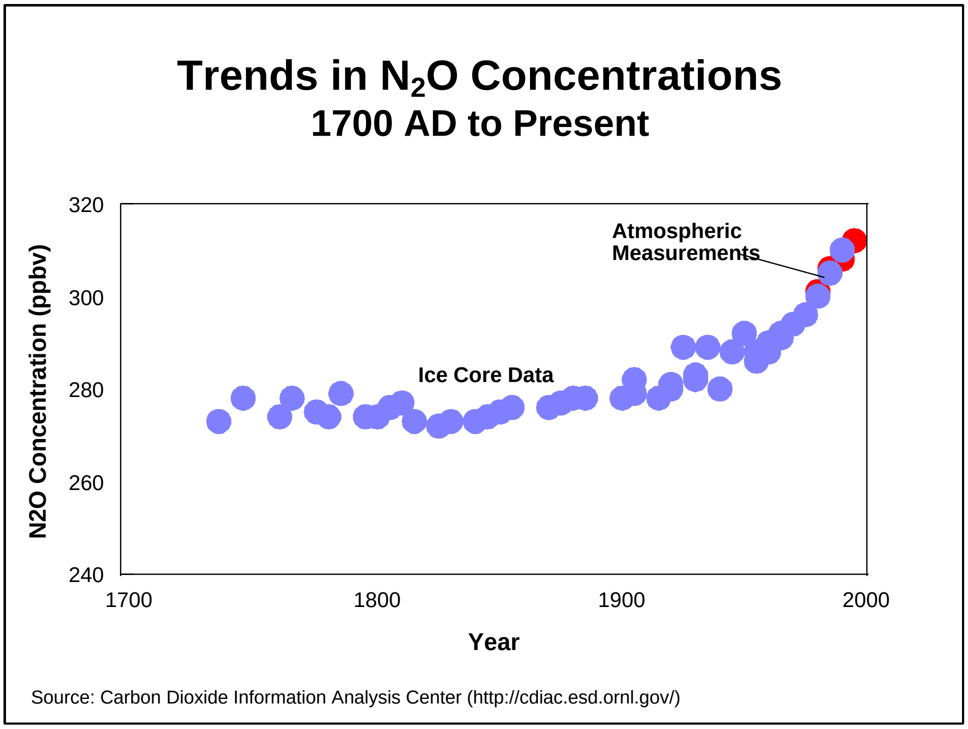
The indicated GWP values are calculated by integrating the effect of emissions on the climate over the next 100 years.

Molecule for molecule, CO_2 is the least effective of the major greenhouse gases. Methane, by comparison, absorbs and reradiates about 21 times as much heat energy.

However, the overall contribution of each greenhouse gas depends on several other factors as well, including:

- the amount of the gas released into the atmosphere each year
- the atmospheric lifetime of each gas
- the indirect effect that emissions of each gas will have on atmospheric chemistry.

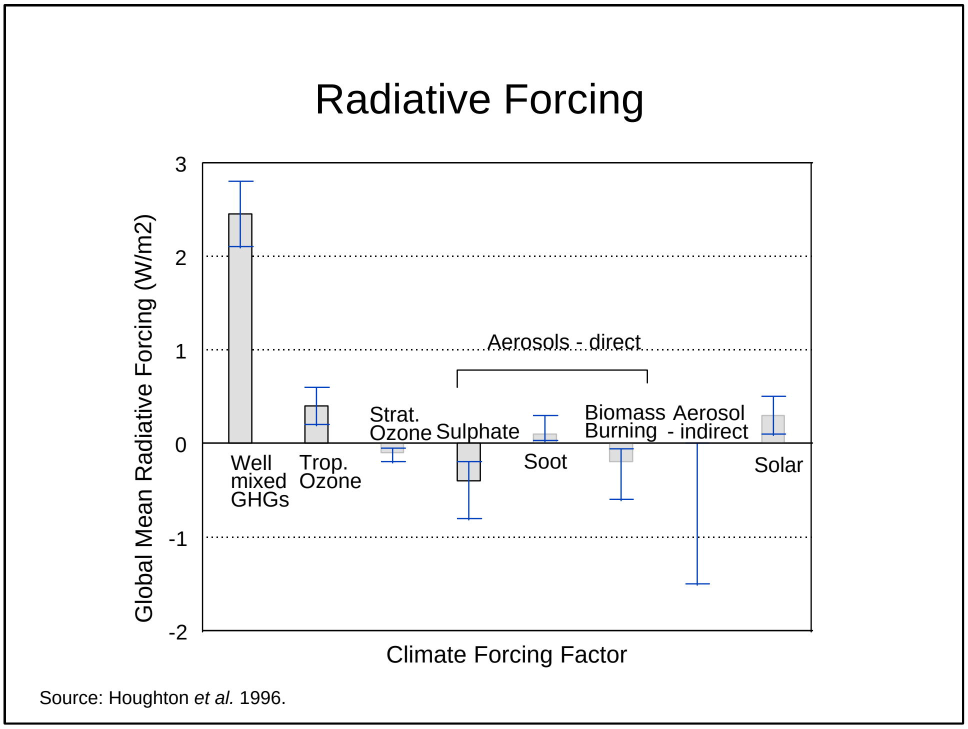
Source: J.T. Houghton *et al.* 1996. Climate Change 1995: The Science of Climate Change. Cambridge, Cambridge University Press.



Nitrous oxide (N_2O) concentrations over the pre-industrial period of the past 10,000 years have varied around a mean value of 275-280 ppmv.

Concentrations have increased by 15% above this level during the past two centuries.

Source: Carbon Dioxide Information Analysis Center (http://cdiac.esd.ornl.gov/)



This diagram provides best estimates for current changes in the net radiative energy flowing into the lower atmosphere due to changes in concentrations of various greenhouse gaes and aerosols emitted by human activities. That for natural changes due to increased intensity of sunlight is included for comparison.

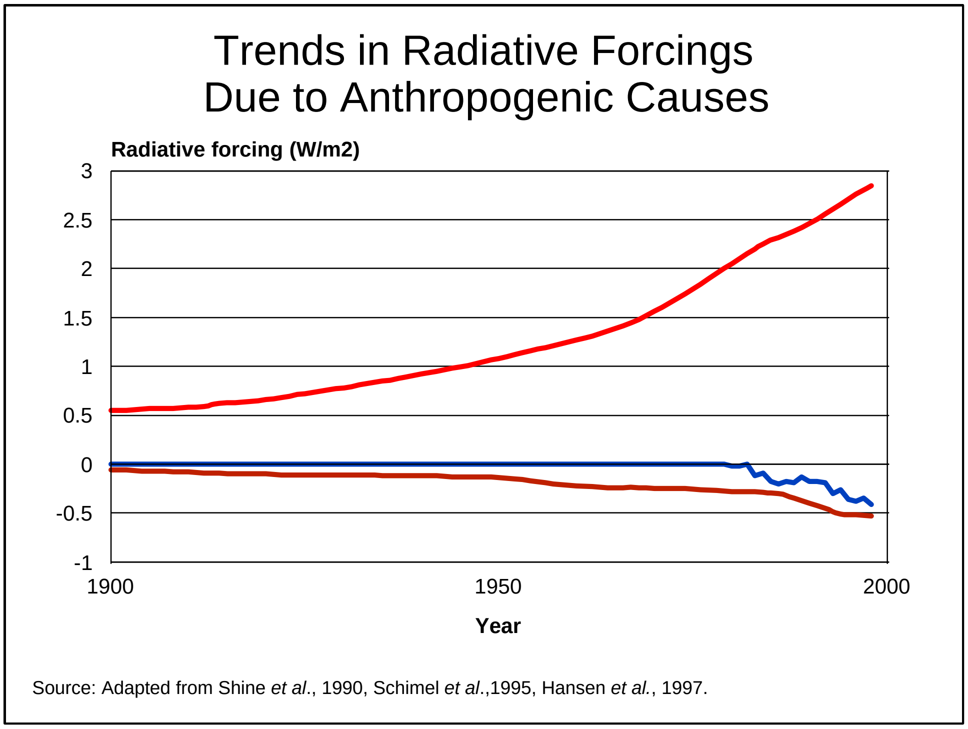
The error bars indicate the level of confidence in the estimates. Changes in well mixed greenhouse gases have had the largest influence on the energy flux, and hence on climate. Those changes are also estimated with greatest confidence.

Effects of increased tropospheric ozone and solar forcing may have added another 25% or so to that of the well mixed greenhouse gases, although the magnitude of these effects remain uncertain.

Aerosols have in general caused direct cooling effects that may have masked up to 30% of the influence of the well mixed greenhouse gases, although the effect varies by region and aerosol type.

Indirect aerosol effects remain highly uncertain but could be large.

Source: J.T. Houghton *et al.* 1996. Climate Change 1995: The Science of Climate Change. Cambridge, Cambridge University Press.



The effects of human activity on the climate system varies with time and space and the type of forcing.

The radiative effects of changing concentrations of well mixed greenhouse gaes on the net radiative energy entering the lower atmosphere, and hence on the climate system, has increased steadily during the past century.

By comparison, the cooling effect of increasing concentrations of sulphate and biomass aerosols, which has potentially masked the climatic effects of increasing greenhouse gases, increased quite rapidly in industrialized areas in the middle of this century, then stabilized somewhat due to air pollution controls. In recent decades, emissions have increased significantly in southeast Asia and other industrializing regions.

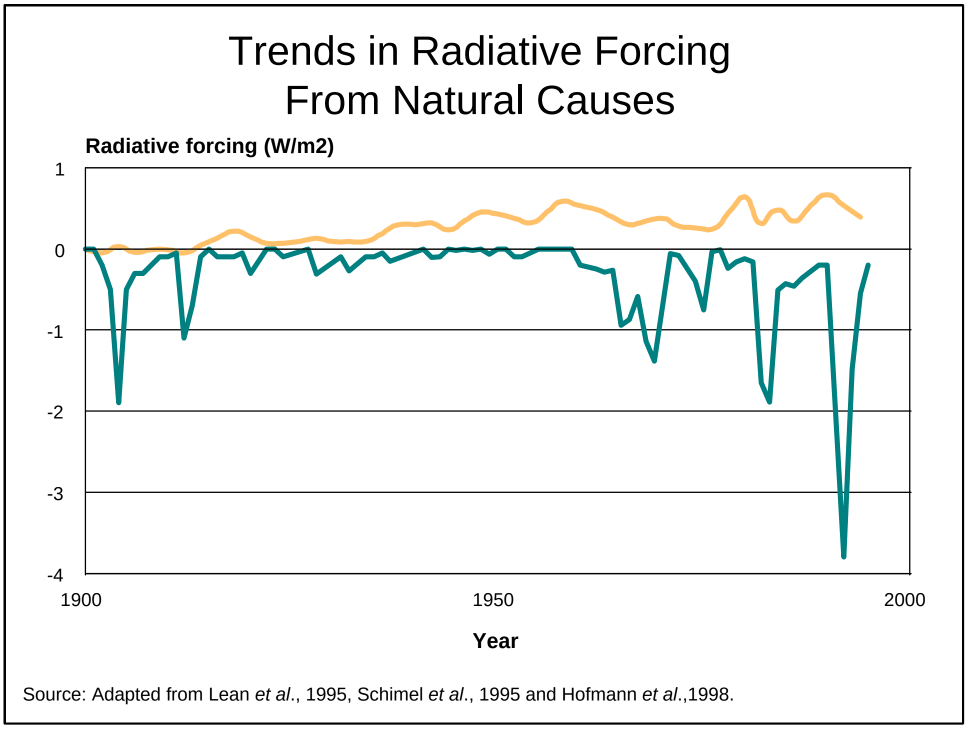
Stratospheric ozone depletion is believed to have caused a global cooling effect since 1980.

Source: Adapted from:

Shine, K.P., R.G. Derwent, D.J. Weubbles and J.J. Morcrette. 1990. Radiative Forcing of Climate. In *Climate Change: The IPCC Scientific Assessment.* J.T. Houghton, G.J. Jenkings and J. J. Ephraums, eds. Cambridge University Press, Cambridge;

Schimel , D.S. 1995. Terrestrial and biogeochemical cycles: global estimates with remote sensing. *Remote Sensing of the Environment* 51(1): 49-56;

Hansen, J.M., M. Sat, R. Ruedy et al. 1997. Forcing and chaos in interannual to decadal climate change. *Journal of Geophysical Research* 102(D22):25,679-25,720.



The two primary natural causes of climate change and variations over the past century are changes in the sun's energy and the emission of sulphate aerosols into the stratosphere from volcanic eruptions.

The climatic effects of changes in the energy from the sun appears to have increased during the past century, but have varied considerably.

The effects fo volcanic eruptions are short-lived (up to 5 years after eruption) but can cause episodes of significant global cooling.

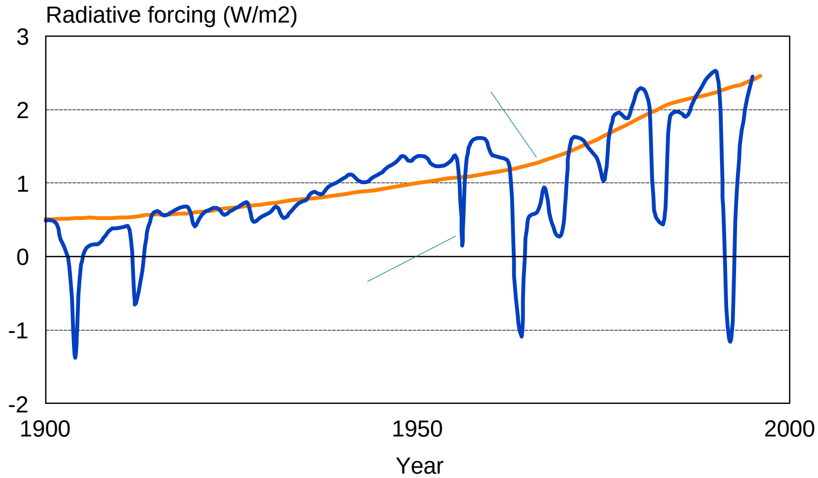
Source: Adapted from:

Lean, J., J. Beer & R. Bradley. 1995. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Reseach Letters* 22: 3195-3198;

Schimel , D.S. 1995. Terrestrial and biogeochemical cycles: global estimates with remote sensing. *Remote Sensing of the Environment* 51(1): 49-56;

Hofmann et al. 1998. An analysis of 25 years of balloonborne aerosol data in search of a signature of the subsonic commercial aircraft fleet. *Geophysical Research Letters* 25:2433-2436.

Comparison of Trends in Radiative Forcings



Source: Adapted from Shine *et al*., 1990, Schimel *et al*.,1995, Hansen *et al.*, 1997, Lean et al., 1995 and Hofmann et al.,1998.

When estimates of the radiative effects of all the various human and natural causes of climate change are added together, their net effect is, on average, very similar to that of increasing greenhouse gases and sulphate aerosols from human activities only.

Source: Adapted from:

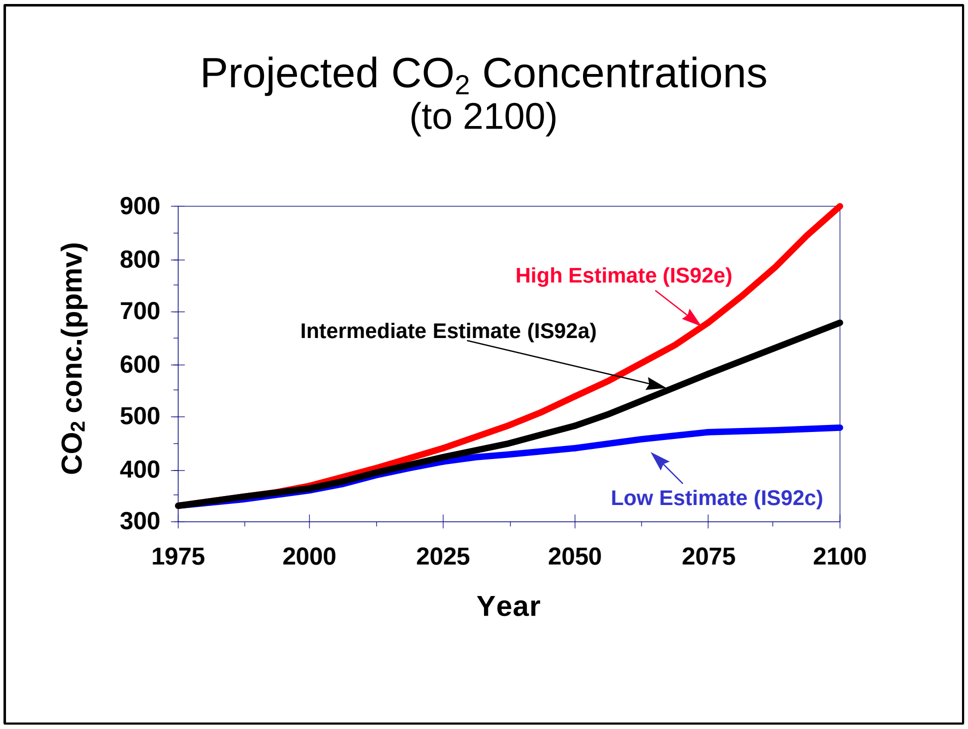
Shine, K.P., R.G. Derwent, D.J. Weubbles and J.J. Morcrette. 1990. Radiative Forcing of Climate. In *Climate Change: The IPCC Scientific Assessment.* J.T. Houghton, G.J. Jenkings and J. J. Ephraums, eds. Cambridge University Press, Cambridge;

Schimel , D.S. 1995. Terrestrial and biogeochemical cycles: global estimates with remote sensing. *Remote Sensing of the Environment* 51(1): 49-56;

Hansen, J.M., M. Sat, R. Ruedy et al. 1997. Forcing and chaos in interannual to decadal climate change. *Journal of Geophysical Research* 102(D22):25,679-25,720;

Lean, J., J. Beer & R. Bradley. 1995. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Reseach Letters* 22: 3195-3198.

Hofmann et al. 1998. An analysis of 25 years of balloonborne aerosol data in search of a signature of the subsonic commercial aircraft fleet. *Geophysical Research Letters* 25:2433-2436.



The IPCC has developed a range of plausible scenarios for future CO_2 emissions from fossil fuel combustion, and hence future concentrations of atmospheric CO_2.

The highest of these scenarios (IS92e) assumes high economic growth and an increased use of coal globally. It suggests concentrations could reach 950 ppmv by 2100 AD (more than 3 times pre-industrial levels).

The lowest of these scenarios (IS92c) assumes a very low growth in global population and intensive conversion to renewable energies. It projects a concentration of about 500 ppmv (about 75% above pre-industrial) by 2100. Stabilizing global emissions at 1990 levels would provide a similar scenario.

The intermediate estimate for emissions (IS92a), often used as the IPCC reference scenario, projects concentrations of about 700 ppmv by 2100 AD (more than 2 time the pre-industrial level).

The Science of Climate Change

Part 2: Temperature Trends

Updated April 2001

Environment Canada Environnement Canada

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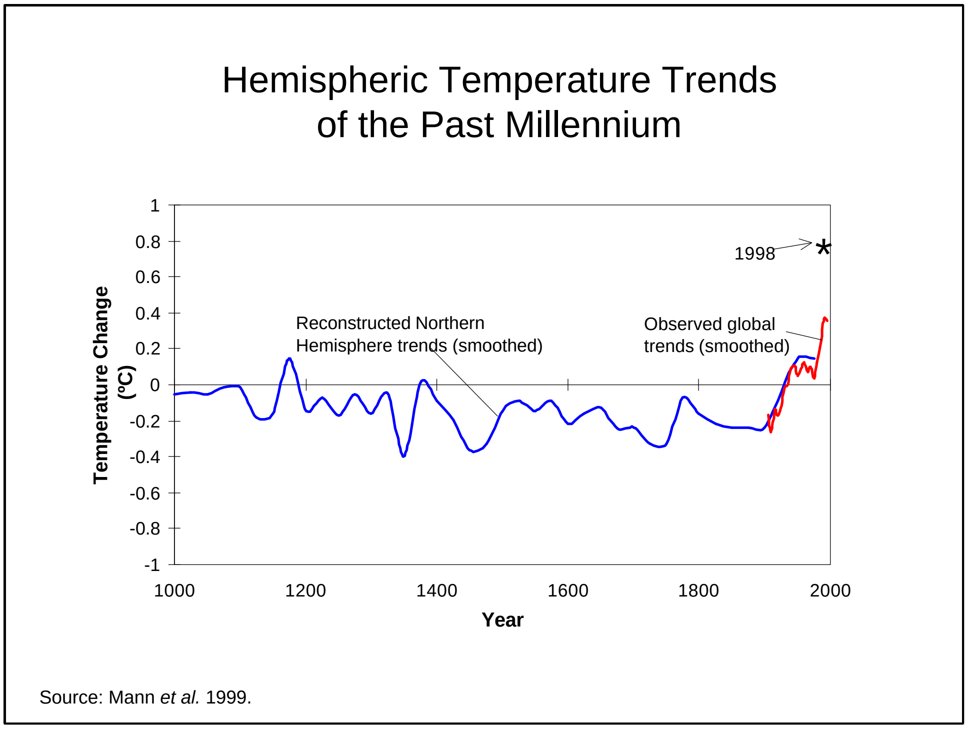


Reconstructed temperature trends from tree rings and ice cores by a team of US scientisits suggest that the latter 20th Century is anomalous in the context of at least the past millennium.

