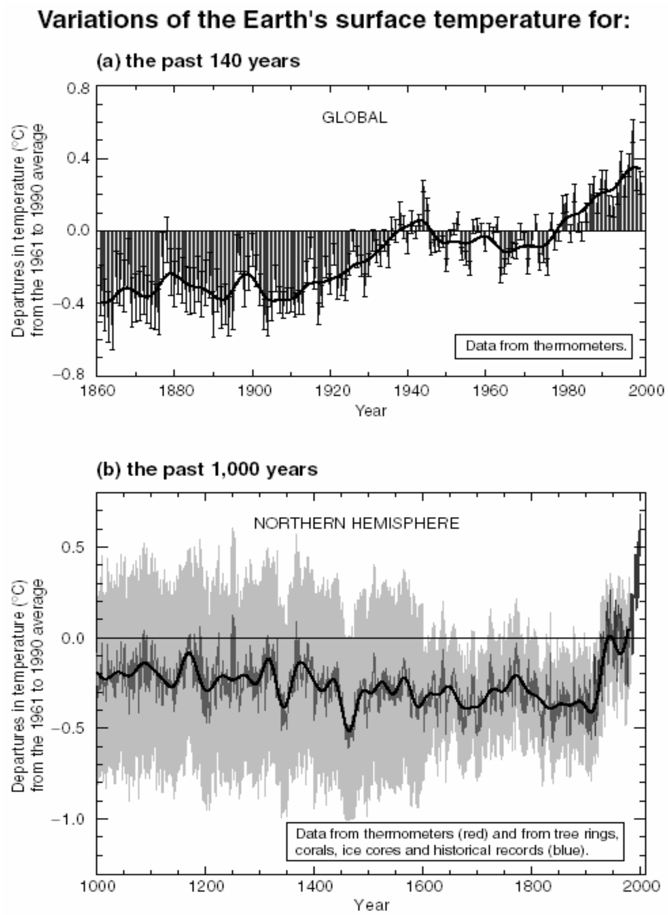
Global Warming and Climate Change: The Scientific Argument for Carbon Abatement

The Evidence for Global Warming

Evidence that the global average temperature increased significantly in the 20th century relative to pre-industrial levels is available both from direct temperature measurements over the last century and a half, as well as from natural indicators reflecting climatic conditions in prior centuries. Since approximately 1860, temperature records have been collected from thermometers sufficiently accurate and dispersed to permit computation of a global average temperature. Over the 140 years that such records have been available, they show an increase of 0.6 degrees Centigrade in the earth's average temperature. These historical temperature records show that a particularly marked increase in average temperature occurred in the second half of the 20th century (see Exhibit 15). Longer-term temperature records have been constructed by climatologists using over 100 natural indicators related to temperature, including tree rings, the extent of mountain glaciers and changes in coral reefs. While there is considerable uncertainty associated with such estimates, the natural evidence is consistent with a trend of declining average temperatures from 1000 to 1900 C.E., followed by a sharp upturn in the 20th century (see the bottom chart in Exhibit 15). Such long-term estimates suggest that the decade of the 1990s was not only the warmest of the century, but also the warmest of the entire millennium.

The measurement of surface and atmospheric temperatures became increasingly precise in the second half of the 20th century. These measurements show that the average temperature on the earth's surface and in the lowest 8 kilometers of the atmosphere has increased by about 0.1 degree Centigrade per decade through the last 50 years. On average, between 1950 and the 1990s, night-time minimum air temperatures over land increased by about 0.2 degrees Centigrade per decade, while daytime maximum air temperatures increased by 0.1 degrees Centigrade per decade. This gradual but steady increase in global average temperatures is reflected in a series of biological and physical indicators of climate change, including the widespread retreat of glaciers, significantly reduced snow cover, shorter duration of ice cover of rivers and lakes, a longer growing season, the poleward and upward shift of plant and animal ranges, earlier plant flowering and bird arrival in the spring and, finally, an increase in the global mean sea level. The changes in these biological and physical indicators are summarized in Exhibit 16.

