AREVA

Kiggavik Project
Final Environmental Impact Statement

Tier 3 Technical Appendix 4D:
Baker Lake Long-term Climate Scenario

September 2014

Baker Lake Long-term Climate Scenario,

Up to 150,000 Years After Present

Report Prepared for

AREVA Resources Canada

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Project Number 0401

August 2011

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1 Context for Climate Scenarios

This study has been prepared to support the thermal modelling that is being undertaken for Areva Resources Canada‟s Kiggavik-Sissons project. This work is intended to strengthen confidence in long term thermal and related groundwater transport modelling as it relates to potential changes in permafrost conditions over time at the site.

Weather forecasting is not an exact science, with tomorrow‟s prediction frequently stated as a percentage chance of rain. Trying to find a reliable five day forecast is even more difficult and the better 10 day forecasts are generally so unsuccessful that most people don‟t bother with them. Contemplating a 10,000 year weather forecast is therefore a real stretch on credibility for almost all observers and scientists. However, it is important to understand the difference between daily weather and climate following long-term trends. Weather is the diurnal range of temperatures, precipitation, wind etc. that occur at a specific time and place; whereas, climate is looking at longer term trends that describe the averages of the weather for larger areas. This report, therefore, focuses on future climatic trends and is not a weather forecast. Specifically, what is presented in this report is a set of future climate scenarios. A scenario in this context is not a prediction nor a projection, but an anticipated climate regime for a period of time in the future. The scenarios are based on extractions of available information and present a particular viewpoint based on that data. Other perspectives may be possible if different data are used. To this end, the most credible data that are generally accepted and cross referenced in the peer reviewed academic journals have been sought, as by implication the scenario will then be more acceptable.

Possibly the most rapidly currently developing branch of climatology is that which looks at future climate. This has partly been driven by the International Panel for Climate Change (IPCC) publications on climate model outputs predicting future climate change due to increases in greenhouse gases. While this field has created considerable controversy and accusations of poor science and political interference, it has given rise to good scientific questioning and research on understanding what drives climate change and what future climates may look like.

In this report, every effort is made not to enter into the debate on greenhouse gas and short term climate change and the validity of model outputs. However to be clear why model output is not used in this report, a review of recent literature demonstrating the concerns associated with the models is presented. In addition, a review of future energy scenarios is also presented to demonstrate why long term scenarios based on CO_2 are unlikely to be realistic. The case presented in this report will use the IPCC model output as a short term indicator amongst other sources of information and will look to recent research to inform a more comprehensive picture of what future climate change may look like. No new data or research are presented in this report, but interpretations of existing reported data are made to create a possible scenario at different time frames up to 10,000 years into the future.

The report has been prepared so as to make it accessible to a wide range of readers. This has been done to ensure all materials are accessible to all readers and that the basis for the scenario is well understood. More experienced readers may want to focus on the climate scenario as the initial materials should be well known to them.

1.1 Data Reliability and Credibility

A report of this nature will no doubt attract many questions about reliability and credibility. These questions are indeed warranted and welcome, as this is what is driving the vast amount of research that is being undertaken in the world at this time. As a result of these questions, there is now a large body of information that is available that details long term historic trends based on non-greenhouse gas data. In many scientific circles, it is now believed that historic planetary and solar forcing mechanisms as captured in evidence in ice core spanning hundreds of thousands of years capture repeating patterns of climate change. By understanding the mechanisms that created these changes it is thought that future climate trends can be inferred and function as a reliable way to develop potential future climate scenarios. As we know from today, weather systems can bring significant swings in temperature, wind, rainfall and snowfall so it must be recognised that individual weather events may vary widely from the average conditions presented in the climate scenario.

With current understanding, it is unlikely that anyone could reliably predict long-term future weather for a particular place or time. It is; however, plausible that long-term climatic trends represented by a scenario such as the one presented in this report will be followed. The scenario presented in this report draws on data collected from a range of indicators including ocean sediments, ice sheets, other sedimentary deposits such as stalagmites, and biological artefacts such as coral. Based on our current understanding of meteorology, it is also possible to suggest the types of ranges that can be expected from weather that will occur under a potential future climate scenario.

It is important to be cognisant of the limitations of developing a future climate scenario when the actual forcing mechanisms are only beginning to be understood. It is also important to recognise that this report uses available data including IPCC model output. Although these model data are controversial, there is a large body of scientific evidence behind it and it is being refined on a continual basis. Using these data provides only one part of the prediction, up to 500 years, and it is recognised that many scientists argue that the extent of greenhouse gas contribution to climate change is not certain nor necessarily the major forcing mechanism. Indeed, these data are not used as a significant contributor after 500 years into the future as the effect is likely to be minimal by comparison to other forcing mechanisms at that time if greenhouse gas emissions are controlled. A key assumption in this document is, therefore, that greenhouse gases are likely to be managed as new technologies become available.

This document is based on the peer reviewed research of others. No new data are presented, but available data are serially packaged to create a reasonably acceptable continuous climate scenario for the next 10,000 years. This is extended to 100,000 years after present, but with limited resolution. The reference list used in the preparation of this document is presented at the rear. Not all references are cross referenced to make reading easier.

1.2 Published Analogues of this Study

A similar 10,000 year study (Miklas et al 1995) aimed at predicting 10,000 years of future climate change, using a panel technique, was conducted for the proposed high-level radioactive waste repository site at Yucca Mountain, Nevada. Specialist panel members prepared predictions on dominant climate controls as summarised below.

Experts identified climatic controls in order of importance for that site as follows for +100 years After Present:

- The rain shadow effect
- Anthropogenic forcing (greenhouse gases).

Effect of anthropogenic warming on the movement of the atmosphere across the site including:

- Storm tracks moving north
- More tropical air incursion on the Yucca Mountain, Nevada site
- The westerlies move south in winter
- More moisture in the west to east moving air
- Greenland Above circulation causing a change in precipitation at the site.
- One expert saw an enhancement of the El Niño Southern Oscillation (ENS0) discussed in more detail later in this document) resulting in increased precipitation at the site.

The experts saw little additional change at the 300 year time slice.

Experts identified climatic controls in order of importance for that site as follows for +1,000 years After Present:

- The rain shadow effect
- Anthropogenic forcing resulting in a warming of the atmosphere
- Offset cooling of the atmosphere resulting from the effects of Milankovitch orbital variations on the climate
- Atmospheric movement across the site.

These controls persisted through the 3,000 year time slice.

Experts identified climatic controls in order of importance for that site as follows for +5,000 years After Present:

- Rain shadow as the dominant control
- Astronomical forcing (Some variation in ranking order by the panel)
- Greenhouse warming due to anthropogenic forcing (Some variation in ranking order by the panel)
- Westerly wind flow (Some variation in ranking order by the panel)
- Remaining controls included remaining controls included shifting of mid-latitude storm (cyclonic) belts, increased availability of moisture, and meridional flow.
- These controls persisted through the 7,500 year time slice.

Experts identified climatic controls in order of importance for that site as follows for +10,000 years After Present:

- The rain shadow effect
- Anthropogenic warming would still be experienced, although in a waning mode (Some variation in ranking order by the panel)
- Milankovitch orbital forcing will have brought colder temperatures to the site (Some variation in ranking order by the panel)
- Remaining controls included Ice sheets, westerly wind belt migration, and increased moisture availability.

The panel predicted a maximum temperature increase of 3.0°C dropping to -2°C between 100 and 300 years After Present and 10,000 years after present respectively. The panel identified wetter winters during periods with warmer weather due to increased availability of moisture and overall wetter conditions once cooling starts after global warming is no longer as significant. Once cooling continues drier conditions would again return.

1.3 Timeframe of Climate Scenario

In order to constrain the study period into reasonable realms of predictability, time frames have been selected as follows:

- <100 years
- 100 to 500 years
- 500 to a 1,000 years
- 1,000 to 2,500 years
- 2,500 to 5,000
- 5,000 to 10,000 years.

1.4 Site Location

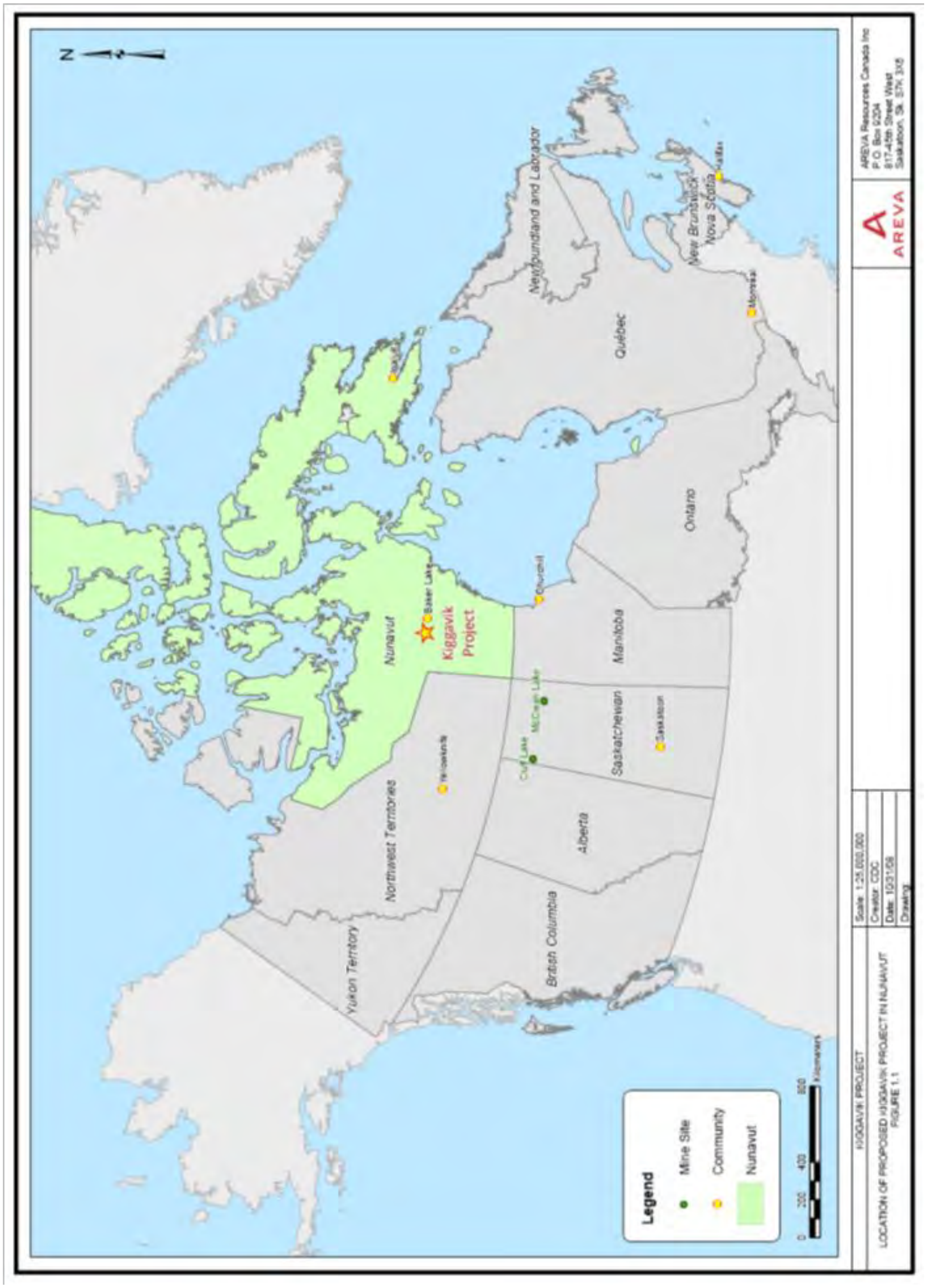


Figure 1: Kiggavik Project Location.

1.5 Existing Weather and Climate

Baker Lake is the closest and longest running weather station in the area. It provides a good proxy for the weather at the site despite the fact that the site does not have a similarly large body of water near it. Data in this section is sourced from:

http://www.climate-charts.com/Locations/c/CN71926023005000.php

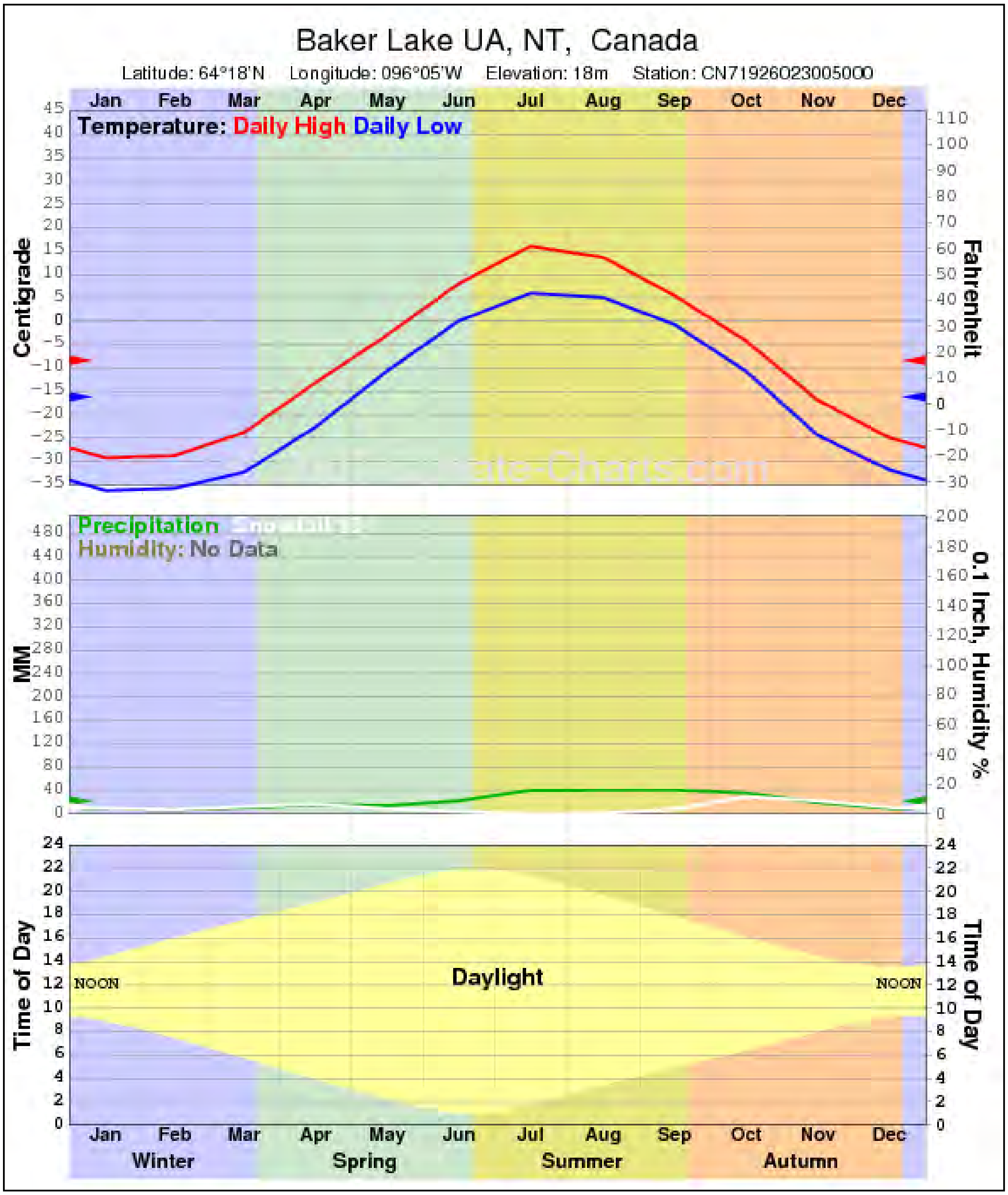


Figure 2: Summary weather charts for Baker Lake.

Table 1: Average Temperature, Precipitation and Snowfall Baker Lake.

NOAA Code	Statistic	Units	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
0101	Temperature Mean Value	F	-26.7	-25.8	-18.4	-0	19.9	39.4	52	48.9	36.3	18.7	-5.1	-18.9	10
0201	High Temperature Mean Value	F	-20.6	-19.7	-10.8	8.4	26.8	46.6	61	56.7	41.9	24.4	1.6	-12.8	17
0301	Low Temperature Mean Value	F	-33.2	-32.3	-26.1	-8.7	12.9	32.2	42.8	41.2	30.7	12.7	-11.9	-25.2	2.9
0615	Precipitation Mean Monthly Value	Inches	0.3	0.3	0.4	0.6	0.6	0.9	1.6	1.7	1.7	1.4	0.8	0.4	0.9
0915	Snowfall Mean Monthly Value	Inches	3.8	3.2	5.1	6.9	3.6	1.7	0	0.5	3.2	12.2	9.2	4.7	4.5
0101	Temperature Mean Value	C	-32.6	-32.1	-28.0	-17.8	-6.7	4.1	11.1	9.4	2.4	-7.4	-20.6	-28.3	-12.21
0201	High Temperature Mean Value	C	-29.2	-28.7	-23.8	-13.1	-2.9	8.1	16.1	13.7	5.5	-4.2	-16.9	-24.9	-8.36
0301	Low Temperature Mean Value	C	-36.2	-35.7	-32.3	-22.6	-10.6	0.1	6.0	5.1	-0.7	-10.7	-24.4	-31.8	-16.15
0615	Precipitation Mean Monthly Value	mm	8.4	6.9	10.5	15.6	13.9	22.1	39.8	40.3	40.5	35.1	19.3	9.4	21.82
0915	Snowfall Mean Monthly Value	cm	9.1	7.7	12.3	16.7	8.7	4.0	0.0	1.3	7.7	29.3	22.1	11.2	10.84

Source: http://www.climate-charts.com/Locations/c/CN71926023005000.php

1.6 Scientific Reports of Canadian Climate Change

The material in this section has been extracted verbatim from the CCME document entitled: *Climate, Nature, People: Indicators of Canada's Changing Climate, 2003*.

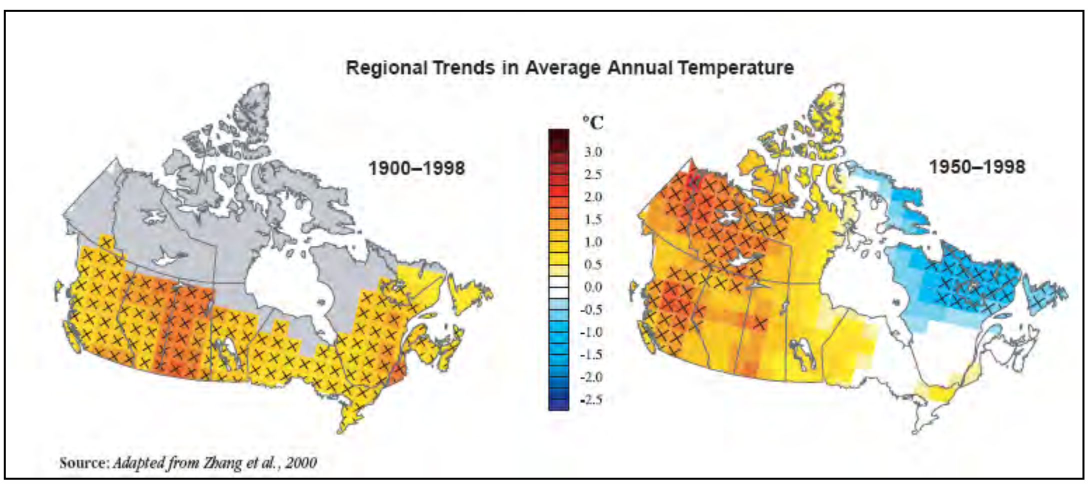
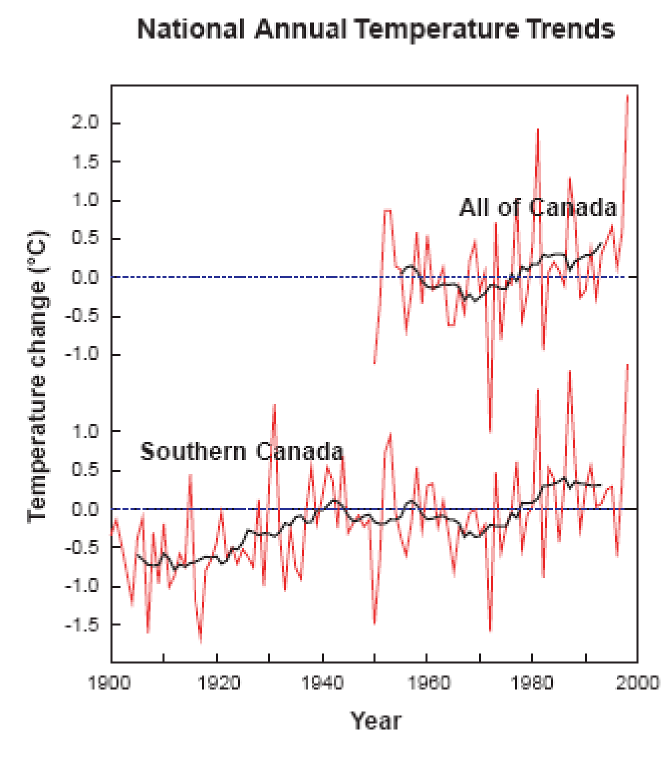


Figure 3: Regional trends in average annual temperature.

Over the course of the twentieth century, all of southern Canada, from B.C. to Newfoundland and Labrador, warmed to some extent. In Figure 4, southern Canada is defined as the region lying south of the 60th parallel (the line that forms the northern border of B.C., Alberta, Saskatchewan, and Manitoba). Over the course of the twentieth century, all of southern Canada, from B.C. to Newfoundland and Labrador, warmed to some extent. In these maps, southern Canada is defined as the region lying south of the 60th parallel (the line that forms the northern border of B.C., Alberta, Saskatchewan, and Manitoba). Since 1950, the greatest warming has occurred in the West and Northwest, while the Northeast has cooled. An x indicates results that are statistically significant. That means that scientists have a high degree of confidence that the changes are part of a real long-term trend and are not just due to chance.



Source: *Adapted from Zhang et al., 2000*

Figure 4: Canadian national annual temperature trends.

Figure 4 shows the difference between each year"s average temperature and the average for 1961 to 1990. The dark line running through each plot smoothes out the year-to-year differences and makes it easier to see the general pattern of change over time. In southern Canada, temperatures rose rapidly between the early 1900s and the 1940s. They then fell slightly until the late 1960s but have continued to rise since then.