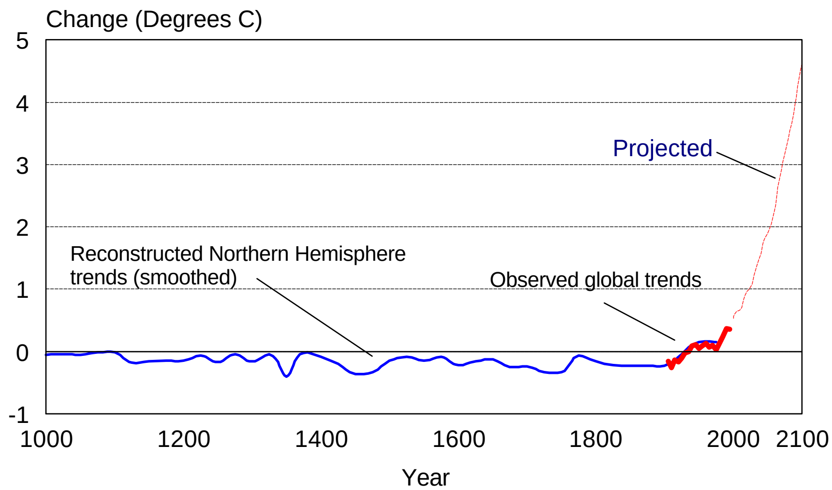
The 1980s and 1990s were the warmest decades and 1998 the warmest year, at moderately high levels of confidence.

Two other independent efforts to reconstruct the global climate of the past millennium show similar results.

These studies indicate that the often-cited Medieval Warm Period was a regional, but not hemispheric phenomena.

Source: Mann, M.E., R.S. Bradley & M.K. Hughes. 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitation. *Geophysical Research Letters* 26:759-762.

TEMPERATURE TRENDS AND PROJECTIONS (1000 to 2100 AD)



Source: Mann *et al*. 1999; NOAA; Boer *et al*

•The Mann *et al*. data is the smoothed curve presented in their paper,

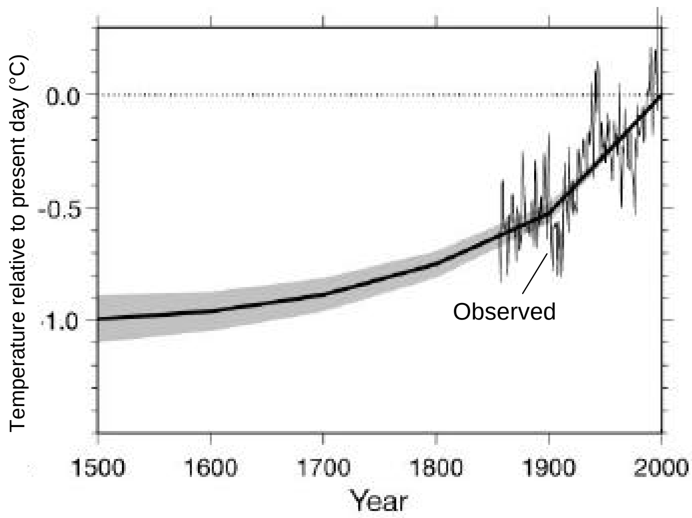
Mann, M.E., R.S. Bradley & M.K. Hughes. 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitation. *Geophysical Research Letters* 26:759-762.

•The future projections are those by the Canadian coupled climate model CGCMI usinng a 1%/year increase in CO2 concentrations

Source: Boer, G. J., Flato, G. M., and Ramsden, D.2000. A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century. Climate Dynamics 16(6): 427-450.

•Results suggest projected temperature change within the next century will be an order of magnitude greater than natural variability of the past millennium

Global ground surface temperature change, 1500-2000



Source: Huang, Pollack, Shen. 2000.

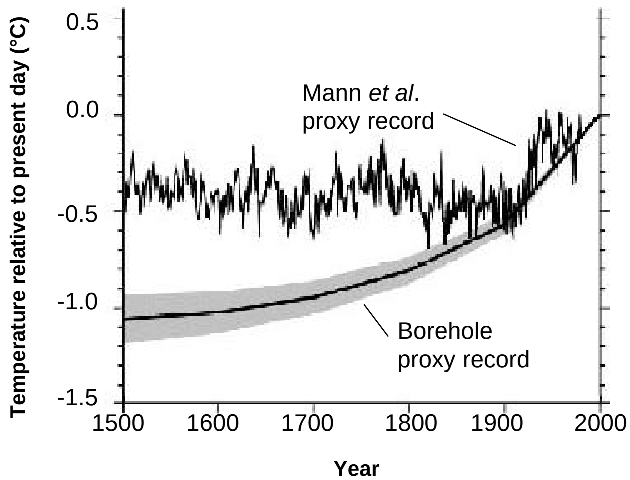
Investigators used over 600 borehole records collected from all continents except Antarctica to reconstruct temperature trends for global land areas over the past 500 years.

Borehole records do not detect year to year climate variability but are considered to be a good indicator of long term climate trends.

The results for the last 150 years agree with instrumental data, and indicate that 20th century temperatures are without precedence during the 500 year period.

Huang, S., H.N. Pollack, P.-Y. Shen. 2000. Temperature Trends over the past five centuries reconstructed from borehole temperatures. Nature 403: 756-758.

Northern Hemisphere Temperature Reconstructions

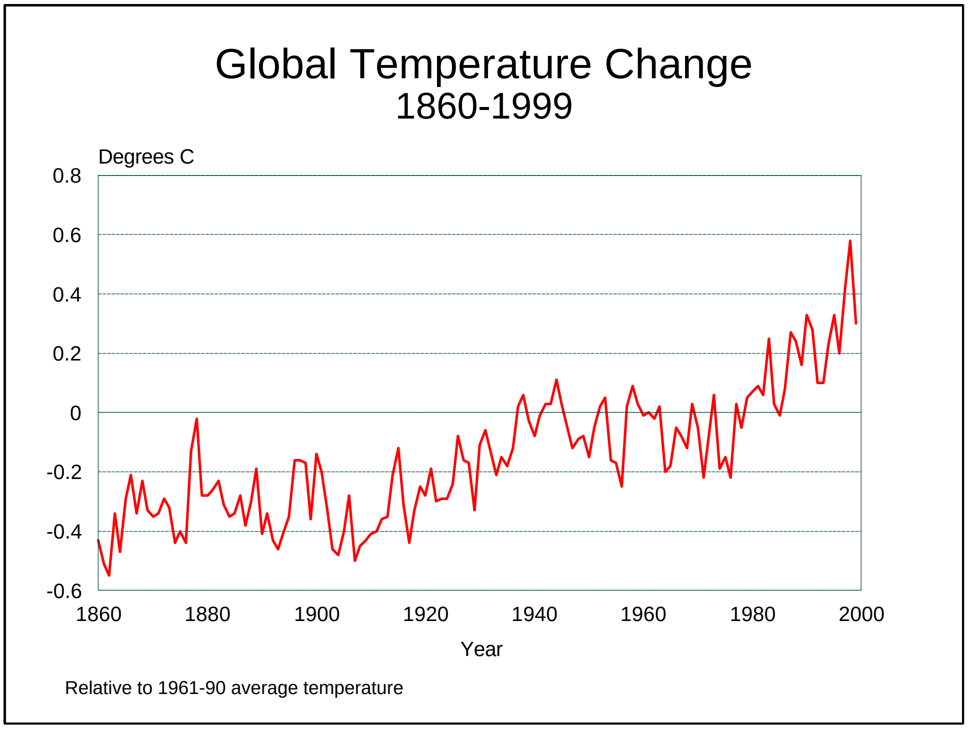


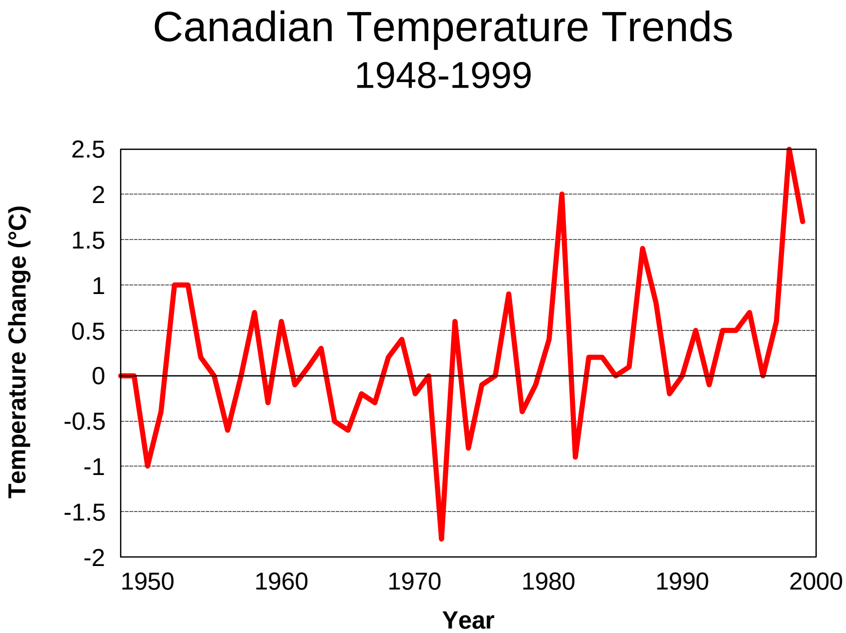
Source: Huang, Pollack, Shen. 2000.

Two independent efforts to reconstruct the global climate of the last 500 years show that temperatures of the 20th Century are without precedence.

The borehole proxy record (ground-based surface temperatures) suggest net warming over the past 500 years to be as much as 1°C, higher than other studies such as the Mann *et al*. ice core proxy record show.

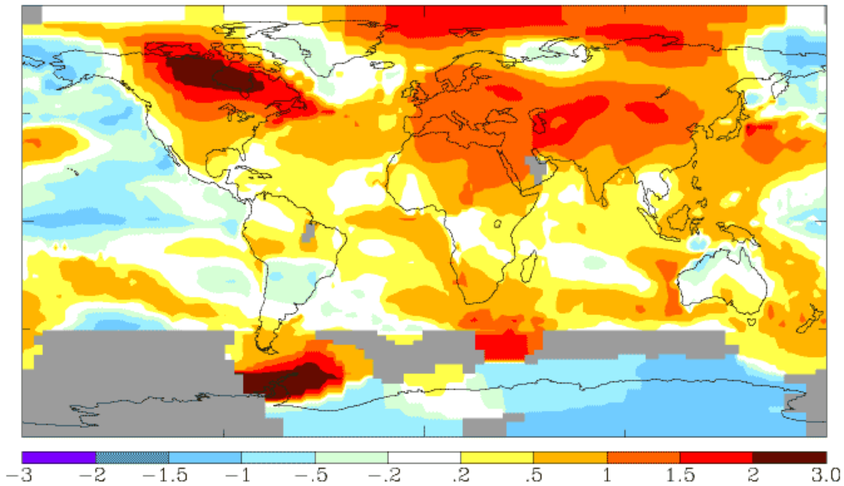
Huang, S., H.N. Pollack, P.-Y. Shen. 2000. Temperature Trends over the past five centuries reconstructed from borehole temperatures. Nature 403: 756-758.


Global Temperature Change
1860-1999
Degrees C
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1860
1880
1900
1920
1940
1960
1980
2000
Year
Relative to 1961-90 average temperature



Source: Meteorological Service of Canada, Environment Canada.

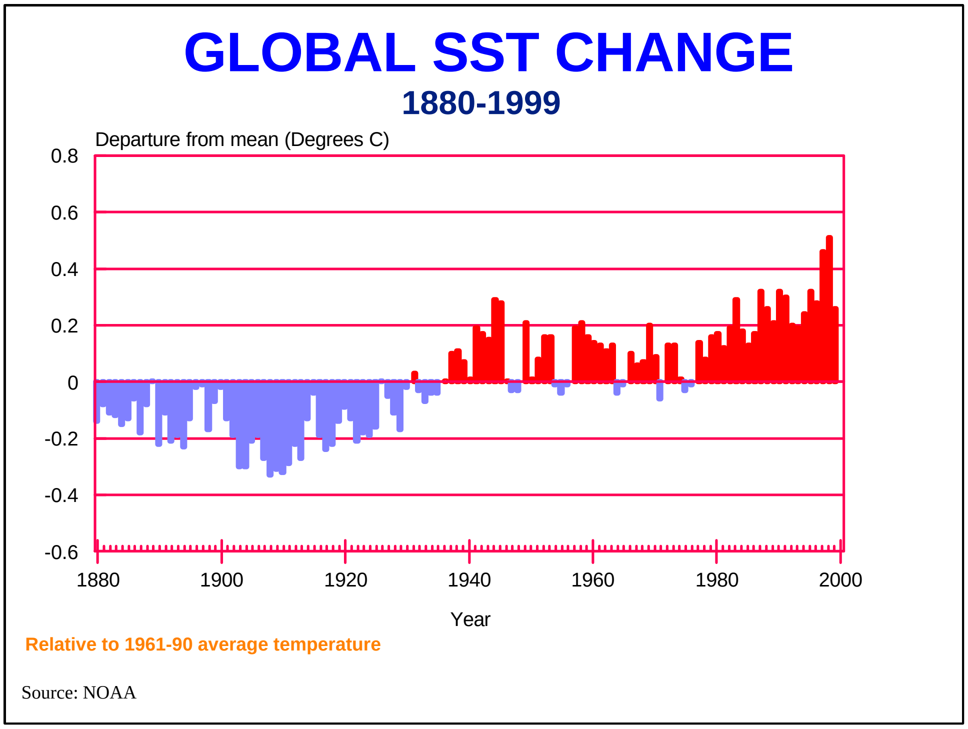
1999 Annual Temperature Anomaly



Source: NOAA.

Canada Reports Greatest Warming Globally for 1999

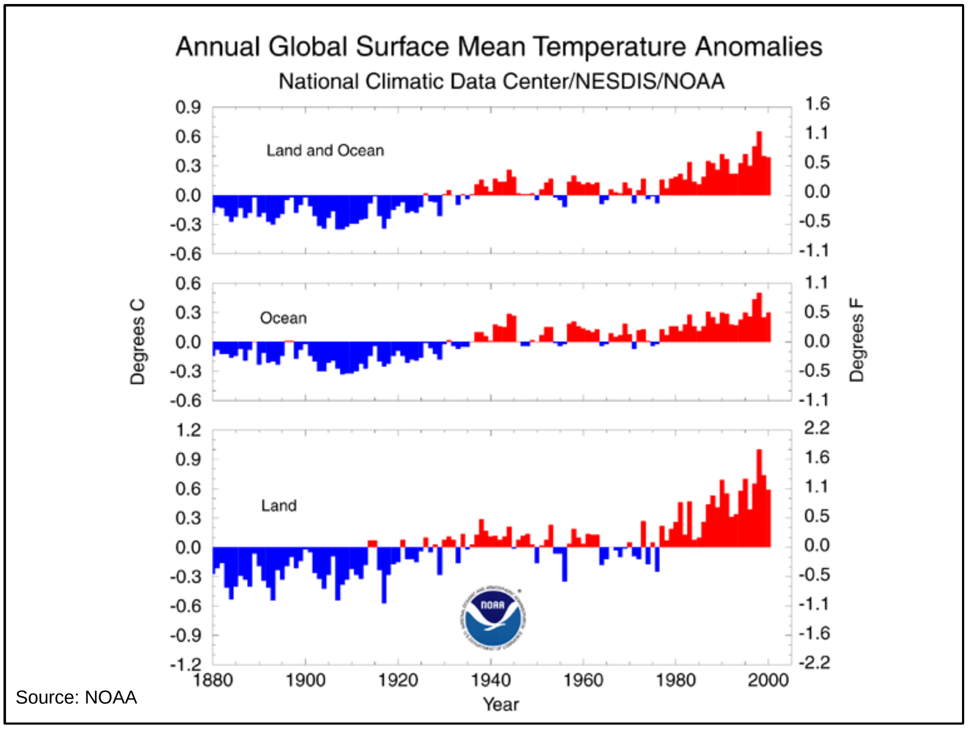
Again in 1999, Canada had the greatest magnitude warm anomaly in the world. This result provides further evidence of the importance of support for climate research in Canada.



•Source: http://www.ncdc.noaa.gov/ol/climate/research/monitoring.html

•Variability appears to be a composite of year to year fluctuations (often linked to ENSO behavior), multi-decadal variability, and a longer term residual trend

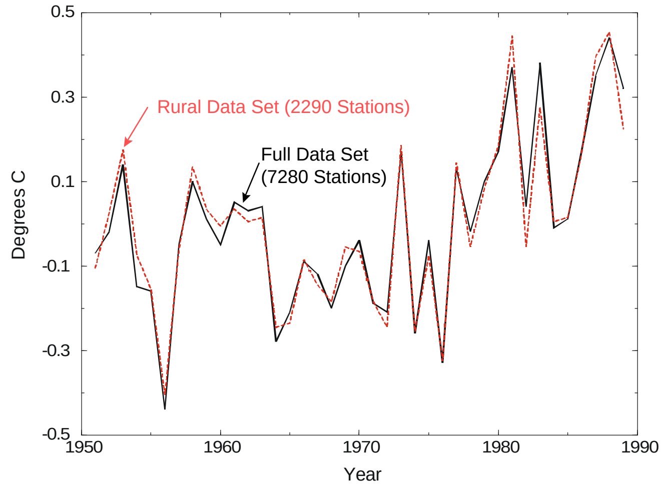
•Temperatures during the 1997-98 ENSO event appear to be unprecdented in the record.



As can be expected, variability in land temperatures shows a pattern very similar to that for oceans, but amplified.

http://www.ncdc.noaa.gov/ol/climate/research/2000/ann/ann.html

Influence of Urbanization on Global Analysis of Temperature Trends



Source: Peterson *et al*. 1999.

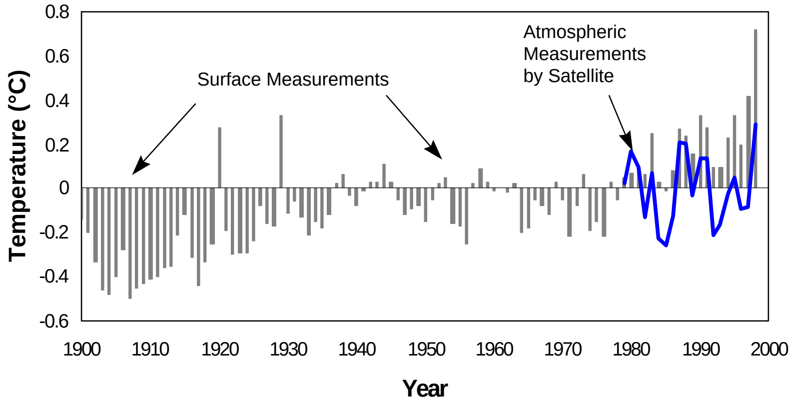
Separating the global rural temperature time series (data from 2200 rural stations) from in situ stations (full data set of 7280 stations) show very little difference in trends.

This confirms that the global data set used for estimating global temperature trends is not significantly impacted by urban warming (heat island effect).

Source: Peterson, L. C., Haug, G. H., Hughen, K. A., and Rohl, U. 2000. **Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial**. Science 290(5498): 1947-1951.

Global Temperature Trends

Surface vs. Satellite Measurements



Source: NOAA/NASA.

Recent studies of temperature trends in the lower atmosphere using satellite data suggest little change in temperature since 1979.

This may indicate that the lower atmosphere is not warming as rapidly as surface temperatures.

However, as suggested by comparison with variable trends in surface data since 1900, the satellite record is still too short to be useful for reliable trend analysis.

