Predictability in Science: Accuracy and Limitations
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UNCERTAINTIES IN CLIMATE CHANGE SCIENCE

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This presentation is about predictability in climate change science. Towards the end of the 19th century, Svante Arrhenius recognized that carbon dioxide was going to accumulate in our atmosphere as a consequence of human activities, and furthermore, that it was going to cause a temperature increase at the surface of about 4 to 5°C, assuming that the concentration would double, a prediction that is remarkably close to what we think today. Earlier in the 19th century, the British scientist Tyndall already knew that the atmosphere would have a heat-trapping effect, and he carried out experiments to measure the infrared absorptivity of clean air. He was disappointed: clean air does not absorb infrared radiation. He later realized that carbon dioxide and water vapor do absorb efficiently this radiation, and that these gases are trace components of the atmosphere; as we now know, these are the most important greenhouse gases. However, the real pioneer was in fact Joseph Fourier, the French mathematician, who had concluded earlier that the amount of energy received from the Sun by the planets, and specifically the Earth as well, equals the amount of energy lost to space (Figure 1, see page 257). This energy emitted by the planets was called 'dark heat', *Chaleur Obscure* (infrared light had not yet been discovered). He did not know that the atmosphere would absorb this dark heat, and thus concluded that the surface of the Earth should be much colder than it actually is. We now know that without an atmosphere the temperature at the surface of the Earth would be about -18°C, and thus the oceans would be frozen. But the atmosphere plays a fundamental role as a warming blanket, and the average surface temperature is instead +15°C.

Carbon dioxide is the main greenhouse gas affected by human activities. It is biologically active; Figure 2 shows how it changes as a function of time and latitude, which is commonly called the pulse of the planet. In the winter its concentration increases due to respiration and in the summer

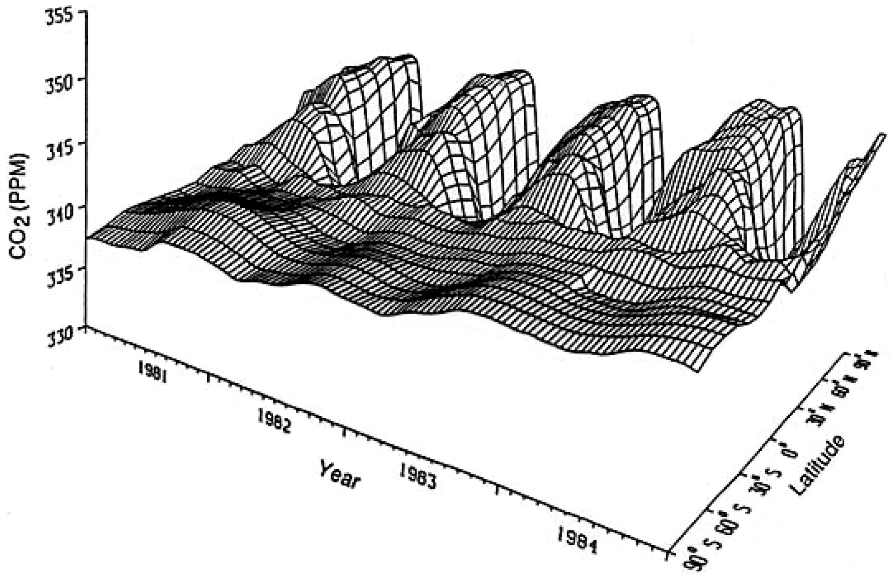


Figure 2.

photosynthesis is at work, absorbing carbon dioxide from the atmosphere. Thus, there is a balance that has been sustained for hundreds of thousands of years. Figure 2 also shows that the oscillations are more pronounced in the northern hemisphere, because of the topology of our planet: most of the continental mass is in the north. Figure 3 shows very clearly that the overall amount is increasing, because human activities are perturbing the balance of respiration and photosynthesis, as pointed out by Arrhenius.

