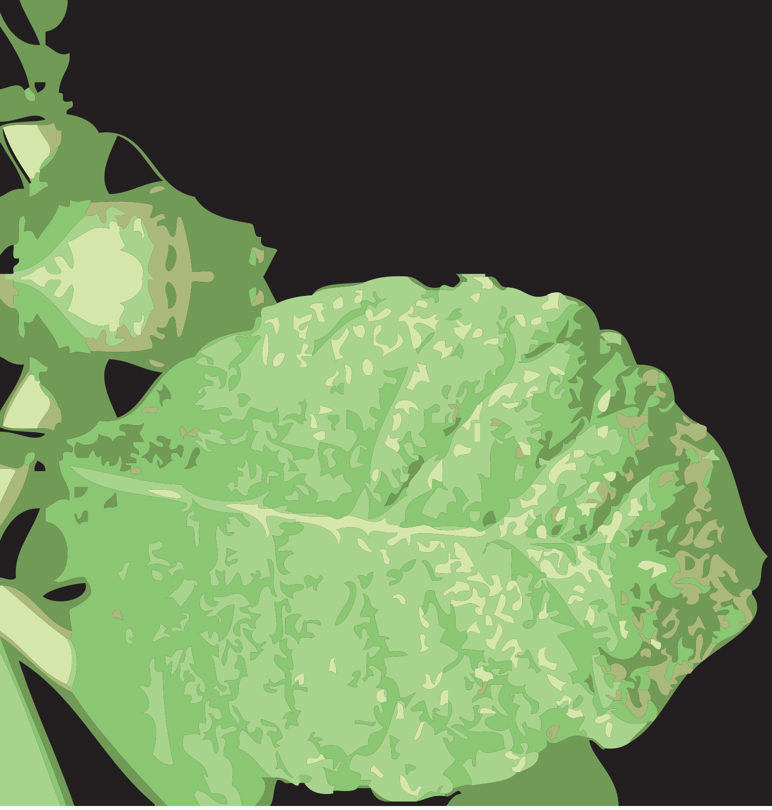

THE FRASER INSTITUTE

Independent Summary for Policymakers
IPCC Fourth Assessment Report

Coordinator: Ross McKitrick, Ph.D.

Writing Team:
Joseph D'Aleo, M.Sc.,
Madhav Khandekar, Ph.D.,
William Kininmonth, M.Sc., M.Admin.,
Christopher Essex, Ph.D.,
Wibjörn Karlén, Ph.D.,
Olavi Kärner, Ph.D.,
Ian Clark, Ph.D.,
Tad Murty, Ph.D., and
James J. O'Brien, Ph.D.

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Development Department, The Fraser Institute,
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Vancouver via telephone: 604.688.0221, ext. 586
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Calgary via telephone: 403.216.7175, ext. 227
via fax: 403.234.9010
Toronto via telephone: 416.363.6575, ext. 232
via fax: 416.934.1639.

Contents

List of Authors

Coordinator

Ross McKitrick, Ph.D. Associate Professor, Department of Economics, University of Guelph and Senior Fellow, Fraser Institute, Vancouver BC.

Writing Team

Joseph D'Aleo, M.Sc. Chief Meteorologist (Ret'd) WSI Corporation. Past Chairman, American Meteorological Society Committee on Weather Analysis and Forecasting. Member, American Meteorological Society Council. Fellow, American Meteorological Society. Certified Consulting Meteorologist.

Madhav Khandekar, Ph.D. Research Scientist (ret'd), Environment Canada. Editor, *Climate Research* 2003-2005. Member, Editorial Board, *Natural Hazards* since 1999. Previously, Lecturer in Meteorology, Barbados (West Indies); International Civil Aviation Organization Expert in Aeronautical Meteorology, Qatar.

William Kininmonth, M.Sc. M.Admin. Head (ret'd) National Climate Centre, Australian Bureau of Meteorology. Previously: Consultant to the World Meteorological Organization Commission for Climatology; Scientific and Technical Review Coordinator, United Nations Task Force on El Niño.

Christopher Essex, Ph.D. Professor of Applied Mathematics, University of Western Ontario, and Associate Director, Program in Theoretical Physics. Formerly, NSERC Postdoctoral Fellow, Canadian Climate Centre.

Wibjörn Karlén, Ph.D. Professor emeritus, Dept. of Physical Geography and Quaternary Geology, Stockholm University, Sweden

Olavi Kärner, Ph.D. Senior Research Associate, Atmospheric Sensing Group, Tartu Astrophysical Observatory, Tõravere, Estonia.

Ian Clark, Ph.D. Professor of Arctic Paleohydrology and Geology, University of Ottawa.

Tad Murty, Ph.D. Adjunct Professor, Departments of Earth Sciences and Civil Engineering, University of Ottawa; Editor, *Natural Hazards*; Associate Editor *Marine Geodesy*; Leader, World Meteorological Organization group to prepare a manual on storm surges from hurricanes and extra-tropical cyclones. Formerly: Senior Research Scientist, Canadian Department of Fisheries and Oceans; Professor of Earth Sciences, Flinders University, Adelaide, Australia; Director of Australia's National Tidal Facility.

James J. O'Brien, Ph.D. Robert O. Lawton Distinguished Professor, Meteorology & Oceanography and Director Emeritus of the Center for Ocean-Atmospheric Prediction Studies, Florida State University. Florida State Climatologist. Fellow of the American Meteorological Society, Fellow of the American Geophysical Union, Fellow of the Royal Meteorological Society, Fellow of the American Association for the Advancement of Science.

Preface

This is an *Independent Summary for Policymakers* (ISPM) of the Fourth Assessment Report (AR4), Working Group 1, of the Intergovernmental Panel on Climate Change (IPCC). In producing this Summary we have worked independently of the IPCC, using the Second Order Draft of the IPCC report, as circulated after revisions were made in response to the first expert review period in the winter and spring of 2006. Section references will be checked against the final IPCC version, as soon as copies are available following the release later in 2007. If, in preparing the final draft of the Fourth Assessment Report, the IPCC substantially rewrites the Assessment text, such that the key summary materials presented herein need to be re-worded, we will do so and publish an Appendix to that effect.

The IPCC was established in 1998 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to assess the risk of human induced climate change. The IPCC is open to all members of the WMO and UNEP. The IPCC has three working groups. Working Group 1 assesses the scientific aspects of climate change; Working Group 2 assesses the positive and negative impacts of climate change and the options for adaptation; and Working Group 3 assesses policy options to mitigate climate change.

The Fraser Institute's Rationale for the ISPM

The IPCC involves numerous experts in the preparation of its reports. However, chapter authors are frequently asked to summarize current controversies and disputes in which they themselves are professionally involved, which invites bias. Related to this is the problem that chapter authors may tend to favor their own published work by presenting it in a prominent or flattering light. Nonetheless the resulting reports tend to be reasonably comprehensive and informative. Some research that contradicts the hypothesis of greenhouse gas-induced warming is under-represented, and some controversies are treated in a one-sided way, but the reports still merit close attention.

A more compelling problem is that the *Summary for Policymakers*, attached to the IPCC Report, is produced, not by the scientific writers and reviewers, but by a process of negotiation among unnamed bureaucratic delegates from sponsoring governments. Their selection of material need not and may not reflect the priorities and intentions of the scientific community itself. Consequently it is useful to have independent experts read the underlying report and produce a summary of the most pertinent elements of the report.

Finally, while the IPCC enlists many expert reviewers, no indication is given as to whether they disagreed with some or all of the material they reviewed. In previous IPCC reports many expert reviewers have lodged serious objections only to find that, while their objections are ignored, they are acknowledged in the final document, giving the impression that they endorsed the views expressed therein.

The ISPM addresses these concerns as follows.

- The ISPM was prepared by experts who are fully qualified and experienced in their fields, but who are not themselves IPCC chapter authors, nor are they authors of the IPCC *Summary for Policymakers.*
- The ISPM summarizes the most important elements of the science, regardless of whether it is given the same level of focus in the IPCC's Summary documents. There is no attempt to downplay or re-word uncertainties and limitations in the underlying science, hence the summary paragraphs in the ISPM may not be identical to those of the Summary produced by the IPCC.
- If a chapter of the Fourth Assessment Report introduces its topic by briefly elaborating on deep uncertainties, then presents results at length as if the uncertainties were not there, the ISPM may devote proportionally more attention to understanding the uncertainties than summarizing all the results, where this is deemed a more pertinent way to characterize the underlying state of knowledge.

- In a number of places the writing team felt the treatment of a topic was inadequate in the Fourth Assessment Report, or some additional comments were needed for perspective. These are noted in separate sidebars. Also, the Fraser Institute will publish a series of short supplementary papers to provide more detailed critical discussion of some technical subjects. These are noted at various points in the ISPM as well.
- The ISPM was subject to expert review by the reviewers listed at the end. Their responses to review questions are tabulated so readers can see to what extent the reviewers agree with the contents of this Summary.

Format Notes

- *Third Assessment Report* refers to the Third Assessment Report (TAR) of the IPCC, Working Group I, published in 2001
- *Fourth Assessment Report* refers to the Fourth Assessment Report (AR4) of the IPCC, Second Order Draft, Working Group 1
- Section references in brackets, e.g., [3.4.3.1], refer to the Fourth Assessment Report of the IPCC, Second Order Draft, Working Group 1. Some references are to Summation Questions included in the Fourth Assessment Report chapters, e.g., [Question 5.1].

Acknowledgments

Stephen McIntyre assisted in collation of data, preparation of many graphs and technical editing of some sections. Nicholas Schneider was involved in this project from inception and acted as the key Fraser Institute staff person. Their contributions are gratefully acknowledged.

Disclaimer

The text presented herein uses our best estimate of the wording of the final version of the Working Group I contribution to the Fourth Assessment Report. Much of the text herein follows wording as set by IPCC Lead and Contributing Authors in the Second Order Draft as of the close of the scientific review period on June 2, 2006, on the assumption that this will also be the wording in the final draft. However a check against the final wording will take place after the IPCC releases the underlying report. The IPCC has indicated that, although they are publishing the Summary for Policymakers on February 2, 2007, they will not release the underlying report until some time in May 2007. Until that time, readers should note that the IPCC has not officially accepted the wording of the underlying report or of drafts on which it is based.

Executive Summary

Observed Changes in Factors That May Influence the Climate

The climate is subject to potential influence by both natural and human forces, including greenhouse gas concentrations, aerosols, solar activity, land surface processes, ocean circulations and water vapor. Carbon dioxide is a greenhouse gas, and its atmospheric concentration is increasing due mainly to human emissions.

The IPCC gives limited consideration to aerosols, solar activity and land-use change for explaining 20th century climate changes. Aerosols have a large potential impact on climate but their influence is poorly understood. Some evidence suggests that solar activity has increased over the 20th century to historically high levels. Land use changes are assumed by the IPCC to have only a minor role in explaining observed climate change.

Observed Changes in Weather and Climate

Globally-averaged measurements of atmospheric temperatures from satellite data since 1979 show an increase of 0.04°C to 0.20°C per decade over this period, at the low end of the IPCC estimate of future warming. Globally-averaged temperature data collected at the surface show an increase from 1900 to 1940 and again from 1979 to the present.

There is no globally-consistent pattern in long-term precipitation trends, snow-covered area, or snow depth. Many places have observed a slight increase in rain and/or snow cover. There is insufficient data to draw conclusions about increases in extreme temperature and precipitation. Current data suggest a global mean sea-level rise of 2 mm to 3 mm per year over the past several decades. In the tropics, there is evidence of increased cyclone intensity but a decrease in total tropical storms, and no clear global pattern since 1970.

Arctic sea ice showed an abrupt loss in thickness prior to the 1990s, and the loss stopped shortly thereafter. There is insufficient data to conclude that there are any trends in Antarctic sea ice thickness. Glaciers have retreated in most places and the loss accelerated in the 1990s.

Climatic Changes in a Paleoclimate Perspective

Paleoclimate refers to the Earth's climate prior to the start of modern instrumental data sets. There are historical examples of large, natural global warming and cooling in the distant past. The Earth is currently within a warm interglacial period, and temperatures during the last interglacial period were warmer than present.

Natural climate variability and the uncertainty associated with paleoclimate studies are now believed to be larger than previously estimated. In general, data are sparse and uncertain, and many records have been questioned for their ability to show historical temperature variability. These uncertainties matter for assessing the ability of climate models to simulate realistic climate changes over historical intervals.

Climate Models and Their Evaluation

Some broad modeling predictions made 30 years ago are consistent with recent data, but there remain fundamental limitations of climate models that have not improved since the Third Assessment Report. Many models are incapable of simulating important aspects of the current climate, and models differ substantially in their projections. It is not possible to say which, if any, of today's climate models are reliable for climate prediction and forecasting.

Global and Regional Climate Projections

Models project a range of forecasts, and uncertainty enters at many steps in the process. Forecasts for the 21st century are inherently uncertain, especially at the regional level.

Current models predict: an increase in average surface temperature; an increased risk of drought, heat waves, intense precipitation and flooding; longer growing seasons; and an average sea levels rise of about 20 cm over the next 100 years.

Glacier mass is projected to decrease. An abrupt change in ocean circulation is very unlikely. Tropical cyclone intensity may increase or decrease.

Attributing the Causes of Climate Change

Attributing an observed climate change to a specific cause like greenhouse gas emissions is not formally possible, and therefore relies on computer model simulations. As of yet, attribution studies do not take into account the basic uncertainty about climate models, or all potentially important influences.

Increased confidence that a human influence on the global climate can be identified is based the proliferation of attribution studies since the Third Assessment Report. Models used for attributing recent climate change estimate that natural causes alone would not result in the climate that is currently observable.

ISPM Overall Conclusions

The following concluding statement is not in the Fourth Assessment Report, but was agreed upon by the ISPM writing team based on their review of the current evidence.

The Earth's climate is an extremely complex system and we must not understate the difficulties involved in analyzing it. Despite the many data limitations and uncertainties, knowledge of the climate system continues to advance based on improved and expanding data sets and improved understanding of meteorological and oceanographic mechanisms.

The climate in most places has undergone minor changes over the past 200 years, and the land-based surface temperature record of the past 100 years exhibits warming trends in many places. Measurement problems, including uneven sampling, missing data and local land-use changes, make interpretation of these trends difficult. Other, more stable data sets, such as satellite, radiosonde and ocean temperatures yield smaller warming trends. The actual climate change in many locations has been relatively small and within the range of known natural variability. There is no compelling evidence that dangerous or unprecedented changes are underway.

The available data over the past century can be interpreted within the framework of a variety of hypotheses as to cause and mechanisms for the measured changes. The hypothesis that greenhouse gas emissions have produced or are capable of producing a significant warming of the Earth's climate since the start of the industrial era is credible, and merits continued attention. However, the hypothesis cannot be proven by formal theoretical arguments, and the available data allow the hypothesis to be credibly disputed.

Arguments for the hypothesis rely on computer simulations, which can never be decisive as supporting evidence. The computer models in use are not, by necessity, direct calculations of all basic physics but rely upon empirical approximations for many of the smaller scale processes of the oceans and atmosphere. They are tuned to produce a credible simulation of current global climate statistics, but this does not guarantee reliability in future climate regimes. And there are enough degrees of freedom in tunable models that simulations cannot serve as supporting evidence for any one tuning scheme, such as that associated with a strong effect from greenhouse gases.

There is no evidence provided by the IPCC in its Fourth Assessment Report that the uncertainty can be formally resolved from first principles, statistical hypothesis testing or modeling exercises. Consequently, there will remain an unavoidable element of uncertainty as to the extent that humans are contributing to future climate change, and indeed whether or not such change is a good or bad thing.

1 Observed changes in factors that may influence the climate

1.1 "Radiative Forcing" as a conceptual tool for comparing climatic effects

1.1a "Radiative Forcing" (RF) is a modeling concept that attempts to summarize the climatic effect of diverse changes in the environment. It is not directly measured, nor is it related to the "greenhouse effect," and overall remains poorly quantified.

- RF is a concept that arose from early climate studies using simple radiative-convective models. It is not directly measured. Instead it is calculated by simplified climate models under the assumption that a comparison can be made between equilibrium states of the climate. The climate does not reach equilibrium, but reflects transient responses to external and internal changes. The RF relationship to transient climate change is not straightforward. To evaluate the overall climate response associated with a forcing agent its time evolution and its spatial and vertical structure need to be taken into account. Further, RF alone cannot be used to assess the potential climate change associated with emissions, as it does not take into account the different atmospheric lifetimes of the forcing agents. [2.2]
- RF itself is not directly related to the "greenhouse" effect as associated with greenhouse gases. [2.3.8]
- Measurement of RF in Watts/square meter is a convention, but RF itself is not a measured physical quantity. Instead it is computed by assuming a linear relationship between certain climatic forcing agents and particular averages of temperature data. The various processes that it attempts to approximate are themselves poorly quantified. [2.2]
- An observed decrease in radiative flux at the characteristic radiation bands of CO_2 and methane between 1970 and 1997 has been associated with changing concentrations. This change is what is meant by the term "enhanced greenhouse effect", but it is not directly related to the "Radiative Forcing" concept. [2.3.8]

SUPPLEMENTARY INFORMATION

Greenhouses and 'Greenhouse Gases'

While use of the term 'greenhouse' is nowadays unavoidable, the term 'greenhouse effect' is an inappropriate metaphor since it suggests a parallel between the mechanism that causes warming in an actual greenhouse and the influence of infrared-active gases, like water vapour and carbon dioxide, on the Earth's climate system. The two mechanisms are quite distinct, and the metaphor is misleading. It leaves out the complexities arising from the nonlinear, dynamic processes of our climate system, namely evaporation, convection, turbulence and other forms of atmospheric fluid dynamics, by which energy is removed from the Earth's surface. Simplistic metaphors are no basis for projecting substantial surface warming due to increases of human-caused carbon dioxide concentration in the atmosphere.

This problem is explored in the forthcoming Fraser Institute Supplementary Analysis Series report, "Why the 'Greenhouse' Metaphor is Misleading."