Some scientists also caution that the satellite data, which is indirectly compiled from measurements from a number of satellite systems, may include significant errors.

The Science of Climate Change

Part 3: Model Results

Updated April 2001

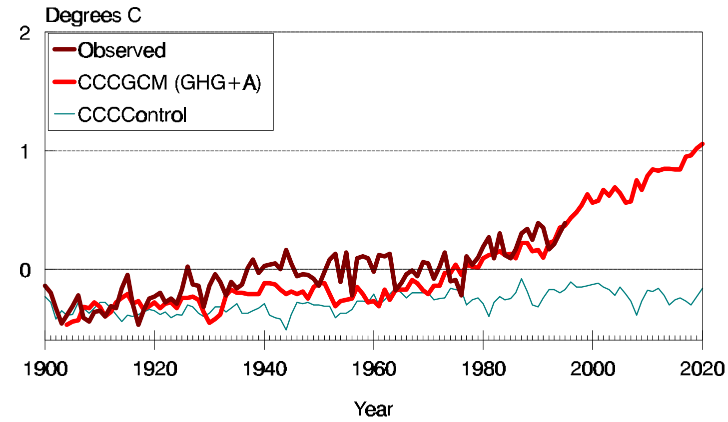
Environment Canada Environnement Canada

Canada

Projected Model Results

Recent Results from the Canadian Centre for Climate Modelling and Analysis Coupled GCM (CGCM1)

Observed and Modelled
Global Temperature Change



Departures from 1951-80 average

Source: Meteorological Service of Canada, Environment Canada.

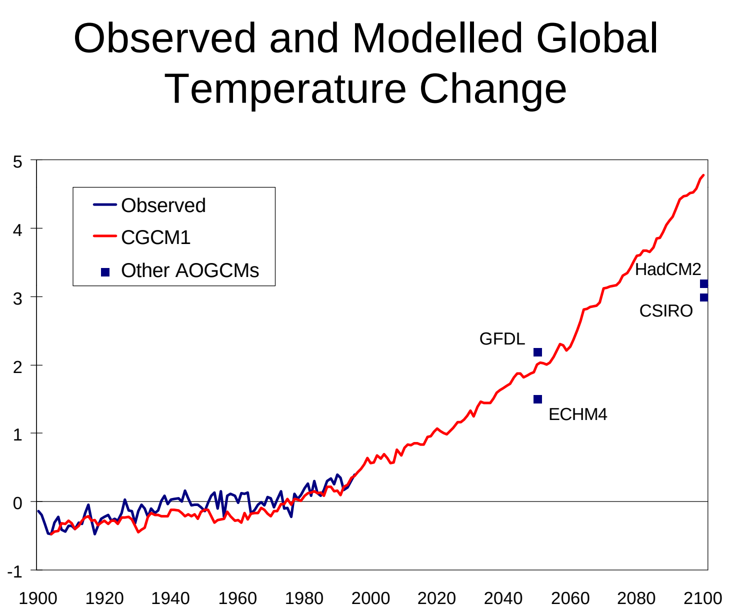
Simulations of past climates with the Canadian coupled climate model, using changes in both greenhouse gases and aerosol concentrations, on average approximate observed globallly averaged surface temperature trends quite well.

Significant short term differences may be related to variations in solar radiation (which were not included in the model simulation) or long-term fluctuations in ocean conditions.

A control run, without changes in greenhouse gases and aerosols, does not show a significant long-term trend.

Other coupled climate models show similar agreements.

Source: Meteorological Service of Canada, Environment Canada.



Source: Meteorological Service of Canada, Environment Canada.

Projections with the Canadian Coupled Climate Model for changes in global average surface temperature to 2100 AD, using changes in greenhouse gases and aerosols similar to the IS92a scenario, suggest increases of about 4ºC over the next century.

This projection is higher than that by most other coupled climate models using similar scenarios.

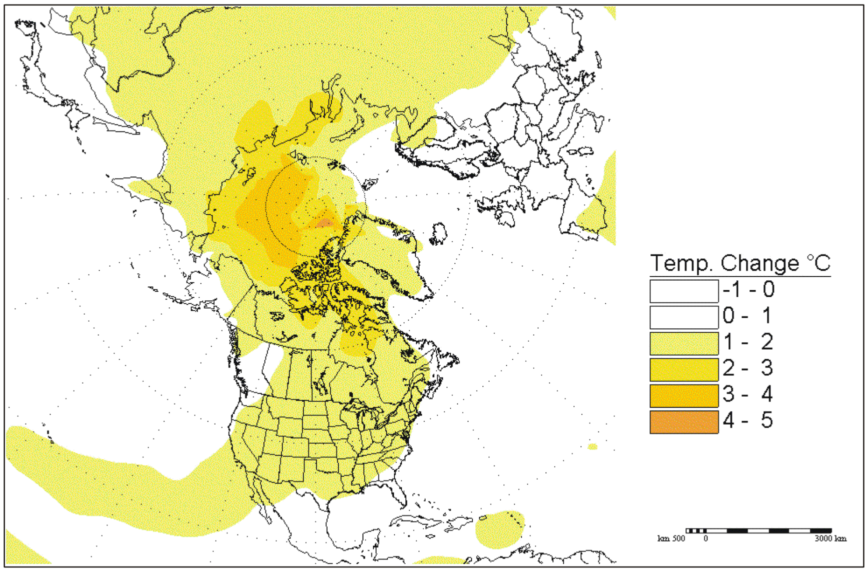
However, the international community considers the Canadian model one of the most credible models now available. Hence, its projections should be taken seriously.

Source: Meteorological Service of Canada, Environment Canada.

eteorological Service of Canada, Environment Canada.

Projected Temperature Change Between 1975-1995 and 2010-2030

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model



Source: Meteorological Service of Canada, Environment Canada.

Like all GCMs, the CGCM1 projects greater warming over land than oceans, at high latitudes than low latitudes.

Warming by about 2020 averages 1-2ºC over most of the Northern Hemisphere land areas and 2-4ºC over Arctic ice covered waters.

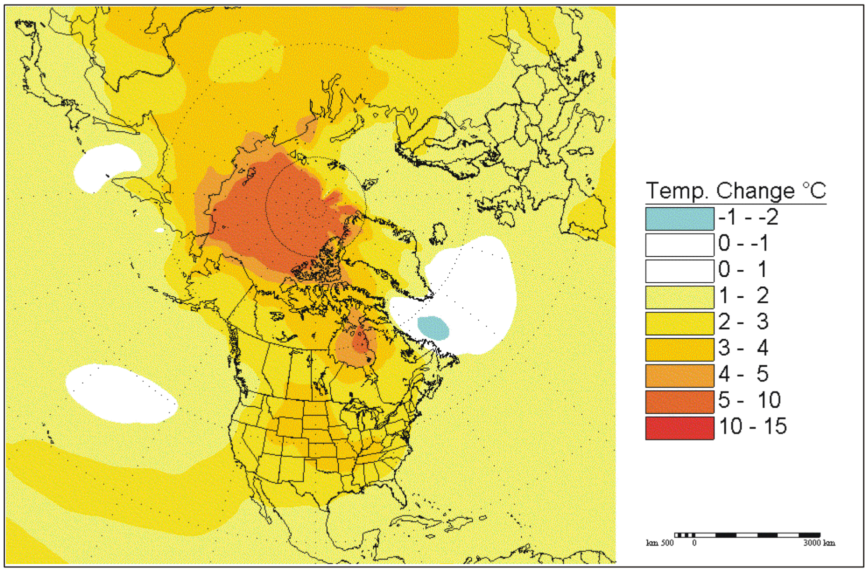
European temperatures are moderated by weaker advection into the region of warm tropical ocean currents.

Snow and ice feedbacks are the primary reasons for enhanced polar warming.

Source: Meteorological Service of Canada, Environment Canada.

Projected Temperature Change Between 1975-1995 and 2040-2060

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model

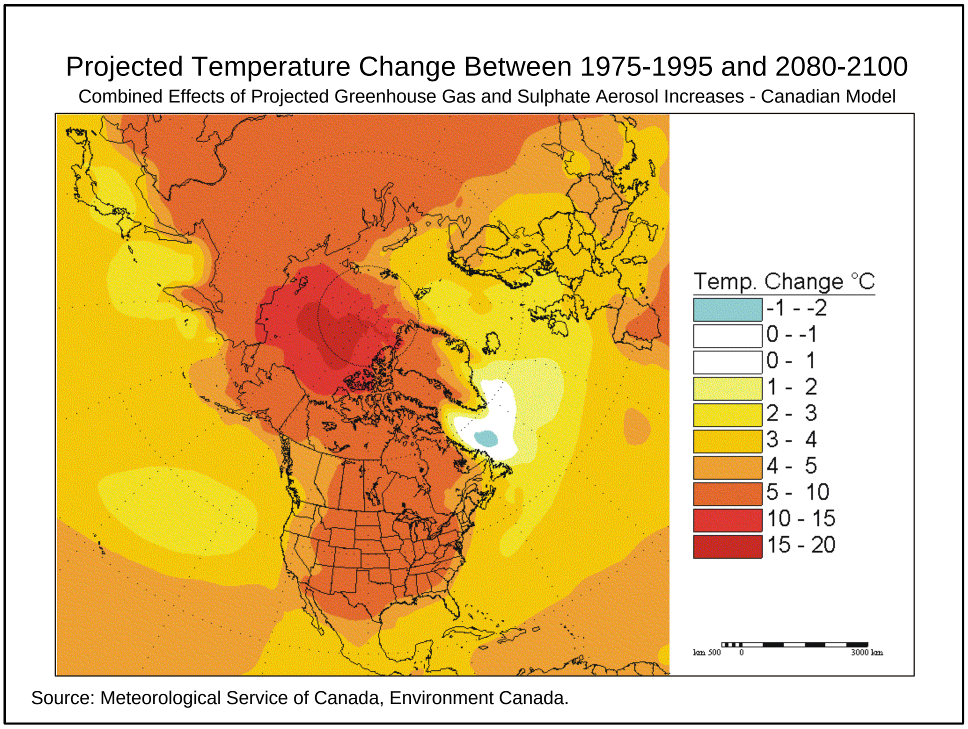


Source: Meteorological Service of Canada, Environment Canada.

By about 2050, warming projected by the CGCM1 experiment for Central North America and Asia exceeds 3ºC, with ice covered waters in the Arctic Oceanwarming by more than 5ºC.

Slower ocean circulation reduced the flow of warm water from the tropics northward and causes an area of cooling off Labrador.

Source: Meteorological Service of Canada, Environment Canada.



By about 2090, most continental regions of the Northern Hemisphere are projected to warm by more than 5ºC, and Arctic waters by 10-20ºC.

The area of cooling off Labrador is still evident.

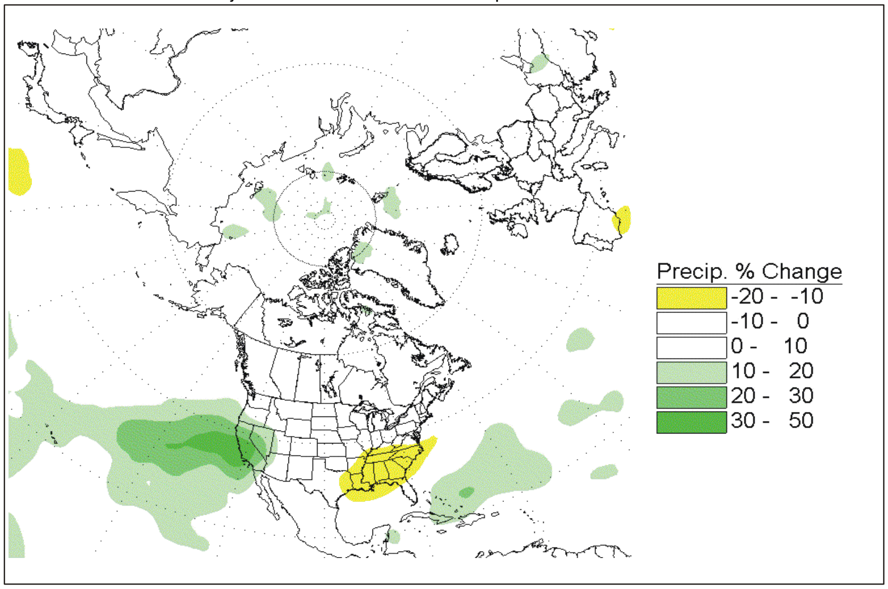
European warming continues to be moderated by a weaker Gulf Stream.

The Arctic ocean is entirely ice free in summer.

Source: Meteorological Service of Canada, Environment Canada.

Projected Precipitation Change Between 1975-1995 and 2010-2030

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model



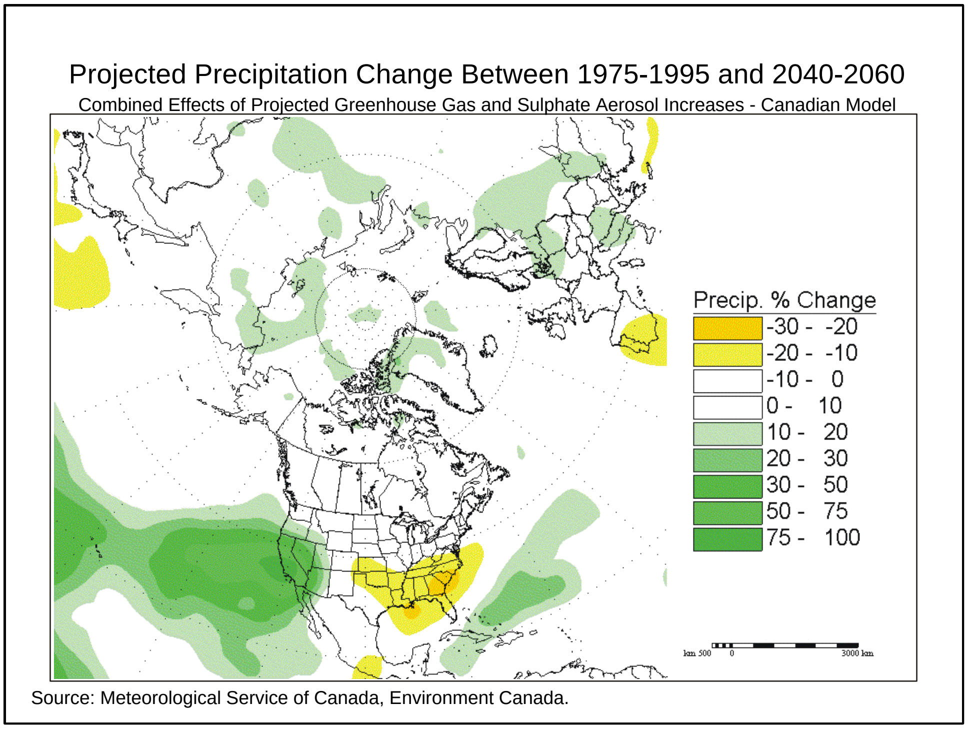
Source: Meteorological Service of Canada, Environment Canada.

By about 2020, precipitation across most of the continents in the Northern Hemisphere are projected to change very little.

Primary exceptions are the southwest U.S. (much wetter) and southeast U.S. (drier).

Concurrent warming causes more evaporation and hence drier conditions in much of the land area.

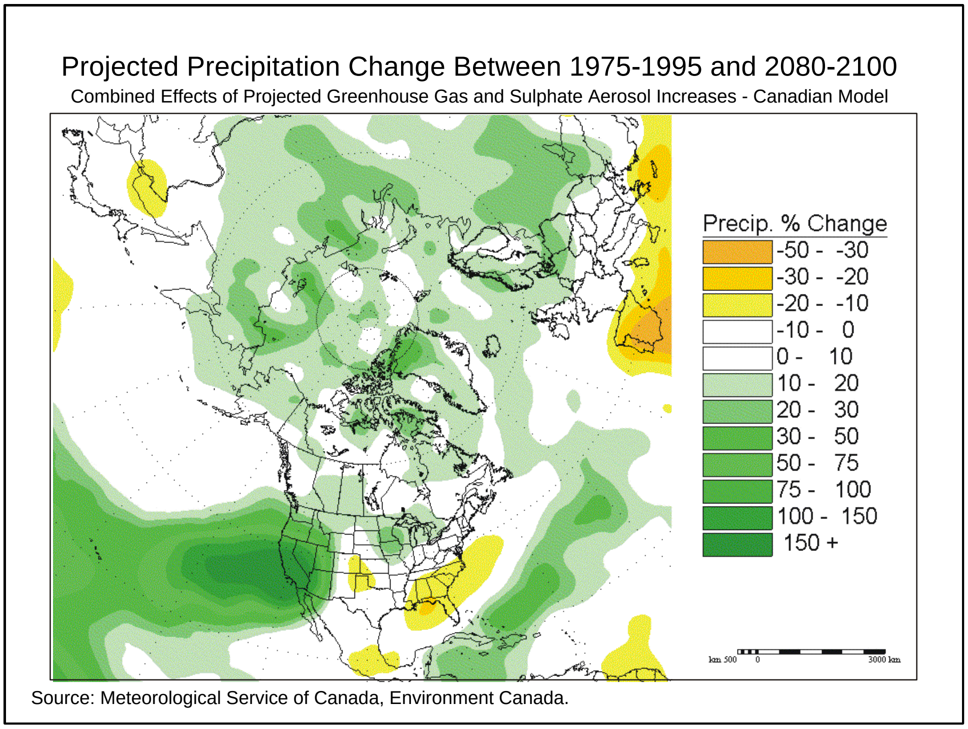
Source: Meteorological Service of Canada, Environment Canada.



By about 2050, precipitation changes across medium to high latitudes remain modest.

Changes in southern U.S. intensify and southern Europe becomes drier.

Source: Meteorological Service of Canada, Environment Canada.



By about 2090, precipitation increases across most land areas, except over the southeastern U.S. and southern Europe.

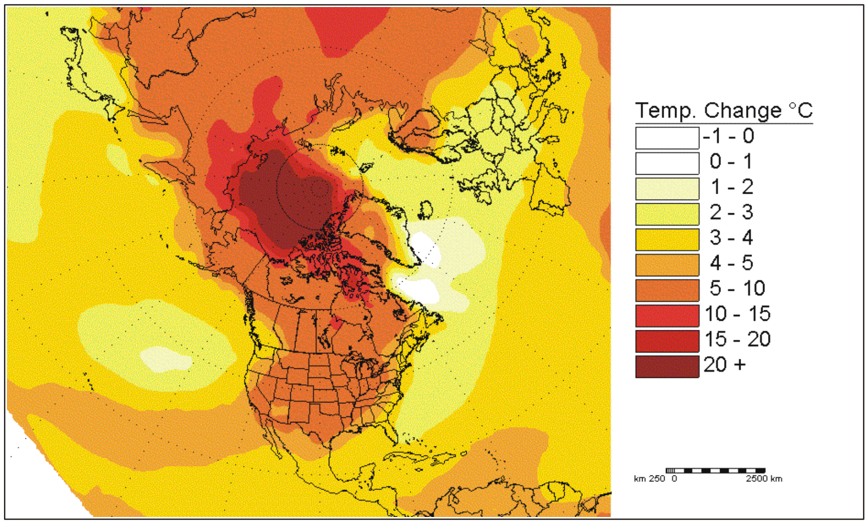
Central North America continues to show little change.

Source: Meteorological Service of Canada, Environment Canada.

Seasonal Temperature and Precipitation
Projections for 2090

Projected Winter Temperature Change Between 1975-1995 and 2080-2100

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model



Source: Meteorological Service of Canada, Environment Canada.

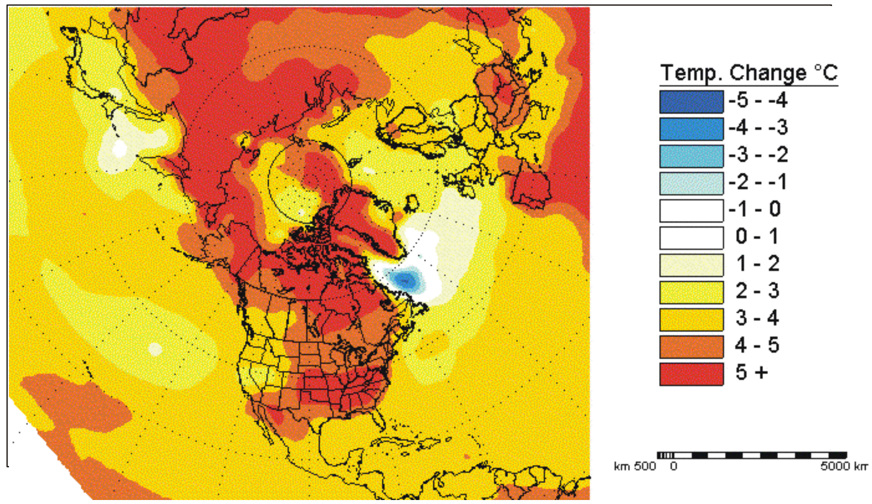
Winter patterns of temperature change is similar to annual projections, but intensified over ice covered waters and central Asia.

