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# Understanding Climate Change

By Nicholas Schneider

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# *Preface*

Global warming, climate change, and greenhouse gas emissions have dominated the news in recent years. Governments and members of the public are grappling with calls for policy responses, of which the Kyoto Protocol is one example. Some world leaders and prominent writers are even saying the future of humanity is at stake. People everywhere are trying to learn what the issues are all about.

*Understanding Climate Change* aims to provide a comprehensive but easily readable summary of the current state of climate change science. It is intended to be more informative and thorough than popular news stories, but not as technical as research reports such as the *Intergovernmental Panel on Climate Change (IPCC)* report. It provides an overview of the many knowns and unknowns that pertain to climate change. By providing enough complexity and detail, *Understanding Climate Change* should allow anyone to more confidently approach discussions about the interaction between earth's climate and human activities.

*Understanding Climate Change* is organized to largely follow the sequence of topics in the most recent IPCC report. The Fraser Institute also published a more detailed summary of the IPCC Report called the *Independent Summary for Policymakers (ISPM)*, which serves as a longer and more technical summary than *Understanding Climate Change*. Readers can therefore refer to the full IPCC report (http://ipcc-wg1.ucar.edu/) and the ISPM (see http://www.fraserinstitute.org/commerce.web/publication_details.aspx?pubID=3184) when they are interested in gaining a more detailed knowledge of any one topic area.

Questions that are specifically addressed in *Understanding Climate Change* include:

- How have climate-influencing factors changed over the last hundred or so years?
- How do we measure climate change, and how much has the atmosphere warmed?
- How have oceans, sea levels, glaciers, and other ice formations changed?
- Are recent changes unusual compared to the last thousand, or hundred thousand years?
- What is a climate model, what are the limitations of climate models, and how do they help us understand the climate system?
- And finally, what are predictions of future climate change?

It is a challenge to summarize such a complex and evolving subject matter into one publication, but for the benefit of the reader, this publication presents evidence to support the following brief conclusion:

*The climate is naturally variable. Evidence shows that throughout earth's history, there have been numerous global climate changes that were much larger than those experienced in recent times. For most of the last 500 million years, the earth was probably much warmer than it is today.*

*Some data suggest that an increase has occurred in average temperatures at the earth's surface of as much as 1°C since the mid-1800s, with continued trends of about one to two tenths of a degree per decade in recent years. There are considerable uncertainties and ongoing scientific debate about the reasons for such changes and what they mean for the future. Computer-run climate models used by the IPCC assign most of the cause for this trend to increases in the atmospheric concentrations of greenhouse gases, due mainly to the burning of fossil fuels.*

*While predictions of climate change 50 or 100 years from now cannot be reliably made, it is plausible that further increases in greenhouse gas levels this century will have an overall warming influence on the climate. But it remains difficult to say how strong the effect will be. The main effect predicted by climate models as a result of greenhouse gas emissions is a strong warming in the mid-layer of the atmosphere over the tropics, and this has not been observed in data to date. If warming at the surface occurs, some scenarios imply effects on sea levels, ice and snow trends, precipitation, storminess, and many other climate properties, though local effects in particular regions are too difficult to forecast reliably.*

## About the author

Nicholas Schneider is a former Policy Analyst with The Fraser Institute's Centre for Risk, Regulation, and Environment. Prior to joining the Institute, Nicholas worked with the International Joint Commissions on emerging air quality issues in the US-Canadian trans-border region, and with the Ontario Ministry of Agriculture, Food, and Rural Affairs on nutrient and pesticide management policy. Nicholas holds a M.Sc. in Environmental and Natural Resource Economics and a B.Sc. in Environmental Science from the University of Guelph. He has written on global climate policy and economics, as well as the compliance costs of the Kyoto Protocol for the Institute. Nicholas now works to find greenhouse gas reduction opportunities for the shipping industry.

# An Introduction to Climate

The earth's climate is a complex natural system of interrelated components. The main features of the climate are reflected in the atmosphere, which is itself influenced by the oceans, cryosphere (ice), land surfaces, and the biosphere (Figure 1).

The term *climate* refers to general weather patterns over decades or longer. The climate of a particular location is usually described based on conditions that last for thirty years or more.

Understanding the response of the climate system to the various natural and human-induced *(anthropogenic)* forces is a central theme of modern climate research.

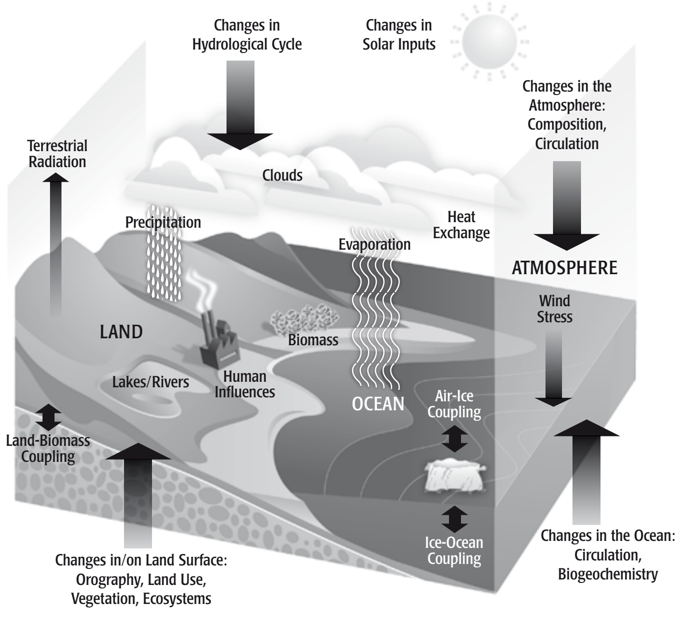


**Figure 1: Global climate system components**
*Source: Artist's representation, various sources*

## Radiation, convection, and the greenhouse effect

The ultimate source of energy for all atmospheric processes is the sun (*solar radiation*). For example, the earth's seasons are caused by changes in received solar radiation due to regular tilts in the earth around its axis each year.