Next, I will mention some results from a report by the Intergovernmental Panel on Climate Change (IPCC), an international group of scientists covering many different disciplines all having to do with climate. The last report (the third assessment report) was released in 2001, and a new one is going to be released in February 2007. There is no doubt that the chemical composition of the atmosphere is changing as a consequence of human activities, as shown in Figure 4 (page 79). Figure 5 (see page 258) shows the temperature change on a millennium time scale; this figure is the so-called hockey stick curve. The red lines represent an average of direct measurements of temperature, and the blue lines represent temperature inferred indirectly from other measurements such as the width of tree rings, coral reefs, etc., as

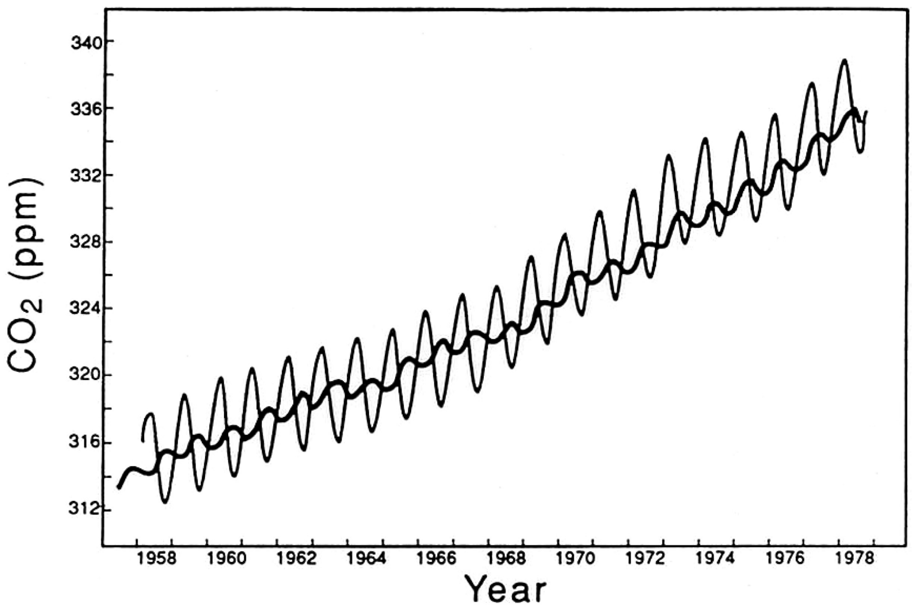


Figure 3.

there were no thermometers a thousand years ago. The important question addressed by the IPCC is the connection between temperature and composition changes: the curves have a similar shape. The conclusion is that there is indeed a connection. One way is to establish this connection is through atmospheric models: Figure 6 (see page 259) shows the results of a model simulation without taking into account the changes in the chemical composition as well as taking into account these changes. Accepting the connection makes it possible to make predictions of what will happen in this century, which depends on what society.

Figure 7 (see page 260) shows that 2005 has been the warmest year so far in the last 1000 years. The figure also shows that the temperature change in the tropics is smaller than in the poles. How has the climate changed on a geological time scale? We can go back half a million years, as shown in Figure 8 (see page 261); it is quite interesting that one can infer the composition of the atmosphere for such a long period of time by measuring the composition of air bubbles trapped in ice cores, and that one can also infer the temperature by measuring the isotopic oxygen concentration in the same ice cores. The oscillations in the figure indicate ice ages and