1.2 Greenhouse Gases

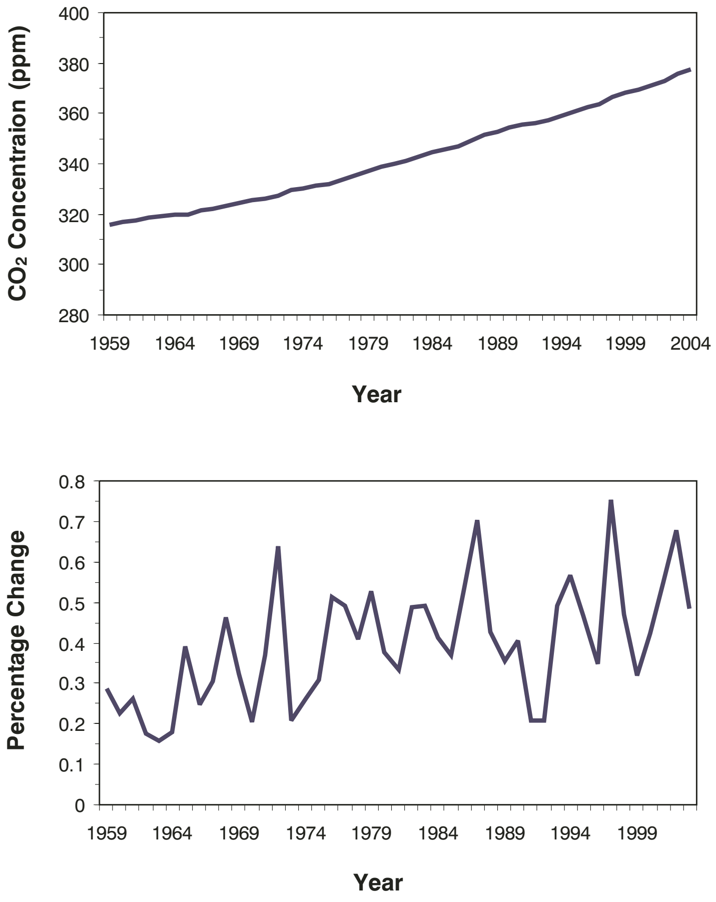


FIGURE ISPM-1: CARBON DIOXIDE CONCENTRATIONS

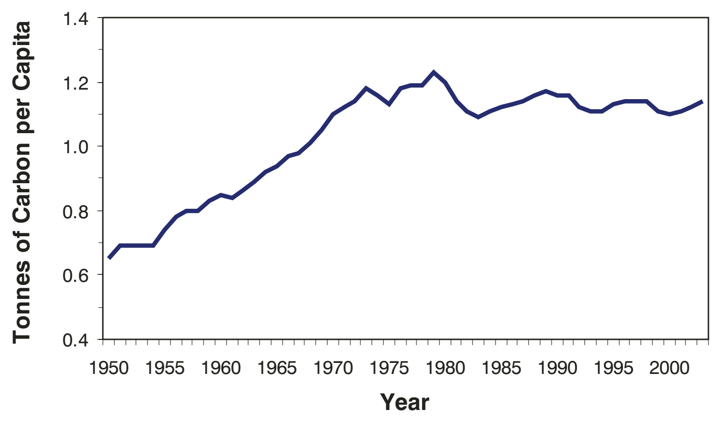
TOP: Annual average atmospheric carbon dioxide concentration since 1958.
BOTTOM: annual percentage rate of change of carbon dioxide concentration.
Source: Marland *et al.,* 2006.

1.2a Carbon dioxide (CO_2) levels in the atmosphere are rising at approximately 0.5% per year.

- Figure ISPM-1(top) shows the atmospheric CO_2 concentration since the late 1950s. The rate has no overall trend but fluctuates around a mean of 0.5% since the early 1990s, up from 0.4% in the 1970s and 1980s (Figure ISPM-1(bottom)).
- The main causes of this accumulation are fossil fuel burning, cement production, gas flaring, and, to a lesser extent, land-use changes such as deforestation. [2.3.1]
- Human activities contribute about 7 Gigatonnes carbon equivalent to the atmosphere each year, up from around 6 Gigatonnes in 1990. [2.3.1]

Per capita carbon emissions have not increased for 30 years

The growth rate of CO_2 emissions (in carbon equivalent) is equal to or slightly below the growth rate of world population (see Figure ISPM-2). Global per capita carbon emissions peaked at 1.23 tonnes per person in 1979 and the per-person average has declined slightly since then. As of 2003 the global average is 1.14 tonnes per capita, an average that has not changed since the early 1980s. If this trend continues, global emissions growth in the future will be constrained by total population growth.



ISPM-2: GLOBAL PER CAPITA CARBON EMISSIONS, 1950-2003
Source: Marland *et al.*, 2006.

1.2b Ice core records indicate that the atmospheric CO_2 levels were constant at about 280 parts per million (ppm) for at least several thousand years prior to the mid-1800s.

- This implies a post-industrial accumulation in the atmosphere of about 100 ppm, yielding the current level of nearly 380 ppm. [2.3.1]
- CO_2 variations over the last 420,000 years broadly followed Antarctic temperature, typically with a time lag of several centuries to a millennium (i.e., atmospheric carbon dioxide levels rise several centuries after the air temperature rises). [6.4.1]

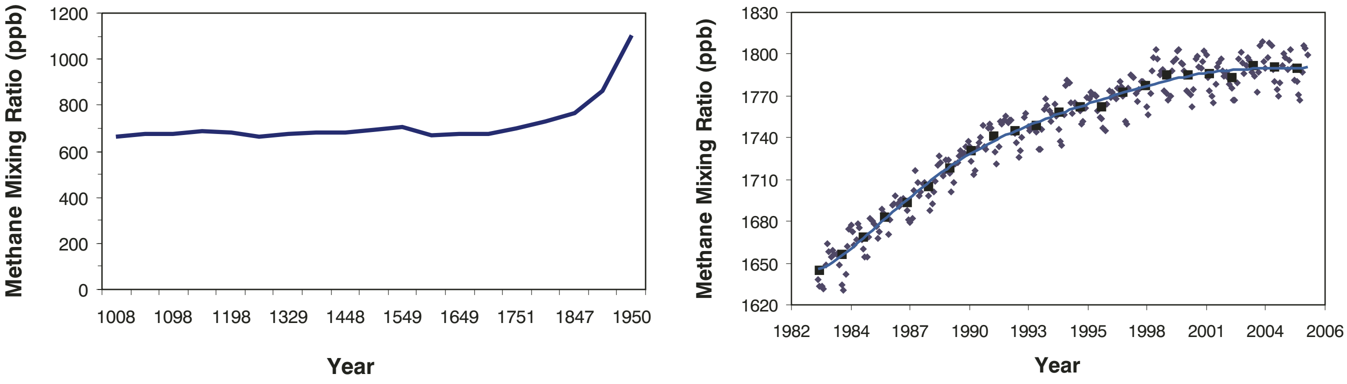


FIGURE ISPM-3: METHANE CONCENTRATIONS
LEFT: Long-term atmospheric methane levels, 1008 to 1950.
Source: Etheridge *et al.*, 2002.
RIGHT: Mauna Loa, Hawaii methane record, 1983-2005.
Source: World Data Center for Greenhouse Gases, 2006.

1.2c Atmospheric methane (CH_4) levels stopped growing in the late 1990s and have declined somewhat in recent years. Sources of methane emissions are poorly understood, but the total appears to be declining. It is not understood how this could be happening despite ongoing atmospheric temperature increases.

- Ice core records indicate pre-industrial methane levels were about 700 parts per billion (ppb), prior to the 18th century. The methane level increased over the next three centuries, and at the global level currently averages about 1,780 ppb (see Figure ISPM-3).
- Overall sources of methane emissions to the atmosphere are poorly known, but are thought to include wetlands, rice agriculture, biomass burning and ruminant animals.
- Emissions from anthropogenic sources remain the major contributor to atmospheric methane budgets. [7.4.1.2]
- Atmospheric methane concentrations peaked several years ago and have been flat or declining since then [Fig 2.5, see Figure ISPM-3, Bottom]. The reason for the recent decline is not understood. [2.3.2]
- The atmospheric concentration of methane is tied to atmospheric temperature, as total emissions increase with atmospheric warming. Total emissions from sources are suggested to have decreased since the time of the Third Assessment Report, as nearly zero growth rates in atmospheric methane concentrations have been observed with no change in the sink strengths. It is not well understood why emissions have decreased despite continued warming of the Earth's surface and the atmosphere. [7.4.1.2]

1.2d Hydrochlorofluorocarbons (HCFCs) and Chlorofluorocarbons (CFCs) are presently covered by other emission control legislation, and are declining.

- HCFCs and CFCs are covered by the Montreal Protocol on ozone-depleting substances. Global emissions have fallen radically since 1990 and their atmospheric levels are slowly declining. [2.3.4]

1.2e Other infrared active gases (Nitrous Oxide (N_2O) and Hydrofluorocarbons (HFCs)) are accumulating slowly in the atmosphere, or are at levels that imply very low climatic effects. [2.3.3; Table 2.1]

1.3 Aerosols

1.3a Aerosols play a key role in the Earth's climate, with a potential impact more than three times that of anthropogenic carbon dioxide emissions, but their influence remains subject to low or very low scientific understanding.

- Aerosols have a significant presence in the global atmosphere. The combined Direct Radiative Effect of natural and anthropogenic sources on climate, is estimated to be about -5.3 Watts/m^2, more than three times the magnitude of the estimated Radiative Forcing of anthropogenic CO_2 (1.63 Watts/m^2) [2.4.2.1.2]
- It is very challenging to distinguish natural and anthropogenic aerosols in satellite data. Validation programs for these advanced satellite-data products have yet to be developed and initial assessments indicate some systematic errors. [2.4.2.1]
- The climatic effect of each type of aerosol consists of both direct and indirect effects, the latter including influences on cloud formation. Overall direct and indirect effects are subject to wide uncertainties, and some important semi-direct effects were not included in the Third Assessment Report. [2.4]

- Effects on cloud formation are not well understood and the magnitude of the effects are not reliably estimated at this time, in part because of the lack of satellite data to support model development and testing. [2.4.6]
- Modelling the cloud albedo indirect effect from first principles has proven difficult because the representation of aerosol-cloud interactions and of clouds themselves in climate models are still crude. [2.4.6.5]
- Although there is agreement about the quality of the basic evidence (data), there is no consensus about the direct climatic (radiative forcing) effect of aerosols on climate, and the overall state of knowledge is categorized as *Low Scientific Understanding*. [Table 2.11]
- All categories of indirect aerosol effect on climate, are characterized by: no consensus; varying confidence in the basic empirical evidence, and *Low* or *Very Low Scientific Understanding*. [Table 2.11]

1.3b Aerosols can affect both cloud lifetime and cloud albedo (reflectivity), though models contradict one another on which effect is larger.

- Whereas some models show that the cloud albedo effect is four times as important as the cloud lifetime effect, other models simulate a cloud lifetime effect that is larger than the cloud albedo effect [7.5.2.4].

1.3c It is generally assumed that aerosols exert an overall cooling effect on the climate. Quantitative estimates of the overall effect vary by a factor of 10.

- The global mean total anthropogenic aerosol effect (direct, semi-direct and indirect cloud albedo and cloud lifetime effect) is defined as the change in net radiation at the top of the atmosphere from pre-industrial times to present-day, and ranges from $-0.2\ Wm^{-2}$ to $-2.3\ Wm^{-2}$. This implies that aerosol emissions exert an overall cooling effect, but the magnitude of this effect is unknown. [7.5.2.4]

1.3d Studies that attribute observed global warming to greenhouse gases are based on models that assume that aerosols exert a large cooling effect.

- The models used for the Fourth Assessment Report assume a large cooling effect from aerosols. [Table 2.12]
- The effect is assumed to be strongest in the Northern Hemisphere. [Figure 9.2.1e]

1.4 Changes in the Sun and Solar-Climate connections

1.4a New studies since the Third Assessment Report have improved empirical knowledge of climate responses to forcing by solar variability on annual to decadal time scales.

- Overall the troposphere is warmer and moister during solar maxima, and thickens in response to solar variability with a distinct zonal signature. [2.7.1.1.2]

1.4b The Third Assessment Report reported that solar activity was exceptionally high in the 20th century in the context of the last 400 years. Since then, new reconstructions of solar activity have indicated modern solar output levels are high, and possibly exceptionally high, compared to the past 8,000 years.

- Solar activity is estimated by historical information on sunspot counts and, prior to that, by cosmogenic isotopes (residual C14 and Be-10). [2.7.1.2.1]
- One reconstruction shows modern solar levels to be exceptional within the past 8,000 years while another shows few comparable episodes. [2.7.1.2.1; see Figure ISPM-4]
- Several reconstructions of solar activity show a strong upward trend from 1700 to the present. [see Figure ISPM-4]
- The minimum in solar activity around 1700 AD (the Maunder Minimum) has been associated with contemporary cold temperatures. [see Figure ISPM-9]

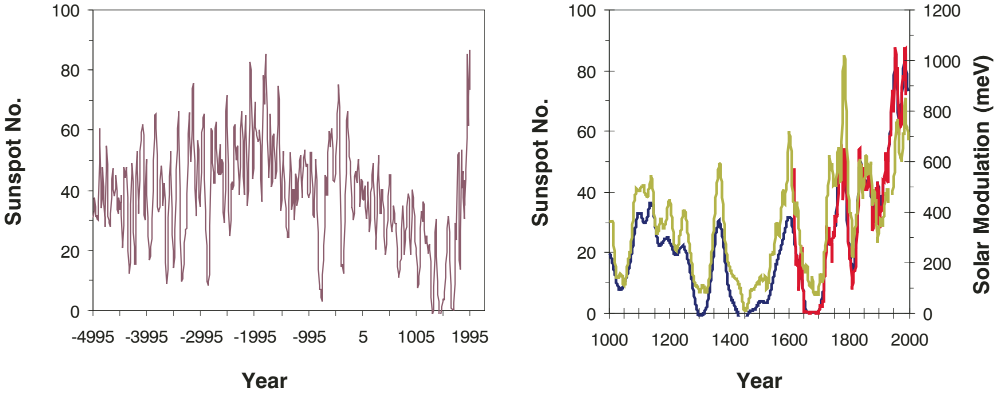


FIGURE ISPM-4: SOLAR ACTIVITY

LEFT: reconstruction for past 8,000 years (Usoskin *et al.* 2006); RIGHT: reconstructions for the past millennium; Blue – reconstruction of sunspot numbers from residual C14 (Usoskin *et al.*, 2006); Red – group sunspot number (Hoyt and Schatten, 1993); Green – reconstruction of solar modulation from residual C14 (meV) (Muscheler *et al.*, 2005).

1.4c Scientific understanding of solar variability remains low.

- Estimates of the change in solar forcing between the Maunder Minimum and the late 20th century range over almost an entire order of magnitude. [2.7, 2.7.1.2.1, Table 2.10; see Figure ISPM-5]
- A new estimate of solar irradiance increase since the Maunder Minimum (0.037% according to Wang *et al.*, 2005) is nearly an order of magnitude lower than another recent estimate of 0.3% by Fligge and Solanki, 2000. [2.71, Table 2.10]

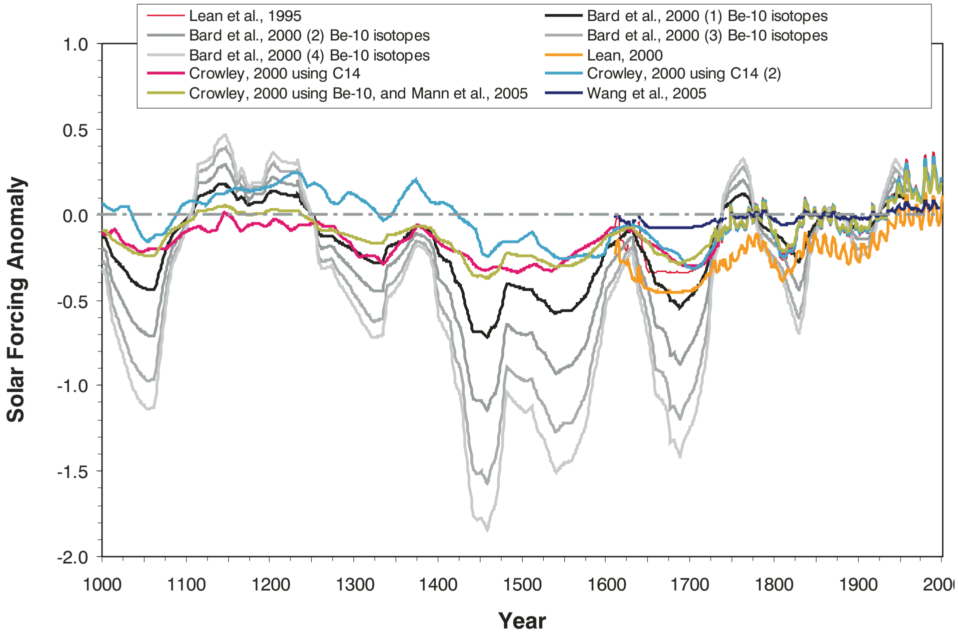


FIGURE ISPM-5: SOLAR FORCING ANOMALY (WATTS/ M^2) FOR THE PAST MILLENNIUM

Forcing anomaly calculated as irradiance divided by 4 and multiplied by 0.7 (albedo) following Table 2.10 of the Fourth Assessment Report. Anomaly centered on 1850-1960.

NOTE: There are four variations from Bard et al., 2000 Be-10 isotopes, and two from Crowley, 2000 using C14.

1.4d Total solar irradiance measurements are subject to important uncertainties due to instrumentation.

- Total Solar Irradiance has been measured only since 1978 and even then only with different instruments, none of which cover the entire interval. ACRIM instruments show an increase in excess of 0.04% between 1989 and 1992. This apparent increase may merely be a result of instrumental changes. [2.7.1]
- A continuous record can be constructed only by combining records from different satellites with different instruments. If the measured change of 0.04% proves accurate, this increase is as large as the increase since the Maunder Minimum. [2.7.1.1.2, Figure 2.19]

1.4e New evidence has emerged of indirect solar effects on climate.

- Although solar UV radiation represents only a small fraction of the energy from total irradiance, UV radiation is more variable by at least an order of magnitude. Since the Third Assessment Report, new studies have confirmed and advanced the plausibility of indirect effects on the climate system involving the modification of the stratosphere by solar UV irradiance variations (and possibly by solar-induced variations in the overlying mesosphere and lower thermosphere), with subsequent dynamical and radiative coupling to the troposphere. [2.7.1.3]
- It is now well established from both empirical and model studies that solar cycle changes in UV radiation alter middle atmospheric ozone concentrations, temperatures and winds. [2.7.1.3]

- When solar activity is high, the more complex magnetic configuration of the heliosphere reduces the flux of galactic cosmic rays in the Earth's atmosphere. Various scenarios have been proposed whereby solar-induced galactic cosmic ray fluctuations might influence climate, possibly through low cloud formation. [2.7.1.3]
- An unequivocal determination of specific mechanisms – whether direct or indirect - that involve solar variability and climate has yet to be accomplished. [2.7.1.3]

SUPPLEMENTARY INFORMATION

The sun and climate change

Solar and greenhouse forcings have both increased through the 20th century, making it extremely difficult to conclusively identify the influence of the sun on the recent climate.

New IPCC estimates of solar forcing are much lower than those used in millennial simulations (e.g., Crowley, 2000; Gonzalez-Rauco *et al.*, 2003; Mann *et al.*, 2005). If the new estimates prove reliable, many explanations of past climate variations relying on former estimates of solar forcing will need to be re-considered.

If the sun does have a strong effect on climate, this adds importance to recent projections that solar output is likely to decline over the next several decades (e.g., Zhen-Shan, 2007)

This topic is explored in the forthcoming Fraser Institute Supplementary Analysis Series report, "Solar Changes and the Climate."