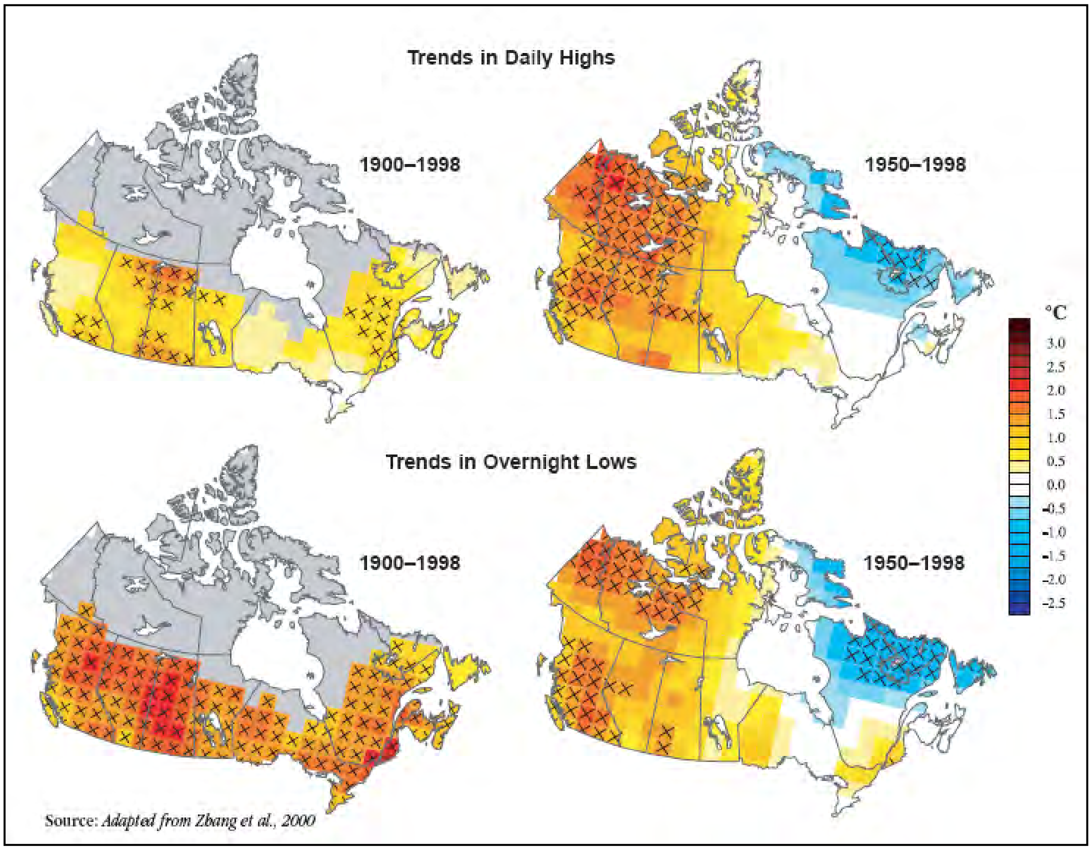


Figure 5: Trends in daily highs and overnight lows.

Over the past 100 years overnight lows warmed than daily highs across all of Canada. For the past 50 years, differences between day time and overnight temperatures have been far less striking. X"s indicate trends that are statistically significant.

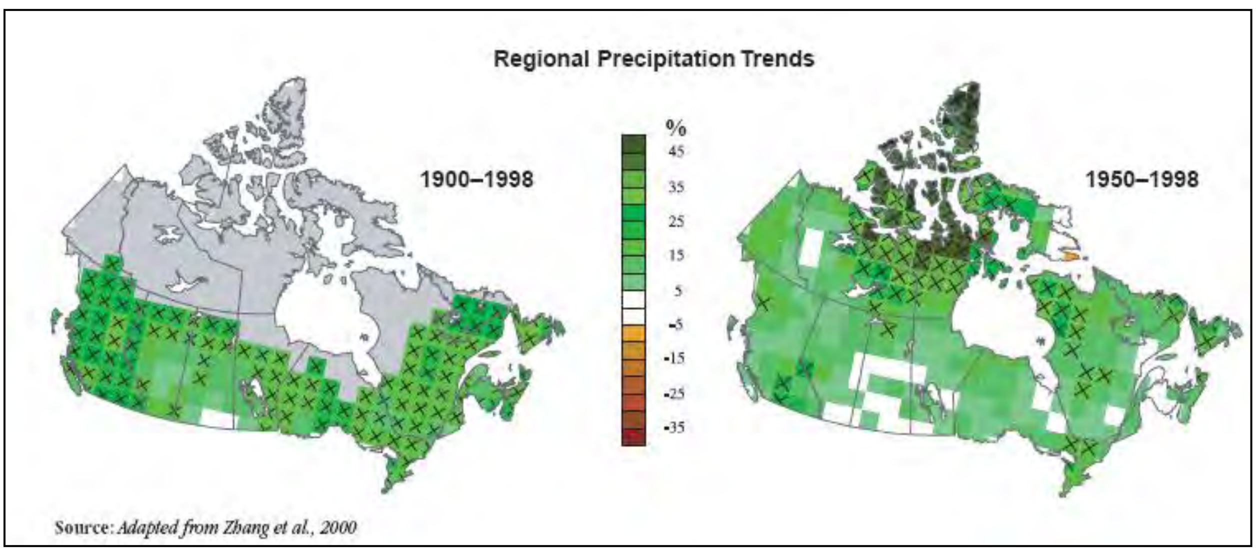


Figure 6: Regional precipitation trends.

Virtually all parts of the country have seen an increase in Annual Precipitation Figure 6. X"s indicate trends that are statistically significant.

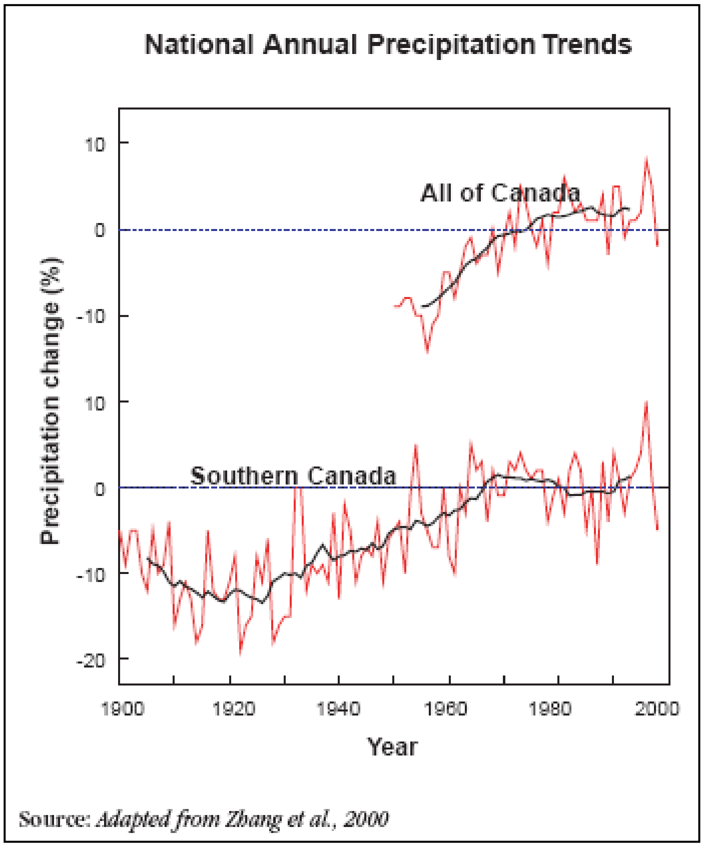


Figure 7: National annual precipitation trends.

Canada has become wetter during the twentieth century. The graph shows the difference (in per cent) between each year‟s average precipitation and the average for 1961–1990. The dark line through the centre of each plot smoothes out year-to-year differences.

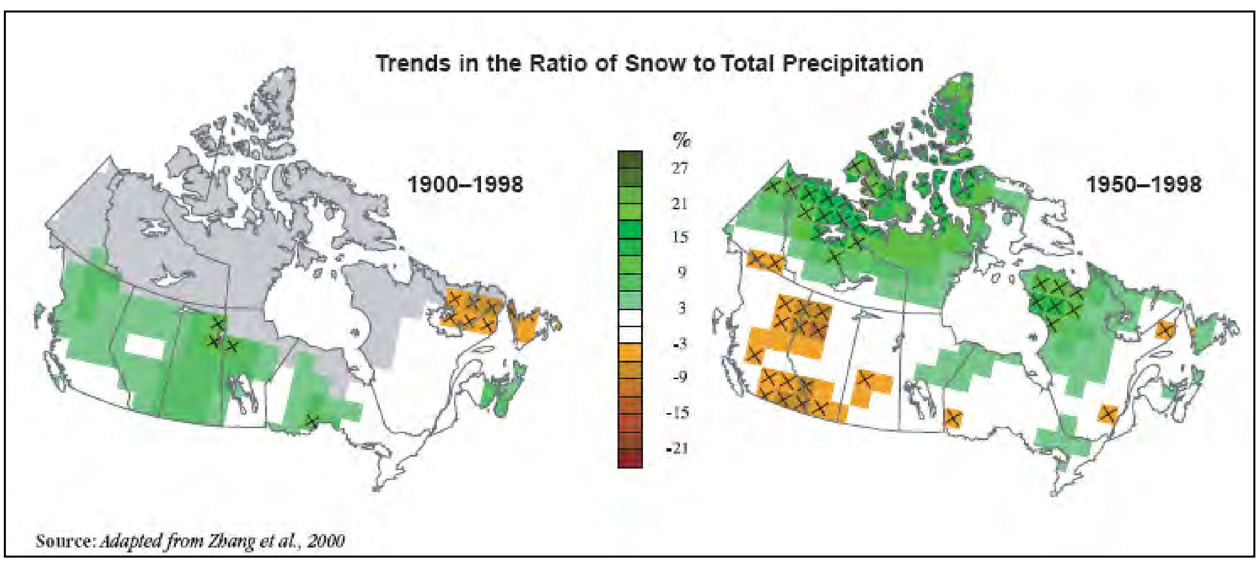


Figure 8: Trends in the ratio of snow to total precipitation.

Virtually across the country a greater proportion of precipitation falls as snowfall (Figure 8).

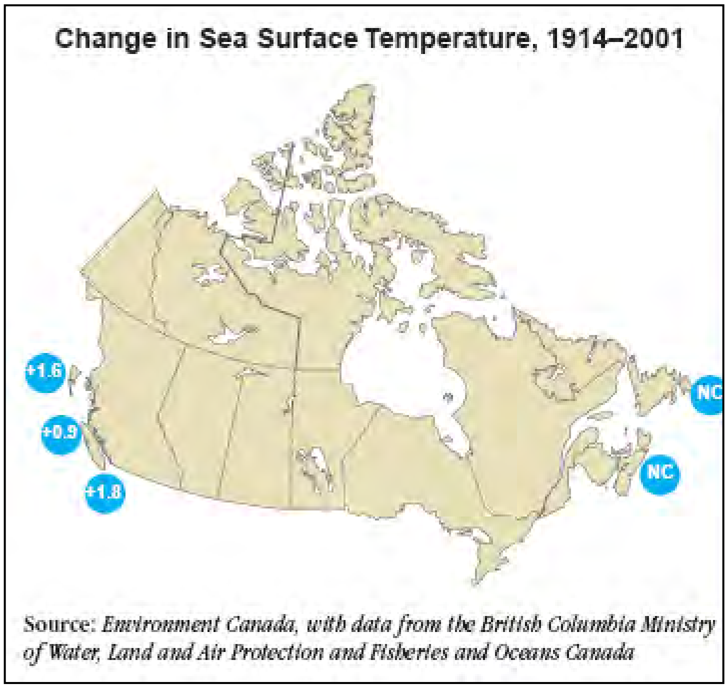


Figure 9: Changes in sea surface temperatures around the Canadian coast.

Sea surface temperatures have risen substantially on the west coast but appear to have changed little on the east (Figure 9). The rate of temperature change (in °C per century) is indicated in the blue circles. NC indicates no change.

1.7 Nunavut People's Perception of Climate Change

In 2005, a survey was conducted by the Government of Nunavut, Department of Environment Environmental Protection Division to determine how people in Nunavut are experiencing climate change. The responses are presented below and in Appendix B:

- Warmer temperatures year-round
- Changes in the length and timing of the Inuktitut seasons
- Unpredictable weather and winds
- Stronger winds
- A change in the direction of the prevailing wind
- Reduced snowfall in Ukiaq (early winter)
- Reduced and more compacted Aput (snow cover) on the land
- Later and slower freezing of the lakes, rivers and the ocean
- Earlier and more rapid melting of ice and snow inland and on the ocean
- Reduced rainfall in Upinngaaq (spring)
- Reduced water levels in the lakes and rivers
- Impaired growth of edible/fruit-bearing plants

- Increased growth of willows and birch
- Movement of the tree-line northward
- Undernourished and diseased species for example caribou and fish
- Polar and grizzly bears encountered over longer time period and in new areas
- Loss of some existing bird species and new insect, bird and mammal species being sighted.

2 IPCC Fourth Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) is an international scientific body for the assessment of climate change established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of climate change and its potential environmental and socio-economic consequences. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data or parameters (http://www.ipcc.ch/organization/organization.htm).

2.1 Greenhouse Gases

Wolf (2008) and many others have demonstrated through the use of ice cores and direct measurement that the atmospheric concentrations for carbon dioxide (CO_2) has increased. The records from Antarctica show that the preindustrial concentration of the gas was about 280 ppmv (parts per million volume) and the concentration has increased to the current level of 375 ppmv. The concentration is thought to have emerged above its natural range in about 1830 AD. Natural variability of CO_2 in the last millennium was about 10 ppmv.

The information that follows presents the output from the IPCC Fourth Assessment Report. Anticipated global temperatures as a consequence of greenhouse gases, primarily as reported by the IPCC, are presented in Figure 10. In this figure the temperatures for the next century are modelled based on various CO_2 emission scenarios. The emission scenarios project an increase of baseline global GHG emissions by a range of 9.7 to 36.7 $GtCO_2$-eq (25 to 90%) between 2000 and 2030 (Figure 11). In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence, CO_2 emissions from energy use between 2000 and 2030 are projected to grow by 40 to 110% over that period.

The A1 scenario assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change.

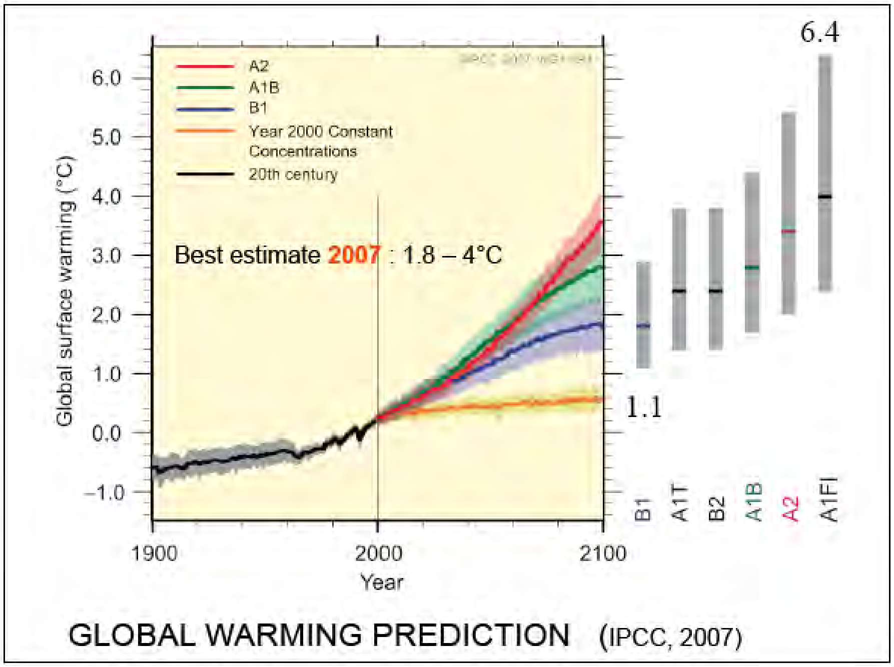


Figure 10: IPCC Global warming predictions based on emission scenarios (2007).

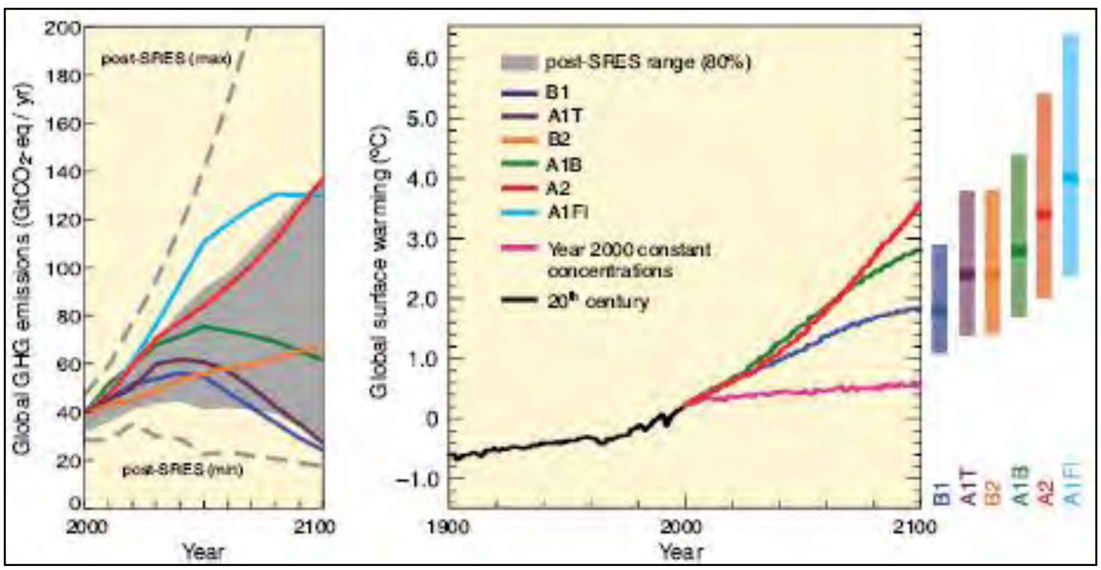


Figure 11: Scenarios for GHG emissions from 2000 to 2100 (IPCC, 2007).

Under these scenarios, a range of 1.1°C to 6.4°C is forecast as the likely increase in temperature over the next century. The best estimate from the IPCC is 1.8°C to 4.0°C warming. Associated with this temperature increase is a sea-level rise based on thermal expansion of sea water and melting snow and ice from only a few glacial sources. This sea-level rise is predicted to be in the range of 0.18 m to 0.59 m over the next century as shown in Table 2.

Table 2: Projected global average surface warming and sea level rise by 2100 (IPCC, 2007).

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

a) Temperatures are assessed best estimates and *likely* uncertainty ranges from a hierarchy of models of varying complexity as well as observational constraints.

b) Year 2000 constant composition is derived from Atmosphere-Ocean General Circulation Models (AOGCMs) only.

c) All scenarios above are six SRES marker scenarios. Approximate CO_2-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the Working Group I TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.

d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

The basis for the modelling undertaken by the IPCC is the values or weightings attributed to each of the GHGs that have been included as forcing mechanisms. Each gas is associated with a differing capacity to absorb energy that provides it with a capacity to cause warming. The various strengths the IPCC has attributed to these forcing mechanisms is presented in Figure 12. Particularly notable in this table is the absence of water vapour, a potent greenhouse gas and the low forcing strength of the solar irradiance.

Based on the modelling the IPCC has undertaken, predictions for future temperature and rainfall have been prepared. For 2100, the projection for Northern Canada is approximately a 5°C to 6°C increase of temperature relative to 1980-1999 temperatures (Figure 13). For 2100, the projection for precipitation in Northern Canada is approximately a 10% to 20% reduction in precipitation relative to 1980-1999 (Figure 14).

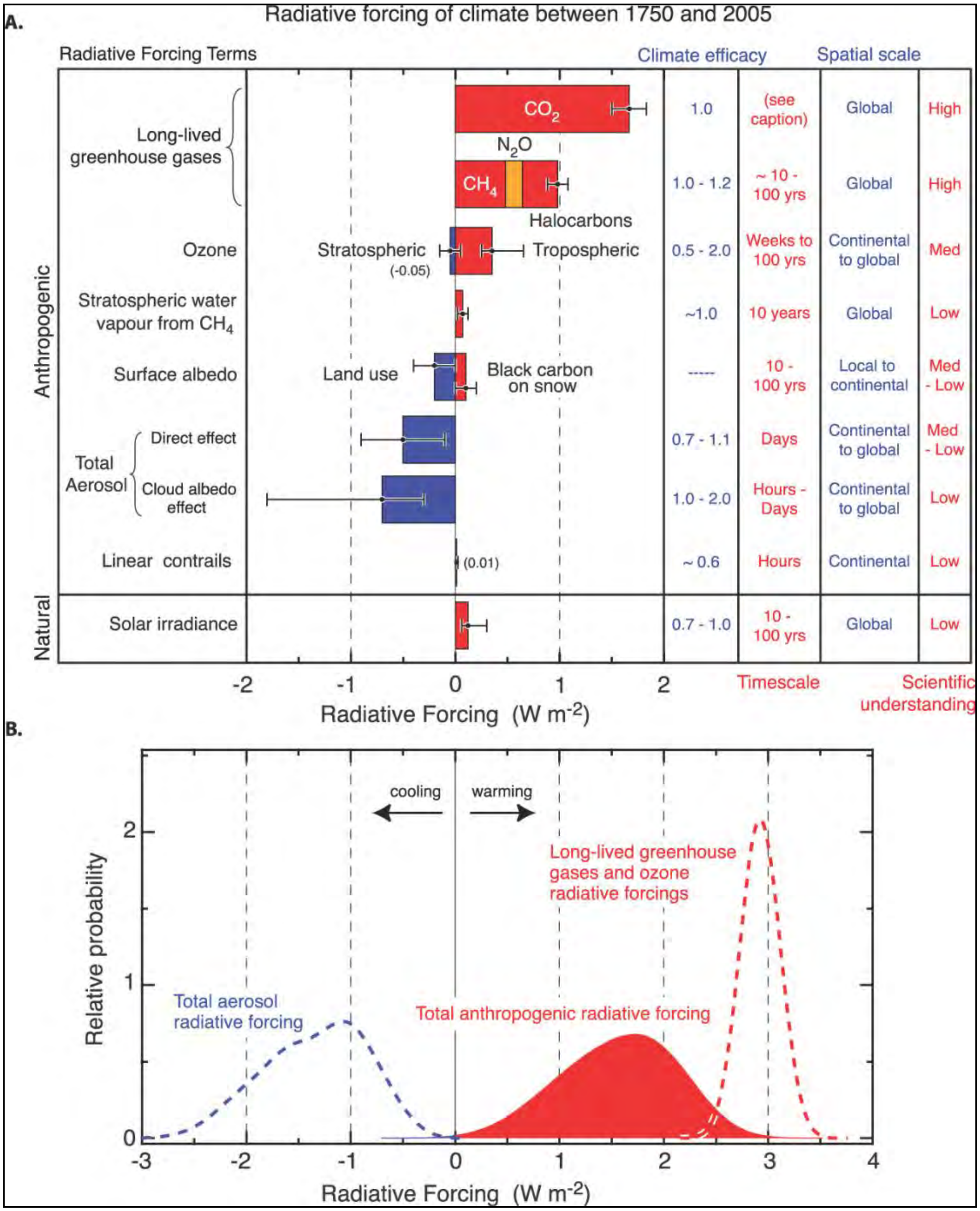


Figure 12: Drivers for radiative forcing (IPCC, 2007).