On average, about 30% of incoming solar radiation is reflected back to space by clouds, particles in the air, and by the earth's surface. Of the remaining solar radiation, about 50% is absorbed at the earth's surface, and about 20% is absorbed by the atmosphere.

The atmosphere both warms and cools the earth's surface. Incoming solar radiation is absorbed by the earth's surface, causing it to warm and emit long-wave infrared radiation. Most of this long-wave radiation is absorbed in the atmosphere by infrared absorbing gases (called *greenhouse gases*, primarily water vapour, carbon dioxide, methane, and other trace gases) and re-emitted back to the surface, which warms the earth's surface and lower atmosphere.

At the same time, warm air at the surface rises and cool air from above descends. This process is called *convection* and transports surplus energy at the surface into the atmosphere. Convection and the emitting of long-wave radiation are the main ways in which solar energy absorbed at the surface is transferred into the atmosphere.

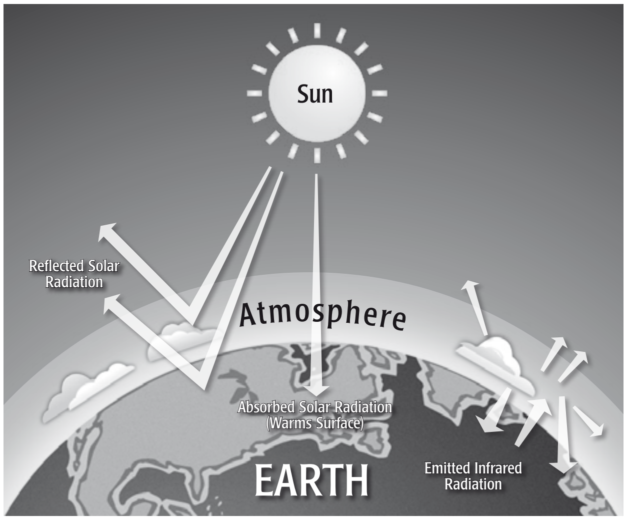


**Figure 2: A simplified representation of the greenhouse effect**
*Source: Artist's representation, various sources*

The natural greenhouse effect in the atmosphere keeps the earth about 33°C warmer than it would be if there was no infrared absorption, making the process essential to life on earth (Figure 2). Without an atmosphere, more of the outgoing long-wave energy would be lost to space, and the earth would be about -18 °C. At the same time, without the cooling influence of convection, temperatures at the surface would increase rapidly, making the earth uninhabitable. The atmosphere, therefore, keeps the surface of the earth from becoming too warm or too cold to support life.

## Large-scale motions of the climate system

If there was no mechanism to redistribute energy around the earth, then polar regions would be much cooler, while the low latitudes (near the equator) would be much warmer than they already are. However, high temperatures over the equator and low temperatures over the poles result in a series of large-scale air circulation patterns in each hemisphere. Together with ocean currents, these circulation patterns distribute energy around the earth.

The earth's climate is also affected by large-scale oceanic systems called *oscillations*. A well-known example is the El Niño phenomenon, which occasionally produces unusually warm weather after Christmas in areas of North America.

## Causes of climate change

Climate can change due to forces *external* to the climate system (e.g., arrangement of continents, volcanic eruptions, and changes in the intensity of sunlight). It can also change as a result of forces *internal* to the climate system (e.g., atmospheric composition, clouds), or because of *anthropogenic* (human-caused) changes (e.g., large-scale modifications of the land surface and atmospheric composition of greenhouse gases).

On geological time scales, there have been great changes in the position and size of continents and ocean basins. These *tectonic* movements, along with the formation of mountains, have influenced the climate at specific locations across the earth, as well as changing the overall average temperature of the earth.

Major changes over about the last one million years are believed to be a result of variations in incoming solar radiation associated with changes in the earth's orbit. The earth's orbit around the sun is subject to long-term variations due to changes in the wobble, tilt, and shape of the orbit. The latter creates an approximately 95,000-year pattern that is linked to the glacial cycles.

During the last 100 years, anthropogenic factors have increased considerably. Large sections of continents have been deforested and cultivated, and various emissions to the atmosphere are associated with the growth of world population and industry.

## Summary

Climate generally refers to the average weather over long periods of time. The climate is affected by changes in solar energy, as well as complex interactions between the air, water, land, ice, and living world. Over billions of years, as the earth has changed, so too has the climate.

One feature of earth's climate is the greenhouse effect. This effect causes the earth's surface and lower atmosphere to be warmer than it would be otherwise. At the same time, the atmosphere also cools the surface through convection of heated air. The following chapters explore in more detail how human and natural factors affect earth's climate, and the changes that may occur over the next 100 years.

# Climate Change and the Radiative Forcing Model

## Climate change and the earth's energy balance

The earth's climate is affected by the balance between incoming and outgoing energy. When there is a change in the flow of incoming energy (e.g., from increased solar radiation) or a change in the way energy is transferred away from the surface, the global climate system will adjust to ensure that an overall balance is maintained.

Changes in climate, whether due to natural or human factors, can cause further changes via feedback mechanisms (Figure 3). Positive feedbacks amplify an initial change; negative feedbacks dampen an initial change. For example, temperature increases can result in larger amounts of water vapour accumulating in the atmosphere; since water vapour is a greenhouse gas, its increase results in a further temperature increase.

Feedback processes are complex and are difficult to quantify, yet are important to understand since the feedbacks may be greater than the initial change and in some cases may go in the opposite direction.