1.5 Changes to the land surface

1.5a Changes in the land surface over the 20th century have likely had large regional and possibly global effects on the climate, but the effects do not fit into the conceptual model used for assessing anthropogenic climate change.

- Changes to the land surface act as anthropogenic perturbations to the climate system and fall at least partly within the "forcing" component of the *forcing-feedback-response* conceptual model. But it is difficult to quantify the pure forcing component of such changes as distinct from feedbacks and responses. A quantitative metric separating forcing from feedback and response has not yet been implemented for climatic perturbation processes which do not act directly on the radiation budget. [2.5.1]
- Attempts to use climate models to convert land use changes into RF measures have produced a wide range of results. Some estimated magnitudes of the local RF effects of agricultural change in North America and Eurasia are considerably larger than that from CO_2 in the atmosphere [2.5.3]. However the data for parameterizing basic RF effects are not consistent and the uncertainties remain large. [2.5.3.1]

1.5b Many studies have found that urban areas are warmer than the surrounding countryside, introducing a "non-climatic" warm bias into local long term weather records. If true, this would imply IPCC climate data overstate the recent global warming trend. Some studies have asserted, however, that urbanisation is adequately corrected in the globally-averaged data. All IPCC analysis assumes the latter to be the case.

- The urban heat island effect is real, and causes temperature records from urban and suburban areas to have an upward trend unrelated to climatic changes. [3.2.2.2]

- Some studies argue that the global climate data sets, which compile urban, suburban and rural records into regional averages, are not contaminated by such upward biases. [3.2.2.2]
- All IPCC usage of climatic data operates on the assumption of no contamination. However many studies have shown that changes in land use and land cover can have large regional effects on the climate that are comparable in magnitude to temperature and precipitation changes observed over the last several decades, and the large numbers of such studies collectively demonstrate a potentially important impact of human activities on climate, especially local climate, through land use modification. [7.2.4.4]
- Detection and attribution studies do not account for urbanization, data quality problems or other non-climatic effects in the temperature data. All observed changes in the data are assumed to be due to climatic changes. [9.4.1.2]

Problems with the surface temperature record

Research on the nature of the surface thermometer network has cast some doubt on the claim of the IPCC that the surface temperature record is free of biases related to non-climatic effects, such as land-use change, urbanization and changes in the number of stations worldwide. For example, studies have shown that the spatial pattern of warming trends over land correlate strongly with the distribution of industrial activity, even though such a correlation is not predicted by climate models (e.g., de Laat and Maurellis 2004, 2006).

These and related issues are explored in the forthcoming Fraser Institute Supplementary Analysis Series report, "Problems in the Surface Thermometer Network."

2.1 Large-scale temperature averages

2.1a Weather satellites collect daily data throughout the atmosphere and are used to measure average atmospheric temperatures. Different teams produce slightly different results based on different assumptions about the way to interpret the data.

- Satellites measure atmospheric radiation from two layers of the atmosphere, denoted T2 and T4.
- T2 radiation mostly comes from the surface and lower troposphere, whereas T4 mostly emanates from the stratosphere. From these radiation readings, temperature averages can be inferred based on an assumed set of weights. [3.4.1.2.2]
- The "true" weights cannot be known with certainty. The weights that yield results most closely matching data from weather balloons shows the least amount of tropospheric warming. [Figure 3.4.3]

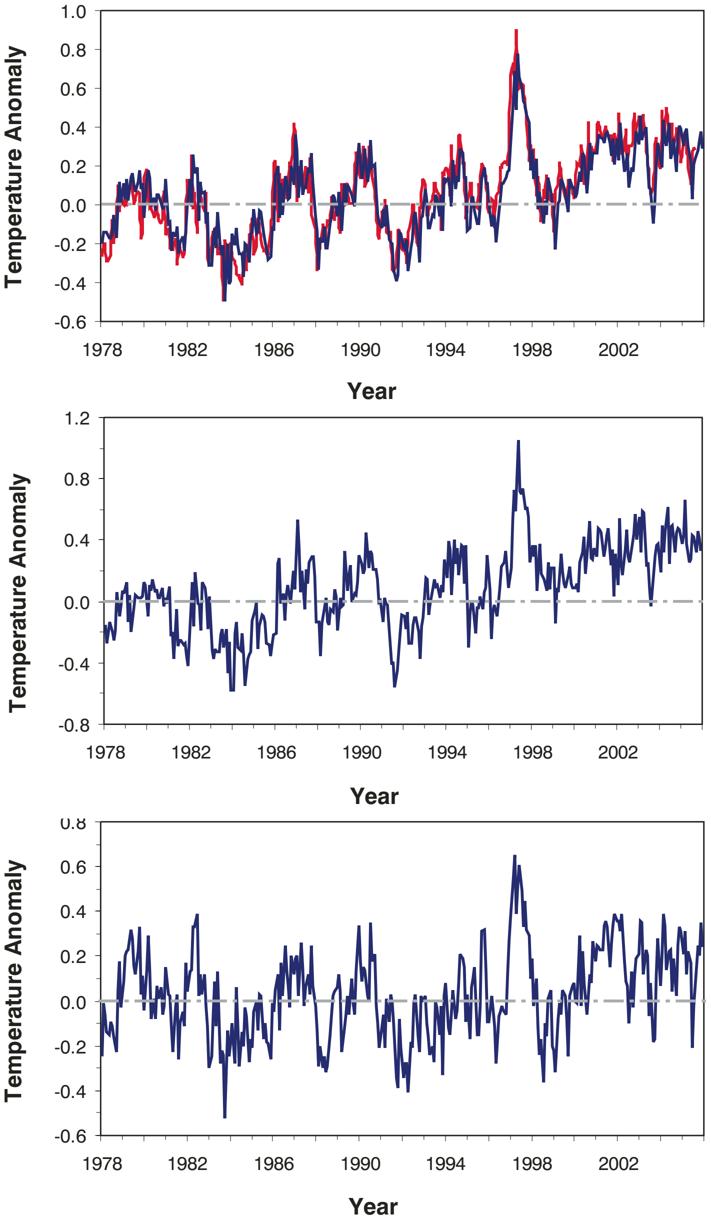


FIGURE ISPM-6: SATELLITE-MEASURED MEAN GLOBAL TEMPERATURE ANOMALIES SINCE 1979 (°C)

TOP: Global average; MIDDLE: Northern Hemisphere; BOTTOM: Southern Hemisphere.

Sources:

Top: Red -Mears and Wentz (2006); Blue - Global Hydrology and Climate Centre – University of Alabama in Huntsville (GHCC-UAH);

Middle and Bottom: GHCC-UAH.

2.1b Satellite-measured trends in global average temperatures since 1979 from the lower atmosphere range from nearly zero up to the low end of computer-based projections.

- Three different teams of analysts have examined satellite-based radiation data spanning 1979 to the present.
- Depending on assumptions about instrument calibration, area-weighting and merging across datasets, the average temperature trend in the lower atmosphere over the period 1979-2004 ranges from 0.04°C/decade to 0.20°C/decade. [3.4.1.2.2; Figure ISPM-6]
- Extrapolated to a century scale this compares to the low end of past IPCC warming projections (0.14 to 0.58°C/decade) as presented in the Third Assessment Report. [3.4.1.2.2]

2.1c There is no significant warming in the tropical troposphere, which accounts for half the world's lower atmosphere. This is where models that assume a strong influence of greenhouse gases forecast some of the most rapid warming should occur.

- The tropics account for half the world's atmosphere. In none of the available data sets is significant warming observed in the tropical troposphere [Figure 3.4.3]. One of the available satellite data sets shows trends consistent with increased warming at higher altitude in the tropics [3.4.1.2.2], while others do not.
- Climate models based on the assumption that greenhouse gases drive climate change predict some of the strongest warming should be observed in the upper troposphere over the tropics [Figure 10.3.4]. This pattern is predicted to be evident early in the forecast period and the pattern is simulated consistently among the models. [10.3.2.1]

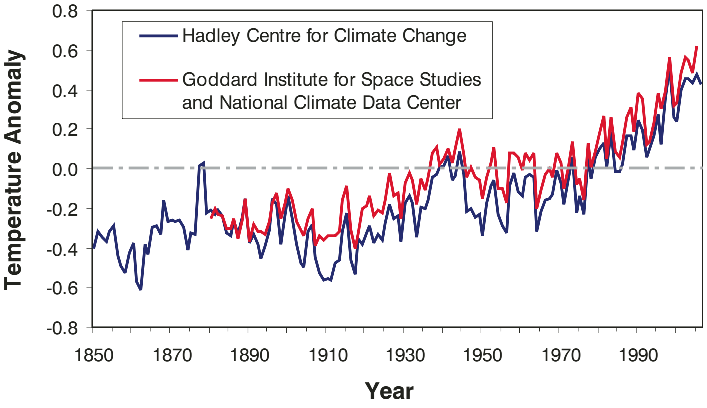


FIGURE ISPM-7: ANNUAL AVERAGE MEAN TEMPERATURE ANOMALIES MEASURED AT THE EARTH'S SURFACE OVER THE LAST 120-150 YEARS (°C)

Sources: Goddard Institute for Space Studies (GISS), National Climate Data Center (NCDC), and Hadley Centre for Climate Change.

2.1d A global average of temperature data collected over land, combined with ocean surface measurements from ships and buoys, with local means removed and some adjustments applied to control for uneven sampling, loss of half the land-based weather stations in the early 1990s, changes in measurement techniques and other potential problems, exhibits an upward trend from 1900 to 1940, and again from 1979 to the present.

- The statistic is commonly called the global mean temperature anomaly or "global temperature" for short.
- The global temperature statistic produced by the Goddard Institute for Space Studies (GISS) and the National Climate Data Center (NCDC) was slightly higher in 2005 than at any time since 1998, while that produced by the Hadley Center peaked in 1998 and has been slightly lower ever since. (see Figure ISPM-7) [3.2.2]
- See also Section 2.1e below.

	1850–2005	1901–2005	1910–1945	1946–1978	1979–2005
Land: Northern Hemisphere					
CRU (Brohan et al., 2006)	**0.063** **± 0.018**	**0.089** **± 0.030**	**0.142** **± 0.057**	−0.038 ± 0.064	**0.330** **± 0.108**
GHCN (Smith and Reynolds, 2005)		**0.072** **± 0.031**	**0.127** **± 0.065**	−0.040 ± 0.074	**0.344** **± 0.121**
GISS		**0.083** **± 0.030**	**0.166** **± 0.061**	−0.053 ± 0.062	**0.294** **± 0.090**
Lugina et al. (2005) up to 2004		**0.074** **± 0.032**	**0.144** **± 0.074**	−0.051 ± 0.061	**0.278** **± 0.096**
Land: Southern Hemisphere					
CRU (Brohan et al., 2006)	*0.034* *± 0.033*	**0.078** **± 0.054**	*0.091* *±0.076*	0.031 ±0.063	**0.135** **± 0.087**
GHCN (Smith and Reynolds, 2005)		**0.057** **± 0.020**	*0.091* *± 0.069*	0.054 ± 0.072	**0.220** **± 0.114**
GISS		**0.056** **± 0.015**	0.033 ± 0.042	*0.060* *± 0.052*	*0.085* *± 0.067*
Lugina et al. (2005) up to 2004		**0.056** **± 0.013**	**0.064** **± 0.046**	0.014 ± 0.052	*0.074* *± 0.062*
Land: Globe					
CRU (Brohan et al., 2006)	**0.054** **± 0.020**	**0.084** **± 0.026**	**0.125** **±0.042**	-0.016 ±0.055	**0.268** **± 0.084**
GHCN (Smith and Reynolds, 2005)		**0.068** **± 0.029**	**0.116** **±0.057**	−0.013 ±0.061	**0.315** **± 0.108**
GISS		**0.069** **± 0.020**	**0.102** **± 0.041**	0.003 ± 0.046	**0.188** **± 0.084**
Lugina et al. (2005) up to 2004		**0.065** **± 0.024**	**0.108** **± 0.043**	- 0.021 ± 0.059	**0.183** **± 0.075**

TABLE ISPM-1: LINEAR TRENDS OF TEMPERATURE (^{o}C/DECADE)

Reproduction of Table 3.2 from the Fourth Assessment Report. Each cell shows the IPCC-estimated trend and 2-standard error confidence interval. 'CRU' denotes Climatic Research Unit; 'GHCN' denotes Global Historical Climatology Network; 'GISS' denotes Goddard Institute for Space Studies. Bold denotes a statistically significant (1%) trend in IPCC methodology; italics denotes significant (1-5%): but see Section 2.1g below.

2.1e Post-1979 trends in temperature data averaged over land areas in the Southern Hemisphere are small compared to those from the Northern Hemisphere, and statistically less significant.

- Temperature trends in land-based data for the Northern and Southern Hemispheres from 1979-2005 are shown in Table ISPM-1. In all cases the Southern Hemisphere trend is small compared to the Northern Hemisphere trend.
- In two of the four surface data sets the Southern Hemisphere trend is less than one-third as large as the Northern Hemisphere trend and is statistically less significant. [Table 3.2]
- Both data sets that merge land-based data with relatively sparse and uncertain sea surface temperature data show Southern Hemisphere trends less than half those in the Northern Hemisphere. [Table 3.2]

2.1f The Third Assessment Report drew attention to the declining Diurnal Temperature Range (DTR) as evidence of global warming (Working Group 1 Summary for Policymakers, page 1). The decline in the DTR has now ceased, and appears to be growing in most places.

- The DTR declined after 1950, but stabilized as of the mid-1990s. [3.2.2.7, Figure 3.2.2]
- From 1979 to 2004, data from many locations on all continents show an increasing DTR, especially in North America, Europe, Australia and South America. [Figure 3.2.11]

2.1g The significance of trends in temperature and precipitation data is likely to have been overstated in previous analyses.

- The climate system responds to change slowly over time, and past changes accumulate through long term persistence to influence ongoing trends. As a result the trend estimation techniques used in recent IPCC Assessments likely overstate the statistical significance of observed changes, and the results of trend analysis often depend on the statistical model used. [3.2.2.1]

SUPPLEMENTARY INFORMATION

Long Term Persistence and Trend Analysis

Methods for estimating trends, and assessing their statistical significance, have undergone considerable advance in the past decade. Technical issues being raised include *nonstationarity* and *Long Term Persistence*. While the literature on these issues originated in hydrology, econometrics, finance and statistics, it has begun to be applied to climate data sets as well. The main findings are that proper treatment of long term processes in climate data often require a major reinterpretation of the significance of recent trends, as the new methods attribute more of the observed changes in climate data to natural variance.

This is explored in the forthcoming Fraser Institute Supplementary Analysis Series report, “Long Term Persistence in Geophysical Data.”

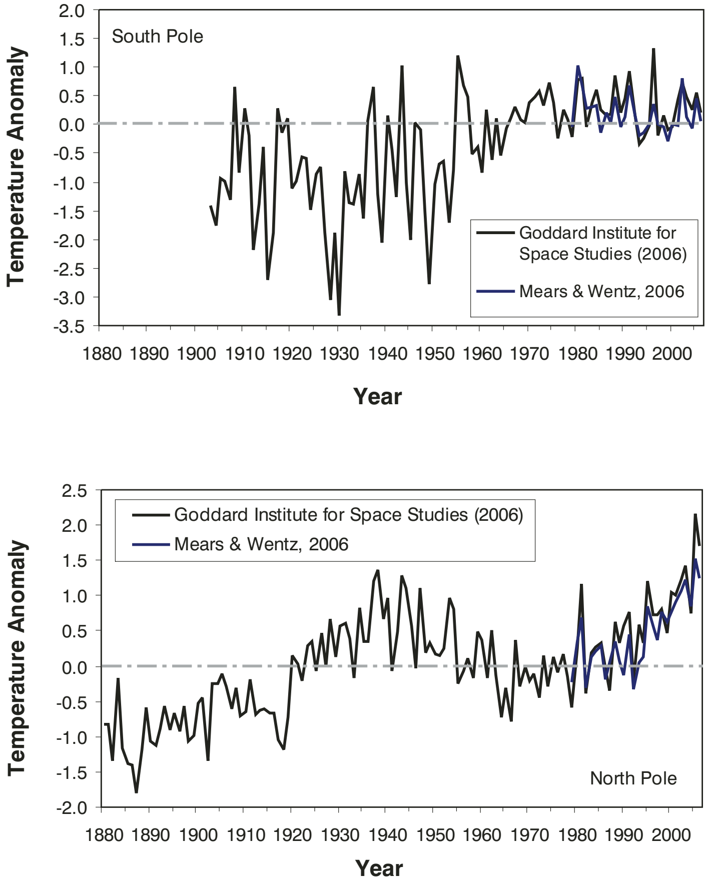


FIGURE ISPM-8. AVERAGE SURFACE TEMPERATURE ANOMALY POLEWARD OF 64 DEGREES LATITUDE (GRAY LINE) AND CORRESPONDING SATELLITE-MEASURED DATA (BLUE LINE)

TOP: South Pole; BOTTOM: North Pole.

Source: Gray-Goddard Institute for Space Studies (2006); Blue- Mears and Wentz (2006).

2.1h There are differences in linear trends of tropospheric temperatures between the high latitudes of the Northern and Southern Hemispheres that are not consistent with computer model projections.

- Geographical patterns of the linear trend in tropical temperature show coherent warming over the Northern Hemisphere but areas of cooling over the Southern Hemisphere. [3.4.1.2.2, Figure 3.4.4]
- The North Pole exhibits a sudden upward trend in mean temperature after 1990, but not the South Pole. (see Figure ISPM-8)
- Model projections suggest greenhouse gas-induced warming patterns at the north and south poles will be nearly symmetrical. [Figure 10.3.5]

2.1i The Earth's climate is characterized by many modes of variability, involving both the atmosphere and the oceans, and also by the cryosphere and the biosphere [1.4.6]. There is an increasing recognition that changes in the oceans may be playing a role in climate change.

- Our understanding of the variability and trends in different oceans is still developing, but it is already apparent they are quite different. The Pacific is dominated by the El-Niño/Southern Oscillation (ENSO) cycle and is modulated by the Pacific Decadal Oscillation (PDO), which may provide ways of transporting heat from the tropical oceans to higher latitudes and from the ocean to the atmosphere. [3.6.3]
- Since 1900, North Pacific Sea Surface Temperatures (SST) show warm mode phases from 1925-1946 and 1977 to 2005. [3.6.3]
- Since the 1850s, North Atlantic SSTs show a 65–75 year variation, with apparent warm phases at roughly 1860–1880 and 1930–1960 and cool phases during 1905–1925 and 1970–1990. This feature has been termed the Atlantic Multidecadal Oscillation (AMO). The cycle appears to have returned to a warm phase beginning in the mid-1990s and tropical Atlantic SSTs were at record high levels in 2005. [3.6.6.1]
- The AMO has been linked to multi-year precipitation anomalies over North America, as well as Atlantic hurricane formation, African drought frequency, winter temperatures in Europe, sea ice concentration in the Greenland Sea and sea level pressure over high northern latitudes. [3.6.6.1]
- The multidecadal variability in the Atlantic is much longer than the Pacific but it is noteworthy that all oceans exhibit a warm period around the early 1940s. [3.2.2.3]

SUPPLEMENTARY INFORMATION

Major Ocean-Atmosphere Climate Oscillations

An important theme in recent meteorological research is the identification of some large-scale atmospheric cycles that operate on time spans of 30 years or more. These oscillations arise from the interaction of the oceans and atmosphere, and are typically measured using pressure gradients across large regions of the Earth's surface. Representation of the oceans in climate models as truly dynamic systems (as opposed to the earlier "slab" ocean models) is only beginning. A comprehensive description of the atmospheric and ocean circulations has been delayed by lack of observations from the high atmosphere and deep oceans.