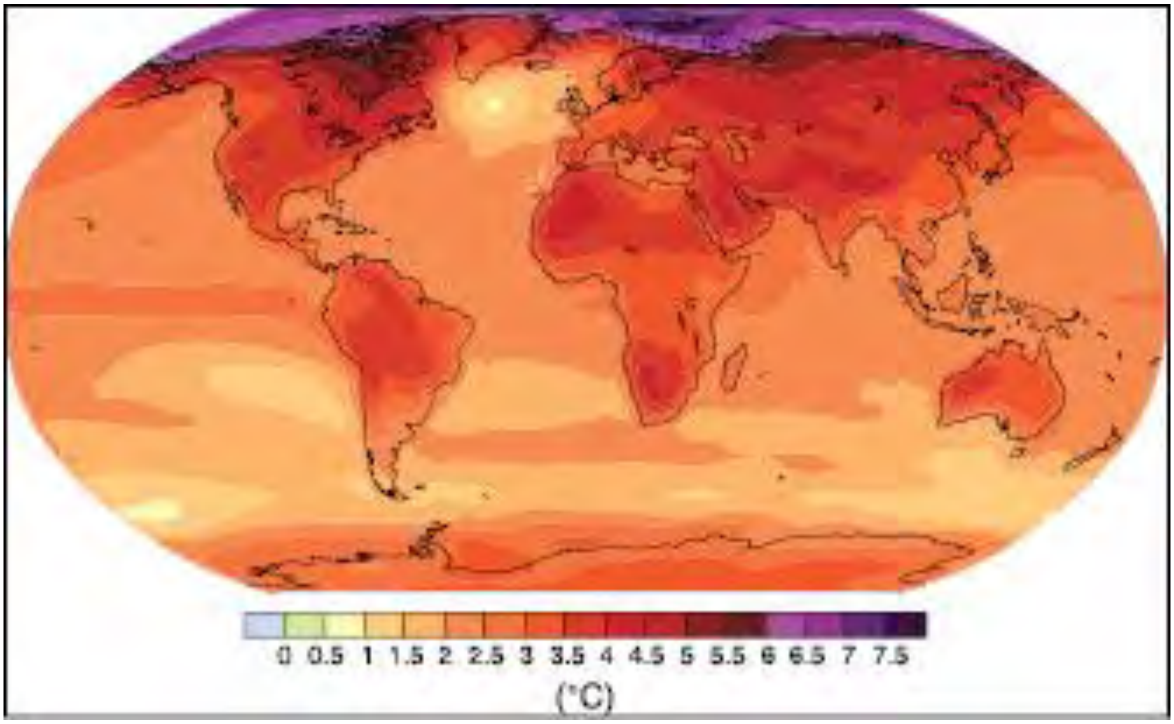
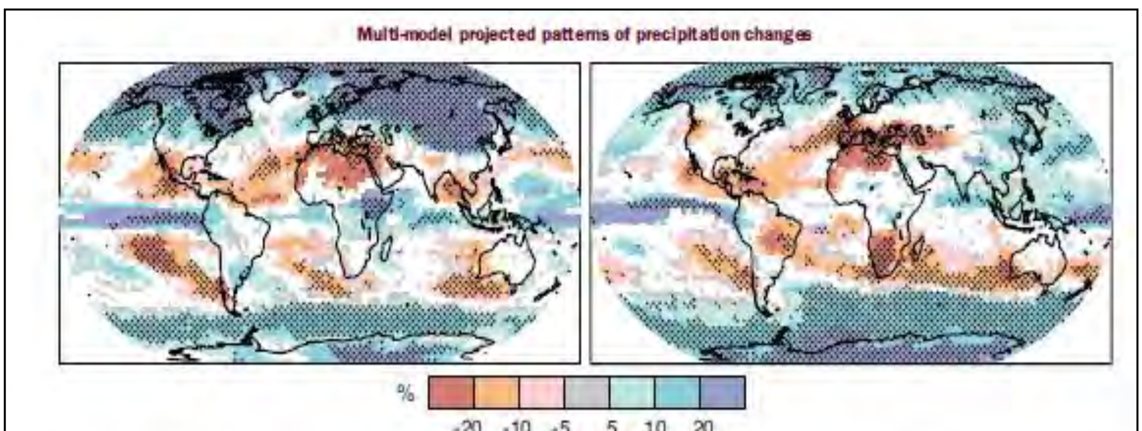


Figure 13: Relative surface temperature changes for 2090-2099 (IPCC 2007).



Left: December to February. Right: June to August

Figure 14: Relative precipitation changes for 2090-2099 (IPCC, 2007).

2.2 Concerns with IPCC 2007 Report

In the latter part of 2009, coinciding with the IPCC Copenhagen conference, a series of email leaks were released on websites. These emails drew attention to a group of sceptical scientists who had been questioning the claims of the IPCC. The leaked emails were those of IPCC authors, and many emails suggested that the modelling and the process followed by contributing authors of the IPCC may not have been robust, transparent or taking into consideration all views on climate change. The emails suggest that data was cherry picked and some data excluded to result in an enhanced warming prediction. Furthermore, several subsequent reviews of the IPCC reports have indicated that statements and time series used in the IPCC modelling may have been without basis, such as claims of Himalaya ice melting by 2020. These emails and close scrutiny of temperature records used have brought into question the validity of the IPCC report and process. A comprehensive evaluation of the emails is presented at http://climateaudit.org/ along with in depth analysis of IPCC model code and statistical techniques. In many cases, both code and statistical techniques have been shown to need improvement to avoid producing incorrect modelling results.

In particular, the following main concerns, partly discussed by Giorgi and Mearns (2002), have been made of the IPCC modelling predictions:

- Over estimation of the effect of CO_2 and under estimation of water vapour.
- Under estimation of the effect of the sun.
- Failure to recognise the medieval warm period and the little ice age. These periods show that current conditions are not abnormal conditions (Soon and Baliunas, 2003).
- Over reliance on models which are tuned on past climate to predict future climate.
- The models inability to predict the levelling off and decrease in temperatures since about 2000.
- The models poor ability to predict precipitation, widely regarded as the key measure of successful models.
- The models limited ability to simulate the long-term oscillations in the climate system.

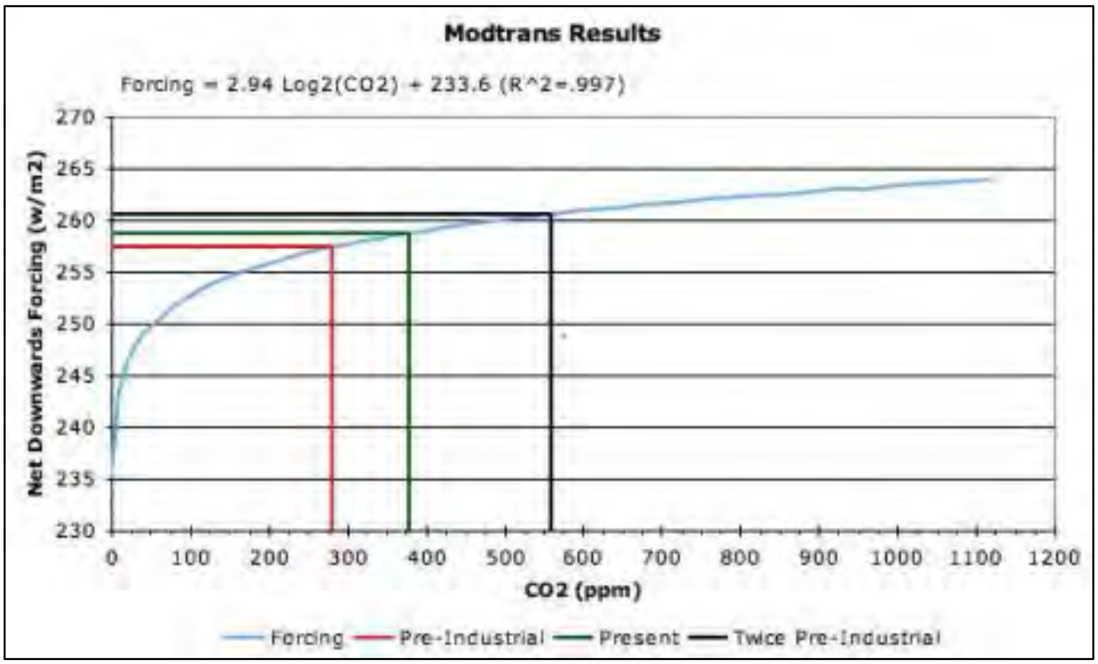
These criticisms suggest that the IPCC 2007 model predictions may be unreliable for predicting future climate and that the over emphasis on CO_2 may have skewed modelling. The IPCC notes that it has confidence in its models, but recognises the models do have problems (http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf). The typical arguments against the models are presented at http://www.john-daly.com/forcing/moderr.htm. Some of the key issues with the IPCC reports, models and data are briefly presented below.

2.2.1 Carbon Dioxide (CO_2) and Water Vapour

CO_2 is considered by the IPCC to be one of the main “Greenhouse Gases” (GHG‟s) which leads to a warming of the earth and its atmosphere. The IPCC reports are focussed on CO_2 as a greenhouse gas, which is reportedly increasing in atmospheric concentration by comparison to pre-industrial concentrations. The pre-industrial concentrations are, to a large extent, derived from ice cores.

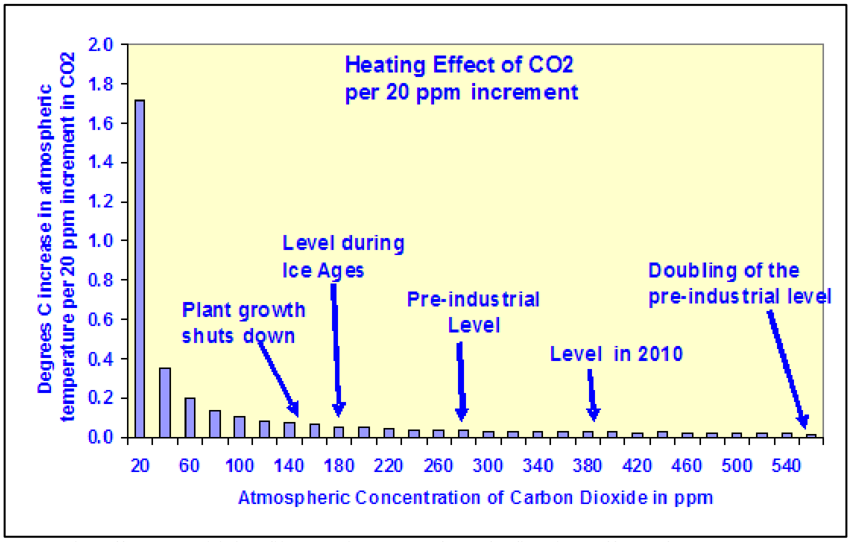
There are, however, scientists who think that the reliance on ice cores to determine CO_2 concentrations is flawed, as they have shown that CO_2 and other greenhouse gases escape from the ice cores once they are drilled and that this leads to lower than real CO_2 concentrations for the past. In essence, they argue the ice cores are not a reliable source of information relating to historic greenhouse concentrations as they under report the atmospheric conditions that really occurred. CO_2 may therefore not be increasing at the rate that scientists generally accept (Jaworowski, 2007), suggesting it is not as important for climate change as suggested by the IPCC.

CO_2 functions as one of many greenhouse gases that keep the earth about 30°C warmer than the minus 15°C it would otherwise be. CO_2 contributes about 10% of that warming, or roughly 3°C. The relationship between CO_2 and temperature is, however, not linear, but logarithmic.



Source: http://wattsupwiththat.files.wordpress.com/2010/03/co2_modtrans_img1.png

Figure 15: Logarithmic temperature response of CO_2.



Source: http://wattsupwiththat.files.wordpress.com/2010/03/heating_effect_of_co2.png

Figure 16: Temperature response to 20ppm increment increases in CO_2 concentration.

From Figure 15 and Source: http://wattsupwiththat.files.wordpress.com/2010/03/heating_effect_of_co2.png

Figure 16, it becomes apparent that the first 20ppm of CO_2 results in over half of the heating that the gas is capable of causing. Even if CO_2 concentration increases further in the atmosphere, there is, because of this logarithmic relationship with temperature, a diminishing capacity for it to cause warming. So, as a doubling to pre-industrial concentrations is unlikely to cause a run-away temperature scenario, the sensitivity of climate to CO_2 as claimed by the IPCC is not accepted by all (Scafetta, 2010).

The IPCC (FAR, 2007) and NASA (Spencer, 2010) claim that the CO_2 will cause a positive feedback with water vapour and that is how the temperature will become elevated. Water vapour is also regarded as one of the greenhouse gases, and in a linear relationship there should have already been 2°C of warming (Archibald, 2010). However, the earth has only experienced about 0.7°C of warming over the 20th Century, the period since this positive feedback should have been detected (Archibald, 2010). This means that either the relationship between water vapour and warming is not coupled with $CO_{2,}$ or the positive feedback mechanism of CO_2 with water vapour is not well understood. The warming predicted from these two gases is therefore not matching the low warming that has been recorded in reality. Consequently, the models are over predicting the temperatures in response to the CO_2 and water vapour. Spencer (2010) goes further, noting that water vapour becomes a negative feedback mechanism, not a positive feedback, as clouds reflect incoming solar radiation. An increase in water vapour does not necessarily mean more heating, but could lead to more cooling if there are more clouds formed.

Furthermore, the role of CO_2 as a driver of climate change is also questionable. In recent papers, Soares (2010) and Bastardi (2010) report that temperature is not linked to CO_2, but to water vapour, and that CO_2 follows temperature change and does not lead it. The main mechanism for the lag in

CO_2 is warming of sea water, which causes CO_2 to be liberated about six months to a year behind the warming. Soares goes further to demonstrate that the areas with high humidity and increasing humidity are the ones that also indicate a warming of the air temperature. Humidity is reported to have increased by 2% over the past 20 years. The areas that are revealing this warming are the mid to high latitude continental areas. Soares notes that the disconnect between CO_2 and warming, the low increase in humidity and the declining intensity of the sun, suggests the near multi-decadal future will be cooler and the last decade of stable temperature was the turning point from warming to cooling.

2.2.2 Computer Modelling

The IPCC has relied extensively on climate models to predict future climate under different CO_2 and greenhouse gas emission scenarios. The results of these circulation models differ widely with outputs, suggesting that the greenhouse gases could lead to a warming of the atmosphere and oceans and that the warming could lead to a melt-water influx into the Atlantic, shut down of ocean currents such as the Gulf Stream and potentially start a cooling process across Europe, with a potential spread into North America (Adams et al., 1999).

However, the data that is fed into these models and the processing of that data has been closely scrutinised (e.g. www.climateaudit.org) and the model outputs verified against reality. This has led many to conclude that the data produced is unreliable at the local, regional and global scales for multi-decadal periods.

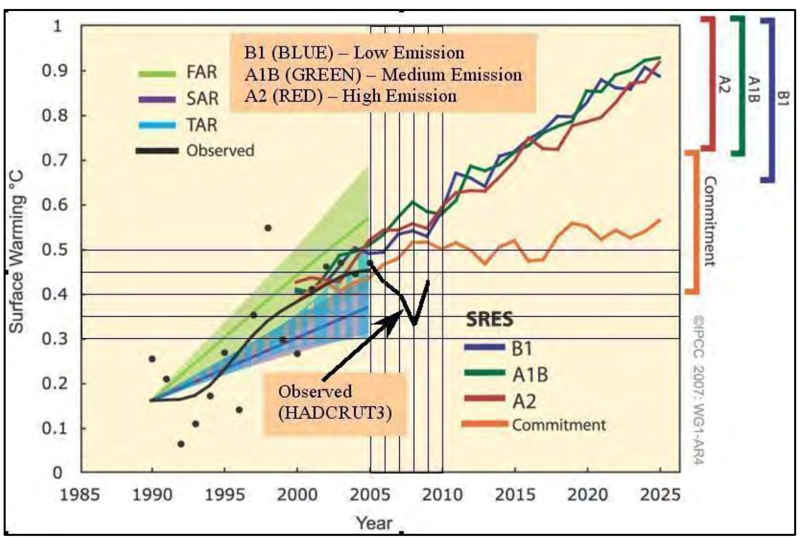
Anagnostopoulos et al. (2010) report their work on validating a model which was claimed to be very accurate at the continental scale and above. "Examining the local performance of the models at 55 points, they found local projections did not correlate well with observed measurements. They also found that the correlation at larger spatial scales, i.e. the contiguous USA, was worse than at the local scale."

Increasing numbers of studies (Anagnostopoulos et al., 2010; Rial et al., 2003; Maue, 2010; Goddard, 2010; Giles, 2007; Pielke et al., 2009; Smith, 2010; Scafetta, 2010) are showing that climate models are not able to model future climate realistically at any scale, as they have too many degrees of freedom and because the climate is complex, uncertain and affected by sources such as nonlinearities, feedbacks, thresholds, etc. Climate is inherently uncertain; models produce unpredictable results with a constant external forcing, suggesting there is limited or no causality relationship between its state and the forcing. In essence, they conclude that climate is unpredictable and uncertain with too many variables to be able to model reliably.

Eschenbach (2010) has also evaluated model performance to determine how they operate and has interesting observations relating to model reliability. Two key findings of the work are that the models will always predict an increase no matter what level of CO_2 is used. Furthermore, it was found that the modellers made up parameters to tune their models in the hind casting verification exercises, and that this action essentially means that the models will appear to predict future climate well, because they performed well in the past. Eschenbach suggests that if tweaking was required to make hind casting match historical temperature trends, then it is unlikely the models will realistically model future climate, as the mechanisms driving the climate are not well accounted for in the models.

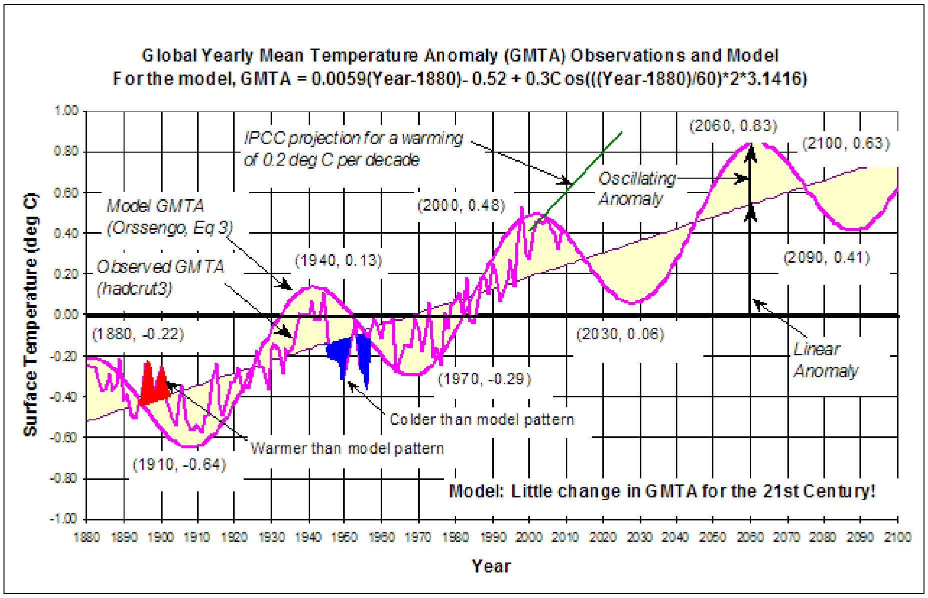
NASA has also recently undertaken modelling studies, showing that plants and trees in a world with doubled atmospheric CO2 would create a new negative feedback, or cooling effect, of -0.3°C to -0.6°C over land (Watts, 2010). Without this feedback, NASA models predicted a warming of 1.94°C globally when CO2 is doubled. This is just one of many examples where the models are currently deficient and overestimate the warming.

Orssengo‟s (2010) research has shown that the IPCC claim for global warming is that “for the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios.” This claim is not supported by observations, as shown in Figure 17. Global mean temperature trend has plateaued for the last decade and is lower than the commitment temperature that would be followed if CO_2 was held at year 2000 concentrations. Orssengo goes further and demonstrates that the IPCC rate of warming projection is overestimated. Orssengo‟s modelling has produced the output, shown in Figure 18, to address the shortcomings of the IPCC modelling approach by including known cyclical functions. This modelling approach begins to show the 60 year cycle thought to exist in the climate system. The warming under this model scenario is also less than the IPCC model predictions.



Source: http://wattsupwiththat.files.wordpress.com/2010/04/orssengo1.jpg

Figure 17: Actual temperatures compared to model scenarios.

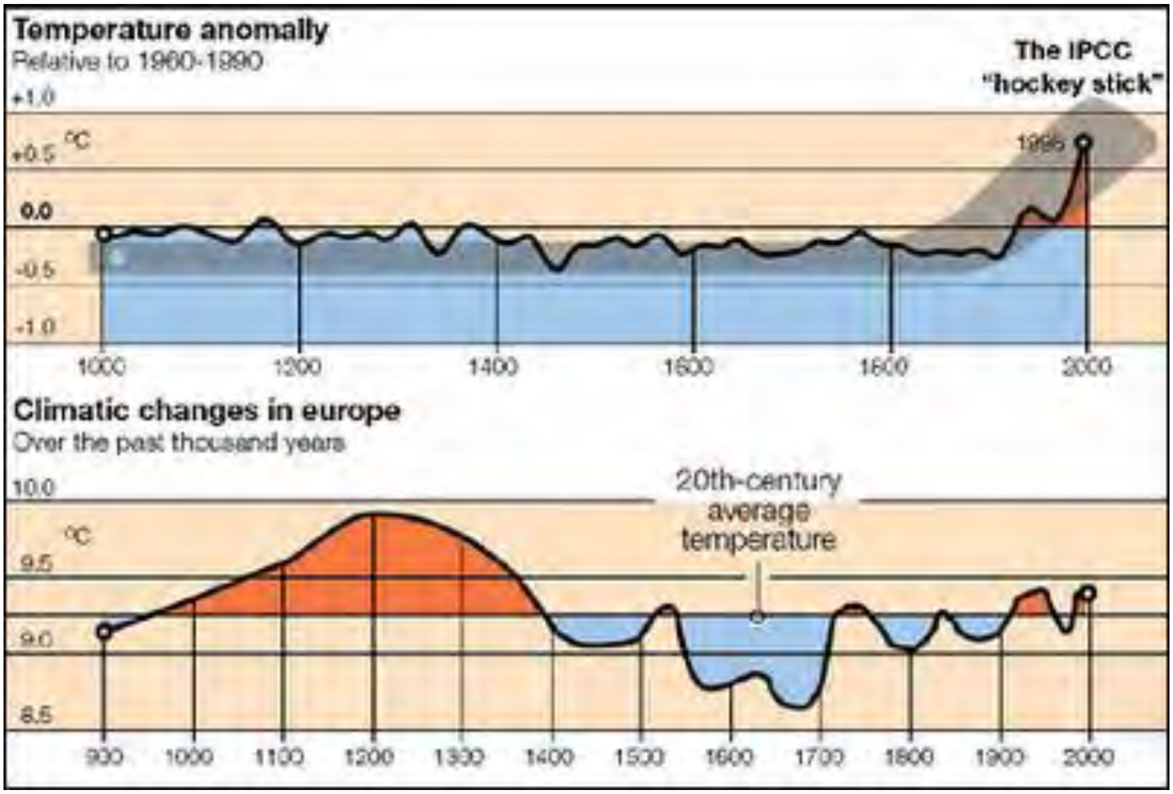


http://wattsupwiththat.files.wordpress.com/2010/04/orssengo3.png

Figure 18: Simple model with 60 year cycle added in comparison to IPCC model output.

2.2.3 Temperature Data

The integrity of the raw temperature data set that is used as the historical basis for refining the IPCC climate models has also been brought into question, as shown in recent reviews (Scafetta, 2010; D"Aleo, 2011) and generally at www.climateaudit.org. Not only is the integrity of this data important for modelling, but it is also important for determining the trend and rate of climate change. The IPCC has used, in many of its reports, a graph that has become known as the “Hockey Stick” graph because of its shape (Figure 19). This graph which is based on data used in the models gives no recognition to the Medieval Warm Period (1000 -1300 AD) nor the Little Ice Age (1500-1800 AD). The Little Ice Age is particularly important, as many argue that the earth is in a recovery period from that ice age and is why increasing temperatures are being experienced. Akasofu (2010), having identified a temperature increase rate of 0.5°C/100 years since the Little Ice Age, suggests we are still on the rebound, and the warming currently being experienced is part of that. The Medieval Warm Period is also important in the debate, as it was a time when Greenland hosted Viking villages and farms on the coastlines, suggesting a warmer climate than today. The IPCC graph does not show either of these periods.