Ocean cooling off Labrador is not as intense as in summer.

Source: Meteorological Service of Canada, Environment Canada.

Projected Summer Temperature Change Between 1975-1995 and 2080-2100

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model



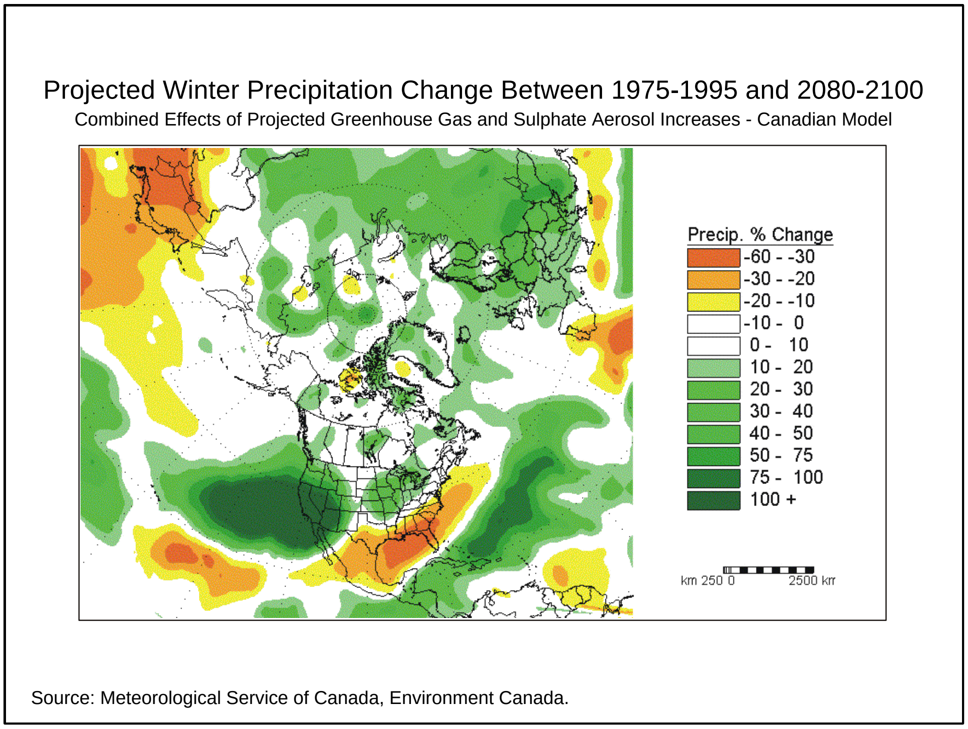
Source: Meteorological Service of Canada, Environment Canada.

By about 2090, summer warming over the central Arctic Ocean is only 1-2ºC and hence much less than the annual average.

Ocean cooling off Labrador is more intense in summer.

Warming over sub-Arctic, central Canada and southeast U.S. is higher than in winter, but somewhat lower along the west side of North America.

Source: Meteorological Service of Canada, Environment Canada.



Much greater winter precipitation increase over the western U.S. than in summer.

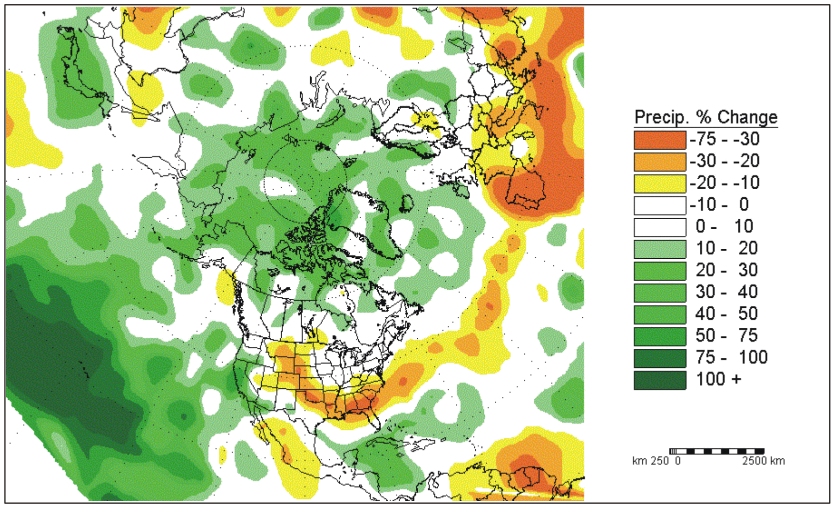
Moderate increase relative to summer for central U.S., the Great Lakes basin, and most of Europe and Asia.

Little change in winter precipitation in the Canadian sub-arctic.

Source: Meteorological Service of Canada, Environment Canada.

Projected Summer Precipitation Change Between 1975-1995 and 2080-2100

Combined Effects of Projected Greenhouse Gas and Sulphate Aerosol Increases - Canadian Model



Source: Meteorological Service of Canada, Environment Canada.

The increase in summer precipitation over western U.S. and central Canada by about 2090 is less than in winter.

Much of the Canadian Prairies, central and southeast U.S. receive less rainfall.

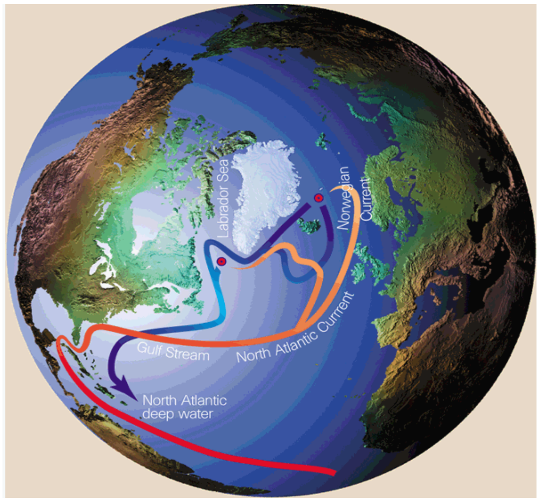
Increased precipitation over Arctic relative to winter.

Significant decrease in summer rainfall over southern Europe.

Source: Meteorological Service of Canada, Environment Canada.

The Thermohaline Circulation System

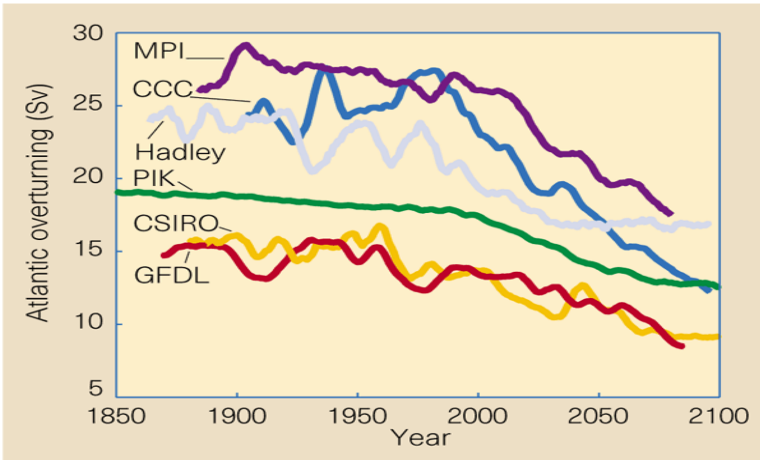
The Thermohaline Circulation System



Source: Rahmstorf 1999.

•Source: S. Rahmstorf. 1999. Shifting seas in the greenhouse? Nature 399: 523-524.

Projected Trends in Atlantic Overturning



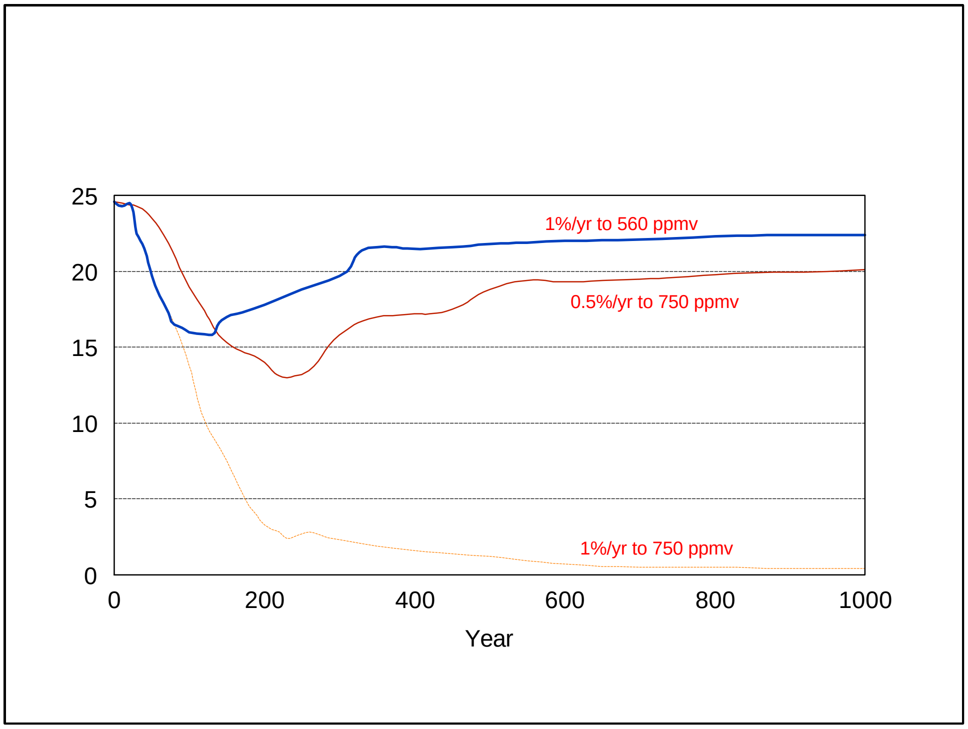
Source: Rahmstorf 1999.

•Source: S. Rahmstorf. 1999. Shifting seas in the greenhouse? Nature 399: 523-524.

•Absoute vaue of the magnitude of Atlantic overturning varies considerably between models, indicative of continuing diffucty in modelling ocean circulation accurately

•However, all models show circulation should begin to decline rapidly within the enxt few decades

•A study by Woods et al in the same issue suggests the decline appears to linked primarily to a possible shutdown of the Labrador deep water formation region, less so with the Greenland Sea deep water formation region



•Adapted from figure 5 in: A. Schmittner & T.F. Stocker. 1999. The Stability of the Thermohaline Circulation in Global Warming Experiments. J.Climate 12(4): 1117-1133.

Scenarios assume increases in atmospheric concentrations of CO_2 at indicated rates to threshold level, that stabilization beyond.

•Thershold levels are achieved in about 75 years for the 560 ppmv scenario, in about 100 years in the fast growth 750 ppmv scenario, and about 200 years for the slow growth scenario

•For the fast gwoth high scenario, the thermohaline circulation is projected to shutdown completely and remain so for the remainder of the millennium

The Science of Climate Change

Part 4: Extreme Events

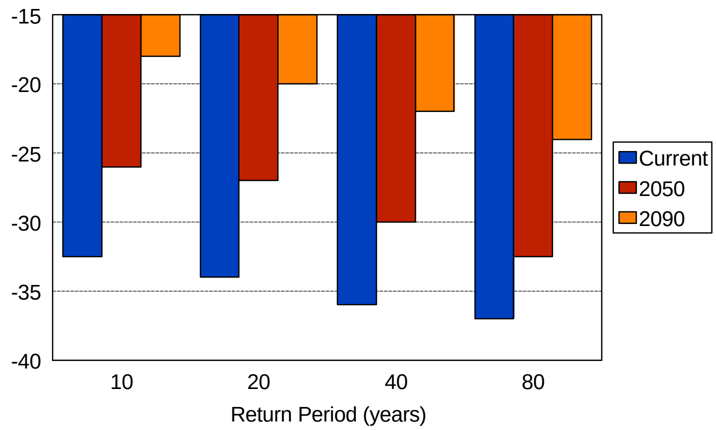
Updated December 2000

Environment Canada Environnement Canada

Canada

Projected Change in Extreme Temperatures (CGCM1)

Extreme Cold Events



Source: Hengeveld 2000

Small changes in average climate conditions can generate significant changes in extremes.

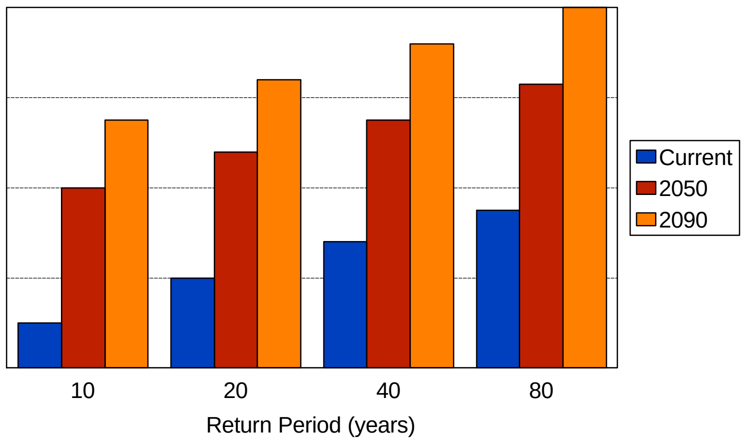
Cold extremes across Canada (as represented by daily minimum temperatures) are expected to become less severe with time. By the 2050s, for example, CGCM1 projects cold extremes that now occur once every 10 years will likely occur less than once every 80 years.

Hengeveld, H.G. 2000. Projections for Canada’s Climate Future. CCD 00-01 Special Ediction.

http://www.msc-smc.ec.gc.ca/apac/climate/ccsci_e.cfm

Projected Change in Extreme Temperatures (CGCM1)

Extreme Warm Events



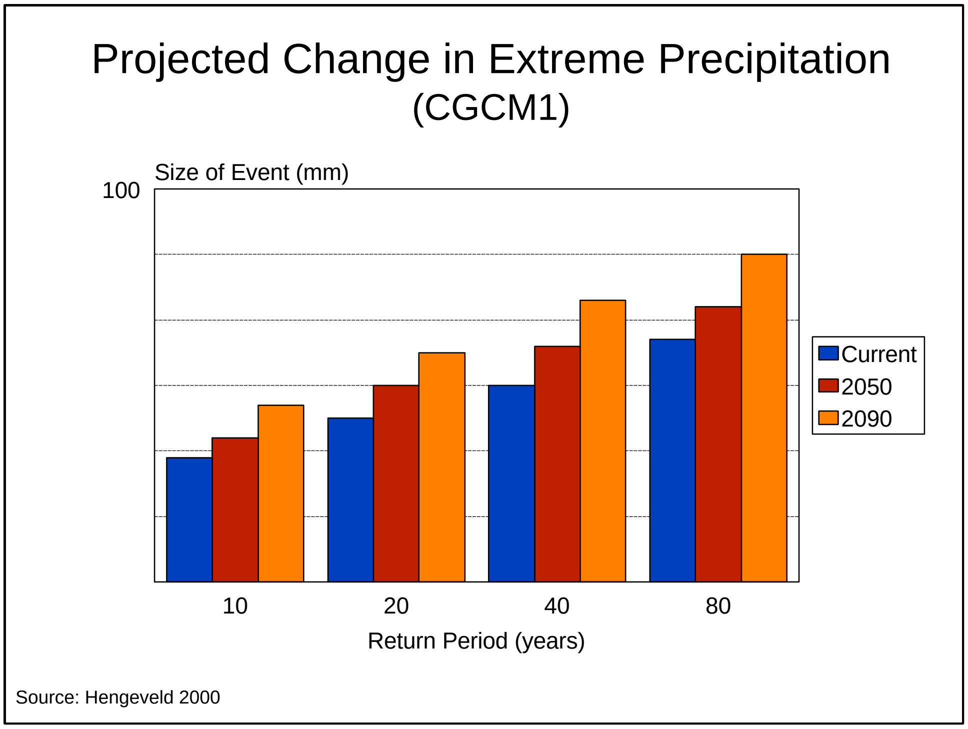
Source: Hengeveld 2000

CGCM1 projections of changes in the magnitude of average Canadian extreme daily maximum temperatures that can be expected to recur once every 10, 20, 40 or 80 years.

This chart shows that an extreme maximum temperature that has an 80-year return period today is likely to occur about once every 10 years by 2050. By the 2090s, the magnitude of these extreme high temperature events are expected to increase, on average, by 4-5°C.

Hengeveld, H.G. 2000. Projections for Canada's Climate Future. CCD 00-01 Special Ediction.

http://www.msc-smc.ec.gc.ca/apac/climate/ccsci_e.cfm



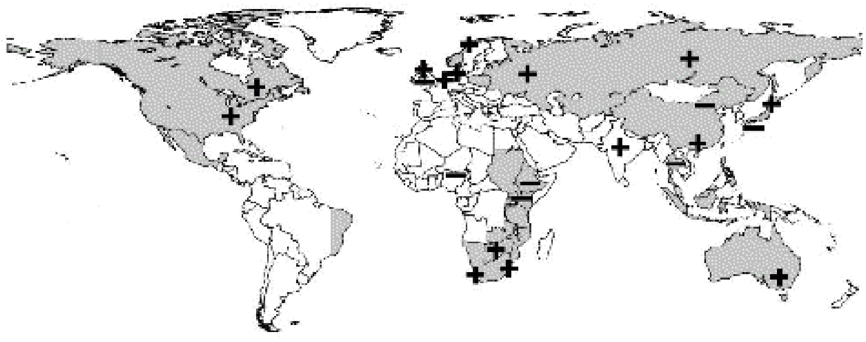
Analyses of the return periods of extreme precipitation events in CGCM1 simulations suggest that rainfall will, on average, become more intense in all regions of the world, although the magnitude of such changes is still rather uncertain.

Over North America, average precipitation rates for the one-in-twenty year extremes are projected to change by up to 10 mm/day by the 2050s. When averaged over all of Canada, today's one-in-forty year extremes could become a decadal occurrence by the 2090s.

Source: Hengeveld, H.G. 2000. Projections for Canada's Climate Future. CCD 00-01 Special Ediction.

http://www.msc-smc.ec.gc.ca/apac/climate/ccsci_e.cfm

Trends in Heavy Precipitation Events

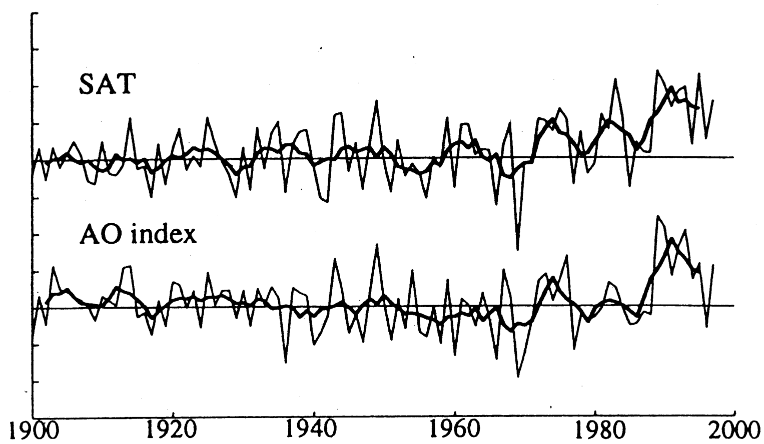


Source: Easterling *et al*. 2000.

Signs (pluses and minuses) indicate regions where significant changes in heavy precipitation have occurred during the past decades. Eastern North America has seen a tendency to more days with heavy 24-hour precipitation totals.

Easterling, DR. et al. 2000. Observed Variability and Trends in Extreme Climate Events: A Brief Review. *BAMS* 81(3): 417-425.