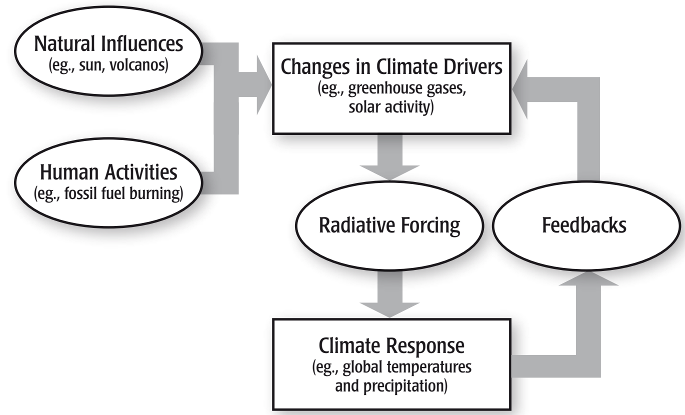


**Figure 3: Forcing and feedbacks in climate change**
*Source: Adapted from IPCC (2007), Figure 2.1*

## Various factors contribute to climate change

The concept of *radiative forcing* is used to compare different factors that affect earth's energy flows in terms of their possible effect (including feedback effects) on average surface temperatures. Radiative forcing isn't a physical property that can be measured. Instead, it is estimated from computer-run climate models as a convenient way of comparing the strength of the possible effect on the climate of widely-varying factors. Not all factors can be expressed in radiative forcing units, and the estimates in some cases are known to be very uncertain.

The IPCC estimates radiative forcing changes since the year 1750, well before human influences on the climate started significantly increasing in the late 1800s. This section summarizes some important natural and human factors that have changed since 1750.

## *Greenhouse gases*

Levels of different greenhouse gases have changed by different amounts:

### Carbon Dioxide

The level of carbon dioxide ($CO_2$) in the atmosphere has increased by 36% since the time of the industrial revolution, and is still rising due mainly to emissions from fossil fuel combustion.

### Methane

After remaining constant in the atmosphere for several centuries, methane ($CH_4$) levels started rising in the 18th century, largely due to human activities (e.g., rice agriculture, the burning of vegetation, ruminant animals, and various industrial sources). Atmospheric methane levels have been flat or declining now for a few years, possibly because global methane emissions have not increased over that time.

### Ozone

Changes in ozone since 1750 are not well-known, but ozone levels are estimated to have increased in the lower portions of the atmosphere and decreased in the upper atmosphere.

### Water Vapour

Water vapour is the most abundant greenhouse gas, and is by far the most powerful absorber of infrared radiation. As such, it is responsible for most of the earth's natural greenhouse effect. However, its global atmospheric concentration is not directly altered by human activities; human emissions are negligible compared to natural sources such as evaporation from oceans. Levels of atmospheric water vapour do, however, respond to climate conditions such as temperature, and therefore changes in atmospheric water vapour are an important climate feedback, albeit one that is difficult to predict.

## *Aerosols*

Aerosols can be created by human and natural processes, such as burning fossil fuels, burning vegetation, blown dust from dry soils, and volcanic eruptions. Aerosols can affect the climate by reflecting and absorbing radiation, which in turn affects the earth's radiation balance. They can also affect cloud lifetimes, as well as the reflectivity of cloud tops.

### *Changes to the land surface*

The local climate, and to a lesser extend the global climate, are affected by changes to the land surface. For example, the conversion of forest to cropland affects local hydrology and the amount of sunlight absorbed or reflected at the surface.

Large-scale changes to the land surface are mainly due to deforestation. Between 1750 and 1990, over 8% of the earth's forests were lost, and the amount of land in pasture or crops increased from about 7% to almost 40%. Smaller scale changes, such as urbanization, can also have significant effects on the local climate. Because of the difficulty translating them into radiative forcing units, many forms of land use change are left out of these calculations.

### *Solar changes*

Historical reconstructions of solar activity show that the sun's energy output has intensified since the 1700s, which explains at least some of the climate changes since then. A number of different reconstructions of solar output over the past four centuries are discussed in the IPCC report, with varying implications about the extent to which they can explain climate trends in recent history.

In addition, the recent IPCC report discusses potential indirect effects from changes in solar activity. A mechanism attracting considerable current interest concerns galactic *cosmic rays*. These are high-energy particles that continuously bombard the earth from deep space. These particles have been hypothesized to play a role in supporting the formation of clouds. In periods when solar output intensifies, the intensified solar wind partly shields the earth from cosmic rays, reducing cloud formation, thereby amplifying the warming effect of the brighter sun. However, this remains an area of considerable scientific uncertainty.

## Estimated radiative forcing levels

The radiative forcing factors calculated by the IPCC imply that carbon dioxide and other greenhouse gases have had a relatively large impact on the climate since the year 1750, while increased solar radiation and other factors have had a smaller impact (Figure 4). The influence of greenhouse gases on climate is considered by the IPCC to be well understood, but the scientific understanding of all other factors ranges from medium to low.

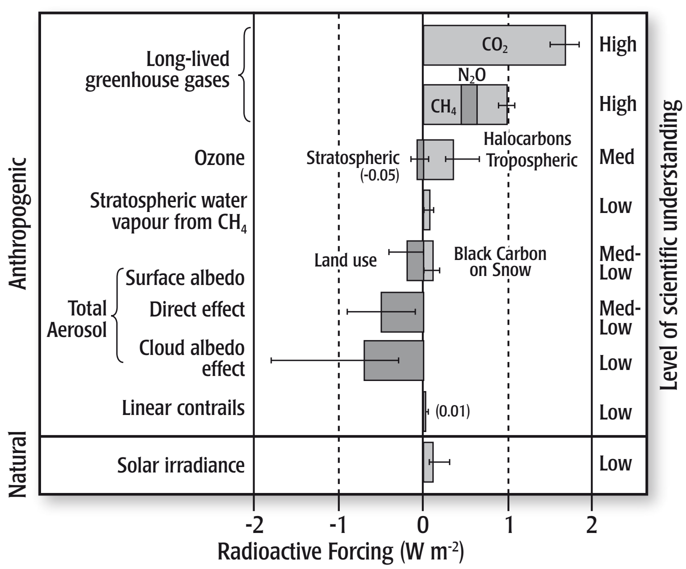


**Figure 4: Radiative forcing of climate between 1750 and 2005**
*Source: Adapted from IPCC (2007), Figure 2.20*

## Summary

Climate is influenced by changes in the earth's energy balance. The concept of radiative forcing has been developed as a tool to compare the relative influence of differing factors that change the earth's energy balance. While some of the largest forcings are well understood, scientists have a medium to low understanding of most of them. The IPCC estimates that the radiative forcing effect of greenhouse gases is relatively large compared to other factors that affect the climate.