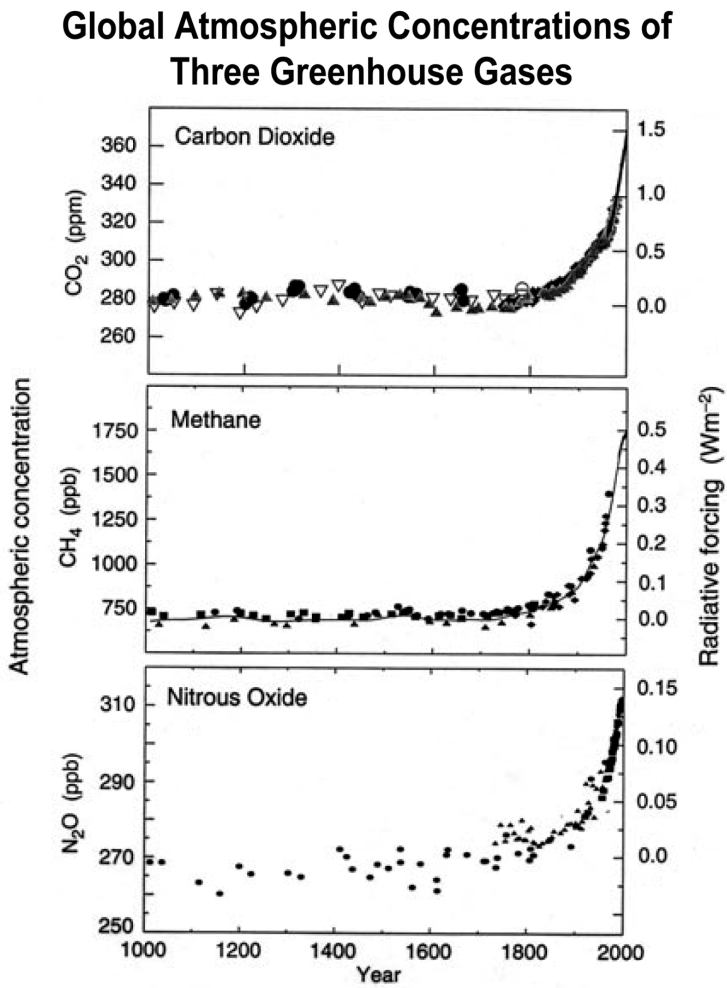


Figure 4.

interglacial ages. They are reasonably well understood: the explanation is given by the Milankovich theory, namely that the periodic temperature variations are a consequence of changes in the orbital parameters of the Earth, such as the tilt of the rotation axis and the eccentricity of the orbit, which change with periodicities of about 10,000, 40,000 and 100,000 years. Based on this understanding we can predict that we should have a reasonably stable climate period for the next thousand years. What we observe instead is a temperature spike taking place in just a few decades, well correlated with a similar spike in the concentration of carbon dioxide and other greenhouse gases. It is possible to carry out a statistical analysis and to estimate the probability that the recent global temperature change is a natural event versus an event connected with changes in the chemical composition of the atmosphere; the results indicate that there is about a 90% probability that the change is indeed related to human activities.

Observations indicate that the Earth's climate is clearly changing. For example, Glacier National Park (Figure 9, see page 261) will have to change its name relatively soon, as there will be no more glaciers in that Park. Yet another example is ice melting in Greenland (Figure 10, see page 262). If all of the ice over Greenland were to melt, sea level would rise about 6 meters. We have seen in recent years increased damage from intense hurricanes, such as Katrina (Figure 11, see page 262), or Wilma. Does this change have anything to do with climate change? Figure 12 (see page 263) shows the results of an analysis carried out by my colleague at MIT, Kerry Emanuel, indicating that the power of hurricanes is extremely sensitive to the surface temperature of the oceans, which has increased recently. It is not possible to establish that Katrina is necessarily a consequence of climate change, but one concludes, however, that statistically the strength of the hurricanes has increased as a consequence of human activities.

There is a now a consensus among scientists and climate experts that it would be very risky to have a temperature change of more than about 2°C or 2.5°C. To minimize this possibility it is necessary to stabilize the emissions of the greenhouse gases. The Stern Review released very recently involves mainly the economics of climate change, but it also summarizes the uncertainties. Depending on the levels of carbon dioxide that we end up having in the atmosphere, there is a 5 to 95% probability that the temperature will change by the amount indicated in Figure 13 (see page 263). So it is going to be quite difficult not to have a temperature change smaller than 2°C, which would require stabilizing carbon dioxide levels below about 550 ppm. If we do nothing, the 'business as usual' scenario, it is quite possible for the temperature to increase by more than 5°C, a change which begins to be comparable to the mean temperature difference between an ice age and an interglacial age.