Normalized Trends in NH Temperature and Arctic Oscillation Index



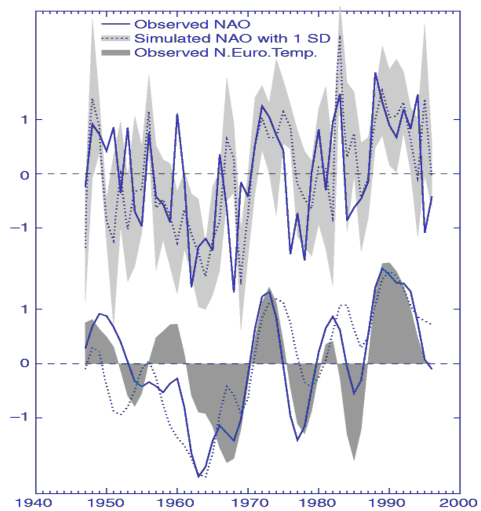
Source: Thompson and Wallace 1998

- The AO index is based on the changes in the leading principal component of the monthly mean sea level pressure field poleward of 20N, between November and April.
- The AO index shows considerable interannual variability and a distinct shift to higher values during the past few decades
- The AO index is well correlated with variability in surface air temperature (SAT) over Eurasia
- This shift has contributed to recent pattern of hemispheric temperature trends, with intense warming over Siberia and over northwestern North America, and cooling over the North Pacific and North Atlantic and eastern Canadian Arctic

Source:Thompson,D.W.J. and J.M. Wallace. 1998. The Arctic Oscillation signature in wintertime geopotential height and temperature fields. Geophysical Research Letters 25: 1297-1300.

North Atlantic Oscillation Index

Winter 1947-97



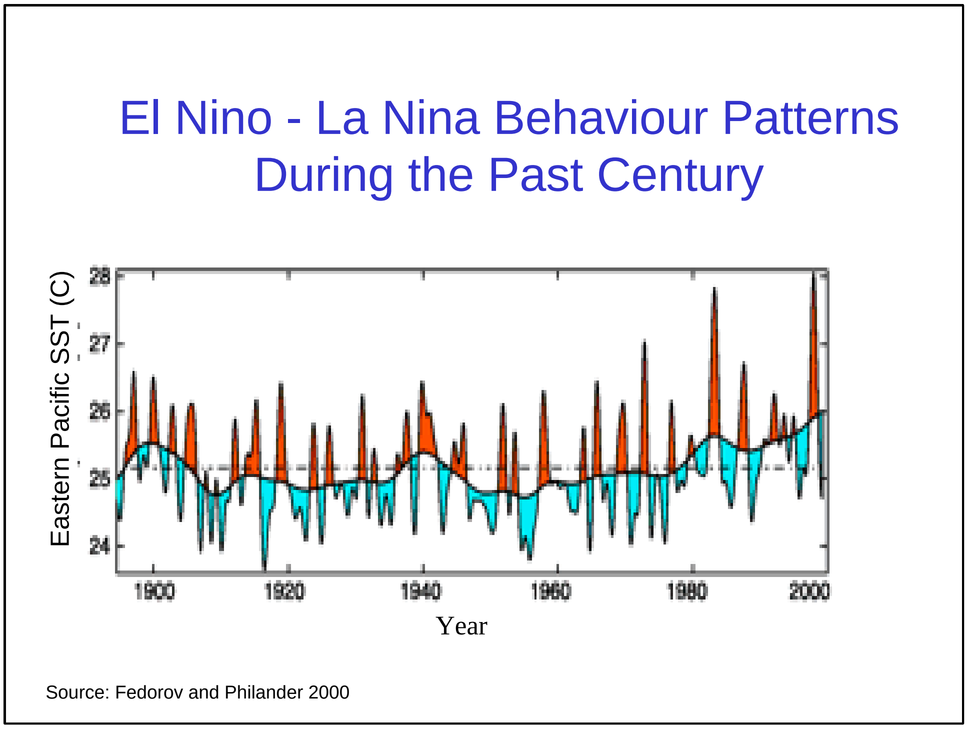
Source: Rodwell *et al.* 1999

•NAO index is based on sea level pressure differences between the Azores and Iceland

•Upper portion compares observed changes in NAO index (solid line) with that simulated by an ensemble of six simulations with a UK global atmosphere model forced with observed sea surface temperatures and ice covers (shaded area).

•The lower graph shows how the interdecadal variability in the NAO index, filtedred to remove variations with frequecies less thatn 6.5 years (solid line), broadly agrees with variability in observed North European temperature(gray area)

Source: Rodwell, M. J., Rowell, D. P., and Folland, C. K. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature* **398**, 320-323 (1999).



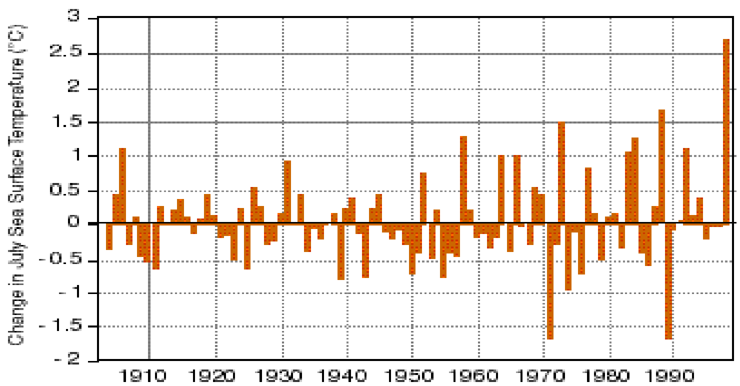
•The figure shows interannual variability in sea surface temperatures in the eastern equatorial Pacific between 5S and 5N, and 80W and 120W, adjusted to remove annual cycle and higher frequency variability

•Theheavy solid line represnts the underlying interdecadal variability, obtained by passing the data through a low pass filter

•The data shows both interdecadal varaibility and a rise in the index in recent decades

Source: Fedorov, A. V. and Philander, S. G.2000. **Is El Nino changing?** Science 288(5473): 1997-2002.

El NINO FREQUENCY AND INTENSITY IN THE 20TH CENTURY



Source: Shugart, personal communication.

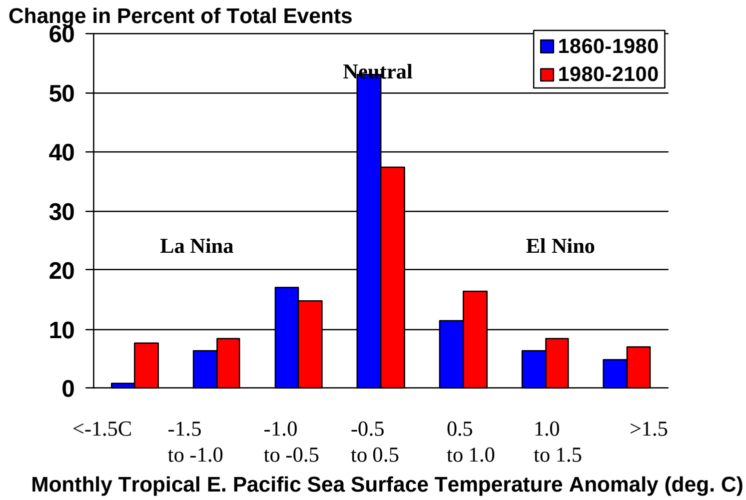
July sea surface temperature values in the eastern tropical Pacific are one indicator of El Nino and La Nina events. Analysis suggests that El Ninos have become more intense and frequent during the past two decades.

It remains uncertain whether these trends are due to long-term natural variability or unprecedented changes in ENSO climates.

Source: Shugart, personal communication in

Francis, D. & H. Hengeveld. 1998. *Extreme Weather and Climate Change*. Environment Canada, Downsview, Ontario.

Projected Changes in El Nino-La Nina Behaviour



Source: Timmerman *et al. 1999*

Climate models suggest that the number of weak El Nino/La Nina events are likely to decrease while the number of stronger events increase.

The changes in projected intensity of La Ninas is much greater than for El Ninos.

Source: Timmerman, A., M. Latif, A. Grotzner, A. and R. Voss. 1999. El Nino frequency in a climate model forced by future greenhouse warming. *Nature* 398: 694-697.

The Science of Climate Change

Part 5: Impacts

Updated April 2001

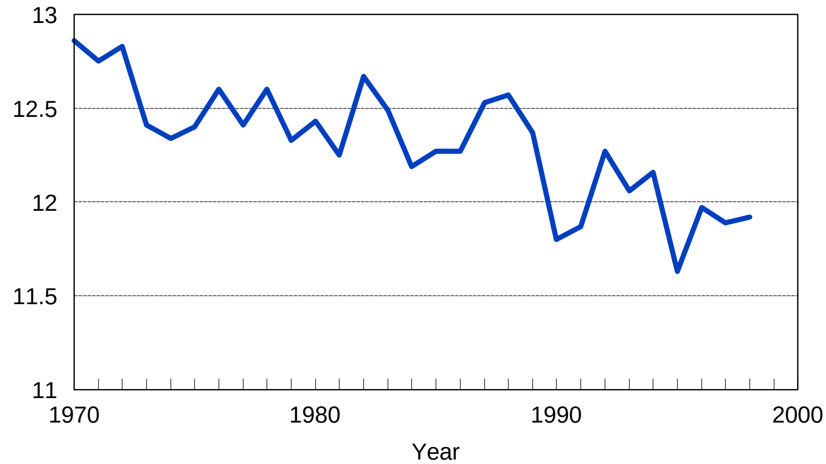
Environment Canada Environnement Canada

Canada

Possible Impacts of Climate Change on Canadians

- Changes over Canada are likely to exceed global averages
- greatest dangers are expected to be due to changed frequency/intensity of extreme weather events
- heat stress, enhanced disease risk and aggravated pollution will directly affect the health of Canadians
- other adverse impacts include reduced lake levels, increased risk of forest fire and disruptive changes in ecosystem boundaries
- Climate change will also provide benefits, such as lower winter heating costs, longer growing season and improved marine transport in ice covered waters.

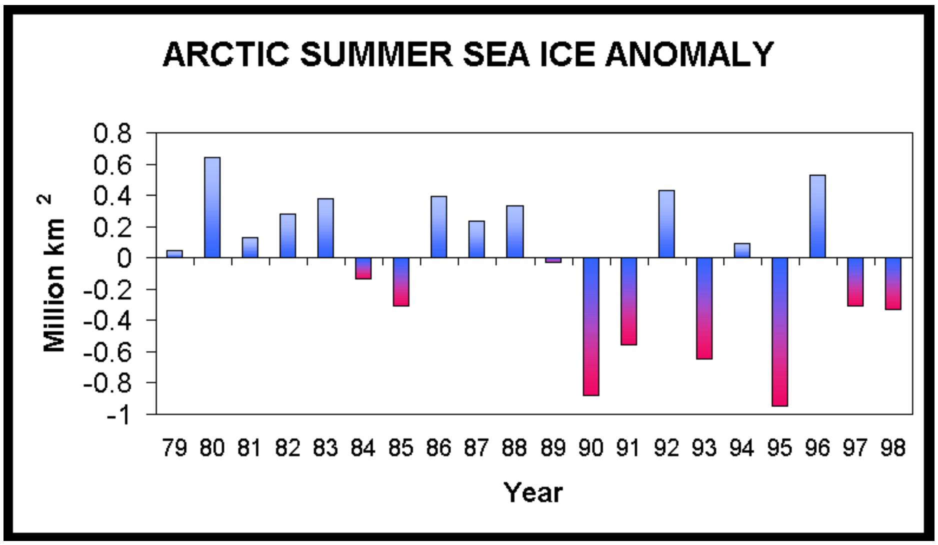
Observed Northern Hemisphere Ice Extent



Vinnikov *et al.* 1999

•Source: Extracted from Figure 1 in Vinnikov, K.Y., A. Robock, R.J. Stouffer *et al.* 1999. Global warming and Northern Hemisphere sea ice extent. *Science* 286: 1934-1937. (although original data comes from Chapman and Walsh)

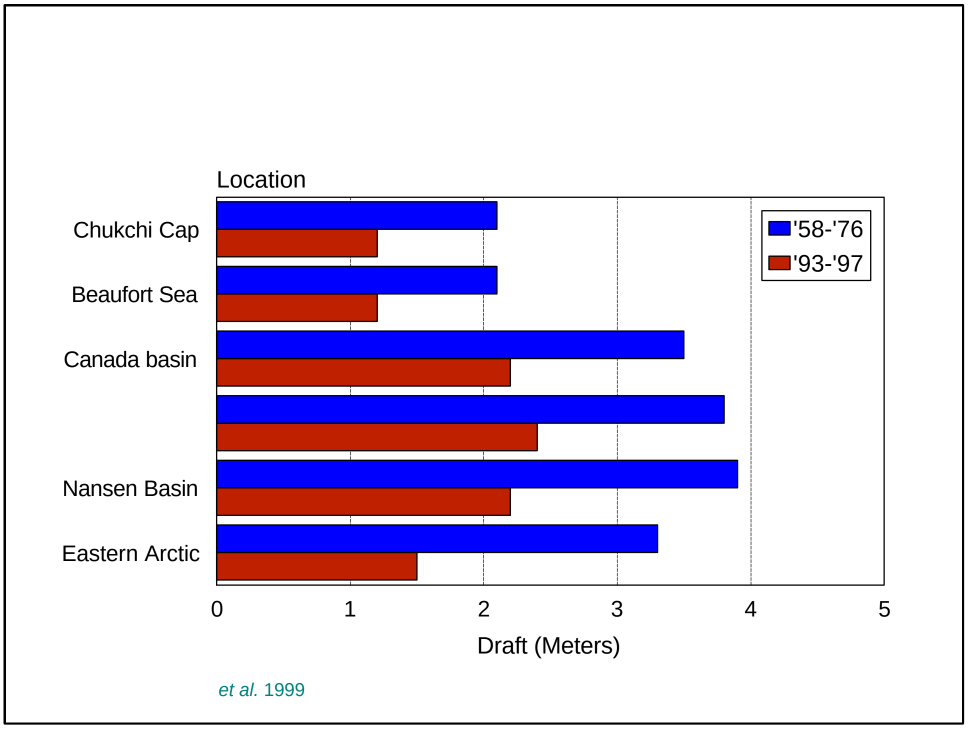
•Authors use model studies to suggest that the observed decline between 1978 and 1998 has a natural probability of occurrence of <2%. Similar trends in a longer record from 1953-98 as a much lower probability of natural occurrence of <0.1%



Source: T. Agnew, MSC.

Summer sea ice cover anomaly over the Arctic Ocean, shows below normal ice cover continued in 1997 and 1998 and that six of the top 10 minimum summer sea ice cover years occurred in the 1990s.

Source: http://www.tor.ec.gc.ca/crysys/tagnew/state/98summer.htm

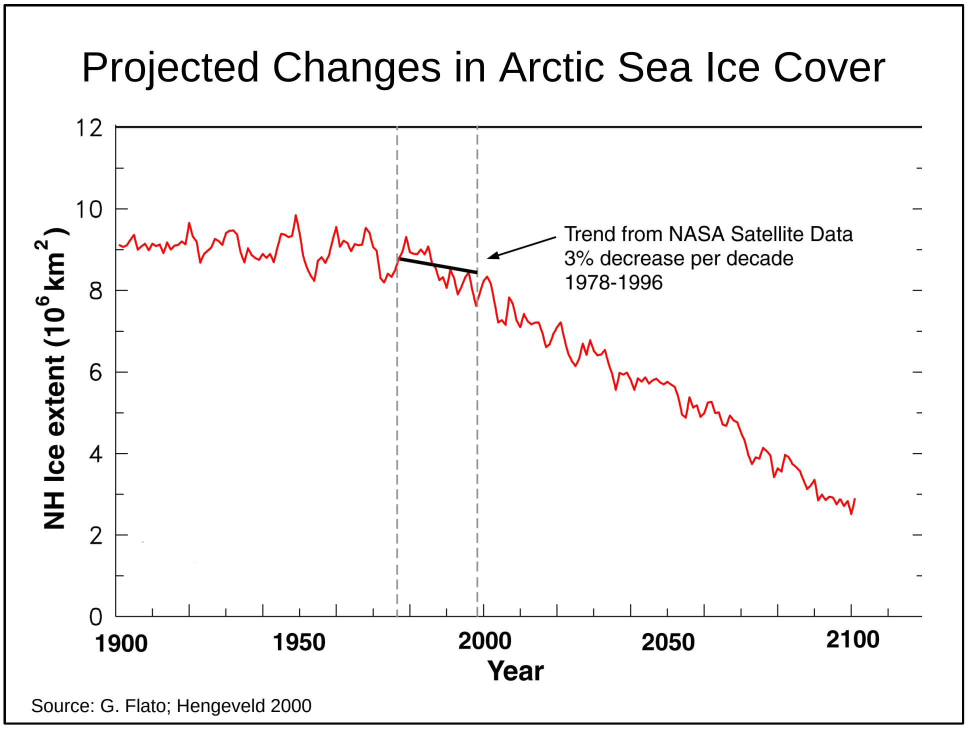


•Data was collected from submarine based measurements taken at the end of melt season

•Thickness has decreased in all areas of the Arctic

•Average decrease is about 42%, with greated reductions in the Eastern Arctic (55%) and least percentage decrease in the Canadian Basin and at the North Pole (37%)

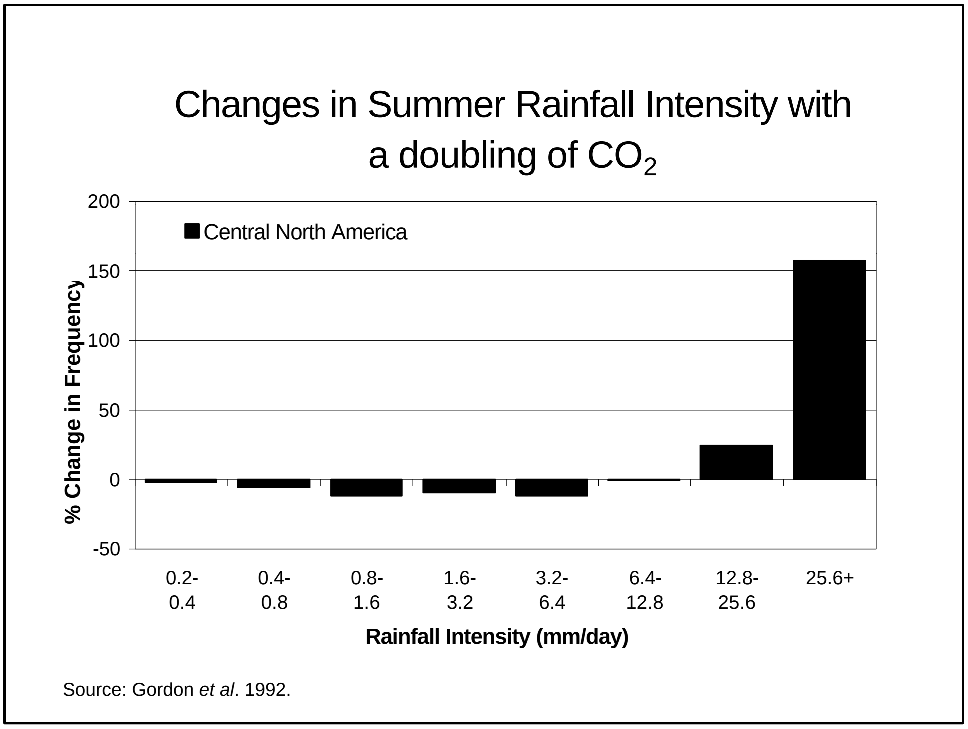
Source: Rothock, D.A., Y. Yu and G.A. Maykut. 1999. Thinning of the Arctic sea-ice cover. GRL 26: 3469-3472.



CGCM1 projects major changes in sea ice coverage in the Northern Hemisphere, with annual mean coverage decreasing by about 40% by 2050 and virtually disappearing by 2100.