# Observed Changes in Weather and Climate over the Past Century

## Changes in temperatures observed on earth

At any moment, temperatures on earth range from about -40 °C to +40 °C, but local temperatures outside of this range are not uncommon. Current estimates obtained from thermometers at ground level, as well as weather balloons and satellite records, show that the earth's average temperature has increased in recent decades, though they differ by exactly how much. Recent increases are on the scale of about one to two tenths of a degree per decade.

### *Measuring temperature using surface thermometers*

The global average surface temperature is estimated by averaging thermometer measurements from thousands of land stations across the earth, combined with those of sea-surface temperature from ships and buoys. Over the past 150 years there have been many changes in the kinds of equipment used, where the monitoring takes place, how many places were sampled, and so forth. Data from over the oceans has been particularly difficult to obtain. Temperature data collected for climate analysis must be adjusted to remove all influences that arise due to urbanization and other land-use changes, as well as changes in equipment, station location, and the number of operational stations over time. The resulting index indicates that average temperature has increased about 1°C over the past 150 years (Figure 5).

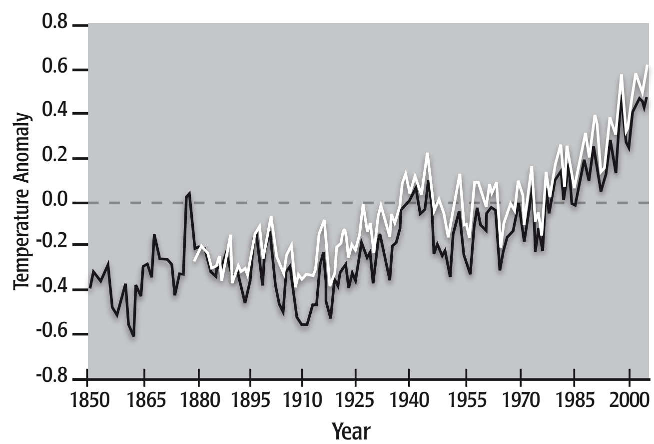


**Figure 5: Estimated annual average temperature at the earth's surface over the last 120-150 years (°C). The units are "anomalies", or differences from local averages.**
*Source: Grey – Goddard Institute for Space Studies (2007), Black – Hadley Centre for Climate Change (2007)*

Many weather stations continue to operate in cities or at airports, where the high concentration of buildings and human activities often causes these areas to be more than a few degrees warmer than the surrounding rural areas. This is called the *urban heat island* effect, and is not related to greenhouse gases. A series of studies in recent years presented evidence that as much as half the increase in the average of temperatures over land since 1980 can be attributed to a failure to fully correct for local urbanization and other land surface changes, as well as other data quality problems (de Laat and Maurellis 2004, 2006; McKitrick and Michaels 2004, 2007). In its recent report, the IPCC acknowledged these studies but dismissed the findings. However, the IPCC did not present any counterevidence.

## *Measuring temperature using satellites*

The average temperature of various layers of the atmosphere is also estimated using orbiting satellite sensors. Estimates from satellite data have to be averaged across different satellites and measurements at different heights within the atmosphere. They show that the average temperature in the part of the atmosphere from about 1 to about 16 km up (the *troposphere*) has been increasing about 0.12°C to 0.19°C per decade since 1979, which is the start of the satellite record. Climate models all predict that greenhouse gases should have their strongest effect in the troposphere over the tropics, a large layer comprising half the lower atmosphere. A variety of satellite series, as well as data from weather balloons, have failed to detect such a change.

## *The difference between temperature changes in the North and South*

The North Pole has experienced the greatest surface temperature increase in recent years, while there has been no measured increase at the South Pole over the last few decades. For the Southern Hemisphere as a whole, the trends from both land-based and satellite-based data are only about one-half to one-third as large as those in the Northern Hemisphere.

## Changes in the earth's other climate properties

### *Precipitation*

There is little evidence of a strong, long term change in precipitation patterns, either globally or regionally. Precipitation has, however, changed abruptly in some areas, and it has increased slightly in many northern regions over the last 100 years. In many northern areas, rising temperatures have resulted in more wintertime precipitation falling as rain rather than snow.

### *Drought*

It is difficult to directly measure drought over the long term. Indirect estimates suggest that drought has been increasing in recent decades over many areas, although some areas have become wetter, and trends in the Southern Hemisphere are generally small.

### *Hurricanes and typhoons*

Strong tropical cyclones are called hurricanes in the Atlantic Ocean and typhoons in the Pacific Ocean. Considerable natural variability in cyclone activity makes it hard to assess trends. There is some evidence that more intense (stronger) cyclones are occurring more often in some regions, even though the total number on average each year may not be increasing.

### *Tornados, hail, and thunderstorms*

Not enough data are available to draw any conclusions regarding local extreme weather events, such as tornados, hail, and thunderstorms. Observed increases are often due to increased efforts to track and record these events rather than increases in actual incidents.

## Summary

The available data imply an increase in the average temperature measured at the earth's surface over the last 150 years, but not consistently over time or equally in each region. There is evidence that temperature data collected over land at the surface are affected by modifications to the land surface, especially over the last 25 years. Temperature data measured by weather satellites show less change over that interval, especially in the tropics where climate models predict the strongest warming. There seem to be no strong long term trends in precipitation patterns, although there is considerable regional change and variation over years and decades. Overall, the lack of reliable long-term records of extreme and rare events such as heat waves, intense storms, cyclones, and tornadoes often makes assessing trends difficult.