Major oscillation systems have been shown to have significant explanatory power for recent climatic changes, including trends in temperature and precipitation. The El Niño-Southern Oscillation (ENSO) is a coupled air-sea phenomenon that has its origins in the Pacific Ocean but affects climate globally. The mechanisms and predictive skill of ENSO are still under development. The North Atlantic Oscillation (NOA, first discovered by Sir Gilbert Walker in the 1930s) is a phenomenon that affects weather and climate and is associated with variability and latitudinal shifts of the westerly winds and jet streams. Despite a long history of observation and research the NAO and its low-frequency variability remains poorly understood.

The IPCC discusses some of these issues, but does not provide adequate detail about the connection between these systems and recent weather changes.

This topic is explored in the forthcoming Fraser Institute Supplementary Analysis Series report, "Major Climatic Oscillations and Recent Weather Changes."

2.2 Precipitation and snow cover

2.2a There is no globally-consistent pattern in long-term precipitation trends.

- At the global level, slight decline was observed in total precipitation from 1950 to the early 1990s, which has since reversed. [3.3.2.1; Figure 3.3.1]
- Precipitation in North and South America has risen slightly over the past century in many places, though in some regions it has fallen. [3.3.2.2]
- The drying trend noted in the 1980s in the Sahel (the coastal region in Africa bordering the Sahara desert) has since reversed considerably. [3.3.2.2]
- Rainfall in India increased from 1901 to 1979 then declined through to the present [3.3.2.2], and there is no overall trend. [3.3.2.2]
- Australian precipitation trends vary by region and are closely linked to the El Niño cycle. [3.3.2.2]

2.2b There is no globally-consistent pattern in snow-covered area or snow depth.

- In the Northern Hemisphere, mean observed snow cover in April declined somewhat from the 1950s to the 1970s, declined rapidly in the 1980s and has increased slightly since 1990. [Figure 4.2.1]
- Over the 1966 to 2004 interval, mean Northern Hemisphere snow cover in October showed a statistically insignificant decline. But over the entire span of available data (1922 to 2004) the mean Northern Hemisphere snow cover in October shows a statistically significant increase. [Table 4.2.1]
- Over the 1966 to 2004 interval, mean Northern Hemisphere snow cover trended downward in spring and summer, but not substantially in winter. [4.2.2.2; Table 4.2.1]
- In North America the trend in November-January snow-covered area over the 20th century is upward overall, with a recent downward trend especially in Western North America. [4.2.2.2.1]
- Snow-covered area in mountainous areas of Switzerland and Slovakia has declined since 1931, but not in Bulgaria. [4.2.2.2.2]
- Lowland areas of central Europe have exhibited decreased snow-covered area, while increased maximum snow depth has been recorded in the former Soviet Union, Tibet and China. [4.2.2.2.2]
- In South America a long term increasing trend in snow days has been observed in the eastern central Andes. [4.2.2.3.1]
- In Southeastern Australia, late-winter snow depth has declined considerably, though winter precipitation has decreased only slightly. [4.2.2.3.2]

2.2c In areas north of 55N latitude, snowfall has increased over the past 50 years. Trends in the frequency of heavy snowfall events vary by region.

- At high latitudes, winter precipitation has increased in the past 50 years [3.3.2.3] and there has been little change in the fraction falling as snow rather than rain. [3.3.2.3]
- In North America, the incidence of heavy snowfall events has increased in Northern Canada and in the lee of the Great Lakes, but decreased in the lower Missouri river basin. [3.3.2.3]
- In some areas, namely Southern Canada and western Russia, the earlier onset of the spring season over the past 50 years has meant an increasing fraction of precipitation falls as rainfall [3.3.2.3]. However other data have shown an overall increase in snowfall in parts of southern Canada. [3.3.2.3]

Recent North American snowfall records

"Record-breaking" local hot weather events are sometimes promoted as evidence of global warming. What can we infer if record-breaking cold weather events begin to accumulate in some local data?

New York City's Central Park has a January (their coldest month) average temperature of 0.1°C and winter average of 1.0°C. For the first time since records began in the 1860s, Central Park reported four successive years of 100 centimetres of snow or more ending in the winter of 2005/06. On February 11-12, 2006, Central Park broke the all-time single snowstorm record with 68.3 centimetres of snow. Also in 1995/96, Central Park and most other cities in the central and eastern US had all-time record seasonal snowfall. In Central Park, that winter brought 192 centimetres of snow.

Not far to the north in Boston, MA where the winter temperature averages -0.1°C, the 12 year average snowfall in the winter ending 2004/05 was 130.3 centimetres, the highest in their entire record dating back into the 1800s. A new all-time single snowstorm record was set on February 17-18, 2003 with 70 centimetres and a new all-time seasonal snowfall record of 273 centimetres was set in 1995/96. In the last dozen years, Boston has recorded their 1st, 3rd, 5th, 7th and 12th snowiest winters.

In the Canadian Atlantic provinces winter snow accumulation has increased in recent years. The city of St. John's (Newfoundland) recorded its highest ever snow accumulation in one season, ~650 cm, from November 2000 through May 2001. This is the highest snow accumulation at a sea-level location any where in the world. In February 2004 the city of Halifax (Nova Scotia) received a record-breaking 100 cm of snow in a 24-hour period.

Data Source: US National Weather Service and Environment Canada

2.3 Storms and extreme weather

2.3a Perceptions of increased extreme weather events are potentially due to increased reporting. There is too little data to reliably confirm these perceptions.

- People tend to hear about extreme events more now because of technology. Pictures shot by camcorders on the news may foster a belief that weather-related extremes are increasing in frequency. [3.8.1]
- Global studies of temperature and precipitation extremes over land suffer from a scarcity of data. In various parts of the globe, there is a lack of homogeneous (i.e., subject to consistent quality control and constant sampling conditions) daily observational records. The lack of homogeneous data has been attributed to, among other things, changes in observing practices or urban heat island effects. [3.8.1]
- Identification of changes in extremes is also dependent on the statistical analysis technique employed. [3.8.1]
- Global studies of daily temperature and precipitation extremes over land suffer from both a scarcity of data and regions with missing data. [3.8.1]
- Analyses of trends in extremes are also sensitive to the analysis period; e.g., the inclusion of the exceptionally hot European summer of 2003 may have a marked influence on results if the period is short. [3.8.1]

2.3b Since 1970, there is some evidence of increased tropical cyclone intensity in both hemispheres, but a decrease in total tropical storm numbers, and no clear global pattern.

- A number of recent studies suggest that cyclone activity over both hemispheres has changed over the second half of the 20th century. General features include a poleward shift in storm track location and increased storm intensity, but a decrease in total storm numbers. [3.5.3]
- Station pressure data over the Atlantic-European sector (which has long and consistent records) show a decline of storminess from high levels during the late-19th century to a minimum around 1960 and then a quite rapid increase to a maximum around 1990, followed again by a slight decline. [3.5.3]
- Data suggest that cyclone activity in the Northern Hemisphere mid-latitudes has increased during the past 40 years, whereas there have been significant decreases in cyclone numbers, and increases in mean cyclone radius and depth, over the southern extratropics over the last two or three decades. [3.5.3]
- With respect to storm data generally, data uncertainties compromise evidence for trends. [3.8.1]
- The considerable inter-decadal variability reduces the significance of any long-term trends. Careful interpretation of observational records is therefore required. [3.8.3]
- The overall power of cyclones has been characterized using the Accumulated Cyclone Energy (ACE) index and the Power Dissipation Index (PDI). The ACE is proportional to the square of the wind speed and the PDI is proportional to the wind speed cubed. The PDI for the world as a whole shows an upward trend since the 1970s, but because of its cubic exponent it is very sensitive to data quality. Pre-1970 data are particularly uncertain [3.8.3]. The ACE index is available in some regions back to 1948 and shows no overall trend over the entire interval. The ACE shows an upward trend after 1980 only in the North Atlantic, but a downward trend post-1980 in the West North Pacific, East North Pacific, Australian-South Pacific, North Indian and South Indian regions [Figure 3.8.4]. At the global level, the ACE Index values for 2004 and 2005 are about average for the whole post-1980 interval. [3.8.3]

2.3c Data are too sparse, and trends inconsistent, to identify a pattern in extratropical cyclones.

- As with tropical cyclones, detection of long-term changes in extratropical cyclone measures is hampered by incomplete and changing observing systems. Some earlier results have been questioned because of changes in the observation system. [3.8.4.1]
- An increase in the number of deep cyclones is apparent over the North Pacific and North Atlantic, but only the North Pacific trend is statistically significant. Significant decreases have been noted in cyclone numbers over the southern extratropics over the last two or three decades, along with increases in mean cyclone radius and depth. [3.8.4.1]

2.3d Evidence for changes in temperature variability is sparse and insignificant.

- Evidence for changes in observed interannual variability is still sparse. Seasonal mean temperature in central Europe showed a weak increase in summer and decrease in winter, for the time period 1961 to 2004. These changes are not statistically significant at the 10% level. [3.8.2.1]

- Regional studies from several continents show patterns of changes in extremes consistent with a general warming, although the observed changes of the tails of the temperature distributions are not consistent with a simple increase in the entire temperature distribution. [3.8.2.1]
- For the period 1951–2003, three-quarters of the global land area sampled showed a significant decrease in the annual occurrence of cold nights; while a significant increase in the annual occurrence of warm nights took place over 72% of the area. This implies a positive shift in the distribution of daily minimum temperature throughout the globe. Changes in the occurrence of cold days and warm days show warming as well, but generally less marked. This is consistent with the increase in minimum as opposed to maximum temperature. [3.8.2.1]

2.4 Ocean temperatures and sea levels

2.4a Regarding the Gulf Stream and the global Meridional Overturning Circulation (MOC), it is very likely that the MOC has changed on annual and decadal time scales, but evidence for overall weakening is mixed and uncertain, and the connection to surface climate is not well understood.

- The global Meridional Overturning Circulation (MOC) consists primarily of dense waters that sink to the seafloor at high-latitudes in the North Atlantic Ocean and near Antarctica. This influences global ocean currents and may influence wind patterns, including the Gulf Stream. [Box 5.1]
- Only indirect estimates of the MOC strength and variability exist, and the best evidence for observational changes in the overturning circulation comes from the North Atlantic. [Box 5.1]
- There is evidence for a link between MOC and abrupt changes in surface climate during the past 120,000 years, although the exact mechanism is not clear. [Box 5.1]
- One recent study concluded that the MOC transport in the North Atlantic at 25°N has decreased by 30% between 1957 and 2004, indicating a stronger mid-ocean return flow in the upper kilometre, though not a decrease in Gulf Stream strength. Note however that this result is based on 5 snapshots in time, and it is not clear whether the trend estimate can be viewed as robust in the presence of considerable variability. [Box 5.1]
- Two other studies examined a model-based relation of MOC transport with interdecadal sea surface temperature patterns and concluded that the MOC has increased since the 1970s. [Box 5.1]
- There is only a low level of confidence that the strength of deep limb of the MOC in the North Atlantic MOC has actually decreased. [Box 5.1]

SUPPLEMENTARY INFORMATION

Questions about the MOC Mechanism

It has not been formally established that deep-water formation drives the MOC. Others have argued (e.g., Wunsch, 2002) that deep-water formation does not provide sufficient energy to drive the MOC, and that it is a largely wind-driven circulation, where the wind field provides the mechanical energy necessary to overcome the natural stratification of the ocean.

A recent paper (Latif et al, 2006) concludes that multi-decadal MOC variations can be understood as the lagged response to the multi-decadal variations in the NAO, and further does not provide any evidence for a sustained weakening of the MOC during the last few decades.

2.4b Regarding sea levels, a critical issue concerns how the records are adjusted for vertical movements of the land upon which the tide gauges are located. Current data suggest a global mean sea level rise of between 2 and 3 millimeters per year.

- Tide gauges provide data about sea level variations with respect to the land on which they lie. However, the Earth's crust is subject to various vertical motions due to geological factors such as tectonics and local subsidences. To extract an accurate sea level signal, tide gauge readings need to be adjusted to compensate for vertical motions. [5.5.1]
- Sea level change based on satellite altimetry measurements is measured with respect to the earth's center of mass, and thus is not distorted by land motions, except for a small component due to large scale deformation of ocean basins from Glacial Isostatic Adjustment (GIA). [5.5.1]
- Models are used to correct recent global tide gauge estimates for Glacial Isostatic Rebound (GIR), but not for other land motions. Adjusted rates could be underestimated by several tenths of millimeters per year in analyses which employ extrapolations of geological data obtained near the gauges. [5.5.2.1]
- Tide gauge data suggests a rise in mean sea level over 1961-2003 of about 1.8 mm/year, ±0.5 mm. [5.5.2.1]
- Satellite estimates of mean sea level yield an accuracy of ±5 mm. Satellite data show a rate of sea level rise of +3.1 ± 0.8 mm per year over 1993-2005. The accuracy of this estimate is partly dependent on the calibration against vertical land motions as measured by tide gauges. [5.5.2.1]
- By comparison, satellite observations show a 15 mm rise and fall of mean sea level and a 0.4°C rise and fall of global mean sea surface temperature accompanying the 1997-1998 El Niño-Southern Oscillation (ENSO) event. [5.5.2.1]

2.4c Regional trends in sea level are quite varied and some regions are experiencing declining sea levels. Changes in air pressure and wind account for some observed sea level increase.

- While global sea level rose by approximately 120 metres during the several millennia that followed the end of the last glacial maximum, the level stabilized between 3000 and 2000 years ago. Since then, paleo sea level indicators suggest that global sea level did not change significantly: the average rate of change from 2000 years ago to about 100 years ago is near zero. [Question 5.1]
- Although regional variability in coastal sea level change had been reported from tide gauge analyses, the global coverage of satellite altimetry provides unambiguous evidence of non-uniform sea level change in open oceans. [5.5.2.2]
- For the past decade, the western Pacific Ocean and eastern Indian Oceans show the highest magnitude of sea level rise, however, sea level has been dropping in the eastern Pacific and western Indian Oceans. [5.5.2.2]
- Except for the Gulf Stream region, most of the Atlantic Ocean shows sea level rise during the past decade. [5.5.2.2]
- Northeast Atlantic sea level records are notable for their 20th century trends that are lower than the global average. Explanations include Glacial Isostatic Adjustment, and air pressure and wind changes associated with North Atlantic Oscillation (NAO). [5.5.2.6.1]
- Arctic Ocean sea level time series have well pronounced decadal variability which corresponds to the variability of the North Atlantic Oscillation Index. In this particular region, wind stress and atmospheric pressure loading contribute to nearly half of the observed Arctic sea level rise. [5.5.2.6.2]

2.4d There is very little sea-level data from Pacific Ocean islands. The available series appear to indicate less than one millimeter sea level rise per year.

- There are only four Pacific island stations with more than 50 years of data. Data from these stations show an average rate of sea-level rise (relative to the Earth's crust) of 1.6 mm/year. Twenty-two Pacific island stations have more than 25 years of data and they indicate an average sea level rise less than half as great, at 0.7 mm/year. However, these data suffer from poorly quantified vertical land motions. [5.5.2.6.3]

2.4e Changes in extreme sea level are due to changes in sea level and storminess. 20th century trends differ by location.

- The annual maximum high water surge at Liverpool since 1768 was larger in the late-18th, late-19th and late-20th centuries than for most of the 20th century. [5.5.2.7]
- The tide gauge record at Brest from 1860 to 1994 shows an increasing trend in storm surges (as measured by maxima and top-1% groups), but shows a decreasing trend during the period 1953-1994. [5.5.2.7]
- Extreme winter surges at San Francisco have exhibited a significant increasing trend since about 1950. [5.5.2.7]
- The rise in extreme sea level along the US east coast is closely correlated to the rise in mean sea level. [5.5.2.7]
- A long term increase in the number and height of extreme daily sea level readings has been noted at Honolulu, but no evidence indicates an increase relative to the underlying upward mean sea level trend. [5.5.2.7]

2.4f Sea level increases over the past decade are not uniform, and it is presently unclear whether they are attributable to natural variability.

- The instrumentally-based estimates of modern sea level change provide evidence for an onset of acceleration at the end of the 19th century. Recent estimates for the last half of the 20th century (1950-2000) give approximately 2 mm/year global mean sea level rise. New satellite observations show that since 1993 sea level has been rising at a rate of 3.1 mm/year. [Question 5.1]
- Satellite data also confirm that sea level is not rising uniformly over the world. [Question 5.1]
- It is presently unclear whether the higher rate of sea level rise in the 1990's indicates an acceleration due to global warming, or a result of natural climate variability, or a combination of both effects. [Question 5.1]

SUPPLEMENTARY INFORMATION

Historical Storm Surges

The greatest storm surge in historical time was 13.6 meters and occurred in 1876 in the Bay of Bengal. The second highest on record was 13 meters in the Bathurst Bay in Australia in 1899. Since 1876, the maximum surge in the Bay of Bengal was about 9 meters in 1970 and 1999. By comparison, the maximum surge by Hurricane Katrina of August 2005 was 8.5 meters.

2.5 Glaciers, sea ice and ice caps

2.5a Glacier archives indicate that most of the Earth's alpine glaciers receded or disappeared between 9,000 and 6,000 years ago.

- Most archives from the Northern Hemisphere and the tropics show small or absent glaciers between 9,000 and 6,000 years ago. [Box 6.3]
- Glaciers began growing thereafter, up to the 1800s. [Box 6.3]
- This tendency is primarily related to changes in the Earth's orbit, however shorter, decadal-scale, regionally diverse glacier responses must have been driven by other factors which are complex and poorly understood. [Box 6.3]

2.5b Glaciers in most places have retreated since the 1800s

- General retreat of glacier termini started after 1800, with considerable mean retreat rates in all regions after 1850 lasting throughout the 20th century. A slowdown of retreats between about 1970 and 1990 is evident in the raw data. Retreats were again generally rapid in the 1990s; though advances of glaciers have been observed in western Scandinavia and New Zealand. [4.5.2]
- There are few records of directly measured glacier mass balances, and they stretch back only to the mid 20th century. [4.5.2] When areal weighting and spatial interpolation are used to estimate large-scale patterns from the available data, the 1990s trend towards glacier retreat appears to have leveled off or reversed after 1998. [Figure 4.5.2]

2.5c Over the last half century, global mean winter accumulation and summer melting of glacier ice have both increased.