Source: Hengeveld, H.G. 2000. Projections for Canada's Climate Future. CCD 00-01 Special Ediction.

http://www.msc-smc.ec.gc.ca/apac/climate/ccsci_e.cfm

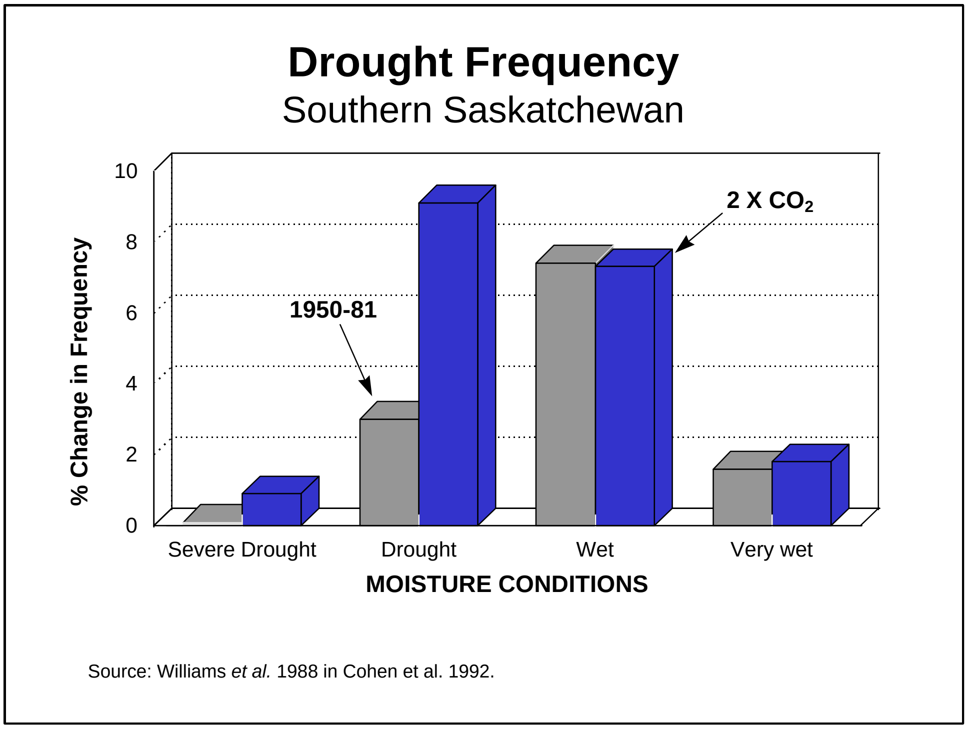


Intense summer rainfall events are projected to become significantly more frequent in the central USA, as in most land areas around the world.

Light rainfall events will become less frequent.

Total number of rain days are expected to decrease.

Source: Gordon, H.B., P.H. Whetton, A.B. Pittock, A.M. Fowler and M.R. Haylock. 1992. Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect. *Climate Dynamics* 8: 83-102.



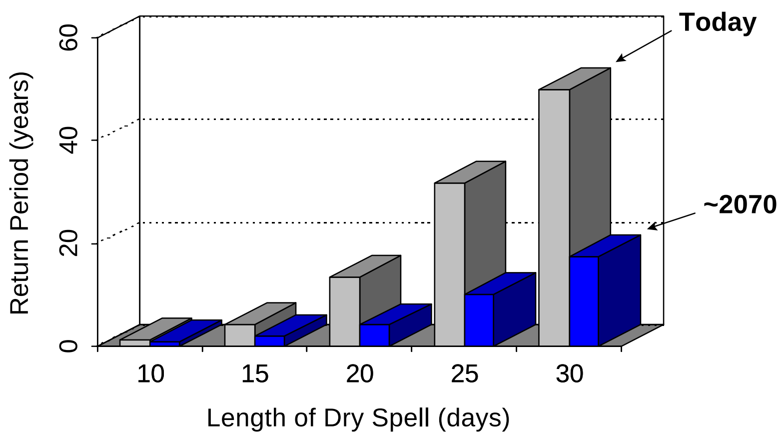
Analysis of drought risks for southern Saskatchewan under several climate change scenarios suggest that soil moisture conditions could become more variable.

During dry summers, higher temperatures under warmer climates will increase evaporation and intensify drought conditions frequency of severe drought (Palmer Drought Index £-6) and drought conditions (PDI between -4 and -6) would increase dramatically.

Conversely, during wet summers, when temperatures are usually cooler, higher rainfalls projected for southern Saskatchewan under some future cliamte change scenarios suggest that soil moisture condtions could become more variable.

Source: Cohen, S., E. Wheaton and J. Masterton. 1992. Impacts of Climatic Change Scenarios in the Prairie Provinces: A Case Study from Canada. SRC Publication No. E-2900-4-D-92, Saskatchewan Research Council, Saskatoon, Canada, 157 pp.

Projected Changes in Drought Frequency
(Central North America)



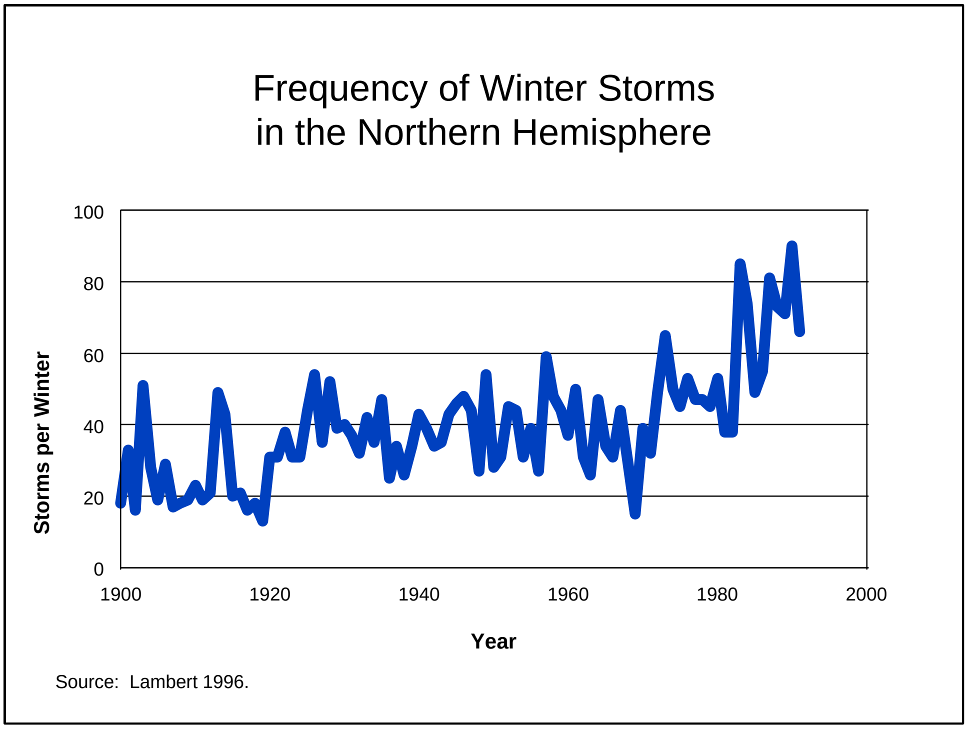
Source: Adapted from Gregory *et al*. 1997.

In much of central North America, the number of rain days are expected to decrease under 2XCO_2 scenarios.

Therefore, there is an associated risk of an increase in the frequency of long, dry spells.

Results from the UK Hadley Centre coupled climate model, for example, suggest that by 2070 the return period of long dry spells over central North America could be about one-third that of today.

Source: Gregory, J.M., J.F.B. Mitchell, A.J. Brady. 1997. Summer drought in northern midlatitudes in a time dependent CO_2 experiment. *Journal of Climate* 10(4): 662-686.

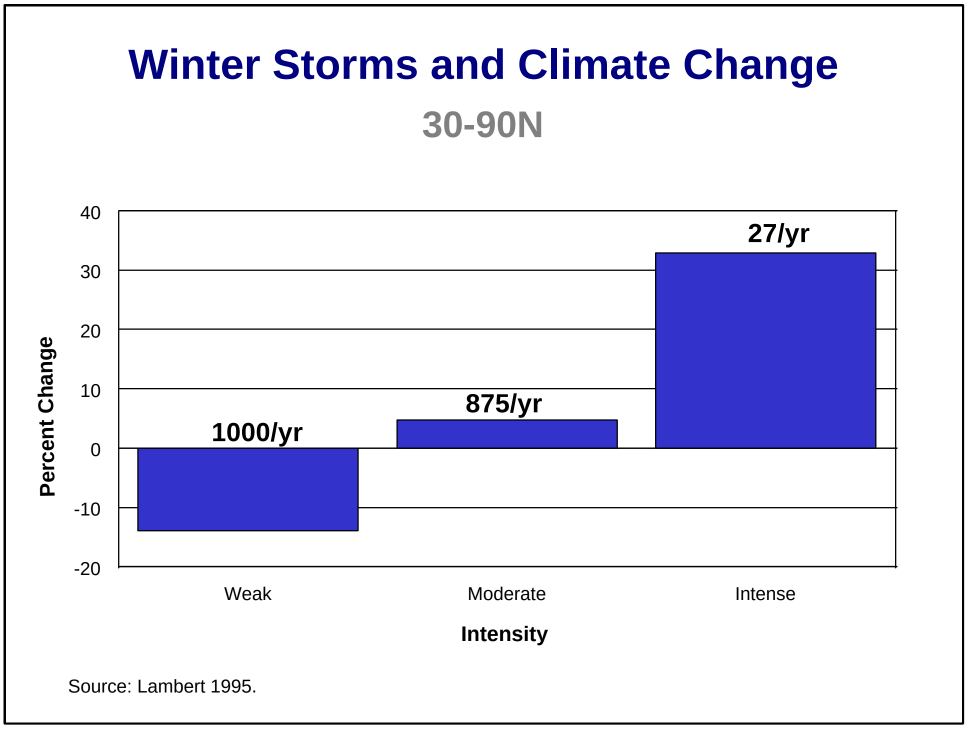


Analysis of intense storm events, based on surface pressure below 970 mb, indicate a significant increase in extreme winter storms in the last few decades.

There are significant concerns about the quality of the historical data used for this study.

However, experts suggest trends are too large to be explained by data problems.

Source: Lambert, S.J. 1996. Intense extratropical northern hemisphere winter cyclone events: 1899-1991. *Journal of Geophysical Research* 101: 21,219-21,325.

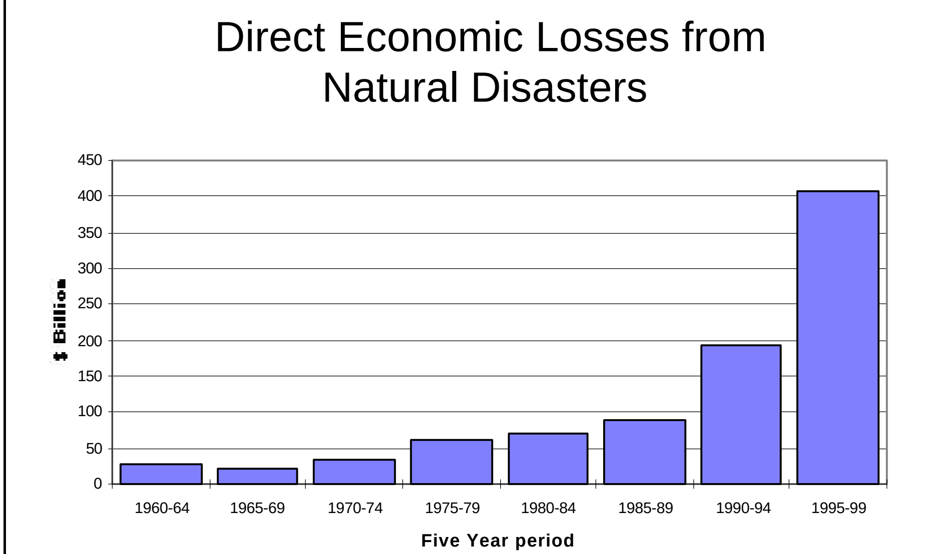


Under a $2XCO_2$ (equilibrium) scenario, the total number of winter storms in the Northern Hemisphere are expected to decrease.

However, studies using Canadian model data suggest that intense winter storms in the Northern Hemisphere are likely to increase by 5- 30%.

Frequency of intense winter storms in the southern hemisphere may increase even more.

Source: Lambert, S.J. 1995. The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *Journal of Climate* 8: 1447-1452.



Source: Adapted from Munich Re 2000.

There have been dramatic increases in global economic losses from natural catastrophes, most of them weather-related.

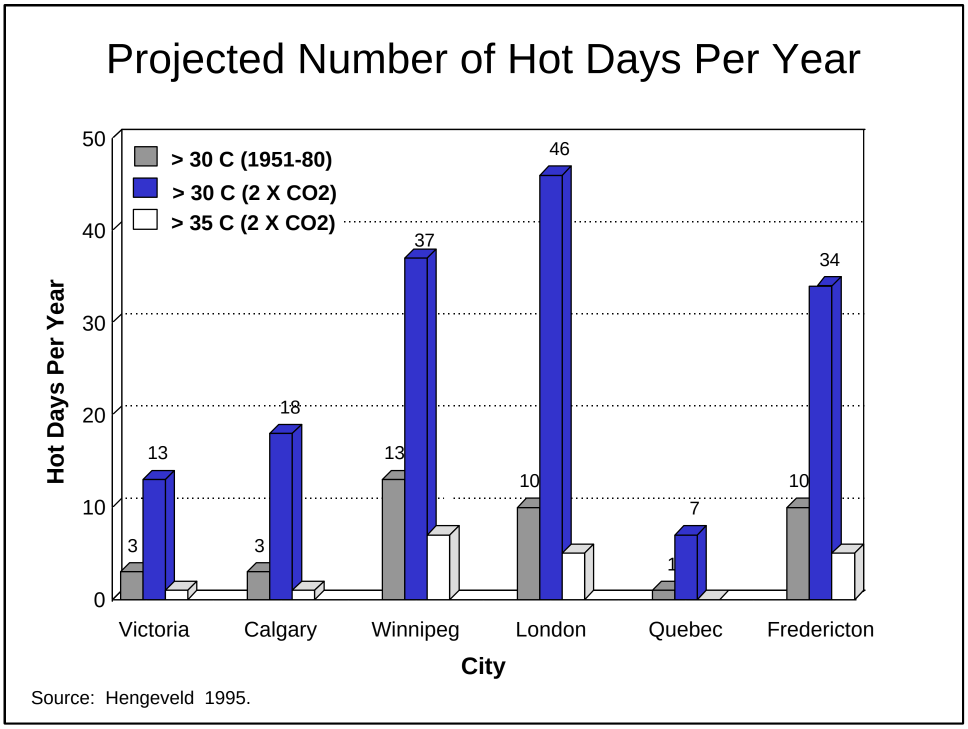
This trend is significantly influenced by socio-economic trends, such as increased concentrations of populations and the value of their property, especially in regions seriously exposed to natural catastrophes such as coastal areas.

However, experts suggest that such demographic factors are unlikely to fully explain the observed trends.

Source: Munich Re Group. 2000. Topics 2000: Natural Catastrophes - The Current Position.

Recent Disasters: Natural Variability or Climate Change?

- Perception of high number of weather related disasters during past decade
- Dramatic increase in economic loss
- Scientific evidence of upward trend in some types of events in some areas, not for others
- Broadly consistent with climate change projections
- However, because of natural variability of weather, cannot tie individual events to specific causes



The number of hot days (defined as over 30ºC) are projected to increase significantly across Canada.

For instance, Winnipeg currently experiences an average of 13 days over 30ºC per year. With a typical 2 X CO_2 scenario, Winnipeg is estimated to experience an average of 37 days over 30ºC per year.

The number of very hot days (over 35ºC) will also increase.

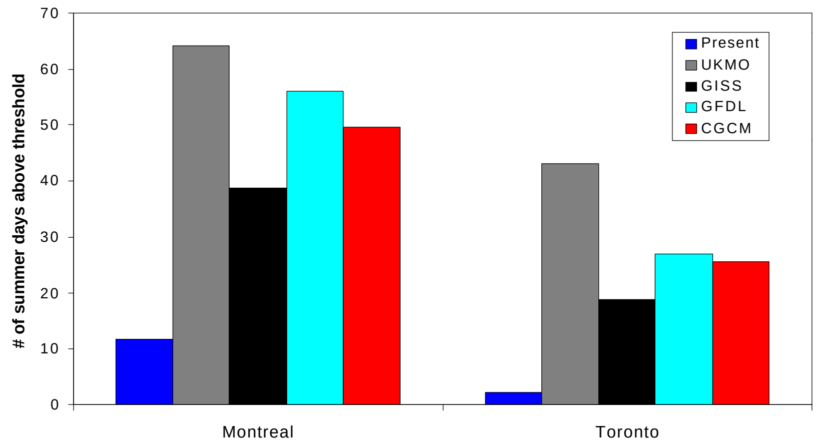
An increase in the number of hot days could increase the risk of heat stress, especially in vulnerable populations such as the elderly, children, and those with chronic lung diseases (e.g., asthma).

Meanwhile, the number of very cold days would decrease significantly, reducing related winter health hazards.

Source: Hengeveld, H.G. 1995. Understanding Atmospheric Change: A Survey of the Background Science and Implications of Climate Change and Ozone Depletion. SOE Report No. 95-02.

Number of Days above Threshold Temperature

Present vs. 2 X CO_2



Source: Duncan *et al.* 1998.

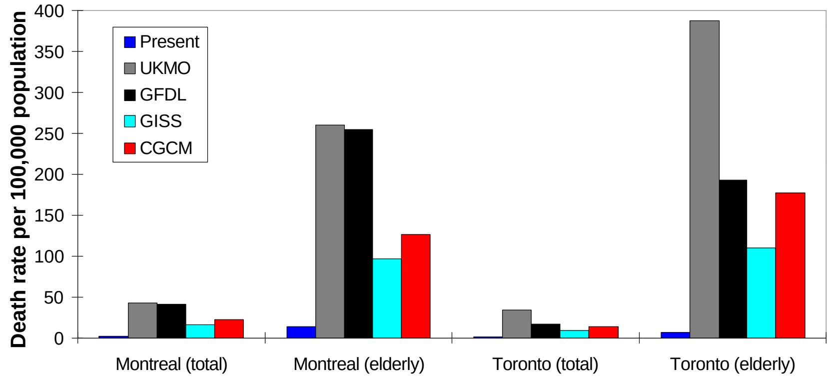
A threshold temperature for a given city represents the daily maximum temperature above which mortality significantly increases.

It has been found that Montreal has a threshold temperature of 29ºC, while Toronto has a slightly higher threshold of 33ºC.

All models project an significant increase in the number of days above the current thresholds. Thus, it is expected that, without acclimatization, heat-related mortality will also increase with a doubling of CO_2.

Source: Duncan, K., T. Guidotti, W. Cheng et al. 1998. Chapter 11: Health Sector. pp501-590, in: Koshida, G. and W. Davis (eds). *Canada Country Study: Climate Impacts and Adaptation*. Vol VII. Environment Canada, Downsview, Ontario.

Estimates of Future Canadian mortality in summer attributed to weather



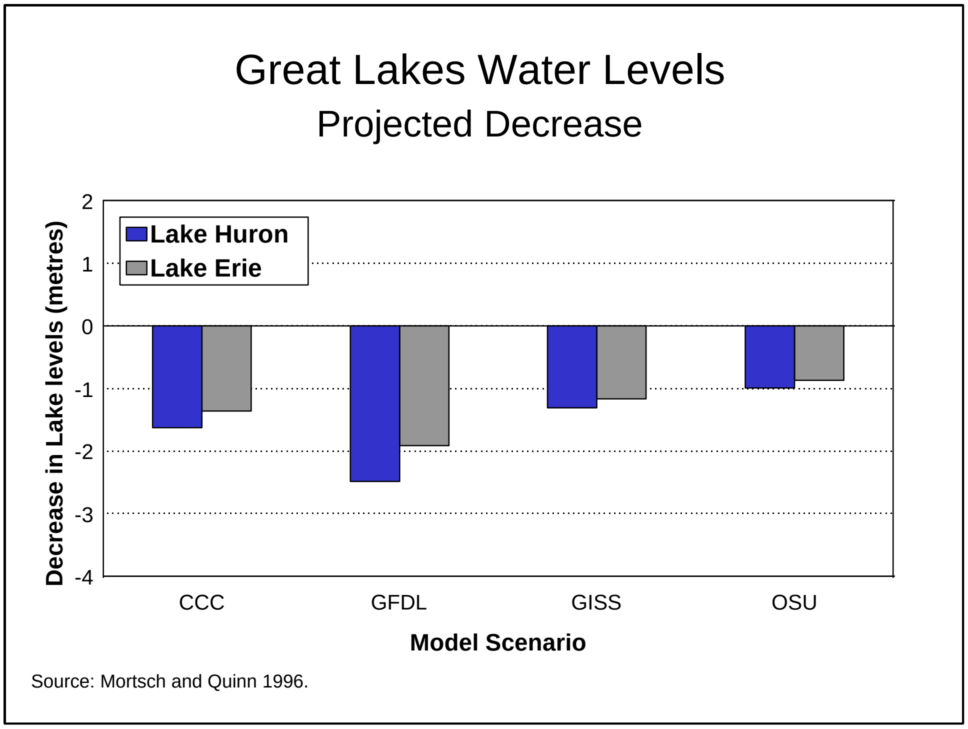
Source: Duncan *et al.* 1998.