Exhibit 15 Variations of the Earth's Surface Temperature



Source: *Climate Change 2001: The Scientific Basis,* Houghton, Ding, Gribbs, Noguer, van der Linden, Dai, Maskell & Johnson, eds.

Exhibit 16 Biological and Physical Indicators of Global Warming in the 20th Century

Indicator	Observed Changes
Nonpolar glaciers	Widespread retreat during the 20th century.
Snow cover	Decreased in area by 10% since satellite observations began in the 1960s.
Duration of ice cover of rivers and lakes	Decreased by about two weeks over the 20th century in mid- and high latitudes of the Northern Hemisphere.
Permafrost	Thawed, warmed and degraded in polar, subpolar and mountainous regions.
Growing season	Lengthened by about one to four days per decade during the last 40 years in the Northern Hemisphere, especially at higher latitudes.
Plant and animal ranges	Shifted poleward and up in elevation for plants, insects, birds and fish.
Breeding, flowering and migration	Earlier plant flowering, earlier bird arrival, earlier dates of breeding season and earlier emergence of insects in the northern hemisphere.
Global mean sea level	Increased by 0.1-0.2 meters during the 20th century.
Artic sea-ice extent and thickness	Thinned by 40% in recent decades in late summer to early fall and decreased in extent by 10-15% since the 1950s in spring and summer.
Coral reef bleaching	Attributable to warmer water temperatures, the bleaching of coral reefs has increased in frequency.

Source: *Climate Change 2001: Synthesis Report,* Intergovernmental Panel on Climate Change.

The Science Behind Global Warming

The earth's surface temperature would remain constant if the rate at which the earth absorbs energy from the sun (235 watts per square meter of the earth's surface) were equal to the rate at which the earth radiates energy back into space. The gradual warming of the earth's surface in the 20th century must therefore reflect an increase in the radiation that the earth receives from the sun or a decrease in the radiation of energy from the earth.

Solar radiation is subject to fluctuation. During the relatively short period over which global warming has occurred, the most important of these variations is associated with increases and decreases in the number of sunspots, a phenomenon that follows an 11-year cycle. The variation in solar radiation reaching the earth as a result of these cycles is roughly 0.1%, which is thought to be enough to change the earth's temperature by roughly 0.2 degrees Centigrade. While sunspot variation helps provide an explanation for periodic fluctuations in the earth's temperature, it cannot explain the secular increase in temperatures observed in the historical record.

Changes in the earth's radiation of energy into space offer a more plausible explanation of global warming. The radiation emitted by the sun and that emitted by the earth differ in frequency and wavelength. The hotter an object, the higher the frequency and shorter the wavelength of the radiation it emits. The sun, at 6,000 degrees Centigrade, emits radiation at wavelengths of zero to two micrometers, which is the spectrum of visible light. The earth, with an average surface temperature of 15 degrees Centigrade, emits radiation with much longer wavelengths, from zero to 40 micrometers, primarily in the infrared portion of the spectrum. For energy balance, therefore, the rate at which the planet loses energy as infrared radiation must equal the rate at which it receives solar energy in the form of sunlight.

Over the last 140 years, however, the earth's ability to reflect infrared radiation back into space has diminished. The gases that make up the earth's atmosphere are largely transparent to visible light. But certain atmospheric gases are not so transparent to infrared radiation. The so-called greenhouse gases — including water vapor, carbon dioxide, methane, nitrous oxide, oxygen and ozone — absorb most of the long-wavelength energy radiated by the earth. This absorption warms the atmosphere, which in turn radiates energy back to the earth as well as out to space. Because the greenhouse gases act as a thermal blanket around the globe, raising the earth's surface temperature, an increase in the atmospheric concentration of greenhouse gases will change the balance between energy received and energy lost.

This change in the balance between incoming solar radiation absorbed by the earth and its atmosphere, and outgoing energy radiated from the earth into space, is referred to as radiative forcing. An increase in radiative forcing contributes to rising surface temperatures. The relationship between radiative forcing and changes in surface temperature is referred to as the climate sensitivity parameter. Research by the U.S. National Academy of Sciences estimates that the climate sensitivity factor falls between 0.3 and 1.0 degrees Centigrade for every watt per square meter of radiative forcing.