- At least in the Northern Hemisphere, winter accumulation and summer melting of glacial ice correlates positively with hemispheric air temperature, whereas the net balance correlates negatively with hemispheric air temperature. An analysis of 21 Northern Hemisphere glaciers found a rather uniformly increased mass-turnover rate, qualitatively consistent with moderately increased precipitation and substantially increased low-altitude melting. [4.5.2]

2.5d While the loss of Northern Hemisphere glacier mass accelerated in the 1990s, loss of Arctic sea ice thickness slowed or stopped during the 1990s

- In the Northern Hemisphere, the rate of glacier mass loss was twice as rapid in the 1990s compared to the period from the 1960s to1990. [4.5.2]
- An early study of Arctic ice found that ice draft in the mid 1990s was less than that measured between 1958 and 1977 at every available location (including the North Pole). The decline averaged about 42% of the average 1958-1977 thickness. Subsequent studies indicate that the reduction in ice thickness was not gradual, but occurred abruptly before 1991, with no evidence of thinning along 150°W from six springtime cruises during 1991-1996. Springtime observations from 1976 to 1994 along the same meridian indicated a decrease in ice draft sometime between the mid 1980s and early 1990s, with little subsequent change. [4.4.3.2]

2.5e On a regional basis the pattern of glacier regimes remains complex. Precipitation and solar changes appear to be important factors, especially in the tropics, including Kilimanjaro.

- Although reports on individual glaciers or limited glacier areas support the global picture of ongoing strong ice shrinkage in almost all regions, some exceptional results indicate the complexity of both regional to local scale climate and respective glacier regimes. [4.5.3]
- Whereas Himalayan glaciers have generally shrunk at varying rates, several high glaciers in the central *Karakoram* are reported to have advanced and/or thickened at their tongues, probably due to enhanced transport of moisture to high altitudes. [4.5.3]
- Norwegian coastal glaciers advanced in the 1990s and started to shrink around 2000 as a result of almost simultaneous reduced winter accumulation and greater summer melting. Norwegian glacier termini farther inland have retreated continuously at a more moderate rate. [4.5.3]
- Glaciers in the New Zealand Alps advanced during the 1990s, possibly due to increased precipitation, but since 2000 they have started to shrink. [4.5.3]
- Tropical glaciers, being in principle very sensitive to changes in both temperature and atmospheric moisture, have shrunk mostly in response to regional changes in atmospheric moisture content and related energy and mass balance variables such as solar radiation, precipitation, albedo, and sublimation during the 20th century. Inter-annual variation in the seasonal pattern of moisture strongly dominates the behaviour of tropical glaciers. [4.5.3]
- Glaciers on Kilimanjaro behave exceptionally. Even though the thickness of the tabular ice on the summit plateau has not changed dramatically over the 20th century, the ice has shown an incessant retreat of the vertical ice walls at its margins, for which solar radiation is identified as the main driver. The mass balance on the horizontal top ice surfaces is governed by precipitation amount and frequency and associated albedo, and has sporadically reached positive annual values even in recent years. In contrast to the plateau ice, the shrinkage of the glaciers on Kilimanjaro's slopes is constantly decelerating. [4.5.3]

2.5f Sea ice thickness is one of the most difficult geophysical parameters to measure on large-scales.

- Because of the large variability inherent in the sea-ice-climate system, evaluation of ice thickness trends from the available observational data is difficult. [4.4.3.7]
- Recent changes have occurred within the context of longer term decadal variability due to both dynamic and thermodynamic forcing of the ice by circulation changes associated with low-frequency modes of atmospheric variability. [4.4.3.7]
- Ice thickness varies considerably from year to year at a given location and so the rather sparse temporal sampling provided by submarine data makes inferences regarding long-term change difficult. [4.4.3.2]
- There are insufficient data to draw any conclusions about trends in the thickness of Antarctic sea ice. [4.4.3.7]

2.5g It is not possible to attribute the abrupt decrease in sea ice thickness inferred from submarine observations entirely to the (rather slow) observed warming in the Arctic.

- Some of the dramatic decrease may be a consequence of wind-driven redistribution of ice volume over time. [4.4.3.4]
- Low-frequency, large-scale modes of atmospheric variability (such as interannual changes in circulation connected to the Northern Annular Mode) affect both wind-driving of sea ice and heat transport in the atmosphere, and therefore contribute to interannual variations in ice formation, growth and melt. [4.4.3.4]

2.5h Estimates of Greenland ice cap changes indicate near coastal thinning and inland thickening.

- Many recent studies have addressed Greenland mass balance. They yield a broad picture of slight inland thickening and strong near-coastal thinning, primarily in the south along fast-moving outlet glaciers. [4.6.2.2]
- Assessment of the data and techniques suggests overall mass balance of the Greenland Ice Sheet ranging between growth by 25 Gigatonnes per year (Gt/year) and shrinkage by 60 Gt/year for 1961–2003. [4.6.2.2]
- This range changes to shrinkage by 50 to 100 Gt/year for 1993–2003 (which translates to 0.1-0.2 mm per year sea level rise: [10.3.4]) and by even higher rates between 2003 and 2005. However, interannual variability is very large, driven mainly by variability in summer melting and sudden glacier accelerations. Consequently, the short time interval covered by instrumental data is of concern in separating fluctuations from trends. [4.6.2.2]

2.5i The ice sheet in Eastern Antarctica appears to have grown while that in Western Antarctica appears to have shrunk. The overall change may be positive or negative depending on assumptions about ice dynamics.

- Assessment of the data and techniques suggests overall Antarctic ice-sheet mass balance ranging from growth by 50 Gt/year to shrinkage by 200 Gt/year from 1993–2003. [4.6.2.2]
- There is no implication that the midpoint of this range provides the best estimate. Lack of older data complicates a similar estimate for the period 1961–2003. [4.6.2.2]
- A pattern of East Antarctic thickening and West Antarctic thinning was observed across several independent studies. [4.6.2.2]
- Considering the lack of estimated strong trends in accumulation rate, assessment of the possible acceleration and of the slow time scales affecting central regions of the ice sheets, it is reasonable to estimate that the behavior from 1961–2003 falls between ice-sheet growth by 100 Gt/year and shrinkage by 200 Gt/year. [4.6.2.2]

2.5j Summing changes in Greenland and Antarctic indicates either a gain or a loss of ice mass over the 1961-2003 interval.

- Simply summing the 1993-2003 contributions from Greenland and Antarctica produces a range from balance (0 Gt/year) to shrinkage by 300 Gt/year, or contribution to sea-level rise of 0 to 0.8 mm per year. [4.6.2.2]
- For 1961-2003, the same calculation spans growth by 125 Gt/year to shrinkage by 260 Gt/year. [4.6.2.2]

2.6 Humidity and radiation flux

2.6a Changes in mid and upper tropospheric water vapour are proposed as an important potential amplifier of climate change. There is evidence of increased specific humidity, but not relative humidity, over the past two decades.

- Water vapour in the mid and upper troposphere accounts for a large part of the atmospheric greenhouse effect and is believed to be an important amplifier of climate change. [3.4.2.2]
- Due to instrumental limitations, long-term changes of water vapour in the upper troposphere are difficult to assess. [3.4.2.2]
- Satellite data indicate that specific humidity in the upper troposphere increased over the period 1982-2004, but changes in relative humidity were negligible. [3.4.2.2]
- This signature is generally consistent with increased tropospheric temperatures, though the increase in specific humidity is strongest over the tropics [Figure 3.4.6] where temperature trends are insignificant. (see Section 2.1g)

2.6b Observed changes in radiation flux at the top of the atmosphere are small and equivocal, and may simply reflect natural variability.

- Although there is independent evidence for decadal changes in top-of-atmosphere (TOA) radiative fluxes over the last two decades, the evidence is equivocal. [3.4.4]
- Changes in the planetary and tropical TOA radiative fluxes are consistent with independent global ocean heat storage data, and are expected to be dominated by changes in cloud radiative forcing. To the extent that the evidence is valid, these changes may simply reflect natural low-frequency variability of the climate system. [3.4.4]

3 Climatic changes in paleoclimate perspective

3.1 Geological evidence of warming and cooling episodes

3.1a On a time scale of millions of years, current temperatures are not unprecedented. Through much, if not most, of the last 100 million years, temperatures were warmer than at present, including a super-warm interval approximately 50 million years ago.

- The earth was ice-free during most of its history [6.3.1]
- The Pliocene (about 3 million years ago) was the most recent time in Earth's history when mean global temperatures were substantially warmer (about 2°C to 3°C warmer) [6.3.2]
- The Paleocene-Eocene Thermal Maximum was several degrees warmer still. [6.3.3]

3.1b On the other hand, temperatures during most of the most recent 1 million years (the Pleistocene) have been colder than at present. Long glacial periods have alternated with short (10 to 30,000 year long) interglacials.

- Continental glaciers covered much of North America, Europe and Asia during the Pleistocene. [6.4.1]
- Ice cores and ocean sediment cores have enhanced our understanding of both glacial and interglacials. [6.4.1]
- Glacials and interglacials are attributed to changes in the earth's orbit: precession, obliquity and eccentricity. [Box 6,1]

3.1c The last interglacial (LIG, 129,000–116,000 years ago) was warmer than the present.

- Globally, there was less glacial ice and higher sea level on Earth during the Last Interglacial than now. This suggests significant meltback of the Greenland and possibly Antarctica ice sheets occurred. The climate of the LIG has been inferred to be warmer than present, although the evidence is regional and not neccessarily synchronous globally. Proxy data indicate warmer-than-present coastal waters in the Pacific, Atlantic, and Indian Oceans and in the Mediterranean Sea, greatly reduced sea ice in the coastal waters around Alaska, and extension of boreal forest into areas now occupied by tundra in interior Alaska and Siberia, during the early LIG. Ice core data indicate Greenland and Antarctic temperatures were 4–5°C warmer than present. [6.4.1.6]
- The length and amplitude of interglacials varied. The shortest lasted only a few thousand years, while the longest (Stage 11) lasted nearly 30,000 years. [6.4.1.5]

3.1d The current interglacial (the Holocene) began about 11,600 years ago and is already longer than some interglacials. Some features are comparable to the unusually long Stage 11 interglacial. [6.5, 6.4.1.5]

- The most recent ice age began about 116,000 years ago. Glaciation reached a maximum about 21,000 years ago. Deglaciation, or the transition to a warm interval, took place between 20,000 and 10,000 years ago. [6.4.1.2, 6.5]
- The present orbital configuration has been compared to the Stage 11 configuration (420,000-395,000 years ago), when there was a long interglacial. [6.4.1.5]

3.1e Large, widespread, abrupt climate changes have occurred repeatedly throughout the ice age/post-glacial interval.

- Abrupt climate change refers to events of large amplitude regionally, typically a few degrees Celsius, and that occur on time scales significantly shorter than 1,000 years. [1.4.2]
- Abrupt temperature events were larger and more widespread during the ice age then during the warm Holocene. The most dramatic of these abrupt climate changes are characterised by a warming in Greenland by 8 to 16°C within a few decades, followed by much slower cooling over centuries. Another type of abrupt change is the Heinrich event, involving sea surface cooling that lasts several thousands of years, followed by abrupt warming over several decades. At the end of the last ice age, as the climate warmed and ice sheets melted, climate went through a number of abrupt cold phases, notably the Younger Dryas and the 8.2 kyr event. [6.4.2.1]
- Abrupt temperature changes were first detected in deep ice cores from Greenland. By the end of the 1990s it became clear that abrupt climate changes, as found in the Greenland ice cores during the last ice age, were numerous, indeed abrupt, and of large amplitude. [1.4.2]
- The importance of internal variability and processes was reinforced in the early 1990s with the analysis of records with high temporal resolution: new ice cores, ocean cores with high sedimentation rate, lacustrine sediments, and also cave stalagmites. Reconstruction of the thermohaline circulation of deep and surface water shows the participation of the ocean in these abrupt changes. [1.4.2]
- There are many examples of abrupt changes that are regional rather than global in extent. [1.4.2]
- Abrupt climate change during both ice age and warm epochs alters the notion of relative climate stability, as previously suggested. Rather there is a coherent picture of an unstable ocean-atmosphere system of global extent. [1.4.2]

3.1f The causes of large-scale climate variations on the century and longer time scales are not well-understood.

- Based on the correlations between changes in climate proxy records and production of cosmogenic isotopes – assumed to relate to solar activity changes – some authors argue that solar activity, through cosmic radiation and cloud nucleation, may be the driver for centennial to millennial variability. Correlations between climate proxy records and geomagnetic field variations suggest further influence on climate by cosmic radiation on millennial and greater time scales. The possible importance of internal climate variability, for instance related to the deep ocean circulation, has also been highlighted. [6.5.1.6]
- However, in many records, there is no apparent consistent pacing at specific centennial to millennial frequencies through the Holocene period, but rather shifts between different frequencies. [6.5.1.6]
- The current lack of consistency between various data sets makes it difficult, based on current knowledge, to attribute the century and longer time scale large-scale climate variations solely to solar activity, episodes of intense volcanism, or variability internal to the climate system. [6.5.1.6]

3.2 Global climate reconstructions over the past 2,000 years

3.2a Natural climatic variability is now believed to be substantially larger than was estimated in the Third Assessment Report, as is the uncertainty associated with paleoclimate studies.

- The Third Assessment Report placed considerable emphasis on the “hockey stick” climate reconstruction, which suggested the late 20th century climate was unusual in the context of the past 1,000 years. This graph has subsequently been subject to considerable criticism [6.6.1.1]
- When viewed together (Fig ISPM-9), the currently available reconstructions indicate generally greater variability in centennial time scale trends over the last 1000 years than was apparent in the Third Assessment Report.
- Proxy evidence cannot characterize the mean Northern Hemisphere temperature to within at least ±0.5°C, and over significant stretches of time the available reconstructions differ by 0.7-1.0°C [Figure 6.10; Figure ISPM-9].

SUPPLEMENTARY INFORMATION

Recent refutations of hockey stick millennial paleoclimatic methods and conclusions.

Two recent, detailed reviews of the methodology of paleoclimatic reconstructions (National Research Council 2006, Wegman et al. 2006) both concluded that there were methodological errors in the “hockey stick” graph of Mann et al. which was prominently promoted in the Third Assessment Report (Summary for Policymakers Fig 1). Both reports concluded that the data and methods did not support the assertions that the 1990s were the “warmest decade of the millennium” and 1998 the “warmest year” of the millennium (NRC p. 109; Wegman et al. p.49). The National Research Council Report also concluded that uncertainties of published paleoclimate reconstructions have been generally underestimated (NRC p. 91).

The National Research Council recommended that proxies sensitive to precipitation be avoided in temperature reconstructions and, in particular, that strip-bark bristlecones and foxtails be avoided. However, none of the IPCC reconstructions for the past millennium observe the National Research Council recommendations.

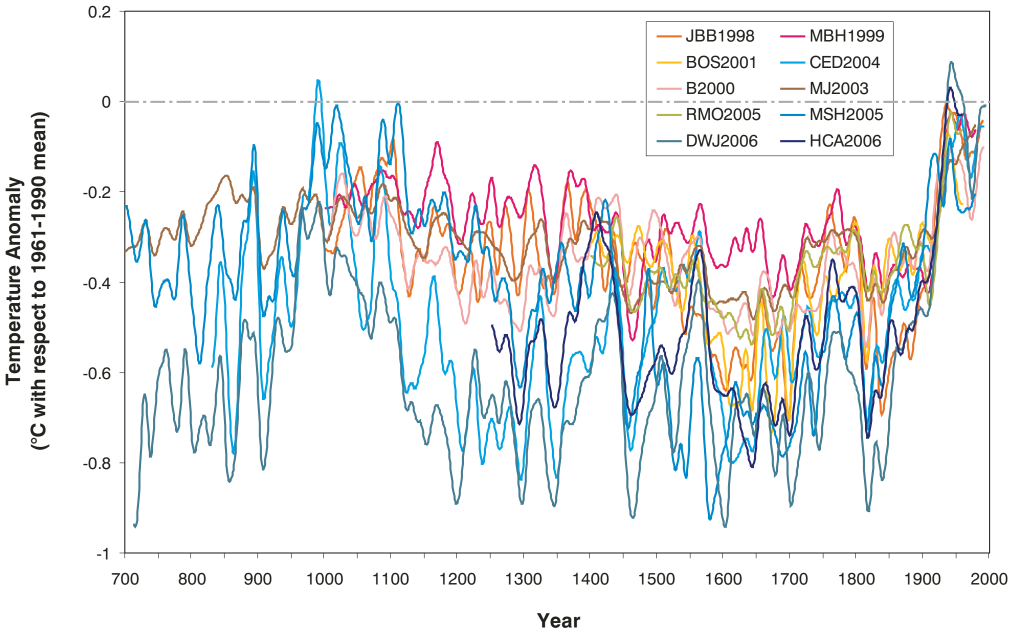


FIGURE ISPM-9: SOME RECENT PALEOCLIMATE TEMPERATURE RECONSTRUCTIONS OF PAST 1300 YEARS FOR THE NORTHERN HEMISPHERE, ALL CALIBRATED OVER THE 1902-1980 INTERVAL

NOTE: Instrumental splice post-1850 has been removed (see Supplementary Information Box below).

Source: Reproduction of Fourth Assessment Report Figure 6-10b. (JBB1998) = Jones et al., 1998 calibrated by Jones et al., 2001; (MBH1999) = Mann et al, 1999; (BOS2001) = Briffa et al., 2001; (CED2004) = Cook et al., 2004; (B2000) = Briffa, 2000 calibrated by Briffa et al., 2004; (MJ2003) = Mann and Jones, 2003; (RMO2005) = Rutherford et al., 2005; (MSH2005) = Moberg et al., 2005; (DWJ2006) = D'Arrigo et al., 2006; and (HCA2006) = Hegerl et al., in press.

SUPPLEMENTARY INFORMATION

The Divergence Problem

A number of recent studies (Briffa et al. 1998, Briffa et al. 2001, d'Arrigo et al 2006, National Research Council 2006) have observed that proxies, especially tree ring proxies, and reconstructions relying on them diverge from instrumental temperature series as temperatures increased in the 1980s and 1990s. This creates a fundamental uncertainty over whether such reconstructions could have detected warming trends in the past (the "Divergence Problem").

The Divergence Problem is a major unresolved problem in millennial reconstructions. Until it is resolved, it is statistically invalid to splice an instrumental series onto a proxy-based series as if the two are interchangeable.

For this reason, Figure ISPM-9 reproduces IPCC Figure 6-10b with the black instrumental series removed.

3.2b Paleoclimatic proxy data are sparse and uncertain, and many appear to be sensitive only to summer temperature, or to precipitation.