Under current climatic conditions, mortality rates due to weather are very low.

Models project a modest increase in future mortality attributed to heat in the general population.

However, a significant increase in mortality due to heat is projected for elderly popluations in both Toronto and Montreal.

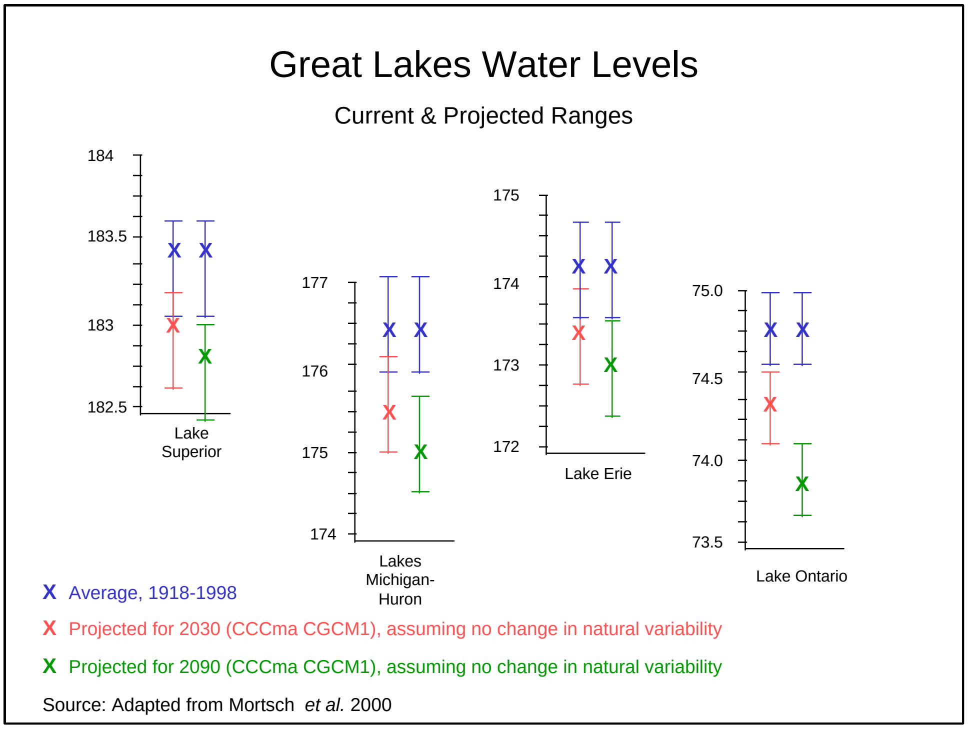
Source: Duncan, K., T. Guidotti, W. Cheng et al. 1998. Chapter 11: Health Sector. pp501-590, in: Koshida, G. and W. Davis (eds). *Canada Country Study: Climate Impacts and Adaptation*. Vol VII. Environment Canada, Downsview, Ontario.



Four different model scenarios for 2 X CO_2 climates all project a minimum decrease of about 1 metre for both Lake Huron and Lake Erie.

Decreases of as much as 2 metres or more are possible.

Source: Mortsch, L.D. and F.H. Quinn. 1996. Climate change scenarios for Great Lakes ecosystem studies. *Limnology and Oceanography* 41(5): 903-911.

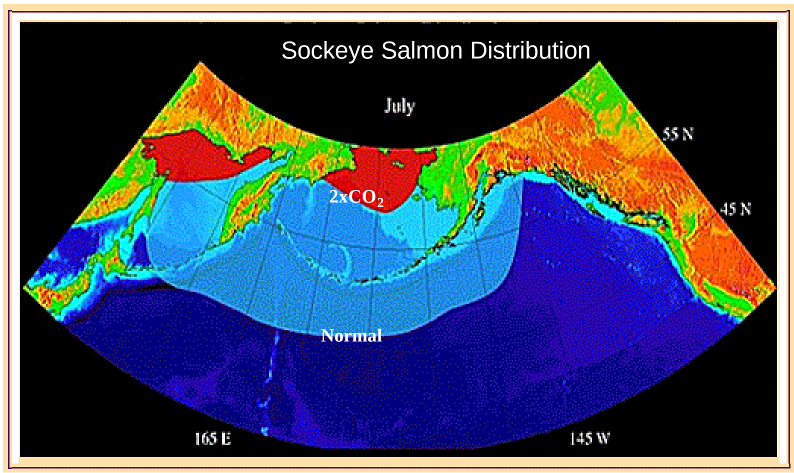


Great Lakes water levels are projected to decrease.

Decreases of 0.5-1.0m are projected by 2030. By the end of the century, water levels are projected to decrease dramatically. The green x and error bar illustrate that average water levels in the Great Lakes in 2090 may be lower than historical minimum levels.

Source: adapted from Mortsch et al. 2000. Climate Change Impacts on the Hydrology of the Great Lakes - St.Lawrence System. CWRJ 25(2): 153-170.

Climate Change and Pacific Sockeye Salmon



Source: Dept. Fisheries and Oceans.

•Our natural resources will be affected by change

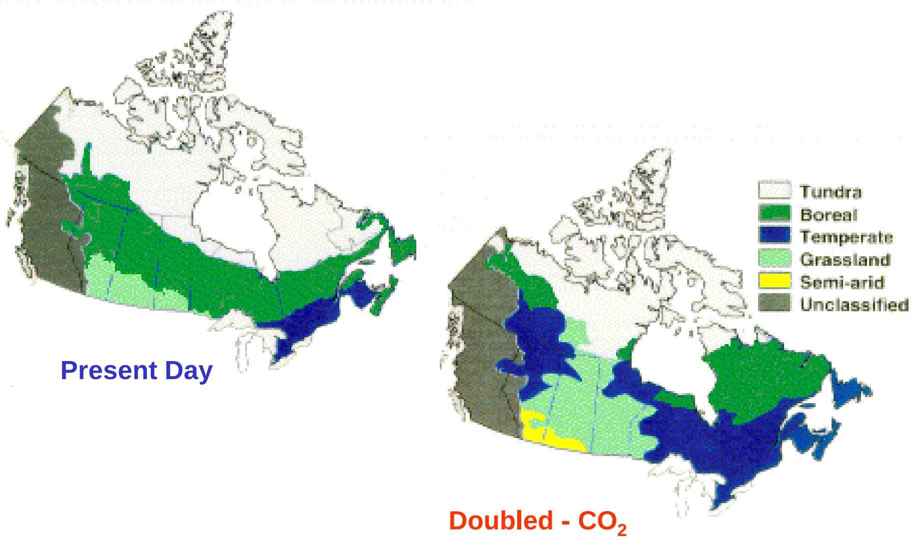
•Dept. Fisheries and Oceans has identified some potential changes to the habitat of sockeye salmon

•light blue line indicates current southern limit of sockeye salmon in July

•red line indicates limit of sockey e salmon under 2xCO2

•such change would have huge impacts on fishery and communities that depend on it

Changes in Forest and Grassland Boundaries



Source: Rizzo 1990.

Climate is a major control on where certain plant species will grow and flourish. Hence, as climate changes, ecosystems, with time, will change their location.

A simple projection of such changes under typical $2XCO_2$ conditions, assuming only climate changes, suggests a significant reduction in the extent of boreal forests in Canada, while the area of grasslands and temperate forests increases.

Since forests migrate very slowly, the transition of these ecosystems to new climatic zones would be out of step with changes in climate.

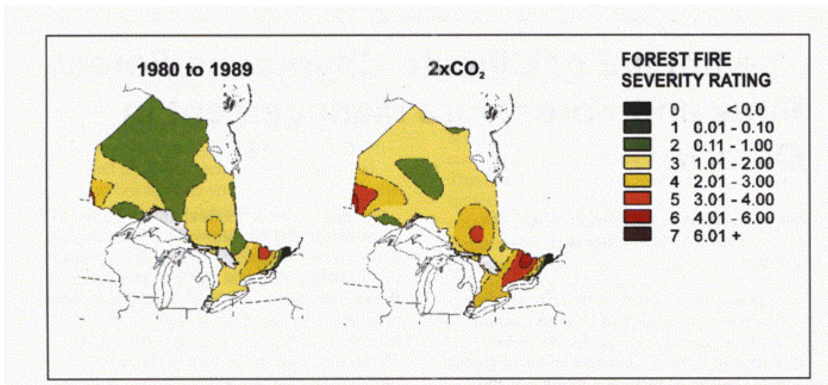
This is likely to cause dieback and loss to insects, diseases and fire in thos ecosystem regions where climate change imposes greatest stress.

Changes in ecosystems are likely to be much more complex that illustrated, since direct effects of increased CO_2 and other factors will also influence ecosystems.

Changes in ecosystems can also, in turn, significantly affect regional climates.

Source: Rizzo, B., Environment Canada. 1990. *Personal Communication*. in: Hengeveld, H. 1995. Understanding Atmospheric Change. SOE Report No. 95-02.

Projected Change in Seasonal Fire Severity Ontario



Source: Colombo *et al.* 1998.

An increase in Ontario forest fire activity is projected with climate change.

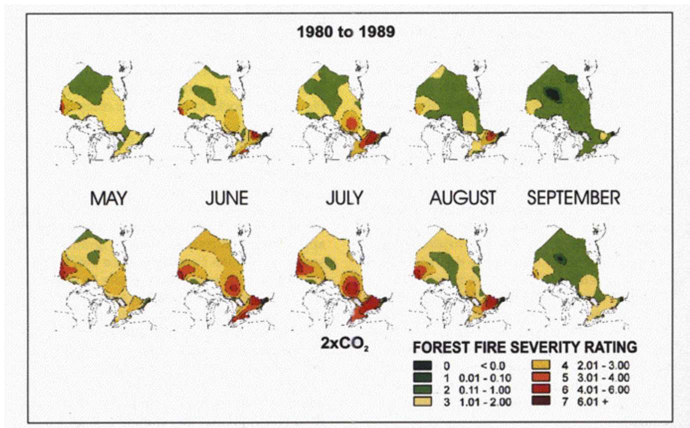
This increase in fire activity (in Ontario) can be attributed to 3 factors:

- •increased frequency and severity of drought years;
- •increased climatic variability and incidence of extreme climatic events;
- •increased spring and fall temperatures.

Largest changes are projected for the extreme west (Kenora area) and southeast (Ottawa area) of the province.

Source: Colombo, S.J., M.L. Cherry, C. Graham et al. 1998. *The Impacts of Climate Change on Ontario's Forests*. Ontairo Forest Research Insitute, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario.

Projected Change in Fire Severity Ontario



Source: Colombo *et al.* 1998.

Under warmer climates, the monthly distribution of fire severity in Ontario is projected to change substantially.

The most pronounced changes will occur during June and July, and to a lesser extent May.

Source: Colombo, S.J., M.L. Cherry, C. Graham et al. 1998. *The Impacts of Climate Change on Ontario's Forests*. Ontairo Forest Research Insitute, Ontario Ministry of Natural Resources, Sault Ste. Marie, Ontario.

The Science of Climate Change

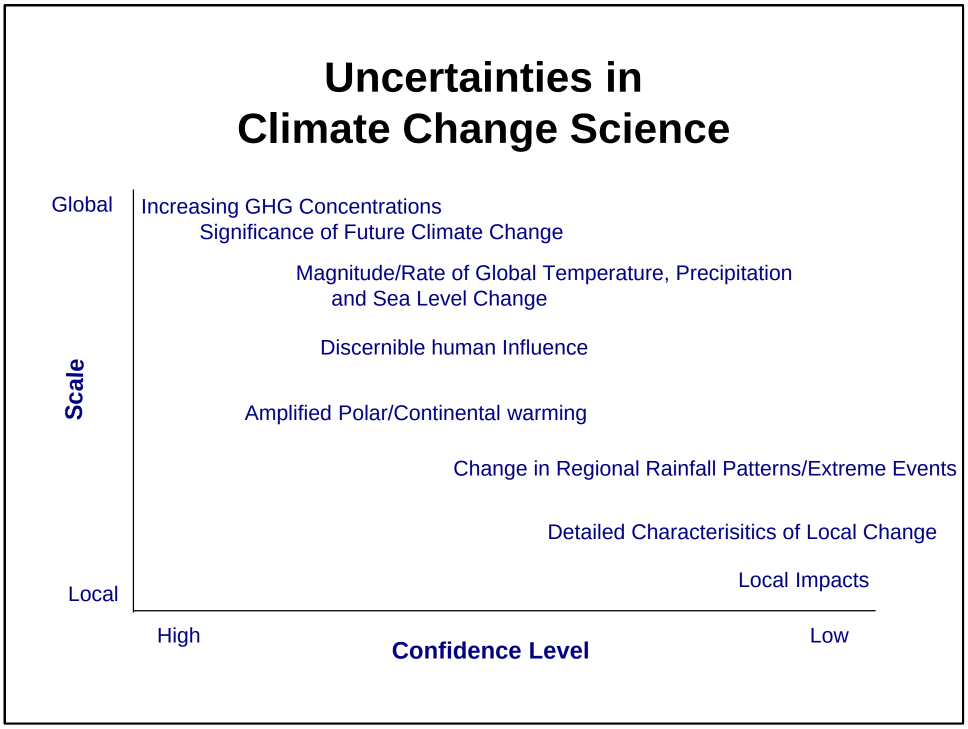
Part 6: Policy & Conclusions

Updated April 2001

Environment Canada Environnement Canada

Canada

Science - Policy Link



Scientists are certain that:

- there is a natural greenhouse effect.
- greenhouse gas concentrations are increasing rapidly

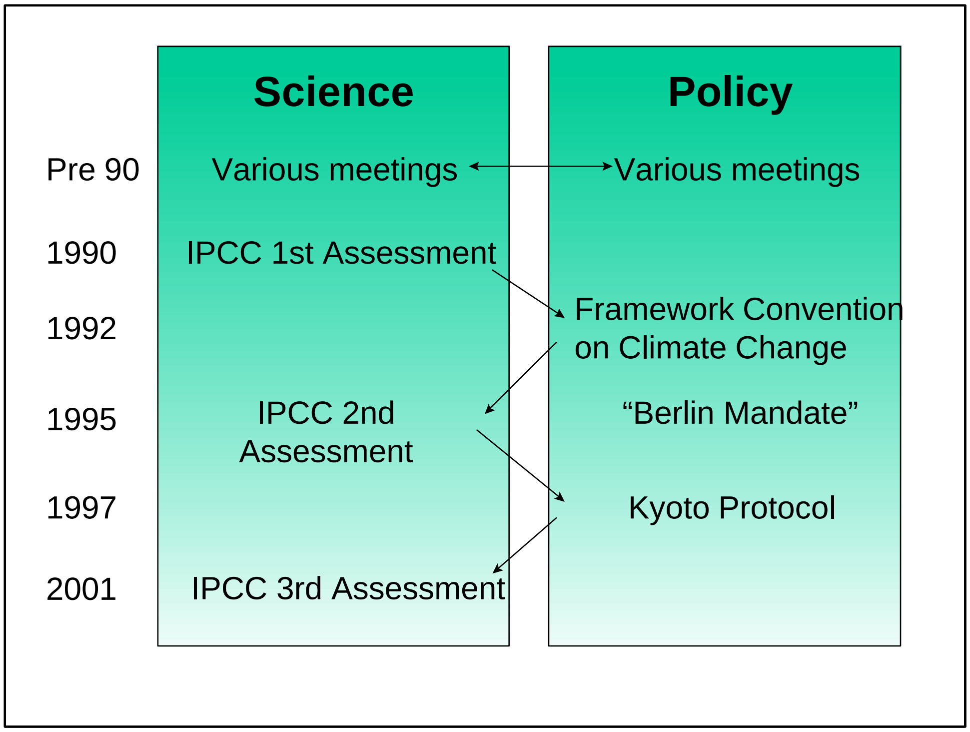
There is good to high confidence that:

- human induced global climate change during the coming century will be unprecedented in at least the past 10,000 years.
- the risks of related dangers are high.
- polar and continental climates will change most.
- human influence on climate is already identifiable.

There are significant uncertainties with respect to the magnitude and rate of global climate change

Greatest uncertainties related to

- regional and local nature of future climate
- detailed characteristics of local impacts



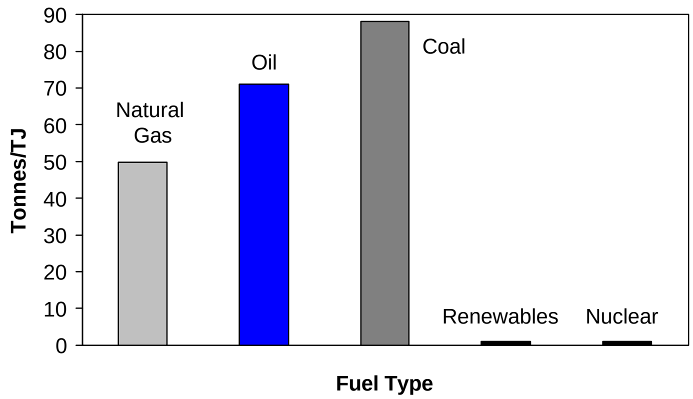
The development of scientific knowledge and of policies to mitigate the dangers of climate change have evolved concurrently and interactively.

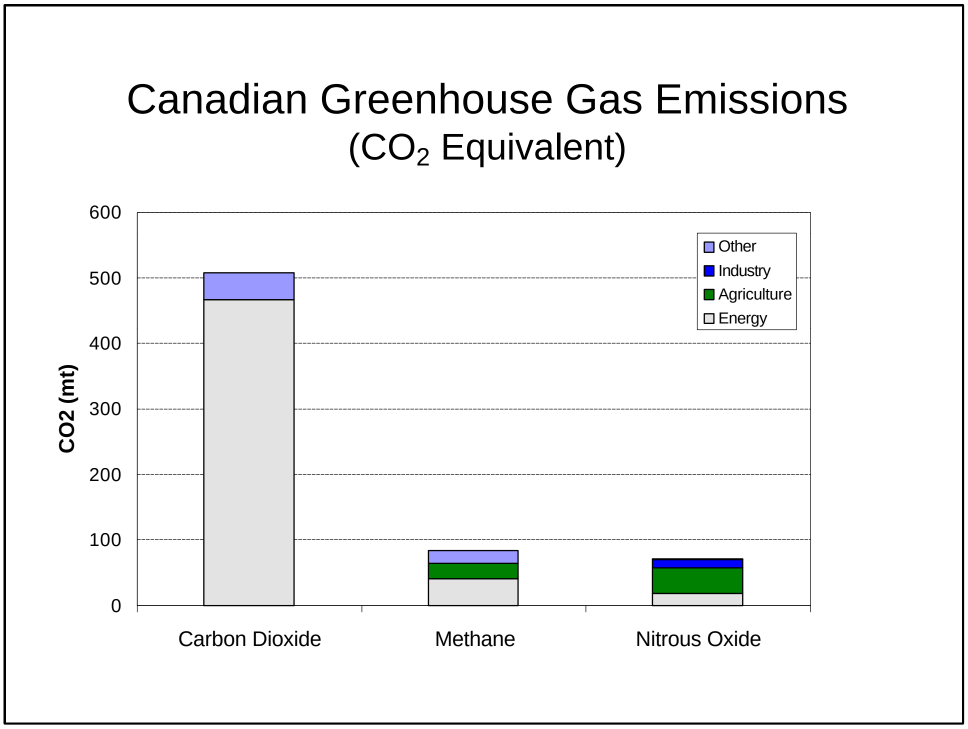
The first IPCC assessment was a fundamental base for discussion leading to the international acceptance of the Framework Convention on Climate Change (FCCC).

The second assessment provided the scientific basis for the development of the Kyoto Protocol.

Future assessments will continue to be a central element of futher policy development.