Source: http://3-b-s.eu/michael-mann-hockey-stick-graph-p-571376.html

Figure 19: IPCC anomaly hockey stick graph and graph of temperatures in Europe.

Temperature measurement is another aspect that has been brought into question and is reviewed by D"Aleo (2011), Scafetta (2010) and Frank (2010) and is presented as an extensive database populated with USA data at http://www.surfacestations.org/. There is considerable evidence that most of the weather stations in the USA (69%), the most weather instrumented land on earth, do not meet the minimum requirements for weather stations, and that the potential error from many of these stations (≥2°C) is greater than the climate variability that has been measured over the past century (0.8°C). A paper recently posted at Wattsupwiththat.com (2011) looks at the physical reading error associated with thermometers and concludes that a ±1.3°C error on mercury and alcohol thermometers is possible. A recent paper by Frank (2010) raises another issue with the measurement of temperature at weather stations. Evaluating sensor measurement uncertainty (±0.2°C) and systematic measurement errors, "a representative lower-limit uncertainty of ±0.46°C was found for any global annual surface air temperature anomaly." The consequence of this is then stated as: "This ±0.46°C reveals that the global surface air temperature anomaly trend from 1880 through 2000 is statistically indistinguishable from 0°C, and represents a lower limit of calibration uncertainty for climate models and for any prospective physically justifiable proxy reconstruction of paleo-temperature. The rate and magnitude of 20th century warming are thus unknowable, and suggestions of an unprecedented trend in 20th century global air temperature are unsustainable."

The analysis undertaken by D"Aleo (2010) suggests location changes, externalities and changing land use and land cover around weather stations has functioned to increase the temperature of the earth surface. In particular, urban heat island effects have been identified in many urban stations. To correct this, D"Aleo (2011) and Long (2010) claim rural stations were adjusted upwards to match the urban stations, and in doing this, the warming at the earth surface was caused. D"Aleo"s analysis also claims that the early 20th Century and late 19th Century were cooled and more recent years warmed, in effect showing an exaggerated rising temperature for the 20th Century (Figure 20). With regards to Arctic temperature, D"Aleo also shows that the data extrapolation in the NASA GISS dataset extends land based temperature records into the Arctic area by as much as 1200 km and causes the Arctic temperature in this dataset to be artificially warm. The warming reported by NASA in GISS is not corroborated by actual station measurements. In summary, D"Aleo claims that the adjustments made by NOAA and NASA to the temperature datasets account for virtually all of the trend in the data. D"Aleo concludes his review with this statement: "These factors lead to significant uncertainty and a tendency for over-estimation of century-scale temperature trends. A conclusion from all findings suggest that global data bases are seriously flawed and can no longer be trusted to assess climate trends or rankings or validate model forecasts. And, consequently, such surface data should be ignored for decision making."

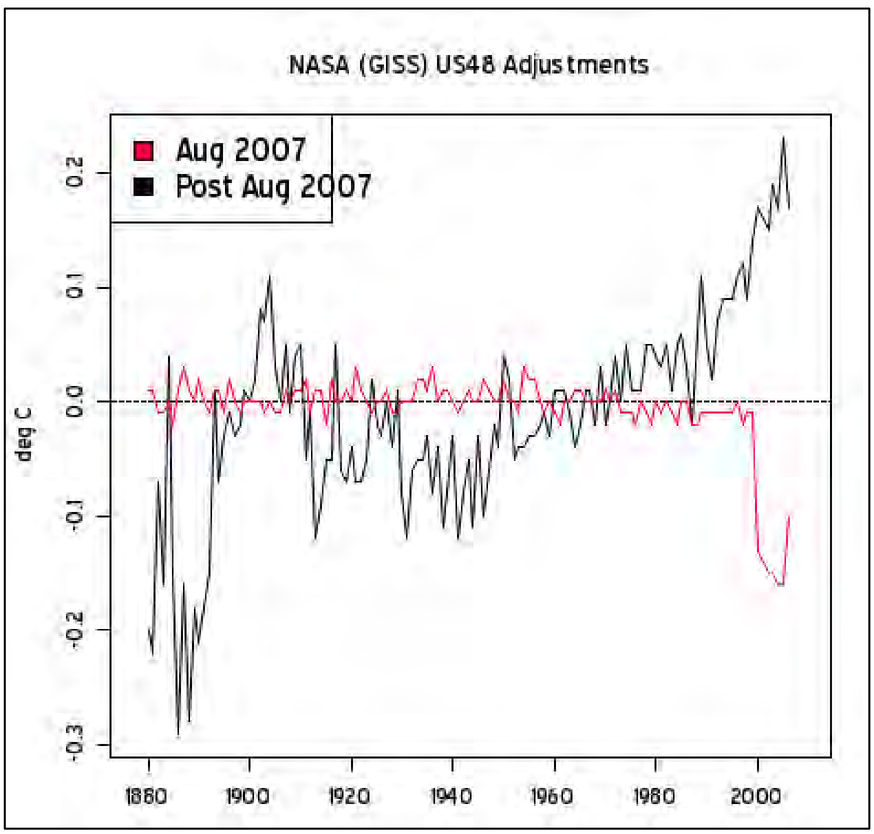
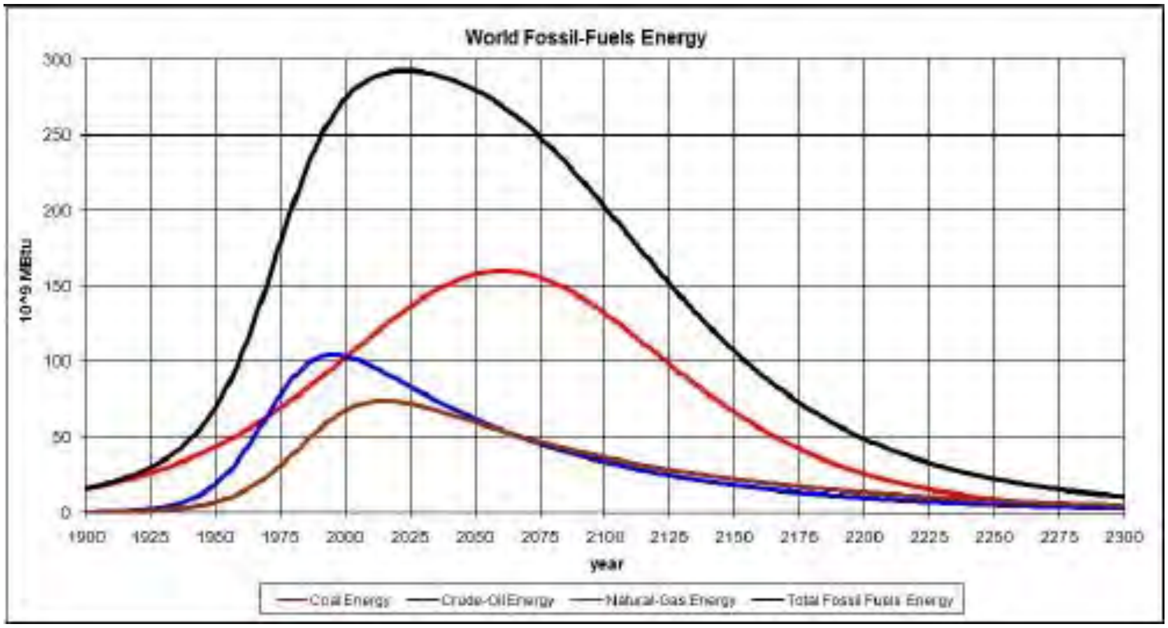


Figure 20: Example presented by D'Aleo to show NASA GISS data adjustments (Red data original data, Black line adjusted data).

2.2.4 Future Energy

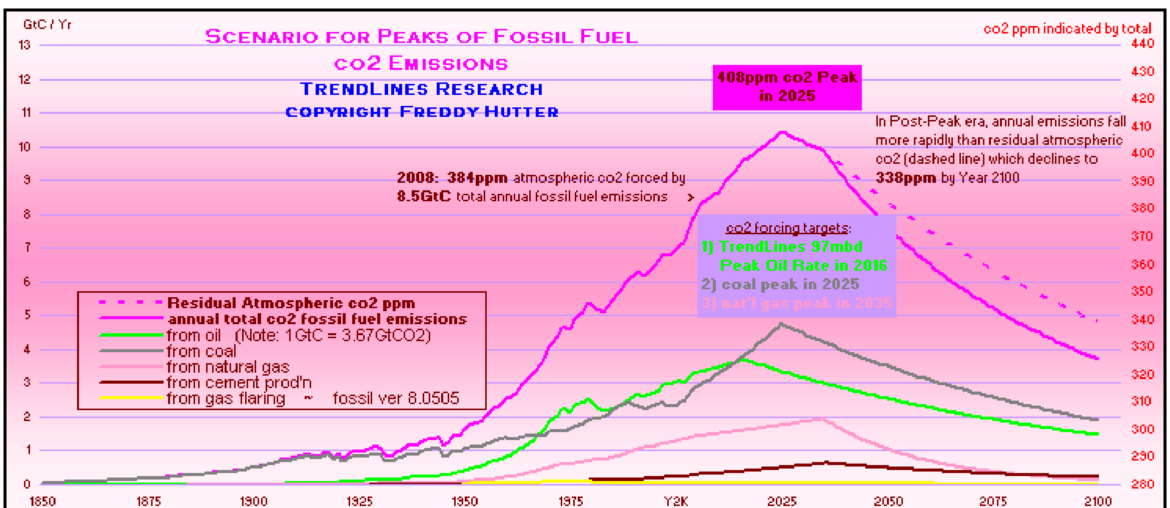
The Greenhouse gas emission scenarios used by the IPCC (Figure 11) are considered by some to be unrealistic, however not all of that debate is of relevance here. One aspect that is of relevance to this report is the long-term emission profile and residual atmospheric residence time of CO_2. It has been noted above that CO_2 has a logarithmic influence on temperature and that a future is predicted by the IPCC to have increasing CO_2 concentrations. From this, it is inferred that increasing amounts of CO_2 in the future will cause limited warming.

It is predicted that CO_2 will peak in the atmosphere in the range of 600-1000 ppm between 2030 and 2200 (Motl, 2011) (Figure 21 and Figure 22). The fossil fuel based fuels will be replaced over time (Nezhad, 2009; U.S. Energy Information Administration, 2010; Shell, 2008; World Energy Council, 2007; Andersen and Nilesen; Mintzer et al., 2003; Kram et al) and the atmospheric CO_2 concentration will start returning to equilibrium with temperature, which Motl describes as being in the range of 2°C to 4°C higher than today. It is anticipated from evidence presented by Motl that the atmospheric CO_2 concentration will return to about 300 ppm within 800 years and probably even less, based on a natural CO_2 absorption rate of 1.7 ppm per year. This absorption rate is expected to be greater at higher CO_2 levels and decline as atmospheric CO_2 concentrations decline. CO_2 absorption is decreased as temperature rises. Therefore, any future cooling will see enhanced CO_2 absorption. On this basis, if CO_2 is responsible for heating the atmosphere, the time period during which it will have an effect on global temperatures will be determined by how quickly other energy sources are developed or how long carbon dioxide will reside in the air or be absorbed. Basing long term future climate models, beyond 200 years after present, on elevated CO_2 scenarios is therefore not realistic as CO_2 production will decrease in the future and CO_2 absorption will continue, tracking temperature changes which some claim may cool over the next 30 years. CO_2 will not be produced in the same volumes in the future and the dominant natural climate drivers will again control the climate in several hundred years in the system as we now understand it. This is a window in time when CO_2 produced by humans is out of equilibrium with planetary temperature and it will return to an equilibrium state in time, as suggested in Figure 22.



http://www.roperld.com/science/energy.htm

Figure 21: Potential future hydrocarbon energy mix to 2300.



d

lines.ca/energy.htm

Figure 22: Peaks of fossil fuel CO_2 emissions till 2100.

2.2.5 Solar Variation

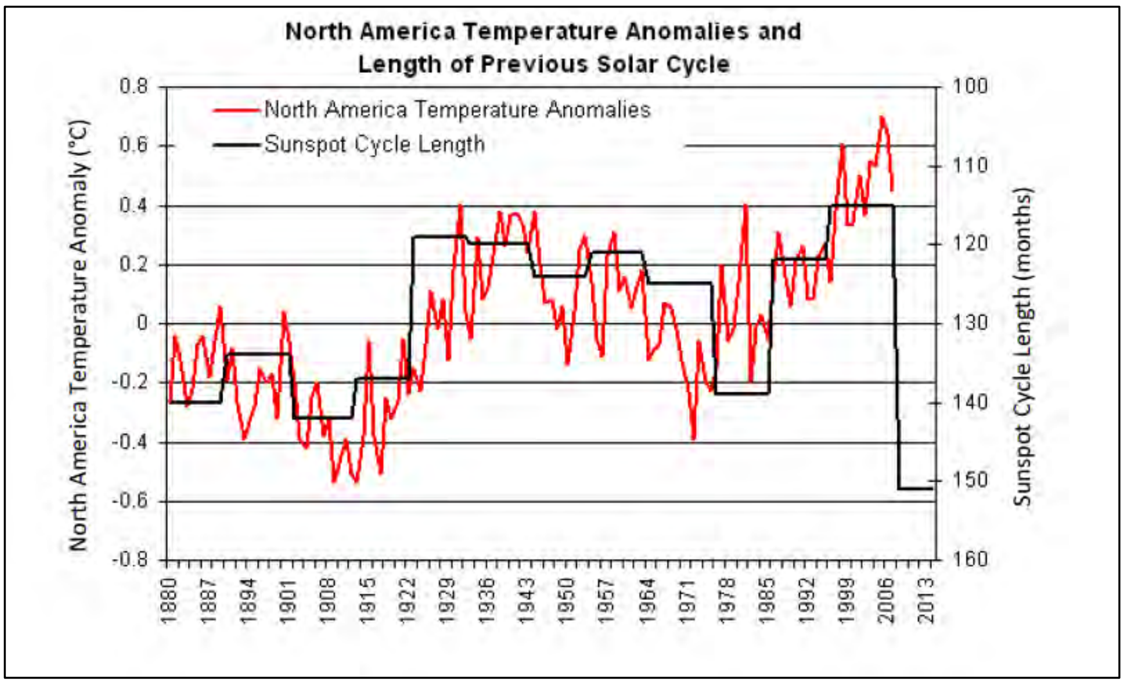
One of the key concerns relating to the methodologies used in the climate models is the strength of and sensitivity to solar radiation. The IPCC reports consider incoming solar radiation to be a natural forcing mechanism (Figure 12), but one with limited influence on temperature (IPCC, 2007; Scafetta, 2010). Studies have shown that the IPCC models do underestimate the influence of the solar contribution and that the climate models do not have the sensitivity that the earth is revealing (Stott et al, 2003; Scafetta, 2010; Krivova et al, 2010), but solar irradiance as measured does not account for the temperature that is experienced on earth. The models that have been evaluated also confirm that the second part of the 20th Century showed a linkage between temperature and CO_2 concentration. Bear in mind however, as noted in the concern described above in Future Energy, that as temperature increases, the ocean‟s capacity to hold gas is reduced, suggesting that the CO_2 may be responding to the temperature and not causing the increase. Many studies have identified a link between solar variations and the earth‟s temperature (Glassman, 2010; D‟Aleo, 2010; Beradelli, 2010; Courtillot et al., 2006; Le Mouel et al, 2009; Hoffman, 2010; Svalgaard, 2007, 2008, 2009; Sharp, 2010; Shindell et al., 2001; Schmitt, 2010), however, until recently, a possible causal relationship has been elusive. Solar input variation to the earth can be can be achieved by:

- Orbital variations as identified by Milankovitch (described later in this report)
- Variations in the emissions from the sun (also described later in this report)
- Variations in the location of the earth in relation to the solar system spiral arms
- Variations in the earth‟s magnetic field
- Reflection from volcanic dust and clouds
- Astronomical origins.

These aspects are explored below as part of a brief review of recent literature relating to the relationship between solar activity and earth temperature.

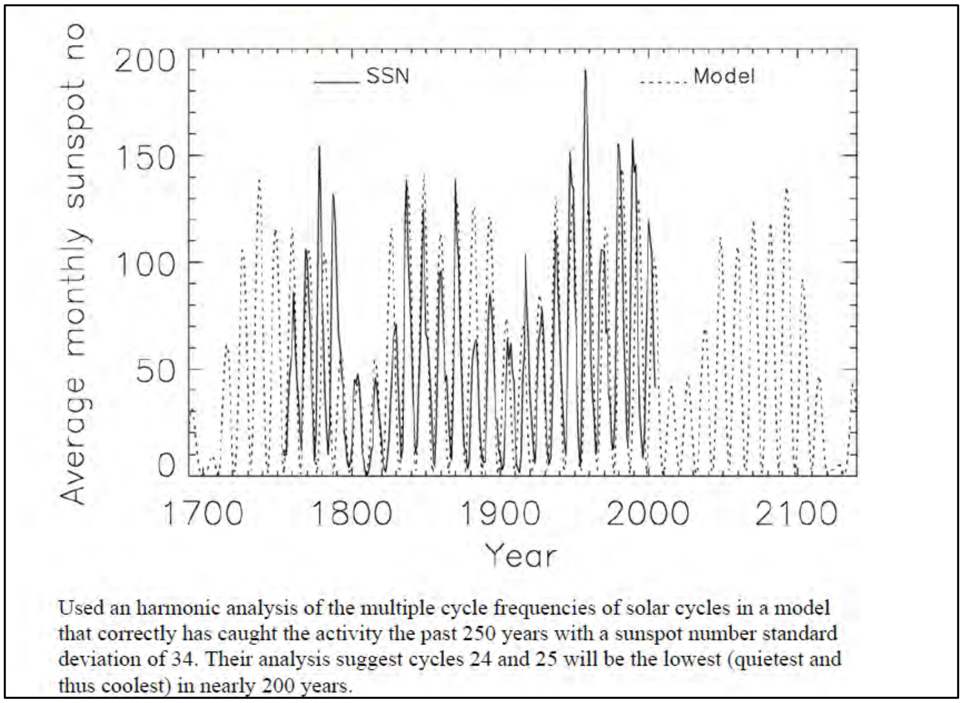
There has been a general increase in the earth‟s temperature from the latter part of the 19th Century and through the 20th Century, a time during which the strength of the solar cycle based on the number of sunspots was also increasing (Whitehouse, 2010). Some insist that this was not a thermal maximum, while others claim that up to 60% of the global warming identified could be attributed to astronomical causes (Scafetta, 2010). In the second half of the 20th Century, four out of five of the most intense solar cycles that have been recorded occurred. Included in this set of four is the one which occurred in the 1950‟s, the strongest yet recorded. It is notable that these strong cycles occurred at the time that the earth experienced its greatest warming from CO_2 based on the IPCC reports. This coincidence is fuelling much research into the linkage between solar output variations and the earth‟s temperature, partly driven by trying to understand what drives solar variation (Sharp, 2009; D‟Aleo, 2010, Gray et al, 2010).

Looking back in history, Whitehouse (2010) also notes that if the cycle length is important as an indicator of future solar activity, then past events matching the current activity may give an indicator of the future. Cycle 22 was unusually short (9.7 years) which is on par with cycles 2 and 3, which occurred just prior to the Dalton Minimum. The Dalton Minimum was a period when temperatures are reported to have dropped over a twenty year period and crop failures due to cold were reported for eastern Canada, the USA and Europe. The last solar cycle (23) lasted 12.6 years, which is on par with cycles 4 (13.7 years) and 5 (12.6 years). During these cycles, Whitehouse notes, "the sunspot numbers declined at the start of the period, the solar cycle became more symmetrical and cycle rise and fall times converged at about 6 years," conditions similar to what are currently expected for cycle 24 and some are suggesting will occur in solar cycle 25, as well (Duhau and De Jager, 2010; De Jager and Duhau, 2011; Rawls, 2011; Livingston and Penn, 2008). Therefore, there appears to be a link between the previous cycle‟s length and the temperature experienced on earth during the next cycles (Rawls, 2011). Rawls quotes Strum, of Frontier Weather Inc., who has calculated that a drop in temperature of 0.6°C to 1.8°C will occur over the next 10 to 12 years (Figure 23). D‟Aleo (2010) has also prepared a review that notes this drop in solar activity and quotes Cliverd et al, (2006) to show the future predictions of the solar cycles to 2100 and beyond (Figure 23 to Figure 25)(Sharp 2009).



Source: http://wattsupwiththat.com/2011/01/02/do-solar-scientists-still-think-that-recent-warming-is-too-large-to-explain-by-solar-activity/

Figure 23: Link between future temperature anomalies and previous solar cycle length.



Source D‘‘Aleo, 2010

Figure 24: Prediction of future solar cycles.

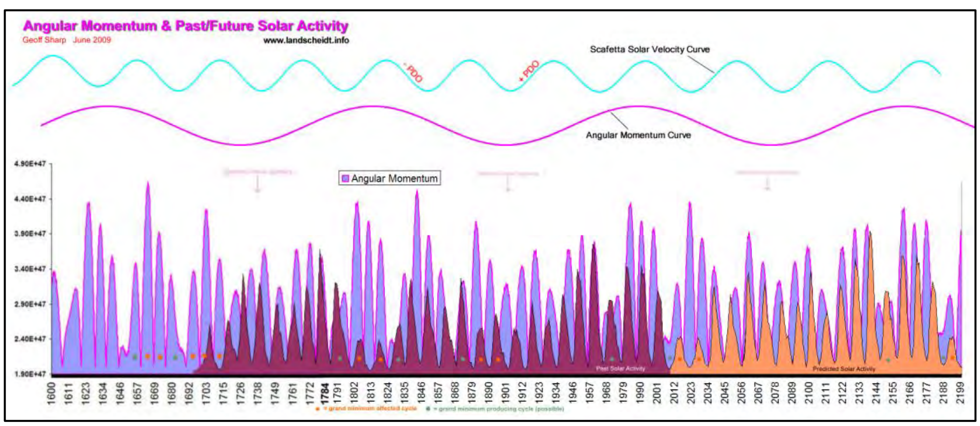
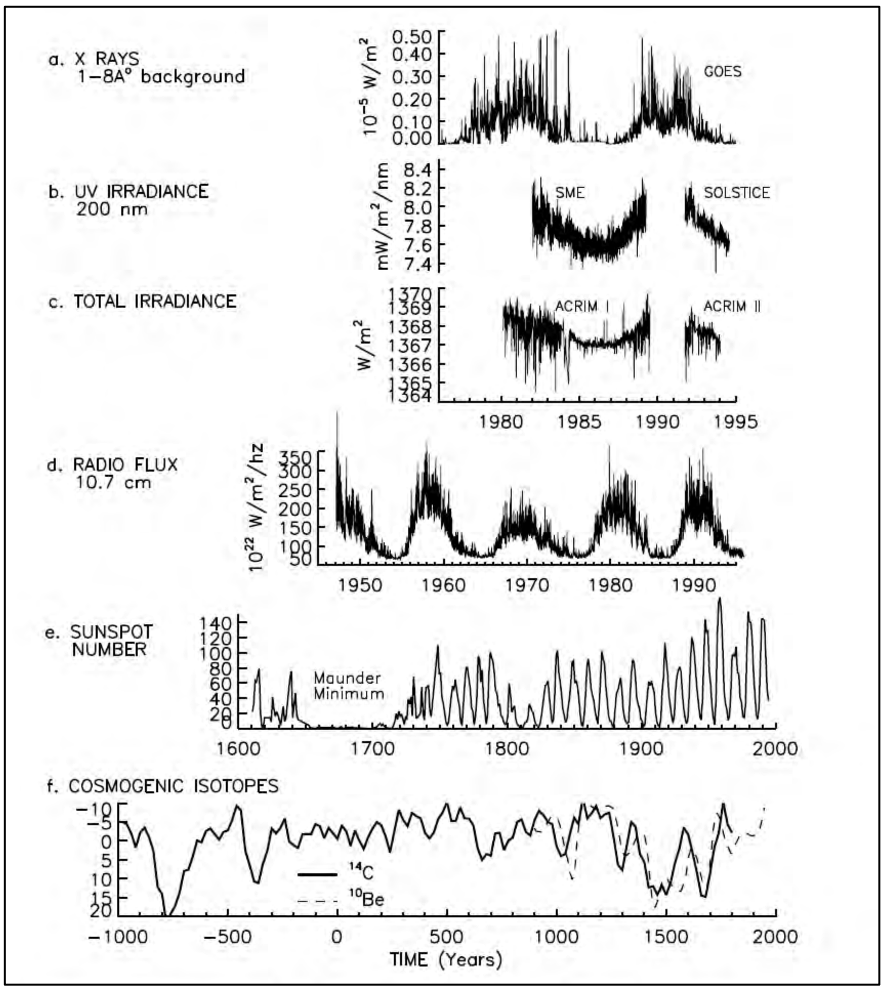


Figure 25: Future solar cycles based on Landscheidt theory (Sharp, 2010).