Exhibit 17 presents four greenhouse gases — carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a category of carbon-based gases called halocarbons — whose atmospheric concentrations have increased significantly over the last two centuries. The second column of the chart shows the increase in atmospheric concentration of these gases over this period, measured volumetrically in parts per million (ppm) or per billion (ppb). The third column shows the increase in radiative forcing, measured in watts per square meter of the earth's surface, attributable to the increased atmospheric concentration of the gas.

Exhibit 17 **Change in Atmospheric Concentrations of Greenhouse Gases and Associated Radiative Forcing**

	Atmospheric Concentration			Radiative Forcing	
	Pre-Industrial	2000	Pct. Change	W/m^2	Pct. of Total
Carbon Dioxide (CO_2)	280 ppm	368 ppm	31%	1.56	64%
Methane (CH_4)	700 ppb	1,750 ppb	127	0.47	19
Halocarbons	na	na	-	0.28	11
Nitrous Oxide (N_20)	270 ppb	316 ppb	17	0.14	6
Total				2.45	100%

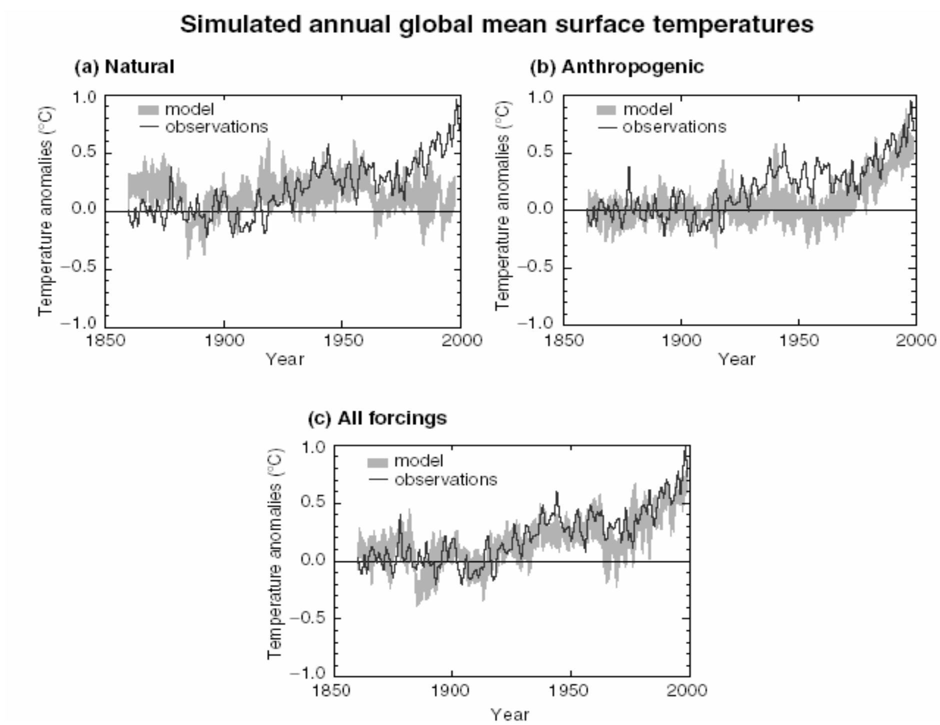
Source: *Climate Change 2001: Synthesis Report,* Intergovernmental Panel on Climate Change; *Introduction to Environmental Science*, Gilbert M. Masters.

(Measures of the atmospheric concentration of greenhouse gases in pre-industrial times are derived from the analysis of air bubbles sealed in the ice caps of Antarctica and Greenland. Much like tree rings, variations in ice density resulting from seasonal snowfall patterns allow scientists to date any given point in the ice. Temperature inference is usually accomplished by comparing the ratio of two different isotopes of oxygen whose uptake in evaporation, and therefore concentration in precipitation and thus in the ice itself, is sensitive to temperature. Ice cores can thus provide an atmospheric record for the last 160,000 years. The cores show a remarkable correlation between surface temperatures and atmospheric concentrations of CO_2 and CH_4. During glacial periods, atmospheric concentrations of CO_2 and CH_4 were low, while during the warmer interglacial periods, they were high. The variation in surface temperature over these intervals is estimated at 6 degrees Centigrade.)