# Observed Changes in the Frozen Parts of the Earth

The *cryosphere* is the frozen part of the earth's water system, and consists of snow, river and lake ice, glaciers and ice caps, ice shelves and ice sheets, and frozen ground.

The cryosphere also provides an indirect way to see the effect of climate, but since it is affected by several factors, interpretation of changes is complex. For example, a local change in ice cover (for instance, the recession of a glacier) may be due to an increase in local average temperature, but it also may be the result of changes in precipitation, local sensitivity to changing solar radiation, or a combination of the above.

## Snow

Snow cover has decreased in most regions compared to the 1800s, especially in the spring and summer. Between 1966 and 2004, there was a decreasing trend in average Northern Hemisphere snow cover in spring and summer, but not substantially less in winter.

## River and lake ice

Long-term (approximately 150-year) records show a general trend towards later freezing and earlier break-up of northern river and lake ice. There is, however, considerable variability in surveys of Canadian rivers since the late 1960s. The IPCC emphasizes that river and lake ice data must be interpreted with care.

## Sea ice

Since satellite measurements began in 1978, the Arctic sea ice area has steadily declined, with the rate of decrease greater in the summer than in the winter. The thickness of sea ice in the central Arctic has decreased since 1980, with most of the decrease occurring abruptly between the late 1980s and late 1990s. However, the IPCC notes that sea ice thickness is one of most difficult climate variables to measure. A study by NASA scientists, published after the IPCC report, concluded that cyclical patterns in the Arctic Ocean circulation, rather than global warming trends, explain many of the recent changes seen in the far North (Morison *et al.* 2007).

Data on sea ice coverage in the Arctic Basin is updated daily at the University of Illinois web site (see http://arctic.atmos.uiuc.edu/cryosphere/index.html). In summer 2007, sea ice in the Arctic Basin fell to its lowest level since 1979, but by January 2008 had fully recovered to its 1979-2000 average (see http://arctic.atmos.uiuc.edu/cryosphere/IMAGES/recent365.anom.region.1.html).

The Antarctic sea ice area has not declined since 1978, and there are no measurements of Antarctic sea ice thickness.

For the Southern Hemisphere as a whole, sea ice coverage is well above its long-term (1979-2000) average extent (see http://arctic.atmos.uiuc.edu/cryosphere/IMAGES/current.365.south.jpg).

## Glaciers

Glaciers are affected by changes in temperature, precipitation, and *solar insolation* (the amount of solar radiation received at the glacier). Data have been collected for relatively few glaciers worldwide, but of those sampled, most have been losing mass over the 20th century. The biggest losses have been in Patagonia, Alaska, northwest USA, and southwest Canada. Regional patterns are complex, and there are places where glaciers have been advancing in the past decade.

The thickness of the glacier on top of Mount Kilimanjaro has not changed much over the 20th century, although the ice is retreating at the vertical walls. Solar radiation has been identified by the IPCC as the main driver of this decrease.

### *Ice sheets*

The world's largest ice sheets are on Greenland and the Antarctic. Studies of the Greenland ice cap show slight thickening inland and strong thinning near the coastlines, primarily in the South. The ice sheet in Western Antarctica appears to have shrunk since 1961, while the ice sheet in Eastern Antarctica appears to have grown. Between 1993 and 2003, it is estimated that the two ice sheets on balance lost more ice than they gained. Therefore, some melting of both of these ice sheets has very likely contributed to sea level rise.

## Frozen ground and permafrost

Frozen ground is the single largest component of the cryosphere. *Permafrost* refers to ground that remains frozen year-round. Of the few long-term records of permafrost temperature, most of which begin after 1970, almost all show trends of increasing temperature. The IPCC reports that the area of ground that freezes and thaws annually decreased by about 7% in the Northern Hemisphere in the 20th century, mostly due to changes in springtime, but with little change mid-winter.

## Summary

The cryosphere is complex, but has likely declined over the 20th century, as indicated by a retreat of Northern Hemisphere ice, shrinking mountain glaciers, and decreased snow cover. Melting of glaciers and land-based ice sheets contributes to sea level rise.

# Observed Changes in the Oceans and Sea Levels

The ocean plays an important role in climate variability. For example, ocean currents transfer heat from one location to another, and the ocean is able to hold about 1,000 times more heat than the atmosphere.

It has proven difficult to thoroughly sample the ocean. Measurements only began in the 1950s and trends are often impossible to identify due to variations in the datasets. Temperatures in some parts of the ocean are difficult to measure, and there are large regions in the Southern Hemisphere that are not well sampled. A worldwide network (www.argo.net) for sampling ocean temperatures, currents, and salinity was only completed in the fall of 2007.

## Heat content

The average temperature of the global ocean between the surface and the top 700 meters is estimated to have risen by 0.10°C between 1961 and 2003. High rates of warming were observed between 1993 and 2003, but the IPCC notes that since 2003, the oceans have started to cool.

## Salinity

Ocean salinity can decrease if fresh meltwater from the cryosphere enters the oceans. Data on salinity are sparse in some areas, particularly in the Southern Hemisphere. However, salinity has decreased in the polar areas of the Pacific, and increased in the tropical areas of the Atlantic and Indian oceans. Current observations do not provide a reliable estimate of a global average change in ocean salinity.

## Carbon absorption

The oceans absorb and store large quantities of carbon. The amount of carbon dioxide captured by the oceans decreased between 1970 and 1994, likely because the carbon content of the oceans themselves has increased, thus limiting their ability to absorb more carbon. This increase in carbon has led to an increase in surface water acidity, which can adversely affect some marine organisms.

## Sea levels

Two major processes change the global mean (average) sea level: *thermal expansion* (the expansion of water as it warms) and the exchange of water between oceans, ice, the atmosphere, and other water reservoirs.

Globally, sea levels are estimated to have risen on average by about 15 to 20 centimeters over the last 100 years, which is an increase of about 1.5 millimeters to 2 millimeters per year. Since the early 1990s, sea levels have been rising at a slightly higher rate of about 3 millimeters per year.