One of the key concerns with the IPCC report of 2007 relates to the IPCC only considering solar irradiance and its variation. The IPCC uses data that shows very little variation between 1978 and 2000 for Total Solar Irradiance (TSI). This is strongly contested by various groups who have demonstrated from measured data that TSI has increased during this time and over the Holocene (D‘‘Aleo, 2010; Solanki et al, 2004; Solanki and Schuessler, 2004; Eddy, 1977; Krivova, 2010). This simple choice of selecting a particular dataset has allowed the IPCC to claim that solar irradiance was of little significance and, therefore, that heating was primarily based on CO_2 concentration increase.

A further issue with only considering TSI is that several other forms of radiation are not considered. The sun emits radiation at specific frequencies, which individually can alter process in the atmosphere and on the earth‟s surface. For example, UV radiation alters ozone (a greenhouse gas); UV causes warming in the stratosphere, which warms the troposphere in low and mid-latitudes during winter; visible light stimulates photosynthesis, which feeds back into biosphere systems; and then the Galactic Cosmic Ray (GCR) flux, which modulates clouds that in turn alter the albedo (Figure 26) (Scafetta, 2010; Erlykin et al, 2009; D‟Aleo, 2010; Lean, 1993; Hodges and Elsner, 2010, Palles et al 2006; Lamb, 2010; Corbyn, 2010; Svensmark, 1999; Frohlich, 2009). None of these components are considered in the IPCC models and the full extent of their influence is still being determined. Some suggest the feedback mechanism may be stronger than the initial signal from the sun (Rind, 2002).



Source: Lean, 1997.

Figure 26: Variations in specific parts of the solar emission spectrum.

Considering the GCR aspect further, it has been suggested that the GCR flux causes low cloud cover extent to vary. When solar magnetic activity increases, cosmic ray flux decreases and less ionisation occurs in the earth‟s atmosphere, resulting in less condensation nuclei being available for cloud formation. Fewer clouds result in a decreased albedo and more solar irradiance reaches the earth‟s surface, resulting in warming. In Scafetta‟s 2011 paper, studies are reported that show just a 5% modulation of the low cloud cover by the sun could have the same radiative forcing impact as net anthropogenic forcing since 1750. The key linkages identified in the work reported by Sacfetta and Fluteau et al. (2006) are:

- Solar magnetic flux increase during the 20th Century correlating with the increased average global surface temperature during the last century.
- GCR flux decrease from the 1970s to the 1990s correlating with the increased TSI activity and possible earth magnetic field changes (as noted in the TSI dataset rejected by the IPCC due to increasing trend) and with the global warming observed from 1970 to 2000.
- Global low cloud cover decrease from 1984 to 2000 linking with the observed warming during this period (data from ISCCP infrared data) and TSI increase.
- It is also suggested that an increase in TSI would warm water vapour molecules reducing the likelihood of their condensation to form cloud droplets.

From this it is inferred that if TSI decreases and GCR increases, as predicted to occur for solar cycle 24, more clouds can be expected, possibly more precipitation will occur and temperatures are likely to decrease as the albedo increases due to the extra cloud and a larger area covered by snow.

2.3 Implications of Concerns

Although the models created for the IPCC by various organisations have contributed enormously to the understanding of the earth‟s climate system, they are repeatedly being shown to be making inaccurate predictions and generally overestimating the future temperature. The review presented in this section has pointed to some of the shortcomings, which range from:

- Historical temperature data set integrity issues.
- Temperature measurement accuracy and instrument error levels being as great as the warming identified.
- Overstatement of the effect of CO_2 and an incomplete inclusion of the climate mechanisms associated with CO_2.
- The models limited capacity to include the cyclicity which is being observed in real weather.
- Using energy scenarios which are not regarded as being realistic in the long-term.
- Underestimating the role of the sun, which has for many years been shown to be linked to earth‟s temperature and recently studies have started to unravel the causal mechanisms.

The literature that has been cited in this section has been selected to show the concerns with linking CO_2 to warming and the inability of the models to predict the current levelling off, if not slight cooling of the global temperature. Any approach used for future climate prediction will inevitably have strengths and weaknesses as there are gaps in our knowledge. By resolving these over time, greater certainty will be achieved. At this time, it would appear that the models have not been able to model climate at a level of accuracy required to substantiate the claims of increasing temperature over the past 10 years. The last 10 years of temperature stabilisation and slight falls at the regional and global scale are not accounted for in most models. If they are unable to reliably model in the near-term, it is unlikely that the long-term monitoring will be reliable at all, at any scale. This review suggests that an alternative mechanism not based on modelling, but rather on an understanding of the climate mechanisms and matching current situations to historical situations can add value to the process for determining a possible future climate scenario for AREVA Resources Canada. This approach can only be as good as the paleo data and cannot predict temperatures, precipitation or other variables which define weather and will also not give the levels of certainty that are required. By providing an alternative approach, the level of certainty or the range of uncertainty can be better defined. This document is not intended to replace the IPCC modelling, nor be pitched against the modelling at a local scale in Canada, but is intended to be read alongside that information in a complimentary manner, so that a better understanding can be achieved. With this in mind, the information presented in this document attempts to create a scenario not based on modelling, but on an understanding of physical processes.

3 Climate Change Cycles

3.1 Climate Cycle Timeframes and Data Types

To understand climate change, it is important to appreciate what weather and climate are and to be aware that there are variations on different time scales. This section has been prepared to show the variability and the timescales involved as well as the source of the data. It is by no means exhaustive but it creates a framework for understanding short term weather against long term climate trends. Indeed, it is possible to see a cyclical nature appearing in the data at the longer time scales which suggests there are some key driving or forcing mechanisms. This section draws on materials from various sources, but extensively from the NOAA Paleoclimatology and Climate Prediction Center, http://www.ncdc.noaa.gov/paleo/ctl/now.html#. This is an excellent summary of the climate cycles within different timeframes. The materials presented below are a concise summary of the various information sources and are fundamental to understanding climate change. The scenario that is developed in this document is based on some of the cyclic trends identified in this section.

3.1.1 Diurnal Cycles (1 Day)

The earth's weather is largely driven by the rotation the earth on its axis and the incoming solar radiation from the sun. A combination of the two we see as day and night or the diurnal cycle. Typically there is a delay between the incoming solar radiation (insolation) on the earth surface and the increase of temperature through the day. The delay is known as the thermal response. Depending on the season and the latitude, the lag can be as long as three or four hours. As an example, the hottest time of day during a typical summer afternoon would be in the mid afternoon, not at solar noon. The suns energy is also needed to drive evaporation which leads to cloud formation and rain. This forms the underlying driver for the daily weather we experience. It is not possible to describe climate variability based on any single day taken in isolation.

In Figure 27 below from the NOAA Climate Prediction Center global and ultraviolet (UV) radiation on a mostly clear day and the variation of surface temperature for the same time period is shown.

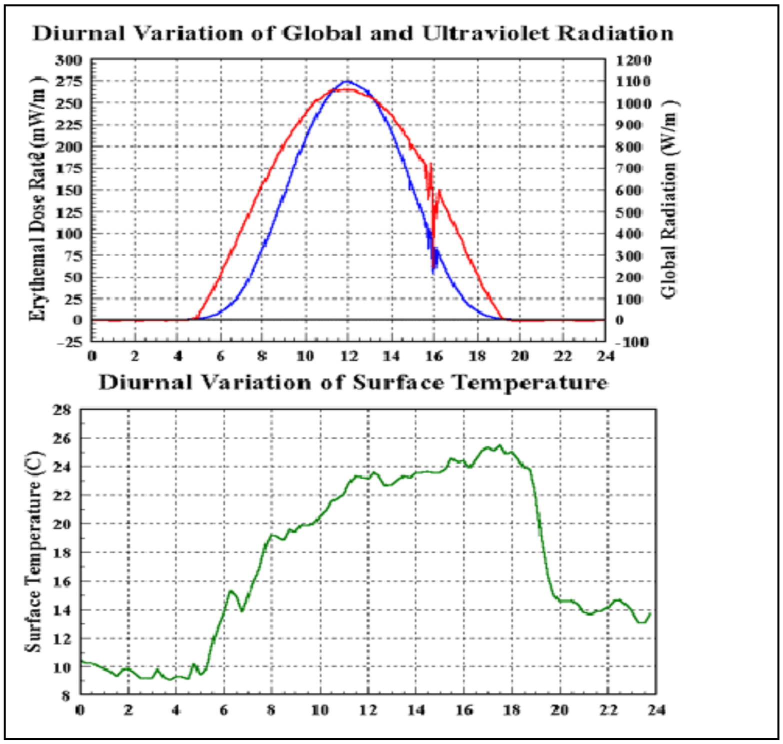


Figure 27: The diurnal cycle for ultraviolet radiation and temperature.

Measures

Measures of weather and diurnal cycles that are frequently used include:

- Weather stations
- Thermometers
- Rain gauges
- Stream gauges
- Tidal gauges.

Proxies

Information about the weather can be stored through processes such as tress rings and can be used to infer the weather that may have occurred in the past and are known as proxies. For diurnal and annual data these are:

- Tree rings
- Coral
- Ice caps and glaciers (Can provide indication of precipitation and extreme events such as fires and volcanic activity. These extreme events can be accurately dated against historic records and are used to aligning data from different sources).

3.2 Annual Cycles (1 Year)

The annual cycle is a complete orbit of the earth around the sun in which there are four seasons caused by the tilt of the Earth's axis, currently at 23.5 degrees. The seasons are caused by the tilt which alters the angle at which solar radiation reaches the surface of the earth and thus the energy available to drive weather systems (Figure 28) (NOAA Climate Prediction Center).

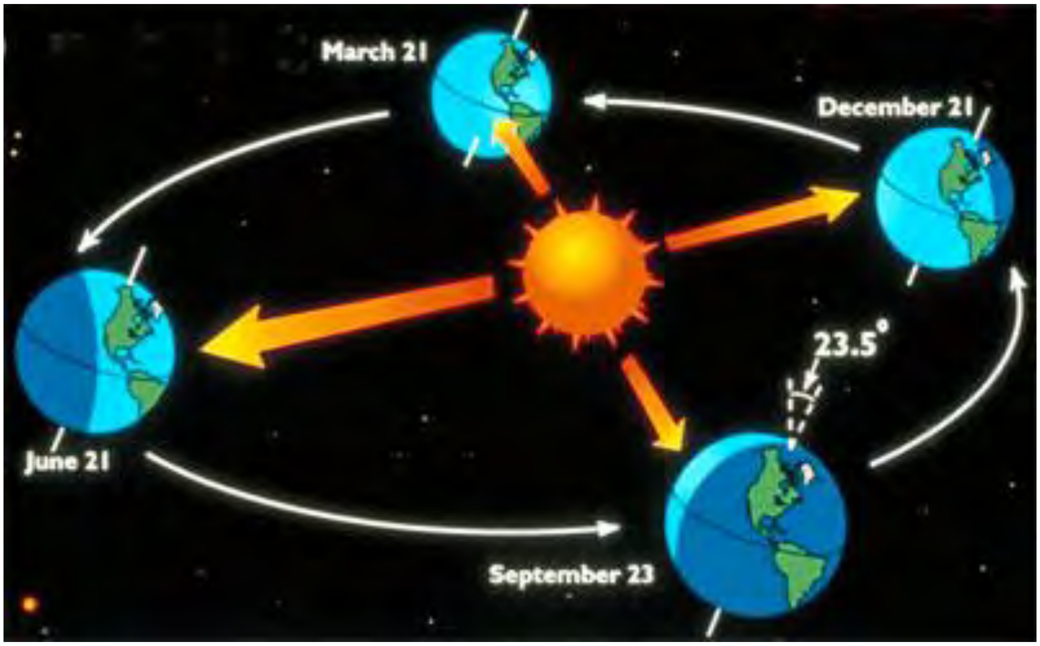


Figure 28: The axis of earth rotation and affects on insolation.

The orientation of the axis remains fixed in space as the earth completes an annual rotation around the sun, producing changes in the distribution of insolation. The earth on an annual basis remains roughly the same distance from the sun. The weather in the seasons is manifest through more extreme seasonal changes generally occurring at high latitudes, and less variation towards the equator. It is easy to discern weather changes by season over a year but difficult to see climate variability within an annual cycle. Climatic variability would require multiple years‟ worth of seasonal comparisons to see a climatic trend, though this will still not describe climate adequately.

Measures

Measures of weather and annual cycles that are frequently used include:

- Weather stations
- Thermometers
- Rain gauges
- Stream gauges
- Tidal gauges.

Proxies

Information about the weather can be stored through processes such as tress rings and can be used to infer the weather that may have occurred in the past and are known as proxies. For annual data these are:

- Tree rings
- Coral
- Ice caps and glaciers (Can provide indication of precipitation and extreme events such as fires and volcanic activity. These extreme events can be accurately dated against historic records and are used to aligning data from different sources).

3.3 Decadal Cycles (10 year)

Over a decade it becomes possible to get a perspective of climate variability as multiple seasonal data can be compared. Decadal cycles and patterns of climatic variability that are starting to be revealed include those related to:

- Sunspots
- El Niño-Southern Oscillation (ENSO)
- Pacific Decadal Oscillation (PDO)
- North Atlantic Oscillation (NAO).

In addition, research of Crowley (2000), suggests that between 40-65% of decadal-scale temperature variations during the past 1,000 years prior to 1850 were caused by changes in solar irradiance and volcanism. While individual volcanoes usually only impact climate for a year or so, clustered eruptions can perturb the climate system for longer periods of time. The four bulleted points above are described in more detail below, though it should be noted that earth based changes such as volcanism can impact climate on this time scale.

3.3.1 Sunspots

Sunspots, although only more recently measured with exacting scientific instruments are now known to follow a roughly11 year cycle. This is based on a historical record of observations spanning hundreds of years. There are now a growing number of scientists who believe the sunspot cycles may play a role in climate processes as they introduce variability into the amount of solar radiation emitted from the sun.

The information in this section is mostly drawn from:

http://solarscience.msfc.nasa.gov/SunspotCycle.shtml

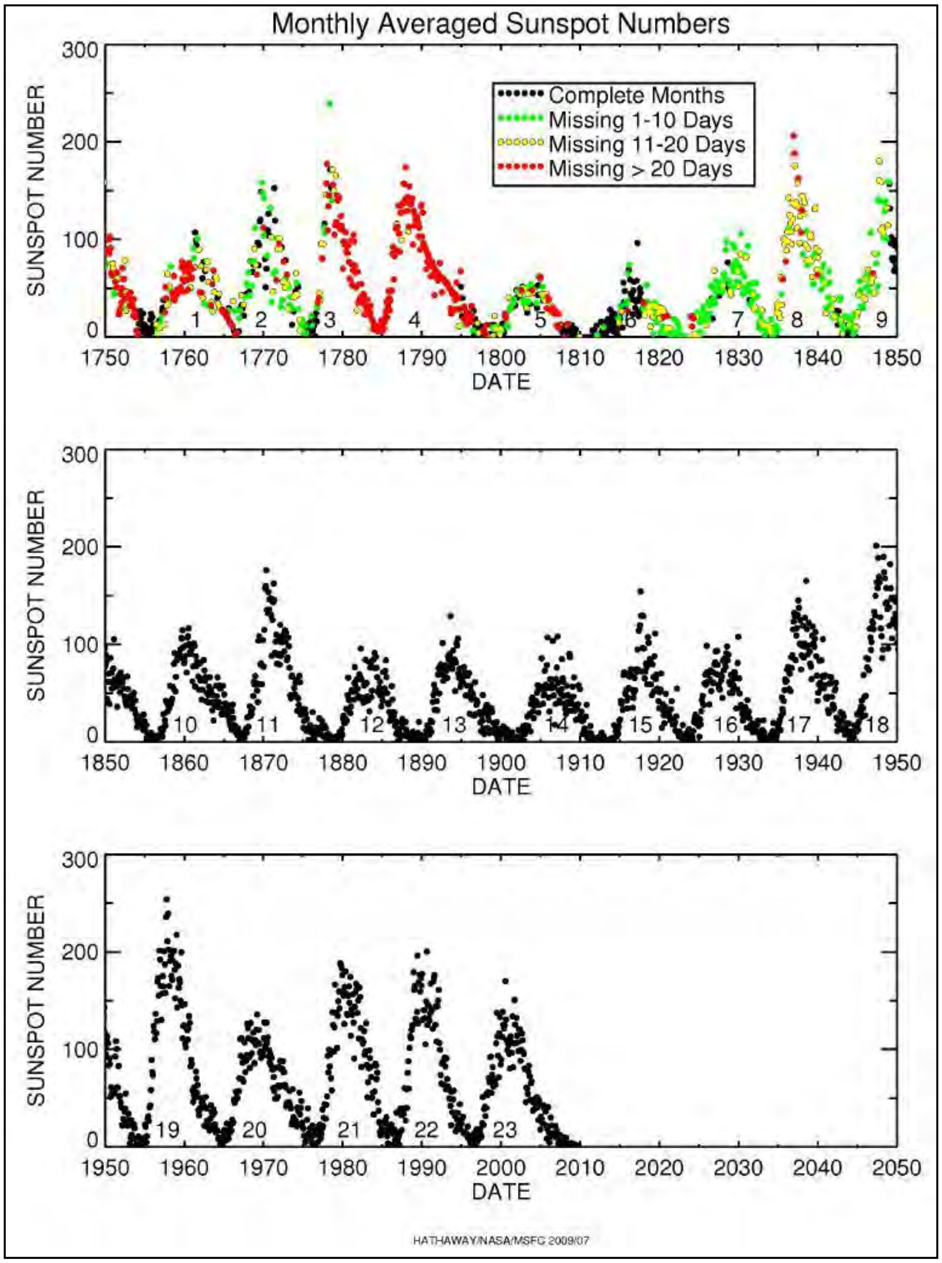


Figure 29: Sunspot data from 1750 to 2009 displaying an 11 year cycle (after Hathaway 2009).

Early records of sunspots indicate that the Sun went through a period of inactivity in the late 17th century. Very few sunspots were seen on the Sun from about 1645 to 1715. Although the observations were not as extensive as in later years, the Sun was in fact well observed during this time and this lack of sunspots is well documented. This period of solar inactivity also corresponds to a climatic period called the "Little Ice Age" when rivers that are normally ice-free, froze and snow fields remained year-round at lower altitudes. There is evidence that the Sun has had similar periods of inactivity in the more distant past. The connection between solar activity and terrestrial climate is an area of on-going research.

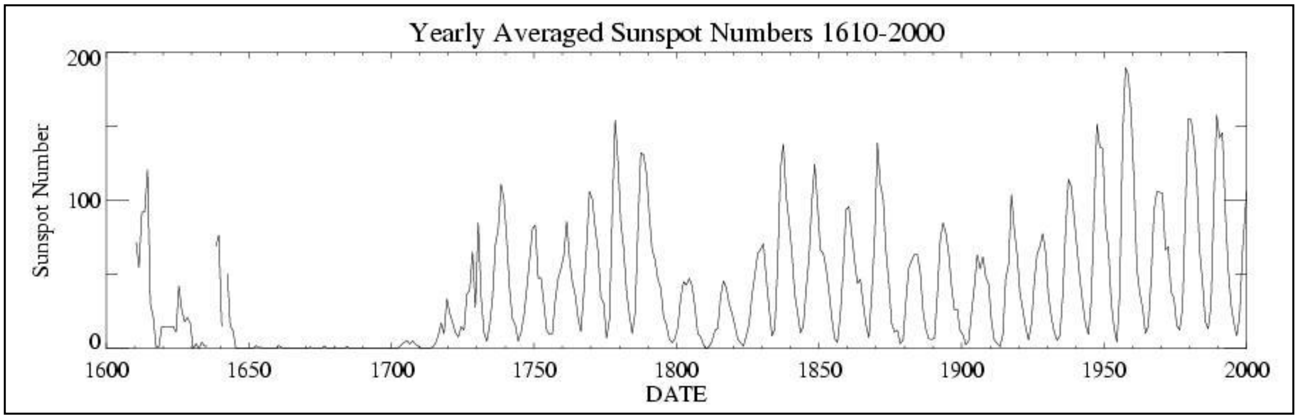


Figure 30: Yearly averaged sunspot numbers 1610-2000.

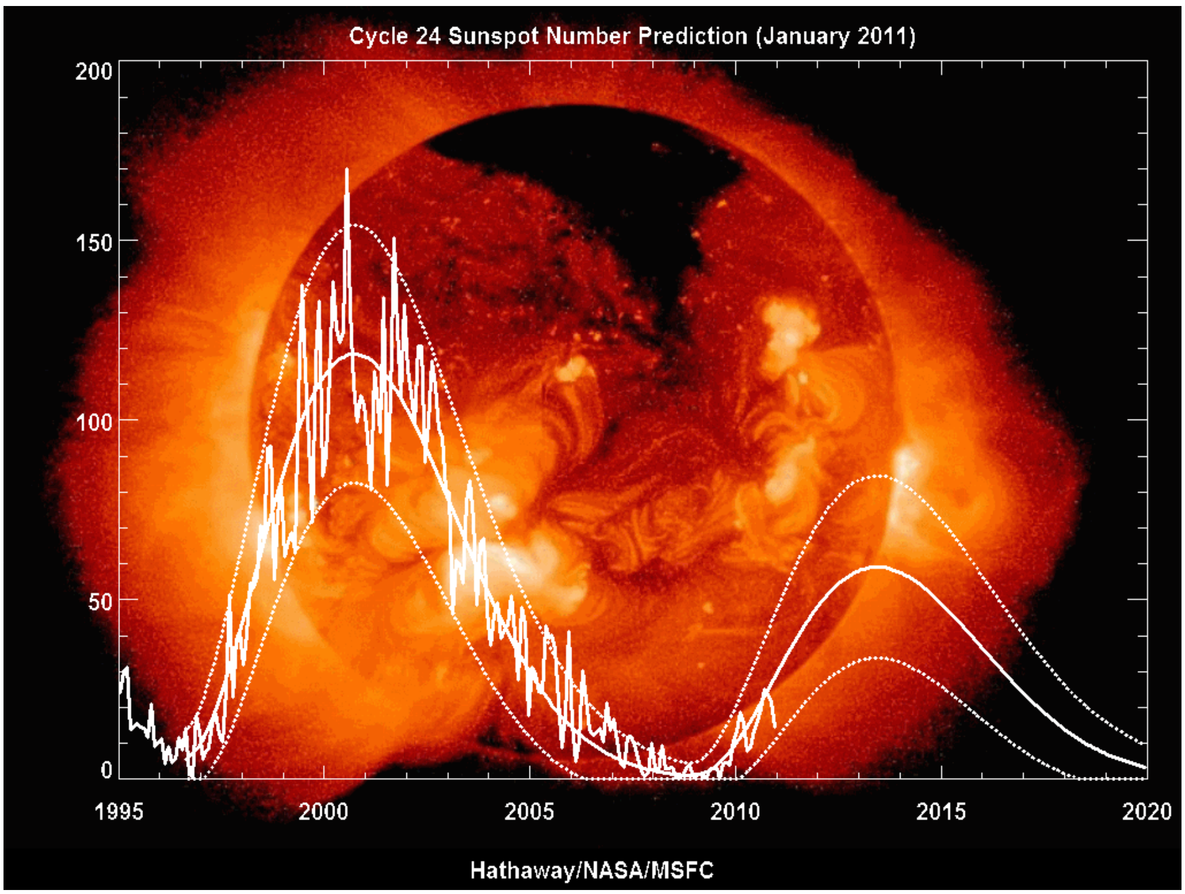


Figure 31: Sunspot number predictions Till 2020 (Updated 2011).