Direct CO_2 Emissions Per Unit of Energy

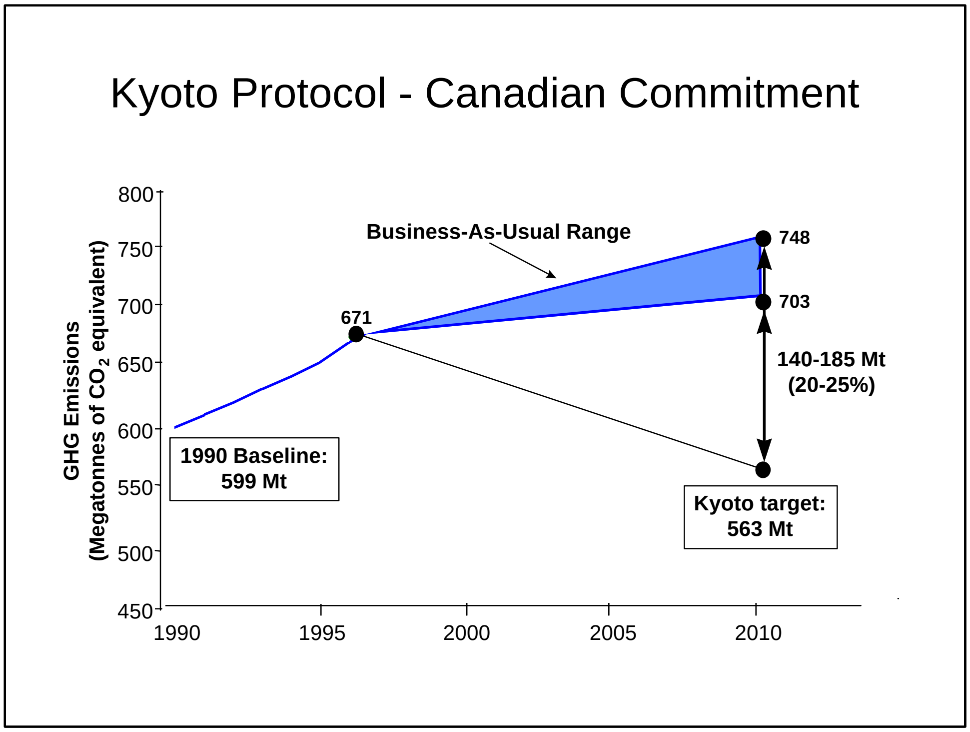




The main human sources of CO_2 emissions in Canada is directly related to the combustion of fossil fuels (92%). Other sources include cement production and non-combustion uses of fossil fuels.

About 49% of anthropogenic sources of methane are released during the production and combustion of fossil fuels. Another 28% is released by the agriculture sector and 23% from landfills.

The largest source of N_2O emissions (54%) is the use of fertilizers in agriculture. Another 25% is released during the combustion of fossil fuels (particularly by cars) and 17% from the production of ammonia and adipic adipic acid.



By 1996, Canada's greenhouse gas emissions have increased to 12% above 1990 levels.

Future projections suggest that, under various business-as-usual scenarios, emissions by 2010 continue to rise to 17-25% above 1990 levels.

This suggests that the real gap between projected 2010 emissions and the Kyoto target is 20-25%.

Even if fully implemented, the Kyoto Protocol will only slow, not stop climate from changing.

Socio-Economic Factors Related to Fossil Fuel CO_2 Emissions

KAYA FORMULA:

CO_2 Emissions = Population

x GDP per capita

(wealth)

x energy/GDP

(energy efficiency)

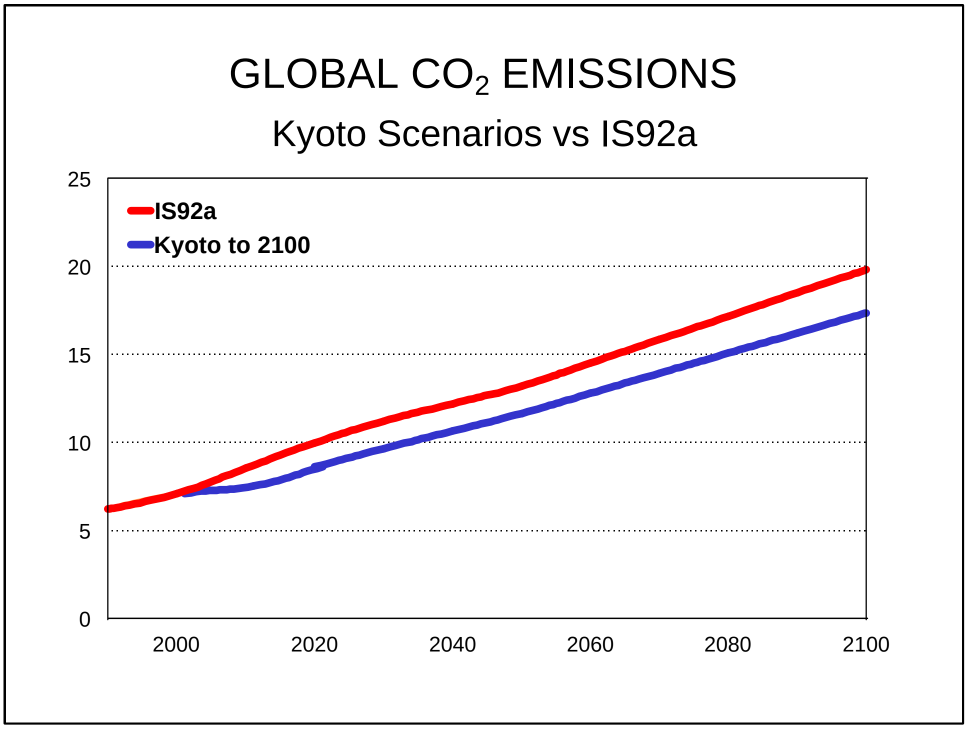
x Carbon/energy

(energy type)

The Kaya formula is often used to show the relationship between CO_2 emissions and variables frequently used to describe social and economic performance.

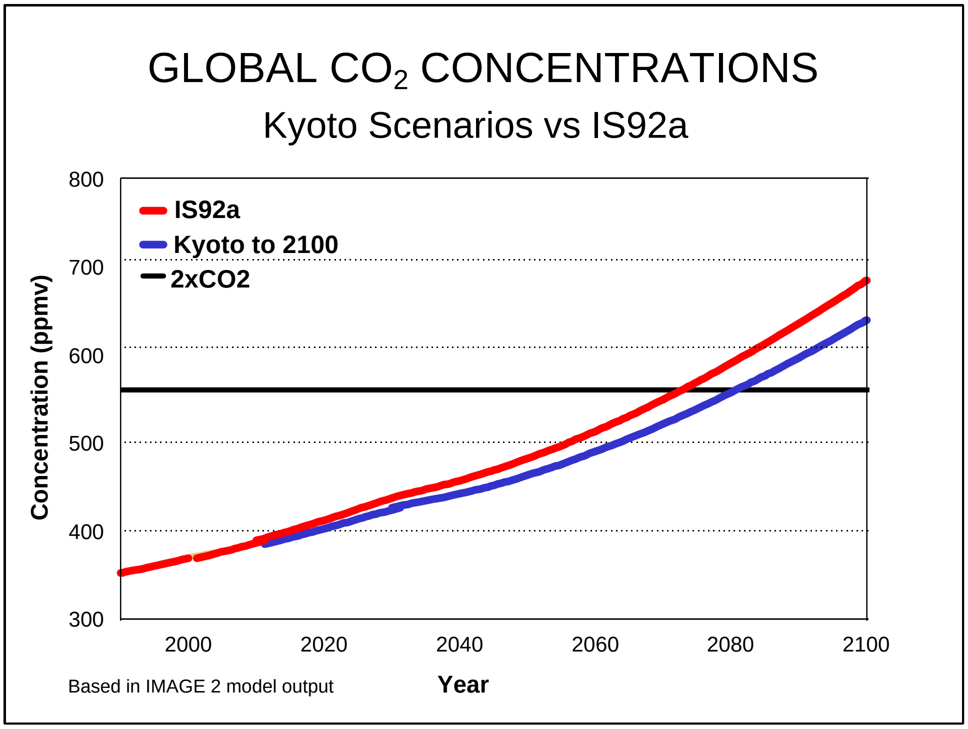
The formula suggests that energy efficiency and energy type are of equal importance in reducing greenhouse gas emissions.

For activities using energies with no carbon content (e.g., nuclear, hydro, solar, witn), the emissions become zero.



CO_2 emissions are projected to rise in the future under a business-as-usual scenario (IS92a).

Full implementation of the Kyoto Protocol will not significantly reduce future emissions of CO_2.



If all Annex I countries comply with Kyoto commitments, projected change in future concentrations of greenhouse gases will decrease only modestly.

A doubling of CO_2 concentrations would still be likely by 2100.

To avoid doubling of CO_2 would almost certainly demand reductions in emissions of non-Annex I countries as well.

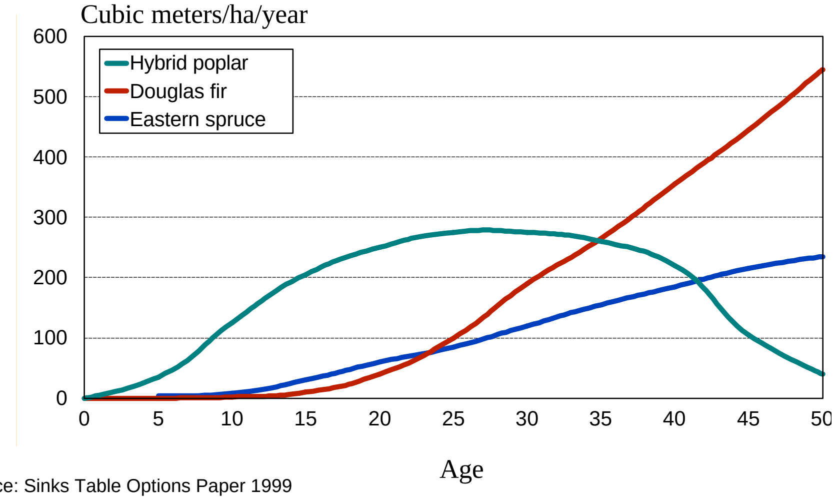
An Early Warning about Adaptation

"Many important economic and social decisions are being made today on long-term projects…based on the assumption that past climate data…are a reliable guide to the future. This is no longer a good assumption…"

UNEP/WMO/ICSU Conference
Villach, Austria 1985

Carbon Sequestration (Sinks)

Growth Rates for Various Canadian Tree Species



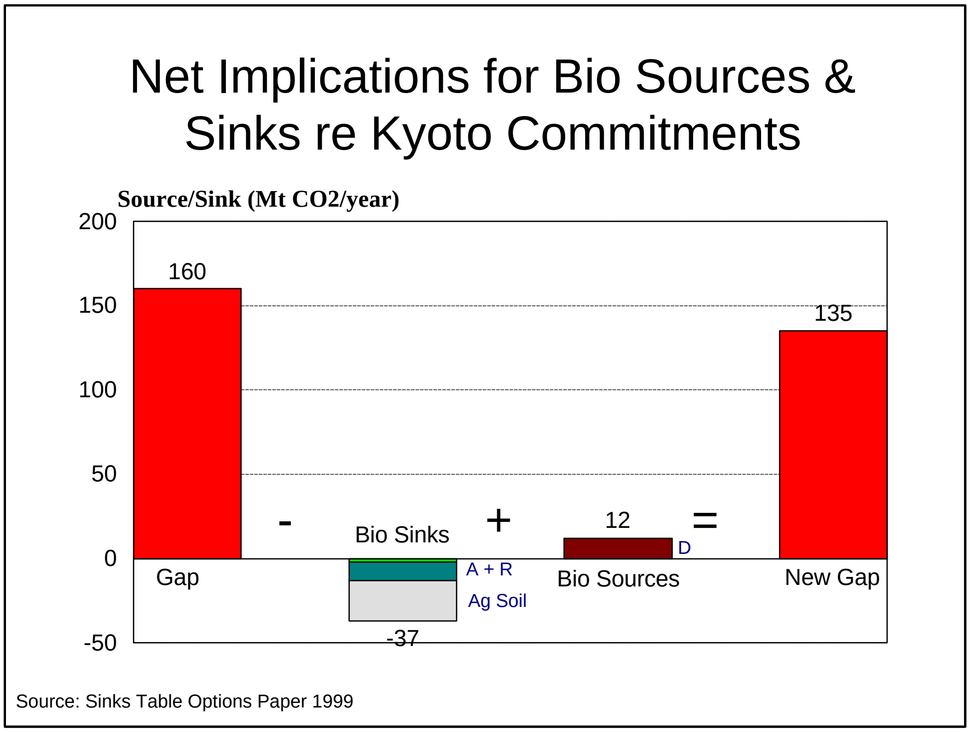
Source: Sinks Table Options Paper 1999

•The rate of CO_2 uptake by trees is very dependent on the type of tree and the age of the stand

•For most species, there is very little carbon accumulation in the first decade of growth

•Fast growing species are the exception, but mature quickly, become saturated as a sink, and unless harvested become a sink again

Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf



•Projected gap between BAU industrial emissions and Kyoto target is 140 to 185 Mt CO2/year by 2010. Estimate of 160 Mt CO2 is intermediate

•Bio Sinks for 2010 include 24 Mt CO2 for Agrciultural Soils, 11 Mt CO2 for reforestation and 2 for afforestation

•Bio Sources include 12 Mt CO2 for deforestation

•Net gap of 135 Mt CO2 suggests RAD and ag soils will address about 8.5% of the 2010 target gap

Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf

Potential Sinks for Canadian Kyoto Forests - Afforestation

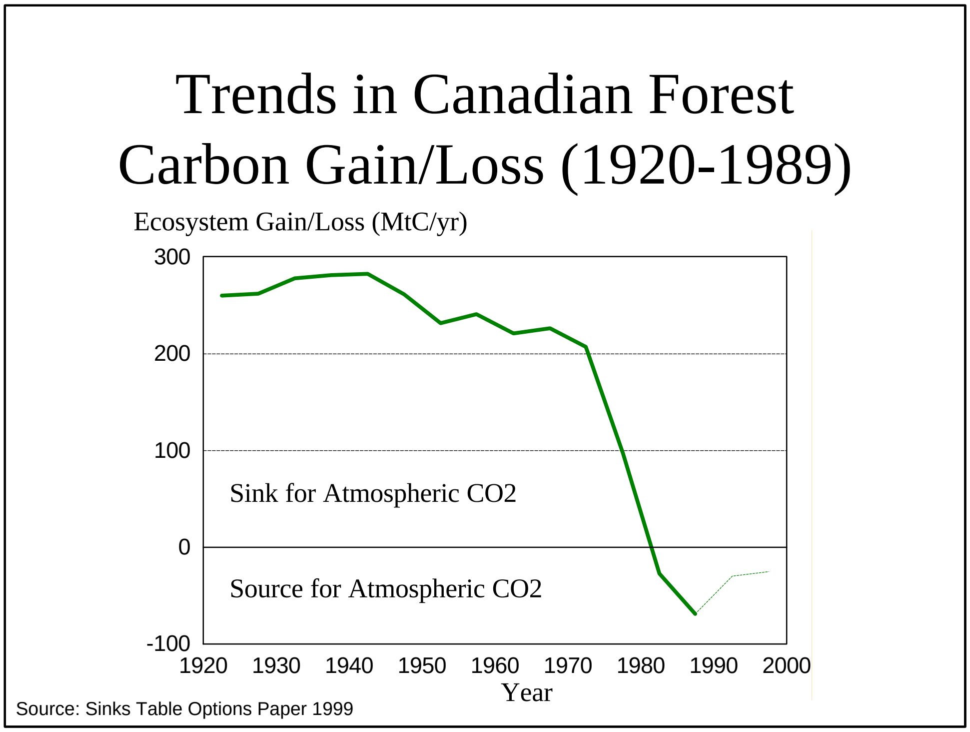
Activity	Sink by 2010 (Mt CO2/year)	Total Sink 2000-2050 (Mt CO2)
Hybrid poplars 50 kha	1.3	na
Prairie shelterbelts 169 kha	0.2	29
Prairie forests 260 kha	0.4	71
BC fir forests 169 kha	<0.1	35
Eastern spruce 195 kha	.2	69
Total (843 kha)	2.1	204 (4/yr)

* Does not include potential increase in methane and N2O emissions

Source: Sinks Table Options Paper 1999

- An agressive afforestation program can provide a subtantial sink over the long term
- The sink is very small in the near term
- Hybrid poplars can contribute to a near term sink, but would need to be harvested (and possibly counted as a source) within the next few decades
- Possible effect on wetalnds within these forests, and on methane and N2O emissions, are not included

Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf



- Canada's forests were a significant part of the uptake of excess CO_2 from the atmosphere
- During the past decade, these forests have changed to a source
- The main reason is increased fire
- Projections suggest that natural regeneration following fire will gradually reduce this net source back to a sink in coming decades
- These projections do not consider the effects of warmer climates on risks of fire and other disturbances

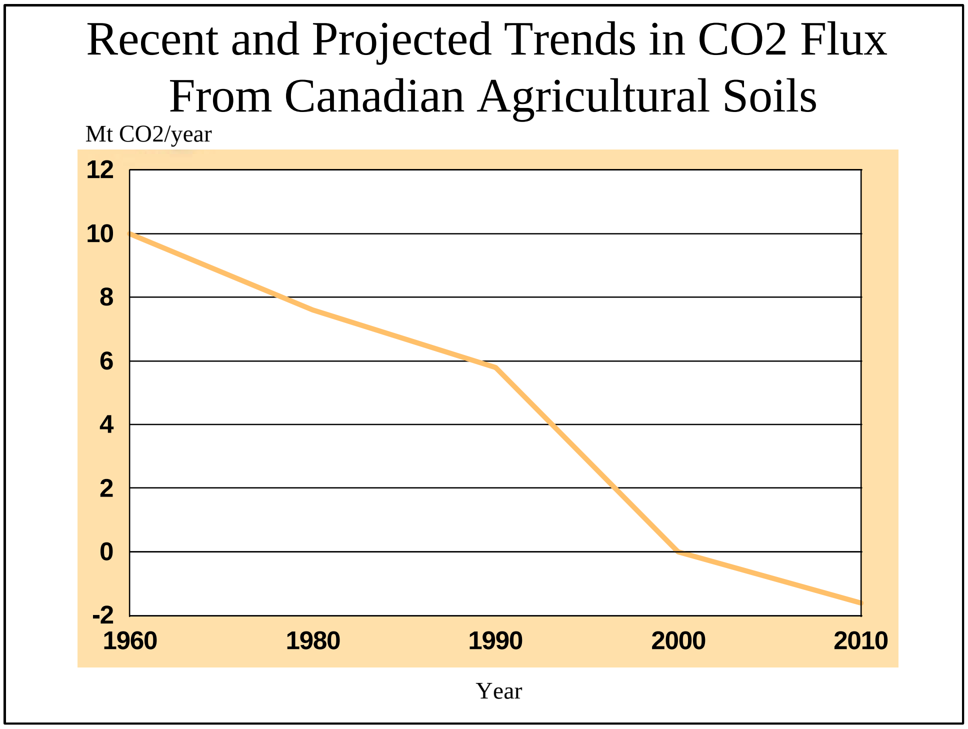
Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf

Potential Sinks for Canadian Kyoto Farms

Activity	Sink by 2010 (Mt CO2/year)	Sink by 2015 (Mt CO2/year)
Minimum Till	18	18
Pasture Management	1	3
More Grass	2	22
Restore Wetlands	3	3
Total	24	46

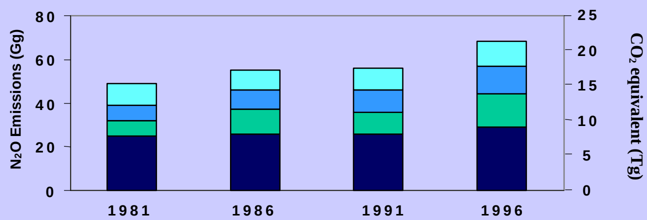
Does not include indirect effects on methane and nitrous oxide emissions

Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf



Source: Sinks Table Options Paper: Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol. National Climate Change Process. September 23, 1999. 169pp. http://www.nccp.ca/html/tables/pdf/options/Sinks_OR-Sep-23-1999_en.pdf

Trends in Direct N2O Emissions from Canadian Soils



Direct N_2O emissions from soils due to N-fixing crops, fertilizer application, crop residues and animal manure.

Total N2O emissions in 1996 of 39 Mt CO2 equivalent

Source: Environment Canada

Conclusions

- The risks of major climate change continue to be real and significant
- There is evidence that such change is already taking place
- Potential impacts on Canadians may be significant, especially in relation to extreme events
- The Kyoto Protocol does not go far enough in reducing emissions and hence adverting future climate change
- Adaptation is an essential component of any climate change strategy

Some Relevant EC Websites

- Environment Canada climate change website
  - **www.ec.gc.ca/climate**
- Science Assessment
  - **www.msc-smc.ec.gc.ca/saib/climate/climat_e.cfm**
- Environment Canada Climate Modelling
  - **www.cccma.bc.ec.gc.ca/**
- Canada Country Study
  - **www.ec.gc.ca/climate/ccs/**
- Climate Trends
  - **www.msc-smc.ec.gc.ca/ccrm/bulletin/**

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