Sea level changes are not the same globally. In some areas, the sea level is rising at several times the average rate, while in other areas sea levels are falling. While scientific knowledge of sea level changes has improved significantly, there are still uncertainties which make it difficult to understand how each of the various processes has contributed to sea level rise over the last 100 years.

## Summary

Changes in the oceans can be observed through measurements of heat content, salinity, acidity, and sea levels. Observations of these properties show that the state of the ocean has changed. However, there are still some uncertainties and limitations in measuring these properties.

# Paleoclimate Estimates of Past Temperatures

The earliest records of weather and climate derived from modern instruments such as thermometers go back only to about 1750. Palaeoclimate science therefore looks to long-term natural records to estimate past climate changes. Many organisms, such as trees, coral, and plankton, exhibit variations in growth due to changes in the local climate, providing a possible means of inferring local changes in the distant past. Non-biological natural records, such as ice-cores, can also help in the estimation of past climate change.

## Many million years ago

For most of the last 500 million years, the earth was probably much warmer than it is today and had no ice sheets. Palaeoclimate records of atmospheric $CO_2$ levels indicate that $CO_2$ varied widely due to tectonic changes, including volcanic activity. About three million years ago, sea levels are estimated to have been about 15 to 25 meters higher than they are today.

## The past few million years

Over the past three million years, climate change has been dominated by 100,000 year cycles that shift between long glacial periods, or ice ages, and brief, warmer interglacial periods. These cycles are linked to changes in the earth's orbit around the sun.

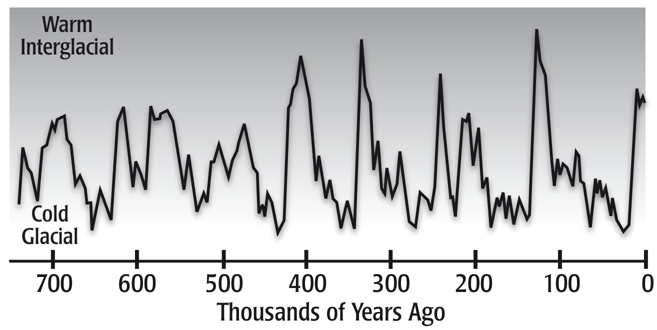


**Figure 6: Indicators of climate change over the last 750,000 years**
*Source: Jouzel et al. (2004)*

Atmospheric $CO_2$ levels tend to rise and fall with changes in temperature. The $CO_2$ levels, however, do not start to rise until several hundred years after temperatures increase, which suggests that $CO_2$ increases responded to temperature changes, but were not the cause of the initial temperature increase.

The earth is currently in an interglacial (warm) period. During the previous interglacial, about 100,000 years ago, there was less ice than now and temperatures were likely warmer than at present. Sea levels were about four to six meters higher during this last interglacial, mostly due to the melting of Greenland and Antarctic ice.

Another aspect of the current climate that is different from past interglacial periods is that atmospheric concentrations of carbon dioxide, methane, and nitrous oxide (three greenhouse gases) are now higher than in the past 650,000 years.

## The past 10,000 years

The current interglacial is called the Holocene, which started about 11,500 years ago. During this time, there were periods when regional, and possibly global, average temperatures were higher than now. Temperatures in the Northern Hemisphere are estimated to have been higher than they are at present for a long interval between 5,000 and 7,000 years ago.

## Temperature changes over the past millennium

Evidence points to a warm interval in the medieval era (900-1300 AD) followed by the so-called Little Ice Age, which lasted into the mid-1800s. Numerous studies have found evidence of local temperatures that were as warm or warmer in the medieval era than in the current era. There have been many recent attempts to estimate hemispheric and global averages of surface temperatures using paleoclimate data. Figure 7 shows several of these recent estimates of temperature changes in the Northern Hemisphere over the last 1,300 years.

Overall, the IPCC states that average Northern Hemisphere temperatures during the second half of the 20th century are probably higher than for any other 50-year period in the last 500 years. Compared to its 2001 report, the IPCC's 2007 report made less definitive claims about whether the Northern Hemisphere is warmer now than during the medieval era. This section of the report continues to be the subject of intense debate.

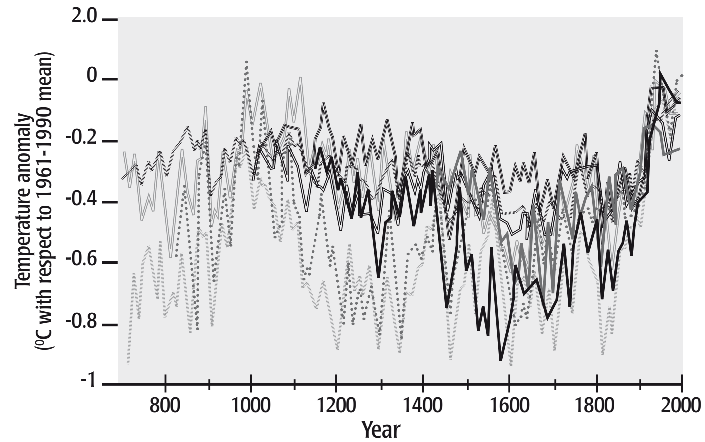


**Figure 7: Several reconstructions of temperature over the last 1,300 years.**
*Source: Independent Summary for Policymakers (2007)*

Reconstructions of temperature before the 1600s are noted by the IPCC as particularly uncertain. There is little knowledge of climate change in the Southern Hemisphere over the last millennium because few palaeoclimate records are available. Furthermore, few records exist for tropical and ocean regions of the Northern Hemisphere. Additionally, some natural temperature records do not match known instrumental temperature changes in recent decades.