3.3.2 ENSO

The ENSO climatic pattern is between the one and ten year time scales and is now known to have a significant impact on interannual climate variability around the world. ENSO is an interannual variation of atmospheric and oceanic conditions in the Equatorial Pacific.

Importantly, climate occurring between one and ten year periods is only starting to be understood as the science is still relatively new. To help build this understanding paleo records are overlapped with instrumental records for patterns such as ENSO. This reveals an ENSO-like climate signature in paleo records going back thousands of years. is an image drawn from NOAA's Paleoclimatology Program showing the variability within an ENSO cycle and the repeating nature or pattern of the phenomenon. The repeatability of the signature as well as recognising which phase it is in allows it to be used to describe potential future climate.

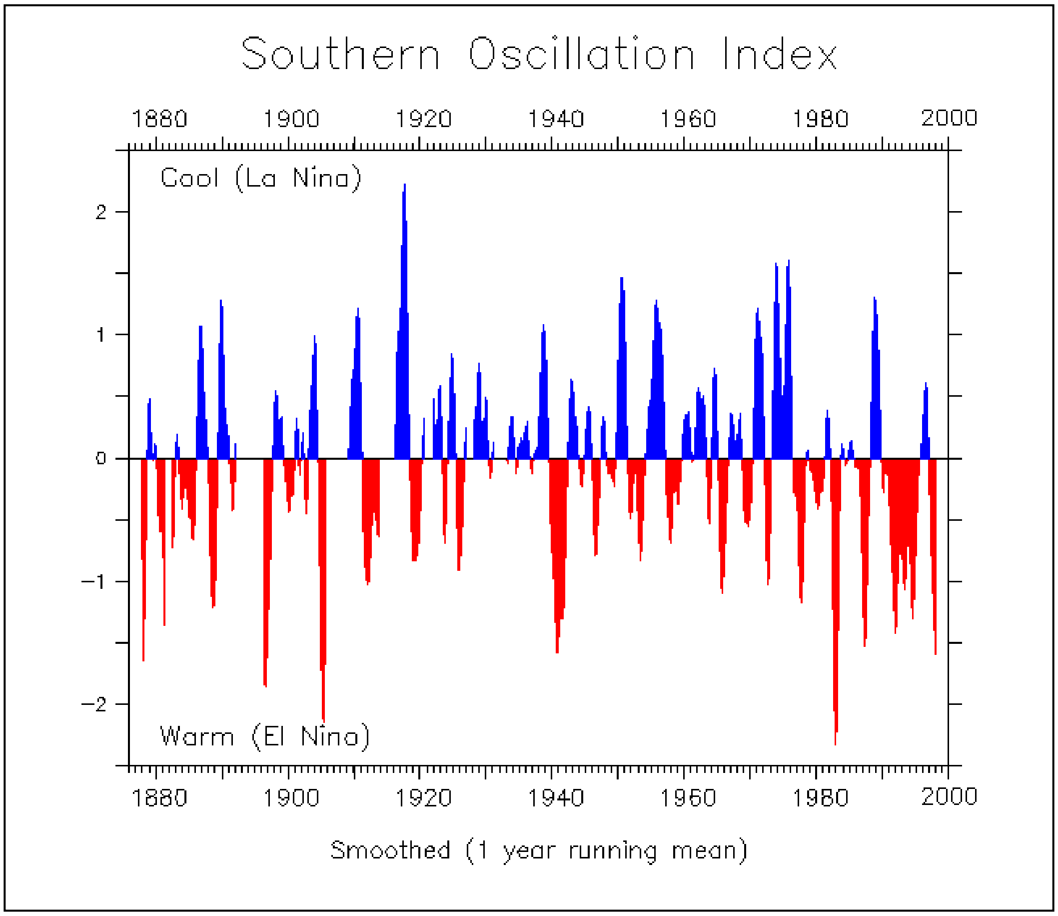


Figure 32: ENSO variability on the decadal scale and pattern on centenial scale.

3.3.3 Pacific Decadal Oscillation

Scientists examining sea surface temperatures (SST) for patterns in the heating and cooling of the ocean systems have identified variability that influence climate and fisheries. One, centered in the north Pacific and most commonly called the Pacific Decadal Oscillation or PDO, seems to have return periods of 15 to 25 years, and of 50 to 70 years. The other, the North Atlantic Oscillation (NAO), has a dominant period of 12 years (Deser, 1993), and as its name implies, it is centered in the North Atlantic.

Similar to and interacting with inter-annual phenomena such as ENSO, these decadal-scale processes appear to play a major role in regional and global climate dynamics.

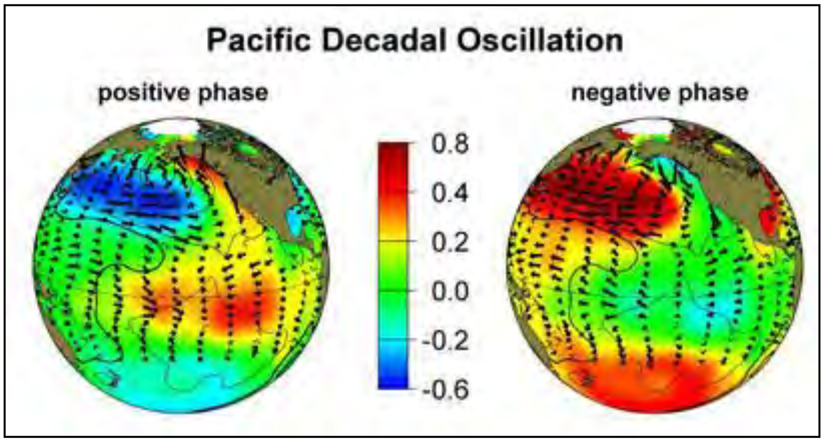


Figure 33: Pacific Decadal Oscillation phase variations.

The term PDO refers to an oscillation marked by a positive phase period when a large pool of colder than average sea surface water in the central north Pacific appears along a narrow band of warmer sea surface temperatures along the west coast of North America. During the negative phase of the PDO, the opposite is observed: a warm pool of sea surface waters in the central north Pacific and cold SSTs along the west coast. The most recent warm phase began in 1977 and may have finished in 1999. In theory, ENSO overlays the PDO's longer pulse.

Not all scientists are convinced PDO is actually an oscillating feature since research on the phenomena is less than a decade old. It has also been suggested by some researchers that PDO may be part of other features such as ENSO, or define the structure of the dynamic differently.

3.3.4 North Atlantic Oscillation - NAO

The North Atlantic Oscillation or NAO has been studied by the Lamont-Doherty Earth Observatory and other researchers for a number of years. Researchers have identified a dynamic process that has particularly important impact on European climate.

NAO varies from year to year (interannual variability) but has a roughly decadal pattern with a dominant period of 12 years (Deser, 1993).

During its positive phase, the NAO shows a stronger than normal subtropical high pressure center around the Azores and a deeper than normal Icelandic low, with increased pressure generating more and stronger winter storms crossing the Atlantic Ocean on a more northerly track. Europe tends towards warm and wet winters while northern Canada and Greenland will usually have winters are cold and dry, with the eastern United States generally experiencing mild, wet winter conditions.

During its negative index phase, NAO is characterized by weak subtropical highs and weak Icelandic lows, with fewer and weaker winter storms that cross on a more west-east pathway, bringing cold air and snowy weather conditions to the U.S. east coast during the winter months, cold air in northern Europe, and moist air to the Mediterranean.

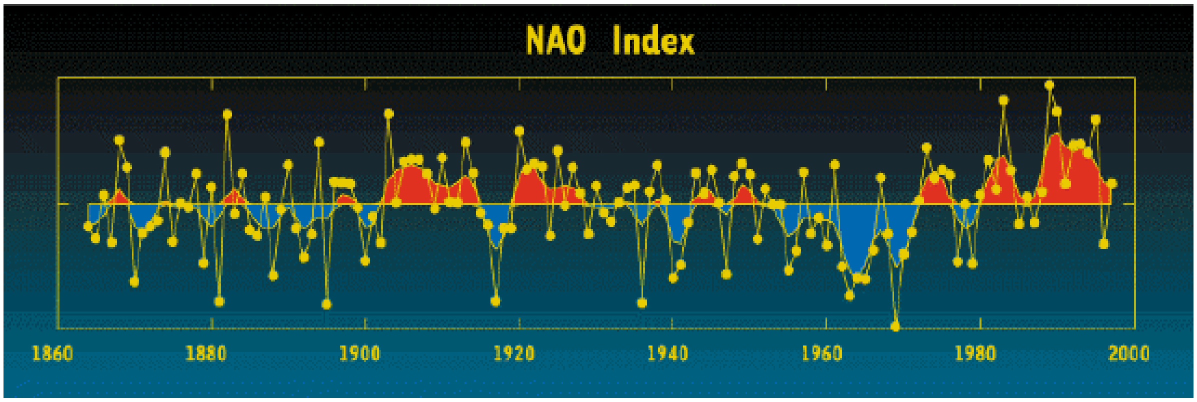


Figure 34: The North Atlantic Oscillation Index.

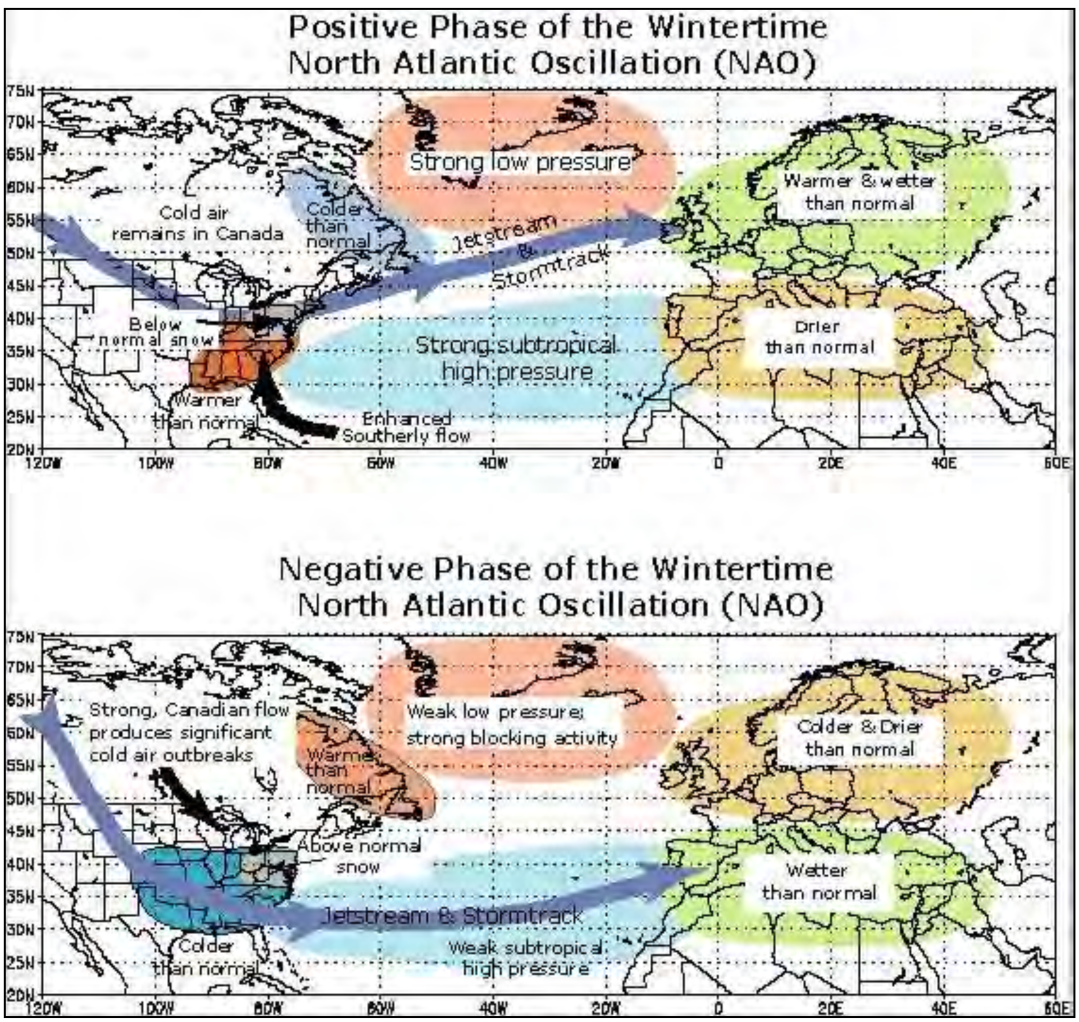


Figure 35: Possible global weather impacts of the North Atlantic Oscillation.

Measures

Instruments used to track decadal variability and climate patterns include:

- Weather Stations
- Thermometer
- Rain gauges
- Stream gauges
- Sea Surface Temperature (SST) is particularly important in tracking ENSO and other ocean oscillations
- Sunspot activity.

Proxies

An ENSO-like signature in some paleo records, including:

- Tree cores
- Corals
- Lake sediments.

3.4 Centennial Cycles (100 year)

Patterns that occur between the decadal and centennial (10-100 year) scales include:

- Greenhouse gases
- Solar cycles.

3.4.1 Greenhouse Gases and Temperature

The past 100 years have seen dramatic climate events and a significant growth in human population, increasing from approximately 1.6 billion to over 6 billion. This rapid growth of the human population has been suggested by many scientists to be an increasingly important factor to consider when assessing climate change. One component of this human factor is greenhouse gas release. One of the greenhouse gases is carbon dioxide which over the past century has seen levels rise from 290 parts per million (ppm) to nearly 370 ppm. The combustion of fossil fuels has been identified as a major factor in the increase of this important greenhouse gases potentially linked to a warming of the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) has been responsible for much of the research conducted in this field. They have used climate models to predict future climate up to 2100. This work is widely criticised for a variety reasons, however there are a large number of scientists who have contributed to this work which is continually being refined and it is becoming more robust under scrutiny. To determine if the models are reliable they have been tested against paleo data and there appears to be generally good correlation with model output. The models are complex and try to incorporate as many variables as possible while still functioning with realistic computing times.

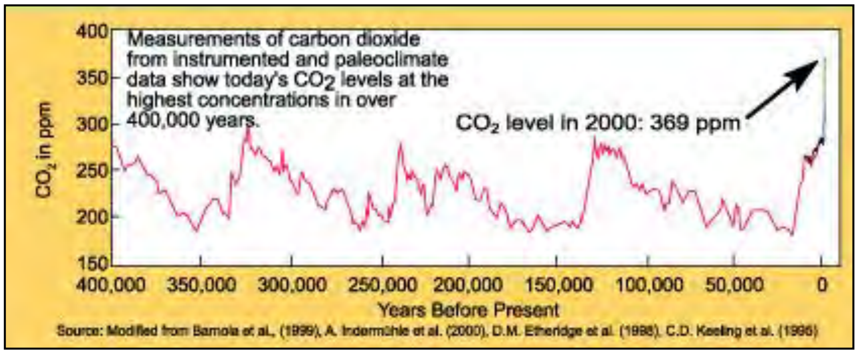


Figure 36: Atmospheric CO_2 concentrations for the past 400,000 years.

To get a flavour of this complexity that needs to be considered in the models: There has been increased cloud cover (cooling), particularly in the Northern Hemisphere during the past century, while water vapour is the most abundant greenhouse gas(warming), low clouds also shade and cool the surface (cooling). During this time carbon dioxide (CO_2) and methane (CH_4) levels have also risen (warming) and the earth is reported by the IPCC to have warmed by 0.6°C over the past 100 years. In addition, sunspot activity peaked during this period (warming) and is now in decline (cooling). It is also important to note that the correlation between solar activity and temperature ended around 1975, temperatures rose while solar activity did not, suggesting that inputs or the extent of amplification may also be changing and that greenhouse gases may be having more influence. All these different variables make for difficult modelling as they need accurate weighting to be realistic.

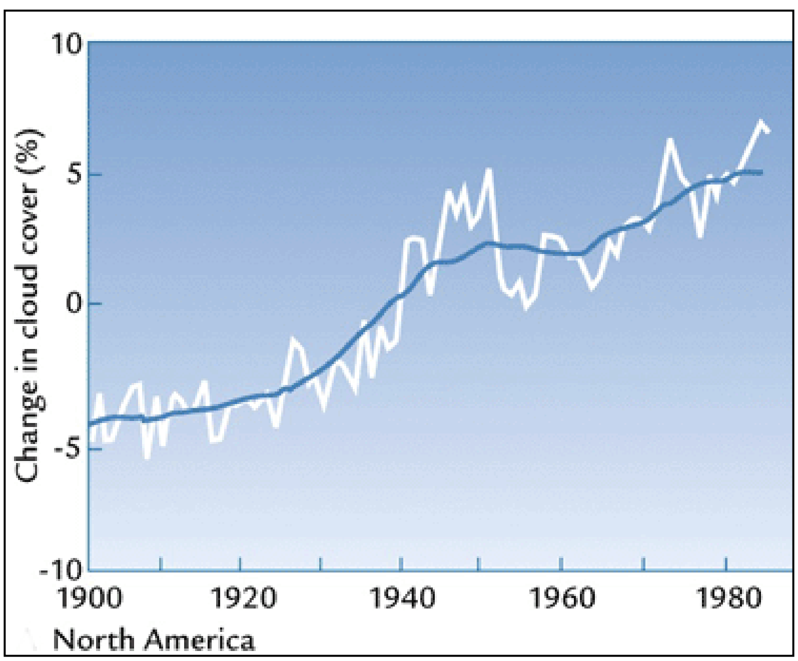


Figure 37: Increased North American cloud cover over the past 100 years.

3.4.2 Temperature and Trends

In the 20th century warming counters a millennial-scale cooling trend caused by long-term astronomical forcing. Simply stated when the key solar input forcing mechanism is weakening, or suggesting a return to cooler temperatures, earth is instead experiencing a slight warming as noted by the IPCC. Figure 38 below, based on data from the National Climatic Data Center, shows observed temperature changes as well as what would be expected from climate forcing mechanisms. CO_2 and other greenhouse gases as well as the vastly increased human population and all the changes they are bringing about in the surface of the earth are all factors that may be influencing temperature. Some scientists believe however, that mans impacts are minor by comparison to the larger forcing mechanisms in operation and hence the controversy in the climate change community.

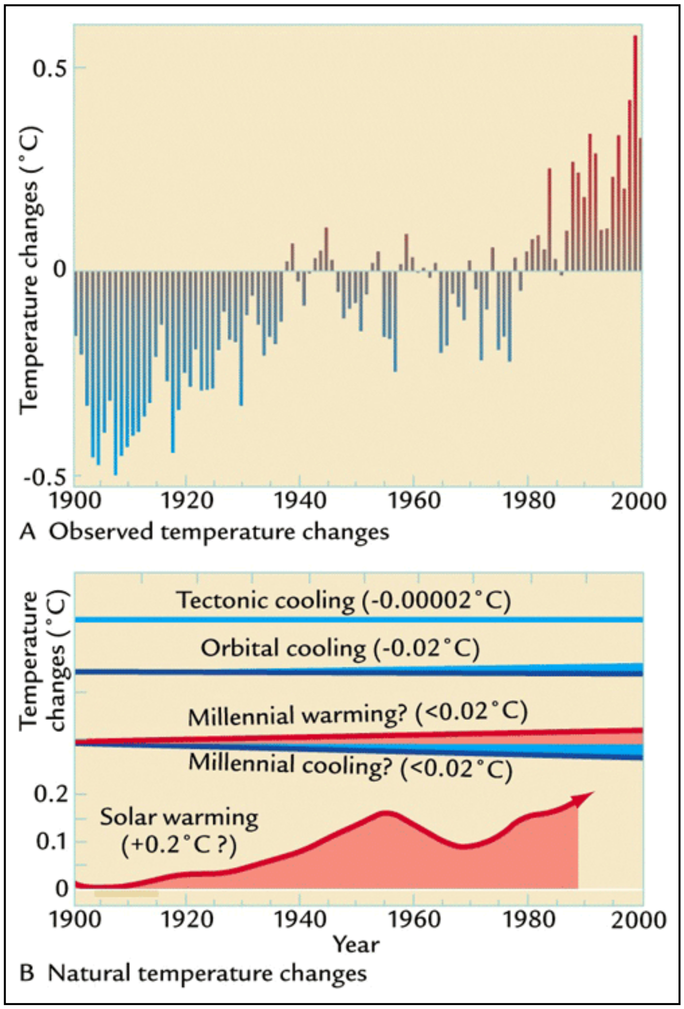


Figure 38: Observed and natural forcing mechanism temperature changes for the past 100 years.

The short term changes, when it is now known that there are long-term mechanisms at play requires that this data be viewed against much longer term records (Millennial and longer cycles) to provide a context. In this context the earth is warmer now than it has been for the past 1,200 years, but is this unprecedented. The dust bowl in the USA for example was a severe drought, but data suggests that it was minor by comparison to droughts that had occurred before and that droughts appear to be returning on a routine and regular basis. This suggests that variations even over a century can be large and that there are larger driving mechanisms at work.

In Figure 39, a comparison between different Northern Hemisphere temperature reconstructions and instrument records are shown. This clearly shows that the temperatures being experienced today are within the range of uncertainty associated with different data sets and that what we are experiencing is not necessarily unprecedented and may have occurred in the past.