The 30% increase in atmospheric concentrations of CO_2 since pre-industrial times is associated primarily with the massively increased use of carbon-containing fuels in the 20th century, particularly coal for power generation, petroleum for transportation and natural gas for heating. In the latter decades of the century, deforestation has also contributed significantly to CO_2 emissions. While rising atmospheric concentrations of CO_2 are responsible for more than 60% of the radiative forcing over the last 150 years, methane, halocarbons and nitrous oxide have also made significant contributions and, on a molecule-for-molecule basis, are much more potent greenhouse gases than carbon dioxide. Methane is produced by bacterial fermentation in anaerobic conditions, such as occur in swamps, marshes, rice paddies, landfills, and the digestive tracts of cattle and sheep. It is also released during the production, transportation and consumption of fossil fuels, particularly natural gas, which is largely methane. The doubling of methane concentrations since pre-industrial times, which has contributed almost one-fifth of the radiative forcing over the period, is in large part the result of human food production, reflecting larger herds of livestock and increased cultivation of rice, as well as the increased use of fossil fuels. Increased atmospheric concentrations of nitrous oxide are also related to rising food production. Newly cleared forest land that is converted to grassland produces significant N_2O emissions for a number of years, and nitrogen fertilizers on cropland provide additional releases. Finally, halocarbons were widely used for much of the 20th century as refrigerants in refrigerators, freezers and air conditioners. Their use has been significantly restricted, however, by the 1987 Montreal Protocol and subsequent changes to the Clean Air Act.

The best explanations of global temperature variations over the last 140 years combine the effects of natural factors, such as sunspot cycles and the cooling effects of volcanic eruptions, with the effects of anthropogenic emissions of greenhouse gases. Exhibit 18 compares the historical temperature record with the results of a climate simulation model when the model outputs reflect (a) natural factors only, (b) anthropogenic greenhouse gas emissions only, and (c) both natural and anthropogenic factors. The fit between the model's predictions and historical results is relatively close when both natural and anthropogenic factors are considered. The successful back-testing of climate simulation models against the historical temperature record gives scientists hope that such models can provide useful, if rough, estimates of likely future climate changes in different emissions scenarios.

Exhibit 18 **Climate Model Simulations of Global Temperature Changes Compared to Measured Changes: Examples of Simulations Based on Natural, Anthropogenic, and Combined Natural and Anthropogenic Forces**



Source: *Climate Change 2001: Synthesis Report,* Intergovernmental Panel on Climate Change.

The Future Course and Consequences of Global Warming

Reflecting their relationship with industrial and agricultural activity, atmospheric emissions of greenhouse gases are expected to increase in the 21st century with population and economic growth. The Intergovernmental Panel on Climate Change (IPCC), an international grouping of climate scientists operating under the auspices of the World Meteorological Organization and United Nations Environmental Program, has prepared a series of forecasts for emissions levels in the 21st century based on various scenarios for population growth and economic development (see *Climate Change 2001: The Scientific Basis*, published by the Cambridge University Press and available on the web at www.grida.no/climate/ipcc_tar/). Atmospheric concentrations of CO_2, having risen from 280 ppm in pre-industrial times to 370 ppm in 2000, are projected to increase to a range of 540-970 ppm by the end of the century. As a result, global average surface temperature is projected to increase by 1.4-5.8 degrees Centigrade. This compares with an observed increase in global average temperature of 0.6 degrees Centigrade over the last 140 years, and an estimated variation in temperature of 6.0 degrees Centigrade between glacial and interglacial periods.