## Summary

Some aspects of current climate change are not unusual in terms of the history of the earth. The world has been much warmer, with much higher sea levels, for most of the past 500 million years. However, during much of this time, the earth as a whole was quite different than it is today; 500 million years ago most of the continents were still joined together. Large climatic changes in the past were caused by natural factors, though this does not mean that current climate changes are also natural. Levels of greenhouse gases are likely higher than they have been in a half-million years. The average temperature of the Northern Hemisphere is likely higher now than in than the past 500 years. The comparison over the past 1,000 years remains disputed, and data for the Southern Hemisphere are sparse.

# Climate Models and their Evaluation

The most complex climate models attempt to simulate various climate components such as the atmosphere, oceans, land, and ice. At the moment, climate models are the most comprehensive tool available for studying and simulating the interaction of diverse climate components and processes.

Despite their usefulness, climate models have important limitations. Even the most complex models cannot calculate every process in the climate, including many that are known to play important roles. Therefore, climate modelers must find ways to simplify and approximate many real-world physical relationships.

## Evaluating the accuracy of climate models

Weather forecasts can be tested against actual observations a few days later to see if the model was accurate, but climate models often make predictions that span decades or longer, which makes it more difficult to confirm their accuracy. Therefore, climate models are often tested by observing how closely they can simulate known past and present climate changes. Overall, the IPCC notes that since its last report in 2001, model performance has improved, though errors and biases remain.

*Temperature:* Models can only simulate annual average temperatures in most regions of the world to within approximately 3°C of observations. Averaging simulations across all models produces slightly better results, but errors in polar regions are larger.

In addition, most models predict that increasing the atmospheric concentration of greenhouse gases will result in a strong warming in the troposphere around the tropics, and the warming there ought to be greater than at the surface. However, since 1979, all but one weather balloon and satellite record has shown less warming in the tropical troposphere than at the surface (See IPCC 2007, Figure 3.18).

*Precipitation:* Models can simulate some large precipitation patterns on a regional scale, but individual models show substantial biases, especially in tropical regions.

*Sea ice:* When averaged across models, the simulation of observed sea ice coverage is reasonably similar to observations. However, the range of estimates among models exceeds 50 percent of the observed mean, and projections into the future remain uncertain. Evaluating the accuracy of the models is also limited by a shortage of real-world data for comparison.

*Climate sensitivity:* Climate sensitivity is referred to as the expected increase in global average temperature if the amount of carbon dioxide in the atmosphere doubles. Climate sensitivity is mostly influenced by feedback processes in the climate, which are difficult to estimate. Without the feedback process, a doubling of greenhouse gases would only raise average global temperatures in a climate model by about 1°C. But, because of the expected positive feedback processes, mainly from water vapour, global average temperatures are projected in most models to increase between 2°C and 4.5°C, with a value of approximately 3°C most common.

Despite much research, the range of climate sensitivity estimates has not changed much over the past few decades. A major source of uncertainty is the difficulty of predicting the response of clouds to temperature increases.

## Summary

Climate models are important for understanding and predicting possible climate changes, but the challenges of representing small-scale climate and weather processes, and the continued discrepancies between projected climate conditions and observations, are important limitations. Since models are used not only for projecting the future, but also for diagnosing the human influence on the current climate, it is important to understand their inherent uncertainties.

# Determining the Causes of Recent Climate Change

The climate is constantly changing, but the IPCC uses the term *climate change* to refer specifically to a statistically noticeable change in the average and/or variability of climate properties, such as temperature or precipitation, that lasts for decades or longer.

The IPCC uses a three-step process to attribute human causation to climate change. The process relies heavily on the use of climate models:

1. Detecting a climate change that is unlikely to be due to random or natural variability alone.
2. Determining that the detected change can be explained by human causes.
3. Determining that the detected change cannot be explained by other natural causes alone.

## Climate fingerprints

In order for the above method to work, it must be possible to distinguish between two factors that could both lead to the same result. For example, both greenhouse gas emissions and solar radiation have increased over the last 150 years and both are expected to raise average temperatures, especially near the poles. If each factor were expected to produce temperature changes in different ways (i.e., at different heights in the atmosphere and locations across the earth) then there would be a unique *climate fingerprint* and attribution of climate change would be more straightforward. However, there is some similarity in the projected effects of different factors, so attribution to individual causes is challenging.

## Causes of temperature change in the industrial era

When climate models leave out anthropogenic factors, they do poorly at simulating the globally-averaged warming trend that has been observed since the 1970s. Most of the models used for attribution in the IPCC report also leave out a number of other forcings as well. For example, about half of the models leave out either, or a combination of, land use change, black carbon (created by the incomplete combustion of fossil fuels, wood, or biomass), or the indirect effects of sulphate aerosols (the *direct* effect of sulphate aerosols is to scatter and reflect light, while their *indirect* effect is to influence cloud lifetimes and reflectivity).

When a strong warming influence from carbon dioxide is included, coupled with a strong cooling effect from aerosols over the mid-century interval, the models provide a closer simulation of the global average (Figure 8). On this basis, the IPCC concludes that recent warming is unlikely to be due solely to natural causes, and instead is "very likely" due to greenhouse gases.