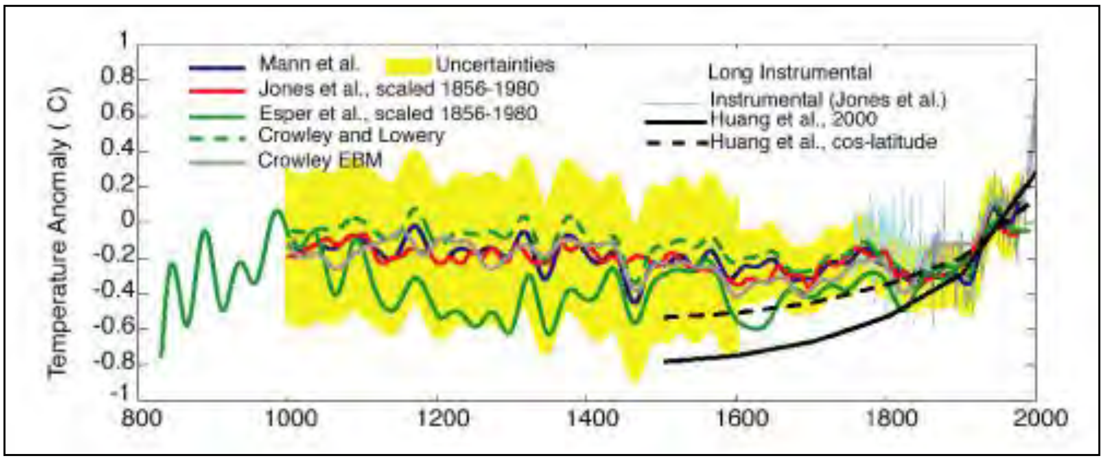


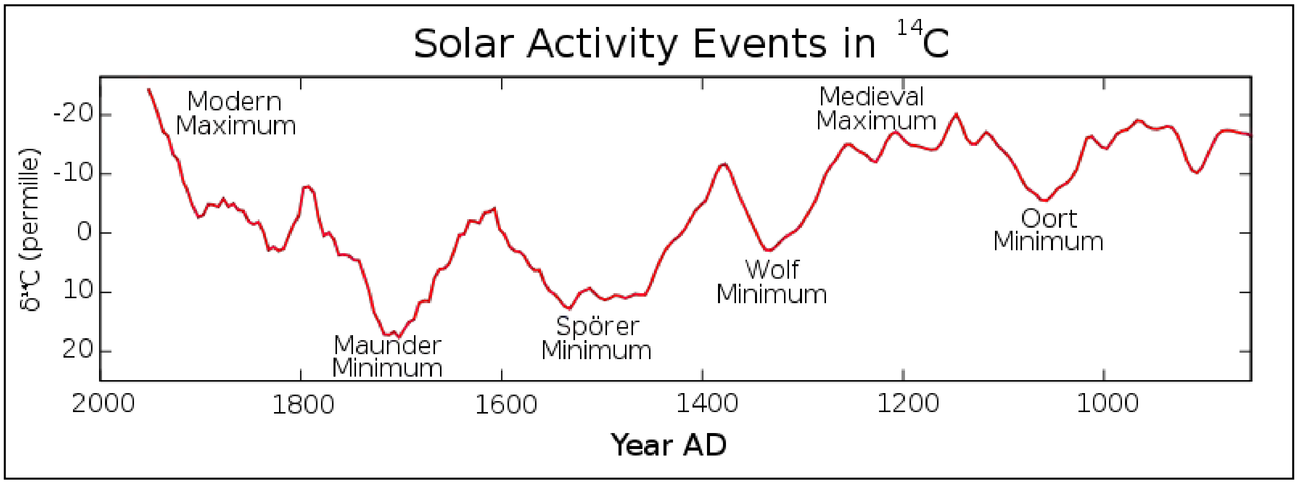
Figure 39: Temperature changes for the 1,200 years suggests we are warmer today than during this period, but within limits defined by uncertainty for past records (after Mann, M. E., Rutherford, S., et. al., 2003).

3.4.3 Solar Variation

The following solar cycles are evident and they do appear to have a connection with the climate that is experienced on the earth, though the exact mechanisms and linkages are not clear. Sunspot activity and changes in the suns magnetic field are thought to play a role. Sunspot cycles are described in the section concerning Decadal Cycles above and are not repeated here. The various solar cycles that are claimed to exist are presented below:

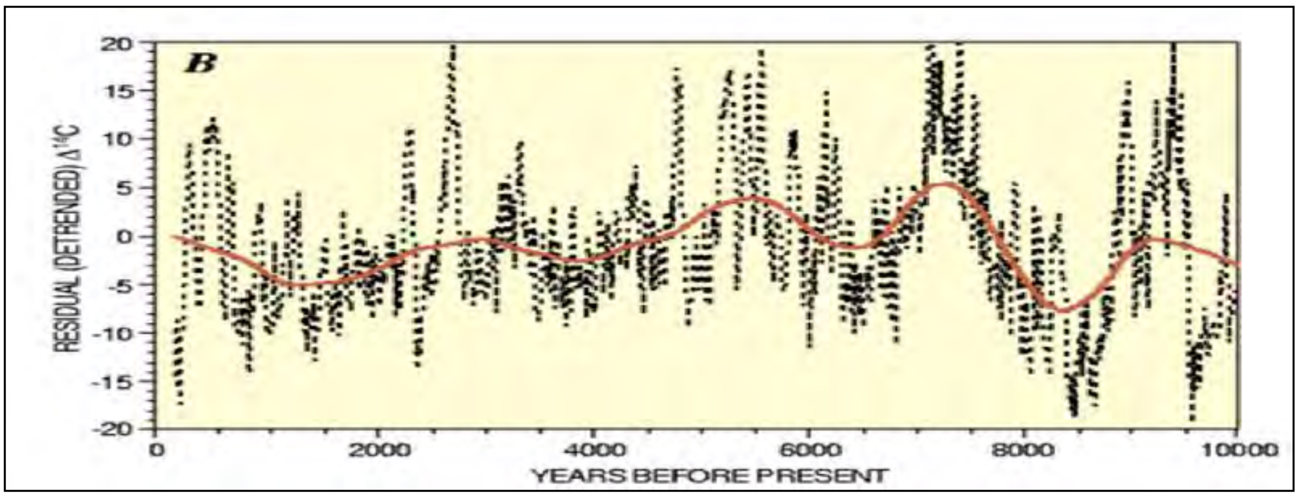
- 22 years: Hale cycle. The magnetic field of the Sun reverses during each cycle
- 87 years (70–100 years): An amplitude modulation of the 11-year Cycle
- 210 years: Suess cycle or de Vries cycle (Figure 40)
- 2,300 years: Hallstatt cycle (Figure 41).

The 200-year solar cycle (Suess or de Vries cycle) is commonly believed to be one of the most intense solar cycles, was a dominant cycle during the Holocene and is associated with the deep Maunder, Spörer and Wolf solar minima (Raspopov 2008).



(Source: http://www.radiocarbon.org/IntCal04%20files/intcal04.14c)

Figure 40: Red curve shows c.210 year solar de Vries cycles.



Source: http://pubs.usgs.gov/fs/fs-0095-00/)

Figure 41: Red curve shows c.2,300 year Hallstatt cycle.

Measures

Instruments used to track centennial variability and climate patterns include:

- Weather Stations
- Thermometer
- Rain gauges
- Stream gauges
- Sea Surface Temperature (SST) is particularly important in tracking ENSO and other ocean oscillations
- Sunspot activity.

Proxies

An ENSO-like signature in some paleo records, including:

- Tree cores
- Corals
- Lake sediments.

3.5 Millennial Cycles (1,000 Years)

http://www.ncdc.noaa.gov/paleo/ctl/cliihis1000a.html

In looking for climate processes and the forces that influence them at periods ranging from 100 to 1,000 years, scientists use weather instrument data with calibrated proxy data from tree rings, ice cores, marine and lake sediments layers, and corals etc as evidence. Climate patterns with possible millennial cycles have been identified though not all of them may remain operational today. It is evident though from paleoclimatic research that there are cycles operating, however the data is sporadic, uncertainty high, resolution low, from various different locations and it is not always possible to date it accurately. For this reason scientists studying climate need to bear in mind the unknowns and uncertainties involved with the data, particularly when attempting to match up records from different types of proxies or different regions.

3.5.1 Insolation

The figure below (Figure 42) is based on a model of solar output, and it shows how these outputs are matched up with actual know climatic events. It is clear that there are millennial scale cyclic patterns occurring and the forcing mechanism appears to be solar output, which reasonably makes sense as the climate system is driven by energy.

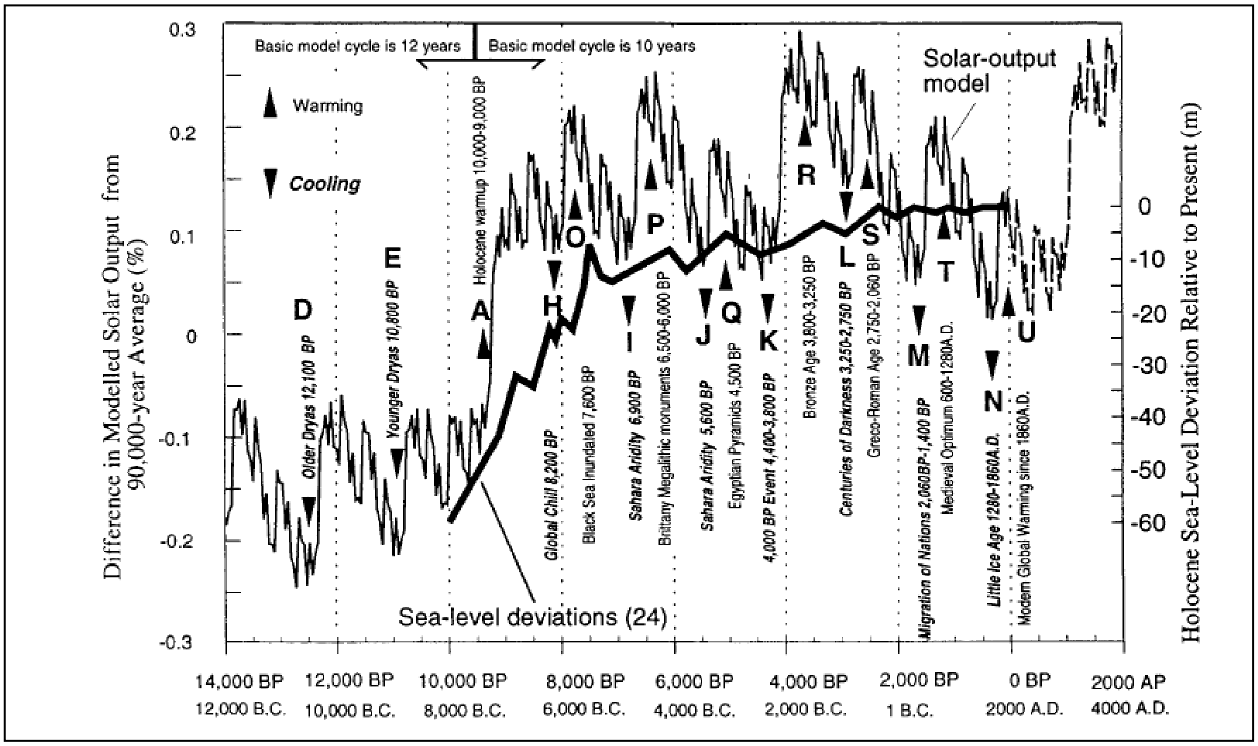


Figure 42: Solar-output model from 14,000 YBP to 2,000 YAP compared with sea-level deviations (24) and selected events (After Perry and Hsu, 2000).

Measures

There are no instrumental records stretching beyond 100‟s of years. Reliance now moves to proxy data.

Proxies

Proxy records such as

- Tree rings
- Sediment layers
- Ice layers.

In looking for climate processes and the forces that influence them at periods ranging from 100 to 1,000 years, paleoclimatologists splice instrumented data with calibrated proxy data such from tree rings, cores from icecaps, glaciers, marine and lake sediments layers, and corals, and evidence of vegetation change found in pollen samples and packrat middens. These proxies can provide an array of information including temperature, precipitation, chemical composition of air or water, biomass or vegetation, volcanic eruptions and solar activity with varying degrees of accuracy and detail.

3.6 10,000 Year Cycles

To identify long-term cycles of 1,000 years or longer a variety of paleo proxies such as tree rings, ice cores and cored from sediment layers from the ocean or lakes are used. In these data sets it is often possible to see abrupt shifts of less than a decade. Figure 43 shows the amount of ice melting from an ice cap in northern Canada. The graph is indicative of the ice loss which is a proxy for warming that has occurred since the last ice age. The extent of the variability, despite the trend, is significant and indicates that short term changes can be counter to a long term trend and that the changes can happen very quickly. This is particularly evident between 8,500 and 8,000 years before Present (BP) and again in the last 100 years. In the last 100 years has been greater than for almost any period in the last 5,000 years (Dashed line in Figure 43).

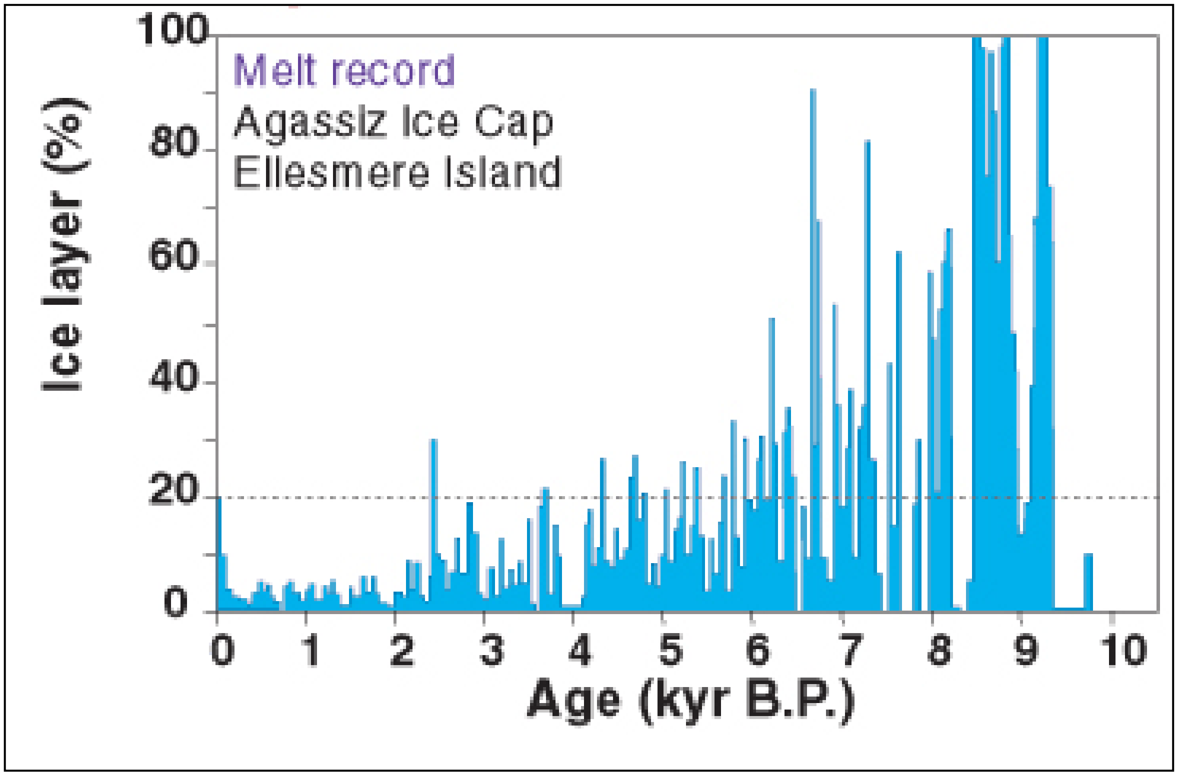
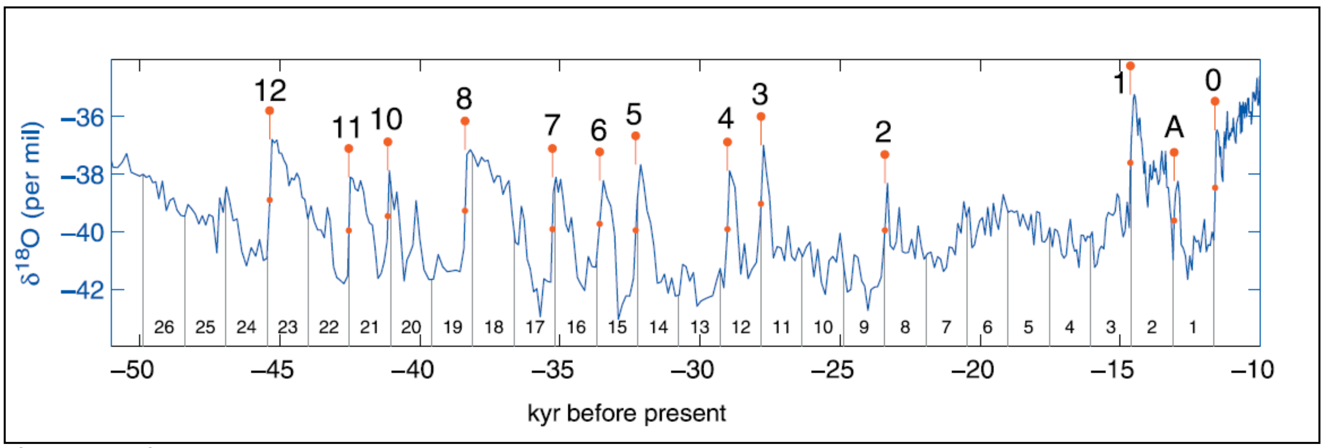


Figure 43: Northern Canadian ice cap melting for the past 10,000 years (CCSP, 2009).

3.6.1 Dansgaard-Oeschger Events

Dansgaard-Oeschger events see a rapid warming of temperature, followed by a cool period lasting a few hundred years (Bond et al, 1999). This cold period sees an expansion of the polar front, with ice floating further south across the North Atlantic Ocean (Bond et al, 1999). Dansgaard-Oeschger events as indicated by ice core $\delta^{18}O$ analysis indicate return periods of close to 1,500 years in length (Ruddiman, 2001). A well described event occurred about 11,500 years ago when average annual Greenland icepack temperatures warmed by about 8°C over 40 years (though temperatures of about 5°C appear more typical. The little ice age of c.400 to 200 years before present has been interpreted as the cold part of a D-O cycle, suggesting we are now in a period of warming climate (Bond et al, 1999). The events are linked to changes in the North Atlantic Ocean circulation, possibly triggered by an influx of fresh water (Bond et al., 1999). The events may be caused by an amplification of solar forcings, cyclic changes in deep ocean currents or "binge-purge" cycles when ice sheets accumulate too much mass and become unstable and collapse.

The solar trigger for this is of important note, as it suggests insolation is key to understanding cyclical nature of climate change. Pronounced solar cycles of 87 and 210 years are known, but a 1,470-year solar cycle has not been detected. However, Braun et al, (2005), using a an intermediate-complexity climate model with glacial climate conditions have simulates rapid climate shifts similar to the Dansgaard–Oeschger events with a spacing of 1,470 years. The basis for the simulation was periodic freshwater input into the North Atlantic Ocean in cycles of 87 and 210 years. They attribute the robust 1,470-year response time to the superposition of the two shorter cycles, together with strongly nonlinear dynamics and the long characteristic timescale of the thermohaline circulation. They conclude that the glacial 1,470-year climate cycles could have been triggered by solar forcing despite the absence of a 1,470-year solar cycle.



After Rahmstorf, 2003.

Figure 44: The GISP2 Climate record for the second half of the last glacial. Dansgaard-Oeschger warming events are labelled with red flags. The grey vertical lines show 1,470-year spacing, small numbers at the bottom count the number of 1,470-year periods from DO event 0.

3.6.2 Heinrich Events

Ice rafting during very short intense cold periods are known as Heinrich Events, and are associated with cold (3-6 degrees lower than normal glacial temperatures) and arid conditions (Adams et al.). During warm periods, debris from rocks are carried by rafts of ice into the North Atlantic, which then melt and deposit the debris in ocean sediments. During colder periods, debris is absent in sediments allowing warm and cold periods to be identified. The Heinrich events have an abrupt onset and last for about 750 years. By comparing the $\delta^{18}O$ ice core record with analysis of sediment cores from the North Atlantic, repeated cycles of slowly developing glacial conditions followed by abrupt shifts back to warmer conditions are evident. The repeating cyclic nature of these events is important as it suggests a forcing mechanism that is linked to insolation. Heinrich events only occur in the cold spells immediately preceding Dansgaard-Oeschger events, leading to suggestions that they are linked (Bond & Lotti 1995).

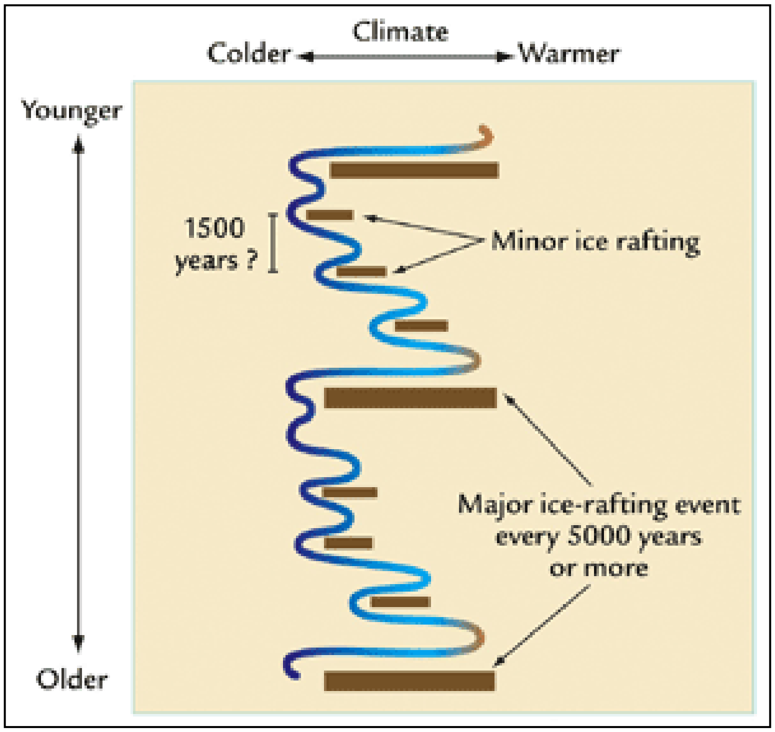


Image from Ruddiman, Earth's Climate: past and future; 2001

Figure 45: Major and minor ice rafting events in the North Atlantic (After Ruddiman; 2001).

3.6.3 Sporadic Events

An influx of freshwater into the Atlantic 8,200 years ago from large lakes in northern Canada may have triggered the coldest climate event for the past 10,000 years Baldini (2002); Von Grafenstein (1998). It is thought this 400 year period of cooling was started by two gigantic glacial lakes in Canada's Hudson Bay region broke some 8,200 years ago when an ice dam from a remnant of the Laurentide Ice Sheet collapsed (Barber, et. al.1999). The flow of cold fresh lake water rushing through the Hudson Strait and into the Labrador Sea is estimated to have been about 15 times greater than the current discharge of the Amazon River. This would have altered the thermohaline circulations of the ocean and altered temperatures warmed by normal currents. These events are also found in the proxy record and can lead to obscuring of the cycles, making for difficult long term trend tracking and use in prediction.

3.6.4 Orbital Forcing

In the mid Holocene, approximately 7,000 to 5,000 years ago, temperatures appear to have been warmer than today. Specifically, temperatures were generally warmer, only in the northern hemisphere summer and are linked to changes in the Earth's orbit. This suggests that there are changes in the amount of solar radiation reaching each latitudinal band of the Earth during each month. Long term cyclical orbital changes can be calculated, and what they indicate is that the northern hemisphere summer would have been warmer and winters cooler than present. Again the key influence of the sun is evident.