In terms of climate change it turns out that it not only matters if carbon dioxide and methane atmospheric levels increase. Air pollution also matters, such as that induced by forest fires and transportation activities in cities. Figure 14 (see page 264) shows a satellite picture of fires in California, and Figure 16 shows savannah fires in West Africa; so we are burning large amounts of biomass in our planet. There is also a brown cloud, shown in Figure 15 (see page 264), described earlier by Professor Ramanathan. Figure 16 (see page 265), taken from the IPCC report, shows the relative contributions from different sources to climate change: first of all, the solar contribution is quantifiable and it is relatively small. The greenhouse gases, mainly carbon dioxide and methane, are the main contributors, but pollution of the type generated over large cities also contributes. The net effect of particles is actually quite complicated, but black carbon has a strong positive effect adding to global warming, as shown in Figure 17 (see page 265), taken from Jim Hansen.

Figure 18 (see page 266) compares the various sources of greenhouse gas emissions. Energy emissions are the largest, but there are also emissions from land use changes and agriculture. There is a way to reduce the energy-related emissions, as explained in Figure 19 (see page 266), taken from my colleagues Rob Socolow and Steve Pacala. The figure shows business as usual emissions going up relatively fast. In order to stabilize the atmospheric levels of greenhouse gases around 550 ppm the emissions have to be significantly reduced, and the figure shows schematically that a number of actions need to be implemented; no single action will do the job. The various actions that are needed are represented in the figure by 'wedges'. For example, more efficient buildings may be a little wedge; improved fuel economy and even nuclear energy are represented by other wedges, but cannot by themselves solve the problem. Another important wedge is carbon capture: instead of emitting to the atmosphere carbon dioxide from power plants, it can be pumped into oil wells or other cavities underneath the Earth's surface, so that it does not escape to the atmosphere. According to the Stern Review the cost of implementing these wedges is of the order of 1% of the global GDP, because the technologies required to address the problem in the next few decades are already available. However, it is very important to develop new technologies so that increasing amounts of energy are available in the future with reduced environmental impacts.

A major problem is that from the point of view of the developing nations, particularly India and China, it will be difficult to reduce emissions because their economies need to grow and this growth has traditionally been tied to an increase in energy consumption. For this reason it is essential for the developed countries to cut emissions to allow for some increase in the developing nations. However, even developing nations have to work

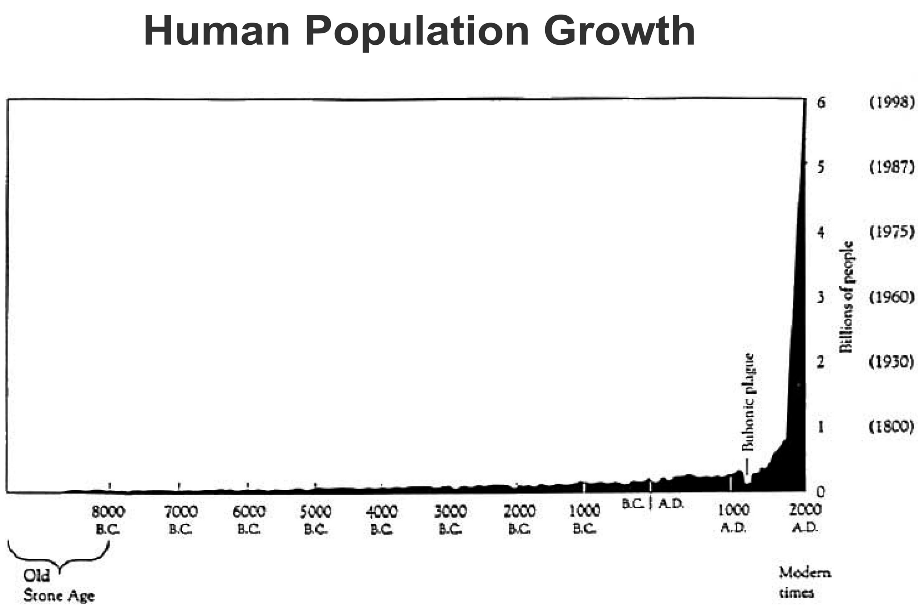


Figure 21.

very hard with energy conservation and with the implementation of the wedges mentioned above in order not to increase their emissions at the current rates (Figure 20, see page 267).