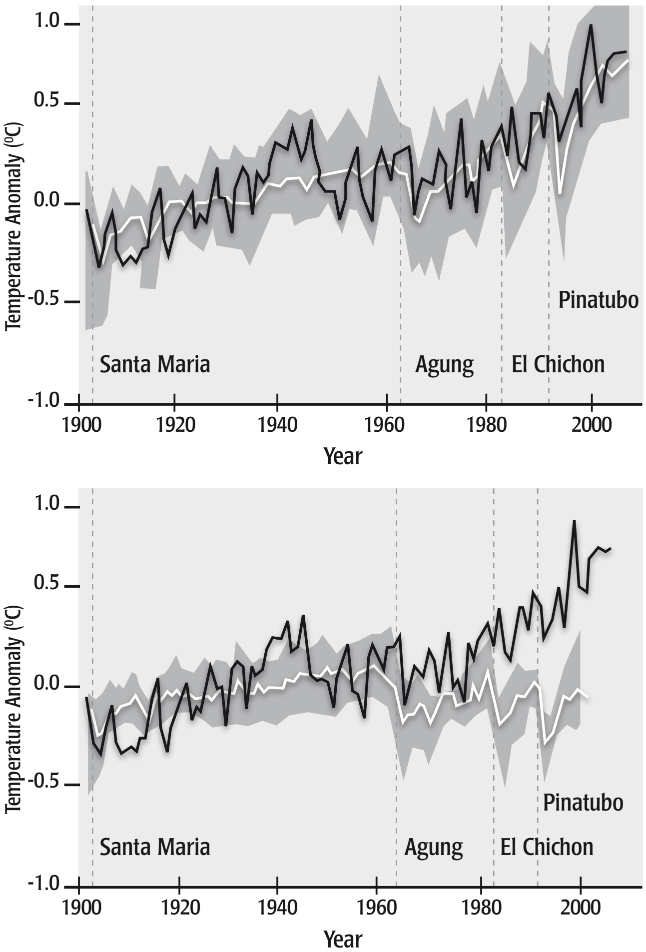


**Figure 8: Simulating global average temperatures with (top) and without (bottom) warming due to greenhouse gases.**
*Source: Black – average of temperatures measured at earth's surface, and Grey – model simulated change. Adapted from IPCC (2007), Figure 9.5*
*Note: The timing of four major volcanic eruptions is shown in the figure. Models predict a strong cooling will occur after a large volcano.*

## Detecting climate changes in other climate properties

The IPCC report also surveys studies that have attempted to identify an anthropogenic influence on other climate properties such as sea levels and ocean heat content, cyclones, precipitation, and changes in ice, snow and glaciers. For some properties, such as sea levels and ocean heat content, an anthropogenic influence is claimed in some studies, while for other properties, such as cyclones, precipitation, and El Niño events, the evidence of a human influence is not clear, or is not detectable.

## Summary

Based on their analysis, the IPCC has concluded that most of the observed warming over the past 50 years is likely due to greenhouse gas emissions. Detection and attribution studies rely on the use of climate models, and the results ultimately involve expert judgment. The validity of attribution studies depends on the range of factors included in the detection analysis and on the validity of model-generated estimates of natural variability and the expected climate response to external forcings.

# Global and Regional Climate Projections

The IPCC report presents many specific forecasts of changes in the earth's weather patterns over the next 100 years, based on the assumption of strong greenhouse gas-induced warming.

## Global climate projections

*Temperature:* Depending on which of several scenarios of future global greenhouse gas concentrations is used, climate models project that average temperatures could increase from a minimum of 1.1°C to a maximum of 6.4°C.

The same models also predict that greenhouse gases will cause warming in the tropical troposphere to be about double the warming at the surface. As of the present, this has not been observed. In most available data series, the troposphere appears to be warming less than the surface.

*Precipitation:* Evaporation and precipitation are expected to increase in a warmer climate. The models predict that precipitation will increase in the tropics and at the poles, and decrease in the subtropics and middle latitudes. The intensity of precipitation is projected to increase, particularly in tropical areas and at the poles.

*Snow and ice:* Current models show a wide range in the response of Northern Hemisphere sea ice to temperature increases, from very little change to a strong accelerating reduction over the 21st century. Antarctic sea ice is projected to decrease more slowly than in the Arctic.

Models project an overall decrease in glacier volume, but there is uncertainty in how to estimate future changes.

In general, snow cover area and the total amount of snow is projected to decrease in the Northern Hemisphere, with increases in a few regions.

*Sea levels:* Depending on the emissions scenario, the average sea level is projected to rise between 18 cm and 59 cm. This will be due mostly to thermal expansion, though melting of glaciers, ice caps, and the Greenland ice sheet is also projected to contribute to the rise.

*Tropical cyclones:* Models that examine tropical cyclones on a large scale predict a decrease in the total number of tropical cyclones and little to no change in the intensity (strength) of individual cyclones on average. On the other hand, models that examine tropical cyclones at a higher resolution and on a smaller scale project that tropical cyclones will become more intense.

## Regional Climate Projections

New sources of uncertainty and complexity arise when attempting to project climate changes at local and regional levels. General projections of regional changes are summarized in the IPCC report; however, at this time, the uncertainties in regional projections are substantial. See Chapter 11 of the full IPCC report for details of the regional projections and their limitations.

## Summary

Projections are useful for understanding how much, and in what ways, the climate may change in the future as greenhouse gas emissions continue to rise. Generally, climate models project an increase in average temperatures and sea levels, and a decrease in the cryosphere. Projections for smaller-scale and rare events are less certain, and more research is needed to improve the reliability of regional climate projections.

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## About The Fraser Institute

Our vision is a free and prosperous world where individuals benefit from greater choice, competitive markets, and personal responsibility. Our mission is to measure, study, and communicate the impact of competitive markets and government interventions on the welfare of individuals.

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# Understanding Climate Change

Global warming, climate change, and greenhouse gas emissions have received extensive media coverage in the past few years. Governments and the public are grappling with calls "to do something." Some world leaders and prominent writers even say the future of humanity is at stake. People everywhere are trying to learn what the issues are all about. This publication takes on the challenge of summarizing this complex and evolving subject matter into one publication.

*Understanding Climate Change* aims to provide a comprehensive but easily readable summary of the current state of climate change science. It provides an overview of the many knowns and unknowns that pertain to climate change.

Questions that are specifically addressed in *Understanding Climate Change* include:

- How have climate-influencing factors changed over the past hundred or so years?
- How do we measure climate change, and how much has the atmosphere warmed?
- How have oceans, sea levels, glaciers, and other ice formations changed?
- Are recent changes unusual compared to the last thousand, or hundred thousand years?
- What is a climate model?
- What are the limitations of climate models, and how do they help us understand the climate system?
- And finally, what are predictions of future climate change?

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FRASER INSTITUTE
The Fraser Institute,
4th Floor, 1770 Burrard Street
Vancouver, British Columbia
Canada V6J 3G7
http://www.fraserinstitute.org