- In the Northern Hemisphere as a whole there are relatively few long and well-dated climate proxies, particularly for the period prior to the 17th century. Those that do exist are concentrated in extra-tropical, terrestrial locations, and many have greatest sensitivity to summer rather than winter (or annual) conditions or to precipitation. [6.6.1.1]
- There are markedly fewer well-dated proxy records for the Southern Hemisphere compared to the Northern Hemisphere, and consequently little evidence of how large-scale average surface temperatures have changed over the past few thousand years. [6.6.2]
- There are very few strongly temperature-sensitive proxies from tropical latitudes. Stable isotope data from high-elevation ice cores provide long records and have been interpreted in terms of past temperature variability, but recent studies indicate a dominant sensitivity to precipitation changes, at least on seasonal to decadal timescales, in these regions. [6.6.1.1]
- Melting of tropical glaciers has been observed in recent decades. [6.6.1.1; see Supplementary Information box below]

SUPPLEMENTARY INFORMATION

Regional paleoclimatic indicators

The Fourth Assessment Report provides a very small survey of regional paleoclimatic evidence from the Southern Hemisphere [6.6.2]. The available literature on location-specific paleoclimatology is very large, and in many locations in both the Northern and Southern Hemispheres indicates periods of anomalous warmth exceeding that in the late 20th century. Little of this information is surveyed in the IPCC Report.

There is evidence that several tropical glaciers (Quelccaya, Puruogangri, Dasuopu) formed after the Holocene Optimum. Radiocarbon dating on fossils disgorged from receding glaciers often yields evidence that tree lines and vegetation were higher in the past and were engulfed by past glacier advances during the past few thousand years and/or the Little Ice Age. This evidence shows that modern recession is not unprecedented even within the Holocene.

The literature is explored in the forthcoming Fraser Institute Supplementary Analysis Series report, "Paleoclimatic Indicators of Medieval Climate Conditions."

3.2c Uncertainties in paleoclimate reconstructions affect climate modeling work since models are tested against results from paleoclimate reconstructions.

- Testing models with paleoclimatic data is important, as not all aspects of climate models can be tested against modern instrumental climate data. Good performance for present climate is not a conclusive test for a realistic sensitivity to carbon dioxide. To test this, simulation of a climate with very different CO_2 levels can be used. [6.2.2]
- Also, many empirical parameterizations describing sub-grid scale processes (e.g., cloud parameters, turbulent mixing) have been developed using present-day observations; hence climate states not used in model development provide an independent benchmark for testing models. [6.2.2]
- Paleoclimate data are therefore key to evaluating the ability of climate models to simulate realistic climate change. [6.2.2]

4.1 Fundamental limitations of climate models

4.1a Early climate models provided some qualitative conjectures at the global scale that are consistent with some observed changes.

- At the global scale, some broad predictions made 30 years ago about the possible response to increased CO_2 concentration in the atmosphere, namely increased average tropospheric temperature, decreased average stratospheric temperature and a more rapid hydrological cycle, are consistent with data that have emerged since then. [8.1.2]
- Even when specific predictions are shown to be correct, models should be viewed critically. [8.1.1]

4.1b The fundamental limitations of climate modeling have not changed since the Third Assessment Report.

- Climate models employ approximations to basic physical processes, some of which are controlled approximations (e.g., those based on large scaled Newtonian mechanics) and some of which are empirically based (e.g., fundamental convection processes). [8.1.3]
- "Parameterization" is the process of constructing empirically-based procedures that account for the significant large-scale effects of processes that cannot be resolved (i.e., represented within the computational scheme) because of basic limits in computational power. These limits are induced by the scope of the climate modeling problem. Empirical parameterizations are not unique. Because empirical parameterizations can be invented to force a model to match observations, the ability of a model to represent observed conditions cannot be cited as grounds for confidence in the model's physical realism. [8.1.3]

SUPPLEMENTARY INFORMATION

Basic Modeling uncertainties

The following observation, made in the Third Assessment Report, remains just as true today. The Fourth Assessment Report had nothing to add to it:

In climate research and modeling, we should recognize that we are dealing with a coupled non-linear chaotic system, and therefore that the long-term prediction of future climate states is not possible. The most we can expect to achieve is the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions. (Third Assessment Report, Section 14.2.2.2)

An extended discussion of this is provided in the forthcoming Fraser Institute Supplementary Analysis Series report "Fundamental Uncertainties in Climate Modeling."

4.1c A model's ability to accurately simulate the current mean climate state does not imply it is reliable for projecting future climate changes.

- Multimodel evaluations have shown that even though a group of climate models of intermediate complexity can all replicate observed mean ocean temperature and salinity, and mean atmospheric temperature and humidity, they are not strongly constrained in their future predictions [8.1.2].
- Figure 8.4.2 of the Fourth Assessment Report shows that different models can produce results spreading over more than a factor of 10 for long (climate) time scales exceeding 100 months.

- Models tuned to “perfectly” reproduce an observed mean climate state have nonetheless shown only a weak ability to predict subsequent climatic conditions. It is not possible to say which, if any, of today’s climate models are reliable for climate prediction and forecasting. [8.3]

4.1d It is not formally known if today’s climate models are a suitable basis for projecting climate.

- A model that has been “tuned” to give a good representation of certain key observations may have a greater likelihood of giving a better prediction than a similar model which is less closely tuned. If the number of tunable parameters of a General Circulation Model (GCM) exceeds the number of degrees of freedom in the observational testing scheme for the GCMs, then the use of GCMs to forecast climate change is not justifiable. There has been no formal evaluation of the extent to which current GCMs satisfy this requirement. [8.1.3.1]

4.1e Some climate models now obey the law of conservation of mass, but it is not known if this is an improvement.

- Numerical advection schemes have been introduced in some cases that do not violate conservation of mass–a fundamental law of nature. However there is no consensus on whether they are better than the alternatives. [8.2.1.1]
- In some cases new schemes do not permit negative concentrations of water vapor. [8.2.1.1]

4.2 Significant known model problems

4.2a The strength of the coupling between land processes and the atmosphere is not known.

- Models strongly disagree on this important feedback. There is insufficient data at the global level to evaluate this feature of GCMs. [8.2.3.2]

4.2b Cryosphere

- Simulation of high latitude processes in models is still enough of a problem that their projections of sea ice extent remain highly uncertain. Northern Hemisphere winter is the best-simulated case, and even here the range of simulated sea ice extent exceeds 50% of the mean, and ice thickness also varies considerably. This is particularly troubling because the model sea ice biases may influence estimated global climate sensitivity. [8.3.3]
- On the continental scale, the peak monthly amount of water in snow integrated over the North American continent in models varies within ±50% of the observed value of ~1500 km^3. The magnitude of these model errors is large enough to affect continental water balances. [8.3.4.1]
- Glaciers are not modeled. [8.2.4.1]

4.2c Clouds

- The relatively poor simulation of clouds in the present climate is a reason for some concern. Cloud feedbacks indicate that climate models exhibit different strengths and weaknesses, and it is not yet possible to determine which estimates of the climate change cloud feedbacks are the most reliable. Cloud feedbacks are a large source of uncertainty in climate sensitivity estimates. [8 Summary]

4.2d Monsoons

- Climate models do not capture the linkage between the equatorial Indian Ocean and the Indian summer monsoon, and a comparison of 15 GCMs found large errors in the simulated precipitation in the equatorial regions and in the Asian monsoon region. [8.4.10]
- The impact of time-varying direct and indirect effects of aerosols is not fully resolved. These effects will become increasingly significant in future due to increasing human activity over south Asia/India. [10.3.5.2]

5 Global and regional climate projections

5.1 Reproduction of the present climate

5.1a Quantitatively, individual climate models are typically unable to reproduce the observed mean surface temperature to better than +/- 3 kelvin, with worse performance near the poles. They are also unable to reproduce the onset of ice ages. The margin of present-day error is similar to the size of the projected global warming trend over a century.

- Errors in polar regions average between 3 and 5 kelvin (K), and on average all climate models overestimate mean Antarctic temperatures by at least 5 K. [Figure 8.3.1]
- The extent to which these errors detract from the models' ability to accurately simulate climate change in response to external perturbation (e.g., GHG emissions) is unknown, but may be significant. [8.3.1]
- Climate models are not able to successfully simulate the onset of an ice age [6.4.1.7], although they are able to reproduce some features of the end of an ice age. [6.4.2.3]
- Models are used to evaluate greenhouse-induced changes that are about 0.3 K per decade, a tenth the size of the annual margin of error for estimates in most regions.

5.2 Forecasts for the coming century are inherently uncertain

5.2a The spread of model outcomes shown in the Fourth Assessment Report forecast ensembles does not span the full range of uncertainty.

- For future climate change in the 21st century, a subset of three scenario simulations have been selected from the six commonly used ones. This subset constitutes a "low", "medium", and "high" scenario among the marker scenarios, and this choice is solely made by the constraints of available computer resources that did not allow for the calculation of all six scenarios. This choice, therefore, does not imply a qualification of or preference over the six marker scenarios. By the same argument, it is not within the remit of this report to assess the realism and likelihood of emission scenarios. [10.1]
- Even though the ability to simulate present day mean climate and variability, as well as observed trends, differs across models, all submitted models are weighted equally in the mean. Since the ensemble is strictly an 'ensemble of opportunity', without sampling protocol, the spread of models is unable to span the full possible range of uncertainty, and a statistical interpretation of the model spread is therefore problematic. [10.1]

5.2b Uncertainties enter model projections at every step in the process.

- There are multiple emission scenarios for the 21st century, and even at this first stage there is uncertainty with regard to the evolution over time of emissions of various forcing agents, such as greenhouse gases. Then these emissions must be converted to concentrations of constituents in the atmosphere. Gas cycle models must be employed, and these models include their own set of parameterisations, assumptions and caveats. Then the concentrations in the atmospheric models produce radiative forcing that acts on the climate system within the atmospheric model components, each with their own radiation schemes and other formulations that affect radiative forcing. Finally, the modelled coupled climate system takes those radiative forcings and produces a future simulated climate. The components of the atmosphere, ocean, sea ice and land surface in each model interact with their sets of strengths and weaknesses to produce a spread of outcomes for future climate. [10.1]
- Thus at every step in this process there are uncertainties and assumptions that must be made to proceed from emissions, to concentrations, to radiative forcing, and eventually to simulated climate changes and impacts. [10.1]

5.2c Few of the climate models used for the Fourth Assessment Report forecasts account for solar changes, land-use changes and indirect aerosol effects.

- Only two out of 23 models account for the effects of time-varying solar changes. [Table 10.2.1]
- Only two out of 23 models account for effects of time-varying land-use changes. [Table 10.2.1]
- Only nine out of 23 models include the first indirect effect of aerosols, only six include the second indirect effect and only four include both. [Table 10.2.1]

SUPPLEMENTARY INFORMATION

Defining 'Climate Change'

The IPCC assumes that climate change can be defined as a change in the mean state of the climate. This assumes that means of climatic variables are stationary and well-defined, something recent research has put into question. If the climate is nonstationary, a change in the mean is consistent with an 'unchanged' climate since the observed mean is dependent on the time period over which the observations are collected. Also the concept of variability is problematic since the variance of a nonstationary process is, in some cases, mathematically undefined.

For more on this topic see the forthcoming Fraser Institute Supplementary Analysis Series report "Long Term Persistence in Geophysical Data."

5.3 Model-generated global warming forecasts

5.3a Climate models predict warming is occurring everywhere on Earth.

- The average across models implies a forecast that, over all land areas on Earth, a warming of 0.5 to 1°C will be noticeable in a comparison of the two decades beginning at 2011 relative to the 1980-1999 interval. [Figure 10.3.5]
- The North and South polar regions are forecast to warm relatively faster, and land areas are forecast to warm faster than adjacent ocean areas. [Figure 10.3.5]
- 1979-2005 trends as measured by weather satellites show temperature trends are 0-0.5°C/decade over land and are not systematically stronger than over adjacent ocean areas. [Figure 3.4.4]
- 1979-2005 trends as measured by weather satellites show Southern Hemisphere warming trends get weaker towards the South Pole, which exhibits zero or negative temperature trends in many surrounding areas.

5.3b On average, models that assume strong greenhouse warming project the tropical troposphere to warm faster than the surface. Current data do not support these forecasts.

- The tropical troposphere is forecast to warm faster than the surface. [Figure 10.3.4]
- This conflicts with current data. (see Section 2.1c)

5.3c All climate models used for the Fourth Assessment Report are tuned so that the average surface temperature will increase between about 2.0°C and 4.5°C in response to a doubling of the atmospheric carbon dioxide concentration.

- The “equilibrium climate sensitivity” refers to a model’s assumed increase in global surface temperature following a doubling of the atmospheric equivalent CO_2 concentration. [10.5.2.1]
- The suite of models used for the Fourth Assessment Report simulations apply an equilibrium climate sensitivity between approximately 2.0°C and 4.5°C. [Figure 10.5.1]

5.3d Models generate many specific global forecasts based on assumptions of significant greenhouse warming.

- **Global Mean Temperature:** Climate models based on the assumption that atmospheric carbon dioxide levels will double over the next century predict that global average surface temperature will increase by between about 2.0°C and 4.5°C. [Figure 10.5.2]
- **Sea Ice:** Models show a range of responses in Northern Hemisphere sea ice areal extent ranging from very little change to a dramatic change, and accelerating reduction over the 21st century. Seasonal ice cover is rather robust and persists to some extent throughout the 21st century in most (if not all) models. In 20th and 21st century simulations, Antarctic sea ice cover decreases more slowly than in the Arctic. Overall models have poor agreement on the amount of thinning of sea ice and the overall climate change in the polar regions. [10.3.3.1; Figure 10.3.10a,b Figure 10.3.11]
- **Ocean Circulation:** Models initialized at the year 1850 have difficulty producing late 20th century values of the Meridional Overturning Circulation (MOC) in the observed range. Of the model simulations consistent with the late 20th century observational estimates, no simulation predicts an increase of MOC during the 21st century; reductions range from indistinguishable within the simulated natural variability to 60% relative to the 1960–1990 mean; none of the models projects an abrupt transition to an off state of the MOC [Figure 10.3.13]. The best estimate of sea level increase from 1993–2003, associated with the slight net negative mass balance from Greenland, is 0.1–0.2 mm per year. The corresponding amount of sea water, even when added directly and exclusively to the North Atlantic, has been suggested to be too small to affect the North Atlantic MOC. Taken together, it is likely that the MOC will reduce, but very unlikely that the MOC will undergo an abrupt transition during the course of the 21st century. [10.3.4, Figure 10.3.13]
- **Temperature Variability:** Climate models predict a decrease in temperature variability during the cold season in the extratropical Northern Hemisphere and a slight increase of temperature variability in low latitudes and in the warm season in northern mid latitudes. [10.3.5.1]
- **Monsoons:** Climate models runs predict that pronounced warming over the tropics in the middle-to-upper troposphere would result in a weakening of monsoon circulations. Also, atmospheric moisture buildup due to increased GHGs and consequent temperature increase is predicted to result in a larger moisture flux and more precipitation for the Indian monsoon. [10.3.5.2]
- **Precipitation:** Climate models predict an increased chance of summer drying in most parts of the northern subtropics and midlatitudes and an associated increased risk of drought. Associated with the risk of drying is also an increased chance of intense precipitation and flooding. Though somewhat counter-intuitive, this is because precipitation is

concentrated into more intense events, with longer periods of little precipitation in between. Increases in the frequency of dry days does not necessarily mean a decrease in the frequency of extreme high rainfall events depending on the threshold used to define such events. The change in the frequency of extreme precipitation at an individual location can be difficult to estimate definitively due to model parameterization uncertainty. Climate models continue to confirm the earlier predictions that in a future climate warmed by increasing GHGs, precipitation intensity would increase over most regions. [10.3.6.1]

- **Temperature Extremes:** The Third Assessment Report concluded that models project that there is very likely a risk of increased temperature extremes, with more extreme heat episodes in a future climate. This result has been confirmed in subsequent climate model simulations. Several recent studies have found that climate models predict that in a future climate there is an increased risk of more intense, longer-lasting and more frequent heat waves [10.3.6.2] though the change does not become strong until after 2020. [Figure 10.3.17]
- **Cyclones:** There have been a number of climate change experiments with global models that can begin to simulate some characteristics of individual tropical cyclones, though studies with classes of models with 100 km resolution or higher cannot simulate observed tropical cyclone intensities. Global climate models with 100 km resolution or higher predict a decrease in tropical cyclone frequency globally, and no change or slight decreases in intensity of cyclones, but some regions may differ. Studies performed with models that use a high resolution (down to 9 km) mesoscale hurricane model predict that future tropical cyclones will be more intense. [10.3.6.3]
- **Growing Season:** Globally, models project an increase in the average growing season length by three to five standard deviations by mid-century. [Figure 10.3.17]
- **Ocean Surface Acidity:** Increasing atmospheric CO_2 concentrations lowers oceanic pH and carbonate ion concentrations, thereby increasing acidity. Surface ocean pH today is already 0.1 unit lower than preindustrial values. By the end of the century, models predict it may decline by another 0.13 to 0.34 pH units. Experimental evidence suggests that if these trends continue, key marine organisms – such as corals and some plankton – will have difficulty maintaining their external calcium carbonate skeletons. [10.4.2, Figure 10.4.5]
- **Sea Levels:** Models project that a doubling of CO_2 levels in the atmosphere (A1B scenario), if accompanied by a warming of 2–4.5°C, will cause a sea level increase of about 20 centimeters, plus or minus 10 cm over the next 100 years [10.6.5; Fig 10.6.1]. However the spatial pattern in projections is not uniform. The geographical patterns of sea level change from different models are not generally similar in detail, but the differences are not as large as they were in the Third Assessment Report. Still, the largest spatial correlation coefficient between any pair is 0.76, and only 20% of correlation coefficients exceed 0.5. [10.6.2]
- **Glaciers:** Since their mass balance depends strongly on their altitude and aspect, use of data from climate models to make projections requires a method of downscaling, because individual glaciers are too small to be handled in typical GCMs. Statistical relations can be developed between GCM and local meteorology but they may not continue to hold in future climates [10.6.3]. Models predict overall loss of glacier volume, but there is uncertainty about how to estimate the dynamics. [10.6.3.3]

5.3e Models have also been used to generate regional forecasts, though the uncertainties are substantial.

- Important details about climate change pertain to geographical details too small to be resolved in global models. Hence regional models have been developed, which involve schemes for downscaling the information from a global model. [11.1.1]
- Downscaling can be done two ways. “Dynamical downscaling” involves feeding information from a global model into a regional climate model, using the data from the global model to impose boundary conditions on the regional model. However this does not necessarily yield a better match to observations. [11.2.1.1.1]
- “Statistical downscaling” involves applying empirical estimates between local variables and global variables to estimate changes in the local variables based on global model forecasts. This requires the assumption that the relationships are stationary – i.e., that the empirical relationship is steady over time and under different climatic conditions. Stationarity remains a concern with statistical downscaling. It is not know whether the cross scale relationships are valid under future climate regimes. This limitation is only weakly assessed through cross-validation tests. [11.2.1.1.2]
- Most sources of uncertainty on regional scales are similar to those on the global scale, but there are both changes in emphasis and new issues that arise in the regional context. Of the climate forcing agents, uncertainty in aerosol forcing adds especially to regional uncertainty because of the spatial inhomogeneity of the forcing and the response. Changes in land-use and cover have an inherently regional scope as well. When analyzing studies involving further layers of models to add local detail, the cascade of uncertainty through the chain of models used to generate regional or local information has to be considered. The degree to which these uncertainties influence the projections of different climate variables is not uniform. Also, the climate may itself be poorly known on regional scales in many data-sparse regions. Thus, evaluation of model performance as a component of an analysis of uncertainty can itself be problematic. [11.2.2.1]

6 Attributing the causes of climate change

6.1 Measuring and analyzing climate change

6.1a There is reliance on computer models both to identify what might be the scales of internal variability and the magnitude of natural forcing, as well as the form of the anthropogenic-forcing signal. It is against these basic shortcomings that attribution studies must be assessed [1.3.3].