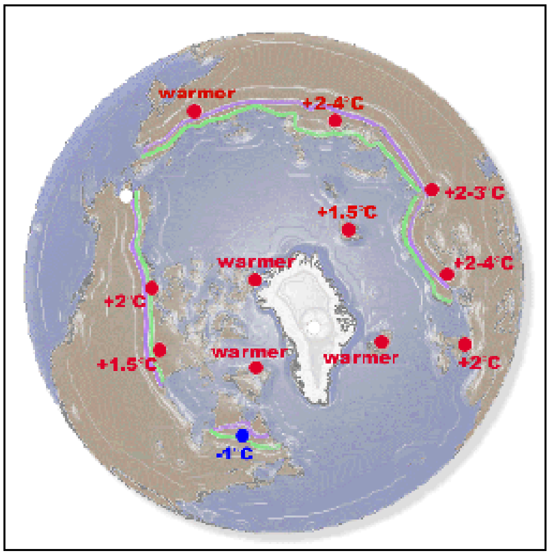


Figure 46: Northern hemisphere summer temperature changes during the Mid-Holocene.

Measures

There are no instrumental records stretching beyond 100‟s of years. Reliance is on proxy data.

Proxies

Scientists examining climate variability of 1,000 years or more have come to rely on studying the δ O^{18} values taken from ice cores and the shells of planktonic foraminifera from marine sediments. The sediments also reveal lithics (rock particles) and dust that offer additional clues of the climate variations thousands of years ago.

3.7 100,000 Year Cycles

Although going beyond the period of interest in this study, it is important to understand that there are cycles happening at the 100,000 year time scale and beyond. Scientists have resolved multi-millennial scale orbital cycles of precession, eccentricity, and obliquity (Described in detail in Section 3) which can play an important role in the rise and fall of ice ages and were first described in detail by Milankovitch. These orbital forces include the 22,000 year cycle of precession, 100,000 and 400,000 cycles of eccentricity, and 41,000-year cycles of Earth's obliquity or axial tilt.

Due to variations in the Earth's orbit, the planet has experienced a series of Ice Ages over the past 2.6 million years. The most recent cycle ended in the Last Glacial Maximum some 18,000 years ago. The northern hemisphere in particular had large tracts covered by ice, nearly 32% of the Earth's land area was covered by ice and sea level was about 120 meters lower than it is today (Ruddiman, 2001). The ice ages are primarily caused by orbital fluctuations that result in a few percent change in the sunlight received yet this now appears to have a significant impact on climate systems.

3.7.1 Insolation and Global Temperature and Sea Levels

Sea level and temperature provides useful proxies of the variations in insolation cycles as determined by orbital variations. Indeed variations in these proxies match the cycles that Milankovitch suggested would be apparent based on orbital variation.

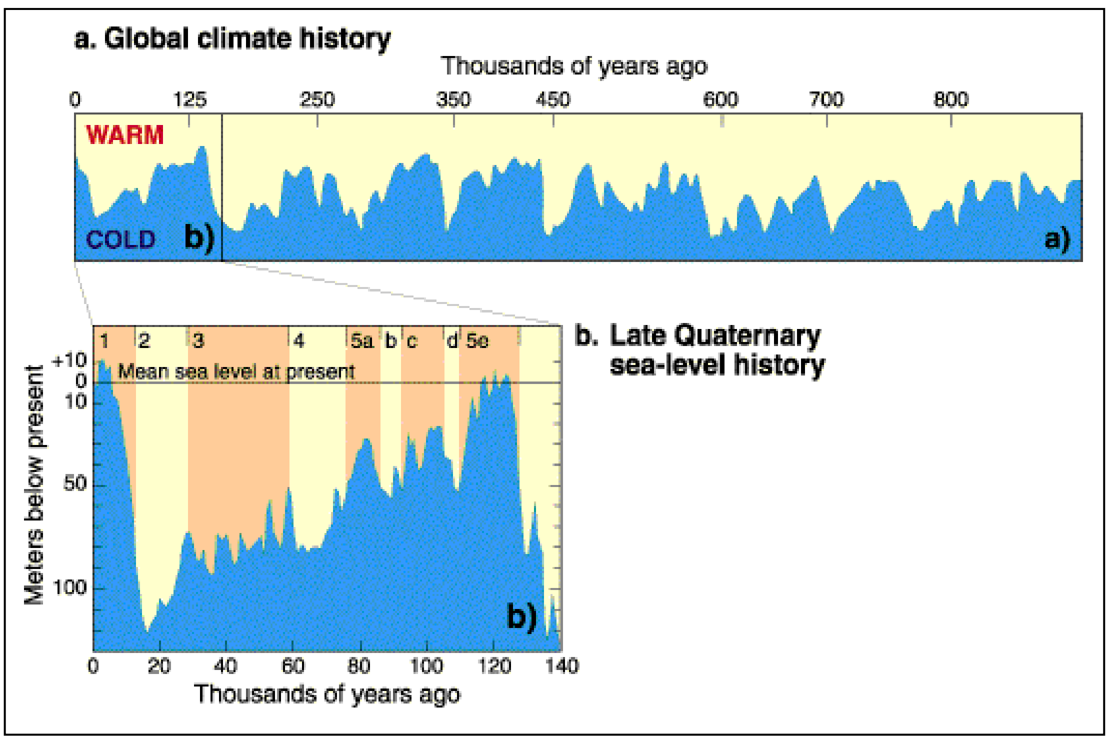


Figure 47: Relative temperature over the past million years and sea level change over the past 140,000 years.

3.7.2 Insolation and Global Ice Volume

When the data for solar insolation and global ice volume over the past 400,000 years are analysed, it is apparent that they fluctuate at the same major frequencies of the:

- Precession cycle of 23,000 and 19,000 years
- Obliquity cycle of 41,000 years
- Eccentricity cycle of 100,000 years
- Eccentricity cycle at 400,000 years cannot be confirmed as data does not extend back far enough.

Importantly, the Milankovitch theory predicts that changes in eccentricity have a smaller effect on climate than variations in precession and obliquity even though climatic records from across the globe suggest that ice sheets have advanced and retreated to a 100,000 cycle. Within this context significant climate changes can be expected to occur on the smaller cycles and this is what was evident in Figure 48and Figure 49 .

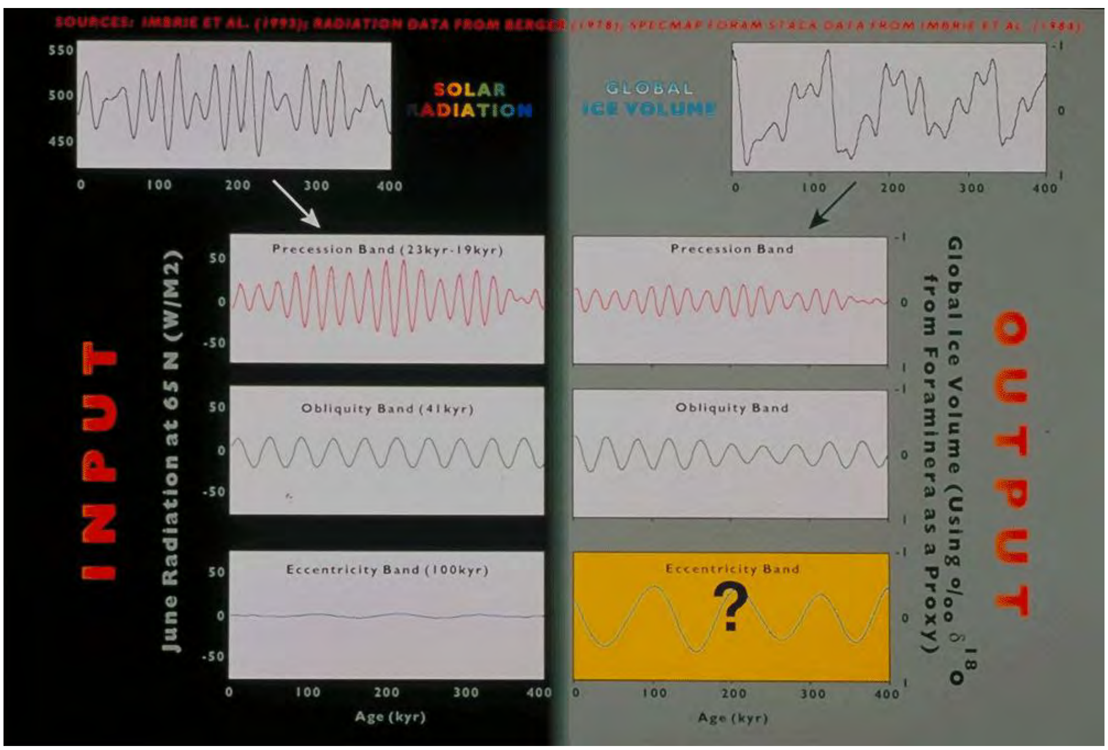


Figure 48: Solar Insolation and Global Ice Volume over the Past 400,000 Years.

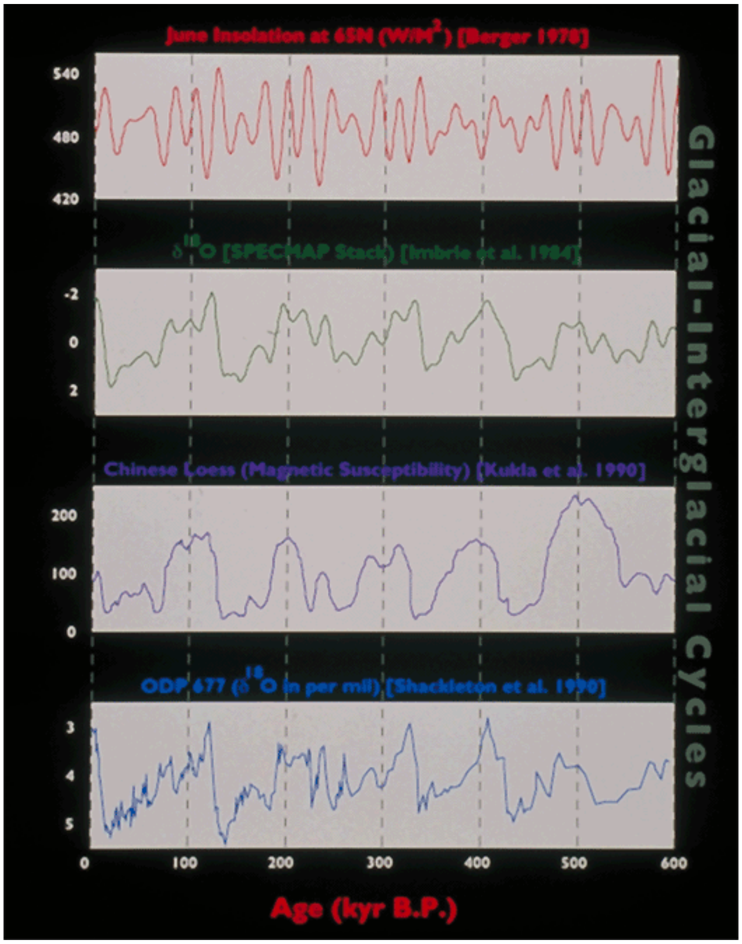


Figure 49: Insolation and Quaternary Climatic records reveal Milankovitch Cycles.

Measures

Proxies from marine sediments, geomorphic features and astronomical observations and calculations provide the means of reconstructing past climate variability at 100,000 year and longer time scales.

4 Forcing and Amplification Mechanisms

Based on the previous section it is apparent that there are a range of mechanisms that can be held responsible for the determination of the climate that is experienced on earth. If the cyclical nature of these events is understood it is possible to determine how future climate will respond to these influences. Some of these forcing mechanisms are external to the planet, like the sun, and some are a result of earth based phenomena such as volcanoes. Of all of these the most important forcing mechanism for our climate appears to be the sun. Indirectly the earth‟s orbit causes variations in the energy received from the sun and the sun itself shows cyclical variations in its output. Factors that can affect the amount of solar radiation reaching the earth include:

- Atmospheric Trace Gases: Greenhouse gases such as carbon dioxide and methane which absorb infrared radiation resulting in greenhouse gas warming
- Orbital Variations: 22,000 year cycle of precession, 100,000 and 400,000 cycles of eccentricity, and 41,000-year cycles of Earth's obliquity or axial tilt
- Solar Variability: The energy output from the sun varies over time with a clear cyclical pattern evident. Lower energy output from the sun means lower energy receipt on earth
- Volcanic Aerosols: Increase the earth‟s albedo (reflectivity) and cool the climate
- Tropospheric Aerosols: Affect the formation of clouds, increase the albedo and cool the climate.

The first three key factors are discussed in more detail below.

4.1 Greenhouse Gases

Although “greenhouse gases” are frequently held responsible for “global warming”, this is somewhat misleading as they on their own cannot create energy to change climate, but only trap energy in the system. In this sense increasing greenhouse gas concentration is seen as an amplifier of the major forcing mechanism which in all likelihood is insolation derived from orbital variation or solar output variation. As an amplification mechanism, a small increase in the input (insolation) or the amount of amplifier (greenhouse gases) could translate to relatively significant increases in the temperatures experienced on earth. Similarly, a small drop in insolation on a strongly amplified signal could lead to a relatively abrupt and steep drop off in the temperature. As amplification of these input variations is considerable, the significant role of greenhouse gases should therefore not be underestimated.

Managing of greenhouse gases and the finding of mechanisms to produce clean energy is a key assumption in this report. It is assumed that greenhouse gases will be managed and that they will have a reduced influence on future climate and that the other forcing mechanisms are therefore likely to play a more dominant role in a future climate scenario. Indeed several scientists have started to speculate that it may be possible to moderate potential future climate cooling by releasing, in particular, carbon dioxide in the future. IPCC predictions for the next 100 years are largely based on greenhouse gas influence in global circulation models. The importance of managing fuel use, energy consumption and emissions remains a priority as it is the basis of good stewardship at a time when it is evident that climate change is occurring and there is not absolute certainty how all the various forcing mechanisms are working together.

4.2 Milankovitch Cycles

4.2.1 Precession of the Earth's Orbit (22,000 Year Cycle)

The earth's orbit wobbles so that over the 22,000 to 23,000 years of a precessional cycle, the North Pole traces a circle in space. This wobble causes the precession of the equinoxes. Precession changes the date at which the earth reaches its perihelion the point in the wobble when the earth is closest to the sun and in so doing serving to amplify or dampen seasonal climatic variability. If the perihelion is reached in the middle of winter then the winters will be mild and if it occurs in the middle of summer then the summers will be hotter. The earth currently reaches its perihelion on January 3, close to the Northern Hemisphere's winter solstice reducing seasonal differences in insolation and creating relatively warmer winters. This means the earth is further away from the sun and relatively cooler during the Northern Hemisphere's summer, reaching its aphelion on July 5. However, 11,000 years ago, the reverse was true: the earth reached its perihelion during the northern summer, increasing the seasonal variability of earth's climate. Since this time the earth has gone through the Holocene warmup as the wobble has brought the perihelion to coincide with winter. It can be inferred that we are therefore now starting on a cooling trend towards another ice age where the summers will be warmer and the winters colder and the seasonal variation in insolation greater. Under these circumstances the winter ice will grow thicker and last longer into the summer and potentially start to build up if there is enough albedo effect to offset the warmer summers. This would be a slower process than the warming and melting of the ice caps as we are witnessing currently and would fit in well with the observed slow glacial formation and abrupt warming saw tooth graphs presented in the previous section. The information in this section is largely adapted from Pisias and Imbrie (1986/1987).

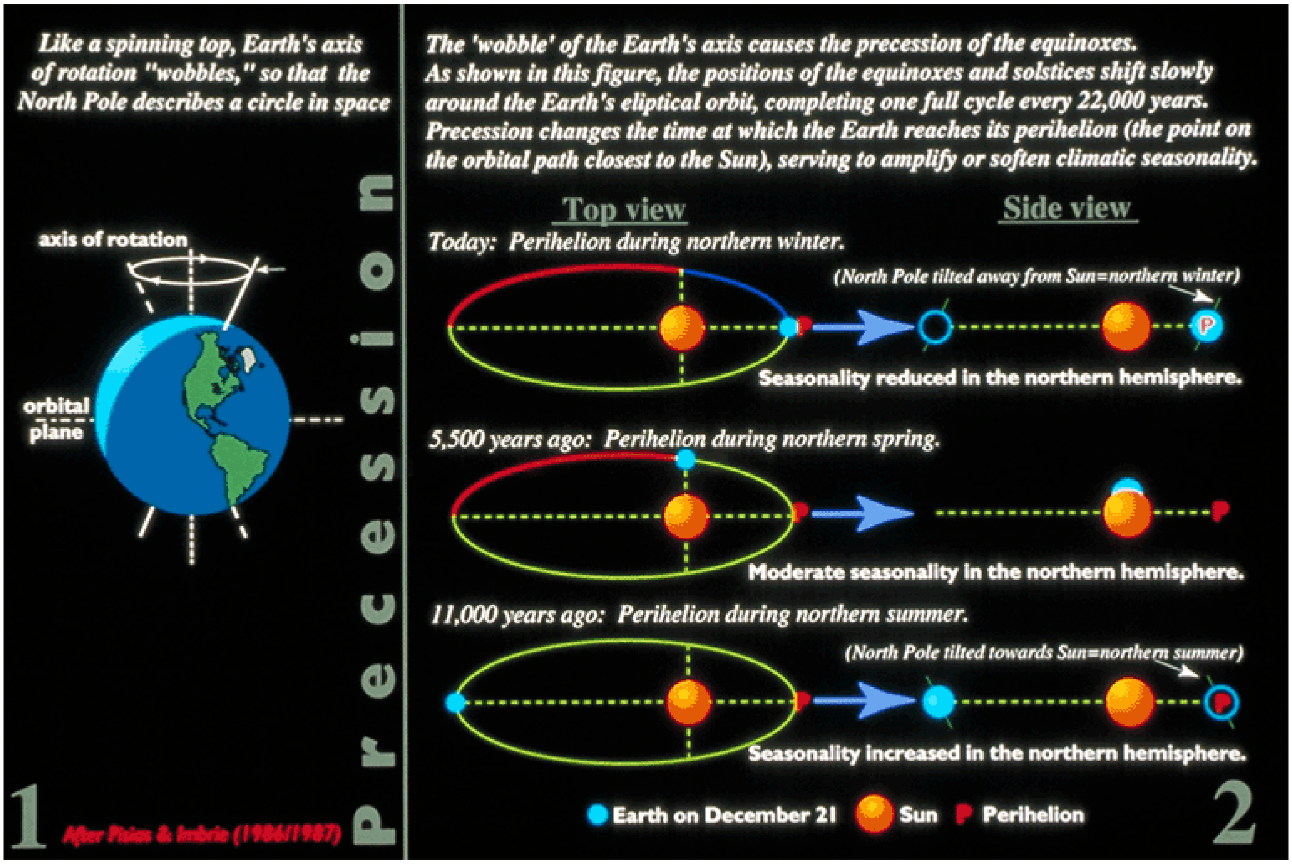


Figure 50: The earth's precession cycle of 22,000 years (After Pisias and Imbrie 1986/1987).

4.2.2 Earth's Axial Tilt (41,000 Year Cycle)

Adapted from Pisias and Imbrie [1986/1987]

The obliquity of earth's axis varies over the course of a 41,000-year cycle during which the earth's axial tilt varies from 24.5 degrees to 22.1 degrees. Changes in axial tilt affect the distribution of insolation received at the earth's surface. When the angle of tilt is low, polar regions receive less insolation and when high they receive more insolation during the course of a year. This in effect influences the relative strength of the seasons and are particularly pronounced in the high latitudes where the great ice ages began.

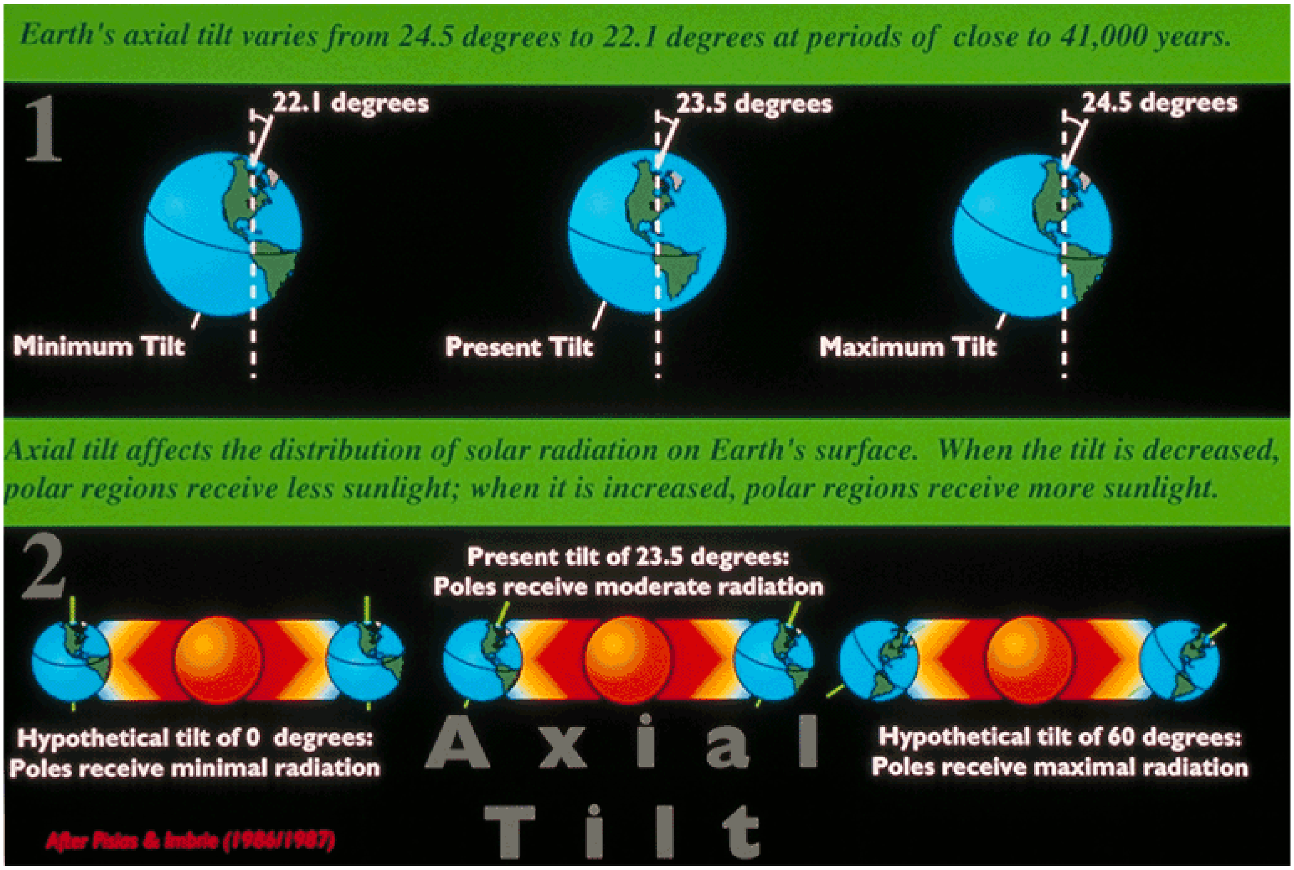


Figure 51: The earth's axial tilt or obliquity cycle of 41,000 years (After Pisias and Imbrie 1986/1987).

4.2.3 Earth's Eccentricity (100,000 and 400,000 Year Cycle)

Adapted from Pisias and Imbrie [1986/1987].

The shape of earth's orbit changes slowly but consistently over time from nearly circular (eccentricity approaching 0.00) to more elliptical (eccentricity=0.06). These variations occur at a frequency of 100,000 years and 400,000 years. Variations in orbital eccentricity have a small impact on insolation at the top of earth's atmosphere roughly 0.1%. Eccentricity and precession can work together either to enhance or modulate insolation. During periods of high eccentricity (elliptical orbit), the effect of precession on the seasonal cycle is strong, whereas when eccentricity is low (more circular), the effect of precession on the seasonal cycle is weak as all points on the orbit are the same distance from the sun.