While it is possible to estimate future rates of greenhouse gas emissions, the resulting atmospheric concentrations of greenhouse gases and the associated radiative forcing, much less certain is the likely impact of these trends on global temperature and climate. This is primarily due to the many feedback effects, both positive and negative, that complicate climate forecasts. (For example, a warmer atmosphere can contain more water vapor, a greenhouse gas; but increased cloud cover may reflect more sunlight back into space). Expert opinion, however, is that it is very likely (implying 90-99% probability, in the terminology of the Intergovernmental Panel on Climate Change) that increased atmospheric concentrations of greenhouse gases over the 21st century will contribute to higher minimum and maximum temperatures over nearly all land areas, a reduced diurnal temperature range over most land areas, and more intense rainfall and snowfall. It is deemed likely (66-90% probability) by the IPCC that higher atmospheric concentrations of greenhouse gases will contribute to more intense summer continental drying, and thus increased risk of drought, over most mid-latitude continental interiors, as well as to increased variation in Asian summer monsoon precipitation. In some areas, increases in tropical cyclone wind speeds and precipitation intensities are deemed likely (see Exhibit 19). Finally, global mean sea level is projected to rise by 0.09-0.88 meters between 1990 and 2100, due primarily to the thermal expansion of sea water and loss of mass from glaciers and ice caps.

Exhibit 19 **Intergovernmental Panel on Climate Change Estimates of Climatic Impact of Global Warming**

Expected Climate Changes in the 21st Century	Confidence in Projected Changes
Higher maximum temperatures and more hot days.	Very likely (90-99% chance) over nearly all land areas.
Higher minimum temperatures, fewer colder days and frost days over nearly all land areas.	Very likely (90-99% chance) over nearly all land areas.
Reduced diurnal temperature range over most land areas.	Very likely (90-99% chance) over nearly most land areas.
More intense rainfall and snowfall.	Very likely (90-99% chance).
Increased summer continental drying and associated risk of drought.	Likely (66-90% chance) over most mid-latitude continental interiors.
Increase in tropical cyclone peak wind intensities.	Likely (66-90% chance) over some land areas.
Increase in tropical cyclone peak mean and peak precipitation intensities.	Likely (66-90% chance) over some land areas.

Source: *Climate Change 2001: Synthesis Report*, Intergovernmental Panel on Climate Change.

While the probability of the climate effects described in Exhibit 19 is relatively high, in the opinion of the climatologists of the IPCC, the effects themselves would not appear to have catastrophic consequences. Much more difficult to predict, but potentially much more serious in its effect, is the potential impact of global warming on ocean currents. Scientists believe that an important stabilizing effect on the global climate is exercised by a huge, cyclical flow of ocean water, known as the thermohaline current, that flows from the Pacific through the Indian Ocean to the North Atlantic. The thermohaline current begins as a warm current flowing near the surface in the Pacific and Indian Oceans. As this current reaches the northern latitudes of the Atlantic, it gradually cools and releases its heat to the atmosphere, warming the continent of Europe. At this point the current sinks and begins its return through the Indian Ocean to the Pacific. The driver of this global current is the thermohaline effect: the tendency of the warm surface stream to grow denser, and therefore sink, as the gradual loss of heat to the atmosphere causes it to grow cooler and evaporation increases its salinity. The cycle reverses as the cooler, saltier stream descends in the North Atlantic and flows back to the Indian and Pacific Oceans, where — as it gradually becomes warmer and relatively less saline — it rises again, to repeat the cycle.

Historical climatological evidence indicates that the thermohaline current was interrupted some 11,000 years ago by glacial meltwater draining from the North American ice sheet into the North Atlantic. This influx of sweet water to the North Atlantic reduced the salinity of the surface waters enough to halt their normal descent, interrupting the global thermohaline circulation. Europe thus lost the warming effect of the current and glacial conditions suddenly returned: The temperature in Greenland dropped by 6.0 degrees Centigrade in 100 years and stayed that way for 1,000 years.

It is feared, therefore, that the relatively benign direct effects of global warming, such as the loss of ice and snow cover due to rising average temperatures, could trigger indirect effects whose consequences could be catastrophic.