- Detection and attribution of climate change are separate processes. [1.3.3]
- Detection of climate change is the process of demonstrating that climate has changed in some statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. [1.3.3]
- Both detection and attribution rely on observational data as well as model output. [1.3.3]
- In practical terms, attribution of anthropogenic climate change is understood to mean:
  - detection;
  - demonstration that the detected change is consistent with computer model predictions of the climate change "signal" that is calculated to occur in response to anthropogenic forcing; and
  - demonstration that the detected change is not consistent with alternative physically plausible explanations that exclude anthropogenic forcing. [1.3.3]
- Estimates of century-scale natural climate fluctuations are difficult to obtain from the observations because of the relatively short length of records. [1.3.3]

6.1b The definition of climate change assumes stationarity of the climate system.

- *Climate change* "refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer". [9.1.1]

6.1c The climate is subject to natural variability on all time scales, from days up to centuries.

- Natural climate variability results from internal climate processes and the climate's response to natural external forcing. Internal variability is present on all time scales from virtually instantaneous (e.g., the triggering of convection) up to years (e.g., tropospheric-stratospheric or inter-hemispheric exchange). Other components of the climate system, such as the ocean and the large ice-sheets tend to operate on longer time scales of decades to centuries. These components produce internal variability directly and by integrating variability from the rapidly varying atmosphere. In addition, internal variability is also produced by coupled interactions between components, such as is the case with the El-Niño Southern Oscillation. [9.1.1.]

6.1d Internal variability and climate change are inherently difficult to estimate, and usually require the use of climate models.

- The climate's internal variability is difficult to estimate because all climate observations are influenced, at least to some extent, by variations in external forcing. However estimates can be obtained from observations or models under certain conditions. [9.1.1.]
- The methods used to identify change in observations are based on the expected responses to external forcing, either from physical understanding or as simulated by climate models. An identified change is *detected* in observations if its likelihood of occurrence by random chance or by internal variability alone is determined to be small.

A failure to detect a particular response might occur for a number of reasons, including the possibility that the response is weak relative to internal variability, or that the metric used to measure change is insensitive to the expected change. [9.1.2]

- The detection of an effect of external forcing on the climate does not necessarily imply that it has an important impact on the environment, biota, or human society. [9.1.3]

6.2 Difficulties in attributing observed climate change to specific causes.

6.2a Detection of climate change relies on model-generated predictions of the response of the climate to external forcing, such as greenhouse gas emissions, and as such can never be absolutely certain.

- Many studies use climate models to predict the expected responses to external forcing, and these predictions are usually represented as patterns of variation in space, time, or both. Such patterns, which are commonly referred to as *fingerprints,* are usually derived from changes simulated by a climate model in response to forcing. [9.1.2]
- The spatial and temporal scales used to analyze climate change are carefully chosen so as filter out internal variability and enable the separation of the responses to different forcings. The choice of filter criteria is based on prior expectations about the time and spatial scales to be analyzed. [9.1.2]
- Because detection studies are necessarily statistical in nature, inferences about whether an external influence has been detected can never be absolutely certain. It is always possible that a significant result at, say, the 5% level, could simply reflect a rare event that would have occurred in any case with less than 1 chance in 20 in an unchanged climate. Corroborating lines of evidence providing a physically consistent view of the likely cause for the change reduces the risk of spurious detection. [9.1.2]

6.2b Investigation of the causes of observed individual climate events can be biased due to “self-selection” phenomena.

- For many decision-makers, the most pertinent detection questions involve a particular observed phenomenon, (for example, whether the drying in the Sahel region can be attributed to greenhouse gases). It is difficult to respond to such questions because of a statistical phenomenon known as “selection bias”. Only large observed climate anomalies in a historical context would be likely to be the subject of such a question. Decision-makers are unlikely to ask about small or non-existent events. Hence the selection of events to analyze is biased towards large, anomalous observations. The fact that the questions are “self selected” from the observations makes it difficult to assess their statistical significance from the same observations. [9.1.2]

6.2c Attribution of the cause in climate change is not formally possible.

- Detection does not imply attribution of the detected change to the assumed cause. *Attribution* “of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence”. As noted in the Second Assessment Report (published in 1996) and the Third Assessment Report (published in 2001), unequivocal attribution would require controlled experimentation with our climate system. That, of course, is not possible. [9.1.2]

6.2d The term “attribution” means consistency with a climate model-generated scenario, rather than formal proof of causality. The same data could be consistent with contradictory hypotheses, including large or small greenhouse warming.

- From a practical perspective, attribution of anthropogenic climate change is understood to mean the detected change is “consistent with the estimated responses to the given combination of anthropogenic and natural forcing”. [9.1.2]
- Any assessment of observed climate change that compares simulated and observed responses will be affected by errors and uncertainties in the forcings prescribed to a climate model and its corresponding responses. [9.2.3]
- Assessment of the consistency between an observed change and the estimated response to a hypothesized forcing is often achieved by determining whether the amplitude of the hypothesized pattern of change estimated from observations is statistically consistent with expectations based on climate model predictions, as measured by statistical tests. [9.1.2]
- Attribution also requires evaluating the possibility that the observed change is consistent with alternative explanations that exclude important elements of a given combination of forcings that are hypothesized to have influenced the climate. Statistical analysis requires that the separate influences on climate are properly accounted for. For instance, the attribution of recent warming to greenhouse gas emissions becomes more reliable if the influences of other external forcings, for example solar forcing, are explicitly accounted for in the analysis. [9.1.2]
- This is an area of research with considerable challenges because different forcing factors may lead to similar large-scale spatial patterns of response. [9.1.2]
- If it is not possible to distinguish the spatial pattern of greenhouse warming from that of fossil-fuel related aerosol cooling, then the observed warming over the last century could be explained by large greenhouse warming balanced by large aerosol cooling or alternatively by small greenhouse warming with very little or no aerosol cooling. [9.2.3]

6.2e Attribution studies rely on the validity of model-generated estimates of the climatic response to forcing, and model-generated estimates of natural variability.

- All three aspects of attribution require knowledge of the internal climate variability on the timescales considered, usually decades or longer. The residual variability that remains in instrumental observations after the estimated effects of external forcing have been removed is sometimes used to estimate internal variability. However, these estimates are uncertain because the instrumental record is short relative to the timescales of interest, and because of uncertainties in the forcings and the estimated responses. Thus internal climate variability is also estimated from long control simulations from coupled climate models. [9.1.2]
- Subsequently, an assessment is usually made of the consistency between the residual variability referred to above and the model based estimates of internal variability. Confidence depends on the ability of models to simulate the various modes of observed variability, comparisons between variability in observations and climate model data and by comparison between proxy reconstructions and climate simulations of the last millennium. [9.1.2]

6.2f The reported uncertainties in attribution studies do not take into account basic uncertainty about climate model parameters. These uncertainties can be considerable.

- Model and forcing uncertainties are important considerations in attribution research. Ideally, the assessment of model uncertainty should include uncertainties in model parameters, and in the representation of physical processes in models (structural uncertainty). Such an assessment is not yet available, although research with that goal in mind is underway. [9.1.2]
- The effects of forcing uncertainties, which can be considerable for some forcing agents, such as solar and aerosol forcing, also remain difficult to evaluate, despite advances in research. [9.1.2]
- There are also very large uncertainties in the temporal forcing associated with solar radiation changes, particularly on timescales longer than the 11-year cycle. Previous estimates have used sun spot numbers to determine these slow changes in solar irradiance over the last few centuries, but are not necessarily supported by current understanding. In addition, the magnitude of radiative forcing associated with major volcanic eruptions is uncertain and differs between reconstructions. [9.2.2.3]
- Detection and attribution results that are based on several models or several forcing histories do provide information on the effects of model and forcing uncertainty that leads towards a more reliable attribution of climate change to a specific cause. Such results suggest that the attribution of a human influence on temperature change during the latter half of the 20th century is robust. [9.1.2]
- In addition to substantial uncertainty in the timing and amplitude of solar variations on timescales of several decades to centuries, uncertainty also arises because the spatial response of surface temperature to solar forcing resembles that due to anthropogenic forcing. These uncertainties in interpretation of the role of different forcings reflects substantial uncertainties in our knowledge about the size of past volcanic forcing and of the timing and size of long-term variations in solar forcing, as well as differences in the way these effects are taken into account in model simulations. [9.3.3.2]
- There remains considerable uncertainty in the forcings that are used in climate models. Estimates of the uncertainties in reconstructions of past solar forcing have increased since the Third Assessment Report, and chemical and dynamical processes associated with the atmosphere's response to solar irradiance are omitted or not adequately resolved in many climate models used in detection studies. Furthermore, some models include the indirect effects of sulphate aerosols on clouds, whereas others consider only the direct radiative effect. [9.4.1.8]

6.3 Assumptions needed to attribute climate change to anthropogenic causes.

6.3a Evidence for a human influence on climate relies on model-based detection studies.

- The evidence that was available at the time of the Third Assessment Report consisted of results from a range of detection studies of the instrumental record, relying on output from several climate models for fingerprints and estimates of internal climate variability. On this basis the Third Assessment Report stated that warming over the 20th century was "very unlikely to be due to internal variability alone as estimated by current models". [9.1.3]
- It is implicitly assumed in these studies that the surface observational record is not affected by nonclimatic trends such as land use change. [3.2.2.2]
- There are now a greater number of attribution studies than were available for the Third Assessment Report, and these have used more recent climate data than previous studies and a greater variety of model simulations. Increased confidence in detection of an anthropogenic signal in the instrumental record refers to this proliferation of studies. [9.4.1.4]

6.3b On average, models used for attributing recent climate change to human interference assume that natural forcings alone would have yielded virtually no change over the 20th century, and global cooling since 1979.

- Climate models that include only natural forcings estimate that over the 20th century there would have been no change or a slight cooling (up to 0.5C) everywhere on Earth. [Figure 9.4.2]
- When the same models are run over the post-1979 interval, they propose that natural forcings alone would have yielded no change, or cooling, everywhere except for a small portion of the Bering Strait and a few other locations. [Figure 9.4.2]

6.3c Attribution studies to date do not take into account all known sources of possible influence on the climate.

- Studies have concentrated on what are believed to be the most important forcings: greenhouse gases, direct solar effects, some aerosols and volcanism. Most analyses exclude some forcings that could potentially have significant effects, particularly on regional scales, but possibly on global scales as well. [9.4.18]
- Observational campaigns have demonstrated the importance of black carbon in the South Asia region and modeling studies have shown that the global forcing from black carbon could be large. Yet few detection studies have explicitly included the temperature response to black carbon aerosols because there are few transient coupled model simulations including this forcing due to large modeling uncertainties. [9.4.18]
- Land use changes are another forcing that could be potentially important, particularly on regional scale. [9.4.18]
- Attribution analyses that use recent model simulations which include carbonaceous aerosols and land use changes continue to detect a significant anthropogenic influence on 20th century temperature changes. [9.4.18]

6.3d Due to the uncertainties involved, attribution of climate change to human cause is ultimately a judgment call.

- The approaches used in detection and attribution research described above can not fully account for all uncertainties. [9.1.2]
- Ultimately expert judgment is used to estimate the likelihood that a specific factor is responsible for a given climate change. [9.1.2]

7 Overall conclusions

The following concluding statement is not in the Fourth Assessment Report, but was agreed upon by the ISPM writers based on their review of the current evidence.

The Earth's climate is an extremely complex system and we must not understate the difficulties involved in analyzing it. Despite the many data limitations and uncertainties, knowledge of the climate system continues to advance based on improved and expanding data sets and improved understanding of meteorological and oceanographic mechanisms.

The climate in most places has undergone minor changes over the past 200 years, and the land-based surface temperature record of the past 100 years exhibits warming trends in many places. Measurement problems, including uneven sampling, missing data and local land-use changes, make interpretation of these trends difficult. Other, more stable data sets, such as satellite, radiosonde and ocean temperatures yield smaller warming trends. The actual climate change in many locations has been relatively small and within the range of known natural variability. There is no compelling evidence that dangerous or unprecedented changes are underway.

The available data over the past century can be interpreted within the framework of a variety of hypotheses as to cause and mechanisms for the measured changes. The hypothesis that greenhouse gas emissions have produced or are capable of producing a significant warming of the Earth's climate since the start of the industrial era is credible, and merits continued attention. However, the hypothesis cannot be proven by formal theoretical arguments, and the available data allow the hypothesis to be credibly disputed.

Arguments for the hypothesis rely on computer simulations, which can never be decisive as supporting evidence. The computer models in use are not, by necessity, direct calculations of all basic physics but rely upon empirical approximations for many of the smaller scale processes of the oceans and atmosphere. They are tuned to produce a credible simulation of current global climate statistics, but this does not guarantee reliability in future climate regimes. And there are enough degrees of freedom in tunable models that simulations cannot serve as supporting evidence for any one tuning scheme, such as that associated with a strong effect from greenhouse gases.

There is no evidence provided by the IPCC in its Fourth Assessment Report that the uncertainty can be formally resolved from first principles, statistical hypothesis testing or modeling exercises. Consequently, there will remain an unavoidable element of uncertainty as to the extent that humans are contributing to future climate change, and indeed whether or not such change is a good or bad thing.

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Appendix 1– Expert Review

The ISPM was sent out to reviewers around the world. We hereby acknowledge with gratitude the extremely helpful feedback given, at short notice, by dozens of colleagues, whose suggestions substantially improved the final edition. The following individuals provided responses as of January 22, 2007.

Alberto Montanari	Hydrology	University of Bologna	Italy
Anastasios Tsonis	Mathematics	University of Wisconsin	USA
Anthony Lupo	Climatology	University of Missouri	USA
Arthur S. deVany	Mathematics	University of California-Irvine	USA
Barrie Jackson	Chemical Engineering	Queen’s University	Canada
Bjarne Andersson	Thermodynamics	Niels Bohr Institute	Denmark
Boris Winterhalter	Oceanography	Geological Survey of Finland	Finland
Christopher deFreitas	Climatology	University of Auckland	New Zealand
David Deming	Paleoclimatology	University of Oklahoma	USA
David Legates	Climatology	University of Delaware	USA
Demitris Koutsoiannis	Statistics	University of Athens	Greece
Douglas Hoyt	Solar Physics	Raytheon Corp. (Retired)	USA
Eduardo Zorita	Paleoclimatology	GKSS Institute of Coastal Research	Germany
Einar Sletten	Chemistry	University of Bergen	Norway
Garth Paltridge	Atmospheric science	University of Tasmania	Australia
Gösta Walin	Oceanography	Goteborg University	Sweden
Harry Lins	Hydrology	United States Geological Survey	USA
John Maunder	Climatology	WMO Commission for Climatology (ret’d)	New Zealand
Keith Hage	Meteorology	University of Alberta	Canada
Larry Hulden	Biology	Finnish Museum of Natural History	Finland
Lena Hulden	Historical Biology	University of Helsinki	Finland
Marcel Leroux	Climatology	University of Lyon	France
Nicholas Scaffeta	Solar Physics	Duke University	USA
Oddbjörn Engvold	Physics	University of Oslo	Norway
Olav Kvalheim	Physical Chemistry	University of Bergen	Norway
Ole Humlum	Physical Geography	University of Oslo	Norway
Olev Trass	Chemical Engineering	University of Toronto	Canada
Oliver Frauenfeld	Meteorology	University of Colorado	USA
Patrick Michaels	Climatology	Virginia Tech	USA
Peter Robinson	Meteorology	University of North Carolina-Chapel Hill	USA
Peter Stilbs	Physical Chemistry	Royal Institute of Technology, Sweden	Sweden
Piia Post	Meteorology	University of Tartu	Estonia
Richard Lindzen	Climatology	Massachusetts Institute of Technology	USA
Ramesh Kriplani	Meteorology	Indian Institute of Tropical Meteorology	India
Richard McNider	Meteorology	University of Alabama	USA
Robert Balling	Climatology	Arizona State University	USA
Robert Carter	Paleoclimatology	James Cook University	Australia
Robert S. Knox	Physics	University of Rochester	USA
Terence Mills	Statistics	Loughborough University	UK
Thomas N. Chase	Meteorology	University of Colorado	USA
Tim Patterson	Paleoclimatology	Carleton University	Canada
William Alexander	Biosystems Engineering	University of Pretoria	South Africa
William Gray	Meteorology	Colorado State University	USA

In addition, 11 reviewers asked to remain anonymous.

Reviewers were asked to respond to the following questions on the indicated scale from 1–5. The scores given are based on 54 reviews received.

1. To what extent does the ISPM cover the range of topics you consider important for policy makers and other general readers who want to understand climate change?

   1 (Quite Inadequately)
   2 (Somewhat Inadequately)
   3 (Neutral)
   4 (Adequately) *Mean response = 4.2*
   5 (Quite Adequately)

2. To what extent do you consider the ISPM to convey the current uncertainties associated with the science of climate change?

   1 (Generally overstates the uncertainties)
   2 (In some cases overstates the uncertainties)
   3 (Is about right) *Mean response = 3.3*
   4 (In some cases understates the uncertainties)
   5 (Generally understates the uncertainties)

3. To what extent to you agree with the Overall Conclusions?

   1 (Strongly disagree)
   2 (Disagree)
   3 (Neutral)
   4 (Agree) *Mean response = 4.4*
   5 (Strongly Agree)

4. Do you support the publication of the ISPM as a means of communicating the current state of climate science to policy makers and other general readers?

   1 (No, strongly opposed)
   2 (No, somewhat opposed)
   3 (Neutral)
   4 (Yes, somewhat in support)
   5 (Yes, strongly in support) *Mean response = 4.7*

About the Authors

Coordinator

Dr. Ross McKitrick holds a BA in economics from Queen's University, and an MA and Ph.D. in economics from the University of British Columbia. He was appointed Assistant Professor in the Department of Economics at the University of Guelph in 1996 and Associate Professor in 2001. In the fall of 2002 he was appointed as a Senior Fellow of the Fraser Institute in Vancouver B.C. His research focuses on the relationship between economic growth and pollution; regulatory mechanism design; and various aspects of the climate change policy debate. He has published numerous scholarly articles in both economics and science journals. His coauthored book *Taken By Storm: The Troubled Science, Policy and Politics of Global Warming* was awarded a prestigious Donner Prize for Best Book on Canadian Public Policy. Professor McKitrick's research has been discussed in such places as *Nature, Science, The Economist, Natuurwetenschap&Techniek, The National Post, The Globe and Mail* and in a front page article in the *The Wall Street Journal* (Feb 14 2005). He has made invited academic presentations in Canada, the US and Europe, as well as professional briefings to the Canadian Parliamentary Finance and Environment Committees, to government staff at the US Congress and Senate and to the US National Research Council.

Writing Team

Joseph S. D'Aleo has over three decades of experience as a meteorologist and climatologist. He holds BS and MS degrees in Meteorology from The University of Wisconsin and was in the doctoral program at New York University. Mr. D'Aleo was a Professor of Meteorology at the college level for over 8 years (6 years at Lyndon State College in Vermont) and was a co-founder and the first Director of Meteorology at the cable TV Weather Channel. From 1989 to 2004, D'Aleo was Chief Meteorologist at WSI and Senior Editor for WSI's popular Intellicast.com web site. Mr. D'Aleo is a Certified Consultant Meteorologist and was elected a Fellow and Councilor of the American Meteorological Society. He has served as member and chairman of the American Meteorological Society's Committee on Weather Analysis and Forecasting. He has authored and/or presented numerous papers focused on advanced applications enabled by new technologies, and the role of natural solar and ocean cycles on weather and climate. His published works include a resource guide for Greenwood Publishing on El Niño and La Nina. He is currently Executive Director for ICECAP, an organization and international web site that will bring together the world's best climate scientists to shed light on the true complex nature of climate change.

Dr. Madhav L. Khandekar holds a B.Sc. in Mathematics and Physics, an M.Sc. in Statistics from Pune University, India, and both M.S. and Ph.D. degrees in Meteorology from Florida State University. Khandekar has worked in the fields of climatology, meteorology and oceanography for almost 49 years and has published well over 100 papers, reports, book reviews and scientific commentaries as well as a book on Ocean Surface Wave Analysis and Modeling, published by Springer-Verlag in 1989. Khandekar spent 25 years as a Research Scientist with Environment Canada (now retired) and has previously taught meteorology and related subjects at the University of Alberta in Edmonton (1971-74) and for two United Nations training programs: Barbados, West Indies (1975-77, World Meteorological Organization lecturer in meteorology) and Qatar, Arabian Gulf (1980-82, ICAO expert in aeronautical meteorology). He has published research on surface waves, arctic sea ice, ENSO/monsoon and global weather, numerical weather prediction, boundary-layer meteorology, and tropical cyclones. He presently serves on the editorial board of the international Journal, *Natural Hazards* (Kluwer, Netherlands) and was an editor of *Climate Research* (Germany) from 2003-2005. Khandekar acted as a guest editor for a special issue of the journal *Natural Hazards* on global warming and extreme weather, published in June 2003. Khandekar has been a member of the American Meteorological Society since 1966, the Canadian Meteorological and Oceanographic Society since 1970, and the American Geophysical Union since 1986.

Mr. William Kininmonth has a B.Sc. from the University of Western Australia, an M.Sc from Colorado State University, and an M.Admin from Monash University. He is a consulting climatologist, and worked with the Australian Bureau of Meteorology for 38 years in weather forecasting, research and applied studies. For 12 years until 1998 he was head of its National Climate Centre. William Kininmonth was Project Manager of an Australian Government project of assistance to the Meteorology and Environmental Protection Administration of Saudi Arabia, based in Jeddah (1982-85). Mr. Kininmonth was Australian delegate to the World Meteorological Organization's Commission for Climatology (1982-1998) and served two periods on its Advisory Working Group (1985-89 and 1993-97). He participated in Expert Working Groups of the Commission and carried out regional training activities in relation to climate data management and climate monitoring. Between 1998 and 2002 he consulted to the Commission, including coordinating an international review of the 1997-98 El Niño event and preparation of a WMO publication, *Climate into the 21st Century* (Cambridge). He was a member of Australia's delegations to the preparatory meetings for the Ministerial Declaration of the Second World Climate Conference (1990) and to the United Nations Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (1991-92). William Kininmonth is author of the book, *Climate Change: A Natural Hazard* (Multi-Science Publishing Co, UK – 2004)

Dr. Christopher Essex Christopher Essex is a full Professor of Applied Mathematics at the University of Western Ontario, where he is Director of the Program in Theoretical Physics. He holds a B.Sc (hon.), from the University of Western Ontario, an M.S. from Rice University and a Ph.D. from York University. He was an NSERC Postdoctoral Fellow at the Canadian Climate Centre and held a Humboldt Research Fellowship at the University of Frankfurt in Germany, and was recently a visiting scientist at the Niels Bohr Institute in Denmark. Dr. Essex specializes in the underlying mathematics, physics and computation of complex dynamical processes such as climate. His research, including discoveries in statistical physics, has been published in leading scientific journals, and he is a frequently invited speaker at professional international science symposia. He is a recipient of the $10,000 Donner Prize (2002) for his book on global warming and is a life member of the Canadian Industrial and Applied Mathematics Society. In 2006 he was appointed by the Governor General of Canada to the Natural Sciences and Engineering Research Council.

Dr. Wibjörn Karlén received a Masters degree at the University of Maine in 1972. The focus of his thesis was the pattern and possible cause of Holocene climatic variations. A few years later he defended a Ph.D. at the Department of Physical Geography at Stockholm University. He has during the following years maintained his interest in the climate of the Holocene. He has collected field data in a number of areas around the world, including Scandinavia, Svalbard, Alaska, Kenya and Antarctica. Between 1984 and 2004 he was appointed professor at Stockholm University, and between 1985 and 1995 was in charge of the Tarfala Research Station, where research focuses on glaciology. After retirement he is now the editor of an international scientific journal, *Geografiska Annaler*. Since 1992 he has been a member of the Royal Swedish Academy of Sciences.

Dr. Olavi Kärner studied mathematics at the University of Tartu, Estonia before receiving his Ph.D. in Atmospheric Physics from the Leningrad Hydrometeorological Institute in 1974. In 1966, Dr. Kärner joined the Tartu Observatory in Tõravere, Estonia, and since 1977 has held the position of Senior Research Associate, Atmospheric Sensing Group. His scientific interests include time series analysis for climate studies, and the development of satellite cloud classification methods for radiation budget calculations. In 1993, Dr. Kärner and co-author, Dr. Sirje Keevallik, published *Effective Cloud Cover Variations* (A. Deepak Publishing). He was born in 1942 in Tartu, Estonia, and is married with three children.

Dr. Ian Clark holds a B.Sc. and M.Sc. in Earth Sciences from the University of Waterloo, and a Ph.D. Sciences de la Terre from the Université de Paris-Sud. Dr. Clark is a Professor in the Department of Earth Sciences at the University of Ottawa. He conducts research on past climates and environmental change in the Arctic since the last ice age. Current programs involve field work with students in the Yukon Territory and on the Mars environment analogue site on Devon Island in Nunavut, which is supported by the Canadian Space Agency. He teaches courses on Quaternary Geology and Climate Change and on Groundwater Geochemistry. Dr. Clark is director of the G.G. Hatch Isotope Laboratory, an internationally-renown facility supporting research in Earth and environmental science.

Dr. Tad Murty completed his early education in India and later received an M.S. and Ph.D. in Meteorology and Oceanography from the University of Chicago. Dr. Murty was a Senior Research Scientist with the Canadian Department of Fisheries and Oceans for 27 years and a Professor of Earth Sciences at Flinders University, Adelaide, Australia. Murty has also served as the Director of Australia's National Tidal Facility, and as a Senior Scientist with Baird & Associates Coastal Engineers in Ottawa, Canada. Dr. Murty retired in 2004 and is now an Adjunct Professor in the Departments of Earth Sciences and Civil Engineering at the University of Ottawa. Dr. Murty has authored, co-authored and edited 18 books and monographs and more than 250 papers in peer reviewed scientific journals. He has served on various national and international committees, and received several awards for original and outstanding research on mathematical modelling of marine hazards. At present, he is the leader of a World Meteorological Organization group preparing a manual on storm surges from Hurricanes and extra-tropical cyclones. Dr. Murty is also the Editor of *Natural Hazards* published by Springer Associate, and the Editor of *Marine Geodesy* published by Taylor& Francis.

Dr. James J. O'Brien Dr. James J. O'Brien is the Robert 0. Lawton Distinguished Professor, Meteorology & Oceanography, and the Director of the Center for Ocean-Atmospheric Prediction Studies at Florida State University. After receiving his Ph.D. in meteorology from Texas A&M University in 1966, O'Brien has published more than 115 scientific publications, and has significantly contributed to the advancement of the science of atmospheric and ocean modeling. O'Brien is a Fellow of the American Meteorological Society, the American Geophysical Union, the Royal Meteorological Society, and the American Association for the Advancement of Science. He is also a Member of the Norwegian Academy of Science and Letters, and a Foreign Fellow of the Russian Academy of Natural Science. He has been the Editor of the *Journal of Geophysical Research:Oceans,* and the Associate Editor of *Monthly Weather Review,* and *Continental Shelf Research.* He is currently an Associate Editor of the *International Journal of Math and Computer Modeling.* A member of Florida State University's Faculty for more than 35 years, he is perhaps best known for his early, basic research into El Niño. Since 1999, O'Brien has been the Florida State Climatologist, and in 2006 he received the prestigious Uda Prize from the Japanese Oceanographic Society.

Glossary

Accumulated Cyclone Energy (ACE)	a measure used by the National Oceanic and Atmospheric Administration (NOAA) to express the activity of Atlantic hurricane seasons
Acidity	the level of hydrogen ion concentration in a solution measured on the pH scale such that the majority of readings range from 1 (very high acidity) to 14 (very high alkalinity)
Aerosols	tiny solid particles or liquid droplets that remain suspended in the atmosphere for at least several hours. Aerosols include volcanic dust, sea spray and its particulate products, wind generated dust, smoke from natural forest fires, and particles emitted during combustion
Albedo	the extent to which an object reflects light; the ratio of scattered to incident electromagnetic radiation power. For example, snow covered surfaces have a high albedo, and dark bare ground has a low albedo.
Altimetry	the measurement of altitude
Altitude	the elevation of an object above a known level; commonly, the elevation of an object above mean sea level
Anthropogenic	resulting from or produced by human beings
Areal	the adjective of area; relating to or involving an area. For example, average rainfall over an area could be referred to as the areal average
Aspect	in geography, aspect refers to the direction a slope is facing
Atlantic Multidecadal Oscillation (AMO)	an ongoing series of long-duration changes in the sea surface temperature of the North Atlantic Ocean, with cool and warm phases that may last for 20-40 years at a time; these changes are natural and have been occurring for at least the last 1,000 years
Biosphere	the outer part of the Earth (including the land, air, and water) in which life occurs
Biota	the flora (plant) and fauna (animal) of a region or time period
Black carbon	a term describing a group of compounds consists mainly of soot, charcoal, and possible light-absorbing organic matter.
Carbonate concentration	the number of molecules of a carbonate (a compound containing carbon and oxygen such as calcium carbonate, which is limestone) in a given volume
Chlorofluorocarbons (CFC)	a family of chemical compounds composed of carbon, fluorine, chlorine and hydrogen that were used extensively as propellants, refrigerants, and solvents.
Conservation of mass	a law of physics that states that matter cannot be created or destroyed only changed in form.
Climate	The IPCC defines climate in a narrow sense as the “average weather”, or more rigorously as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years
Carbon Dioxide (CO_2)	a molecule consisting of one carbon atom bonded to two oxygen atoms. At room temperature it is a colourless and odourless gas
Coral series	coral growth is influenced by temperature (but not temperature alone), and can be used much like tree-ring widths to make inferences about the climate in historical times. A coral series generally refers to a coral sample(s) that is used to estimate past climate changes

Cryosphere	refers to the portions of the Earth's surface where water is in solid (frozen) form, and includes snow, ice, and frozen ground (including permafrost)
Diurnal temperature range (DTR)	the difference between the maximum and minimum temperature in a day
Downscaling	a method for obtaining high-resolution climate or climate change information from relatively coarse-resolution global climate models (GCMs). Typically, GCMs have a resolution of 150-300 km by 150-300 km, but many models require information at scales of 50 km or less, so some method is needed to estimate the smaller-scale information
Dynamical downscaling	a method for obtaining high-resolution climate data from relatively coarse-resolution global climate models which uses a limited-area, high-resolution model (a regional climate model, RCM) driven by boundary conditions from a GCM to derive smaller-scale information; used whenever models require small-scale data
El Niño	otherwise known as the El Niño-Southern Oscillation (ENSO) is a coupled air-sea phenomenon that has its origins in the Pacific Ocean but affects climate globally
Emissions	in the climate change context, emissions refers to the release of a greenhouse gas or its precursors into the atmosphere
ENSO	see El Niño
Equilibrium climate sensitivity	the change in surface air temperature following a unit change in radiative forcing
Extratropical	The extratropics refer to an area outside of the tropics. *Extratropical* is often used to describe storms or cyclones that originate outside of the tropics
Firn	A type of snow that has survived at least one season and has become granular and dense, almost an ice. It is often found under snow that accumulates at the head of glaciers
Fossil fuel	refers generally to fuels such as coal, oil, and natural gas that were formed from decayed plants and animals by exposure to heat and pressure over hundreds of millions of years in the Earth's crust
General Circulation Model (GCM)	a time-dependent, numerical, three-dimensional computer model of the climate system, representing the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries
Glacial Isostatic Adjustment (GIA)	the process whereby the earth's shape and gravitational field are modified in response to large scale changes in surface mass load related to glaciation and deglaciation
Greenhouse gas	any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs) , ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs)
Gulf Stream	a warm, swift, relatively narrow ocean current that flows along the east coast of the United States
Heat island	an urban area that is significantly warmer than the surrounding countryside; otherwise called an Urban Heat Island (UHI) or the 'urban heat island effect'.

Heinrich events	sudden intense cold and dry phases which are the most extreme of a spectrum of abrupt, brief cold events which seem to have occurred very frequently over the last 115,000 years
Holocene	the post-glacial period, between the present and 10,000 years before present
Ice cores	a cylinder of ice removed from an ice sheet containing layers of compacted ice useful for the reconstruction of past environments
Irradiance	a measure of the amount of light energy incident on a unit area per unit wavelength interval (Watts per meter square per nanometer, for example) from all directions
kelvin	the base unit of temperature in the International System of Units. Zero kelvin (0 K) is defined as absolute zero – the lowest possible temperature where no heat energy remains in a substance. A temperature change of one kelvin is equal to a temperature change of one degree Celsius.
Lacustrine	pertaining to or living in lakes or ponds
Last Interglacial (LIG)	the most recent time (115 000 to 125 000 years ago) during which global temperatures were as high as or higher than in the postglacial, when continental glaciers were limited to the Arctic and Antarctic, and sea levels were near current positions
Meltback	a periodic melting of a glacier
Meridional Overturning Circulation (MOC)	sinking and spreading of cold water; for instance, the Atlantic meridional overturning circulation carries warm upper waters into far-northern latitudes and returns cold deep waters southward across the Equator
Monsoon	a thermally driven wind arising from differential heating between a land mass and the adjacent ocean that reverses its direction seasonally
Nonstationarity	see Stationarity
Northern Annular Mode	large-scale modes of climate variability in the Northern Hemisphere also known as the Arctic Oscillation or the North Atlantic Oscillation.
Ozone	a molecule made up of three atoms of oxygen that occurs naturally in the stratosphere and filters out much of the sun's ultraviolet radiation; ozone builds up in the lower atmosphere as smog pollution
Pacific Decadal Oscillation	a pattern of climate and ocean conditions occurring in the north Pacific Ocean that results in shifts in sea surface temperatures and plankton abundance on a decades-long time scale
Paleohydrology	the study of hydrologic processes and events using proxy measures that occurred before the beginning of the systematic collection of hydrologic data
Paleolithic	the Old Stone Age; the archaeological period before c.10,000 BC, characterized by the earliest known stone tool manufacture
Parameterization	the representation of physical effects as simplified parameters in a dynamic model; for instance, cloud formation is calculated from quantities like water vapor, depending on the exact parameterization scheme employed
pH	a measure of the acidity or alkalinity of a solution; pH scale typically ranges from 0 to 14 such that 7 indicates neutral solutions, small numbers indicating greater acidity and large numbers indicating greater alkalinity

Power Dissipation Index (PDI)	for a tropical cyclone PDI is defined as the sum of the maximum one-minute sustained wind speed cubed, at six-hourly intervals, for all periods when the cyclone is at least tropical storm strength; The PDI takes into account the frequency, strength, and duration of tropical cyclones
Proxy record	a substitute measure when direct measurement is not possible
Radiation	energy that comes from a source and travels through some material or through space; light, heat and sound are types of radiation.
Radiation budget	the balance between incoming energy from the Sun and outgoing thermal (longwave) and reflected (shortwave) energy from the earth
Radiosonde	a measuring device attached to weather balloons that directly records various atmospheric parameters
Radiative Forcing (RF)	the net flux of radiation into or out of a system such that there must be some change to the non-radiative energy states of the system such as a change in its temperature
Sea level	the position of the boundary between the air and the sea; serves as the reference point from which all land elevations and water depths are measured. The sea level at any location changes constantly with tide, atmospheric pressure, and wind conditions and is therefore commonly defined as mean sea level (msl)
Sink strength	the degree to which a process capable of removing energy or a substance from the atmosphere; a sink provides storage for a substance; for example, plants act as sinks through photosynthesis, as they transform carbon dioxide in the air into organic matter which either stays in the plants or is stored in the soils
Stationarity	a condition of time series data in which both the mean and variance are finite and constant with respect to time, and the covariance across fixed intervals is constant across time.
Statistical downscaling	a method for obtaining high-resolution climate data from relatively coarse-resolution global climate models which derives statistical relationships between observed small-scale (often station level) variables and larger (GCM) scale variables, using regression analysis or neural network methods
Stratosphere	the atmosphere is categorized into layers; the stratosphere is the layer above the troposphere and below the mesosphere; it is generally defined as beginning at 10km above the earth's surface and ending at 50km above the earth's surface and is characterized by an increase in temperature with height
Sublimation	a phase change of a substance from solid directly to gas
Subsidence	the sinking or downward settling of the Earth's surface
Surface thermometer network	an interconnected system of temperature-measuring devices
Thermohaline Circulation	the flow of ocean water caused by changes in density, which depends on both temperature (thermo) and salinity (haline)
Top of the Atmosphere (TOA)	the upper limit of the atmosphere defined differently depending on the application; in climatology, TOA is the altitude at which air becomes so thin that atmospheric pressure or mass becomes negligible

Troposphere	the atmosphere is categorized into layers, the lowest of which is the troposphere that extends from the earth's surface to approximately 15km; all weather processes take place in the troposphere
Younger Dryas	an abrupt and brief (approximately 1300 ± 70 years) cold climate period at the end of the Pleistocene between approximately 12,700 to 11,500 years Before Present