To finish, Figure 21 shows how the population of the planet has grown in the past few millennia. The current population is over 6 billion people. About one fourth of this population resides in the developed countries, which so far have been responsible for most of the pollution of the planet. The remaining three fourths have the right do develop their economies, striving to reach a standard of living comparable to that in the developed nations. The problem is, however, that the planet does not have sufficient natural resources and capacity to clean pollution from human activities to sustain such an economic growth if it takes place in the same manner as it took place in the past. Thus, it is imperative for developed and developing countries to work together to find new ways to achieve high standards of living in harmony with the environment.


The Earth's Greenhouse Effect
SUN
About half the solar energy absorbed at the surface evaporates water, adding the most important greenhouse gas to the atmosphere. When this water condenses in the atmosphere, it releases the energy that powers storms and produces rain and snow.
About 30% of incoming solar energy is reflected by the surface and the atmosphere.
SPACE
Only a small amount of the heat energy emitted from the surface passes through the atmosphere directly to space. Most is absorbed by greenhouse gas molecules and contributes to the energy radiated back down to warm the surface and lower atmosphere. Increasing the concentrations of greenhouse gases increases the warming of the surface and slows loss of energy to space.
ATMOSPHERE
SURFACE
The surface cools by radiating heat energy upward. The warmer the surface, the greater the amount of heat energy that is radiated upward.

Figure 1.

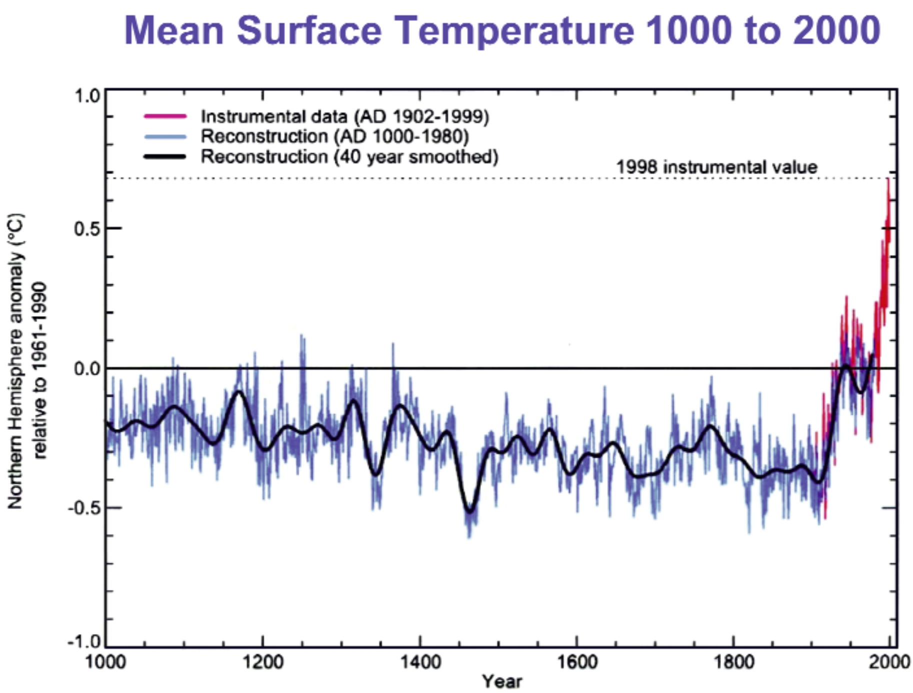

Mean Surface Temperature 1000 to 2000
Instrumental data (AD 1902-1999)
Reconstruction (AD 1000-1980)
Reconstruction (40 year smoothed)
1998 instrumental value
Northern Hemisphere anomaly (°C) relative to 1961-1990
1.0
0.5
0.0
-0.5
-1.0
1000
1200
1400
1600
1800
2000
Year

Figure 5.

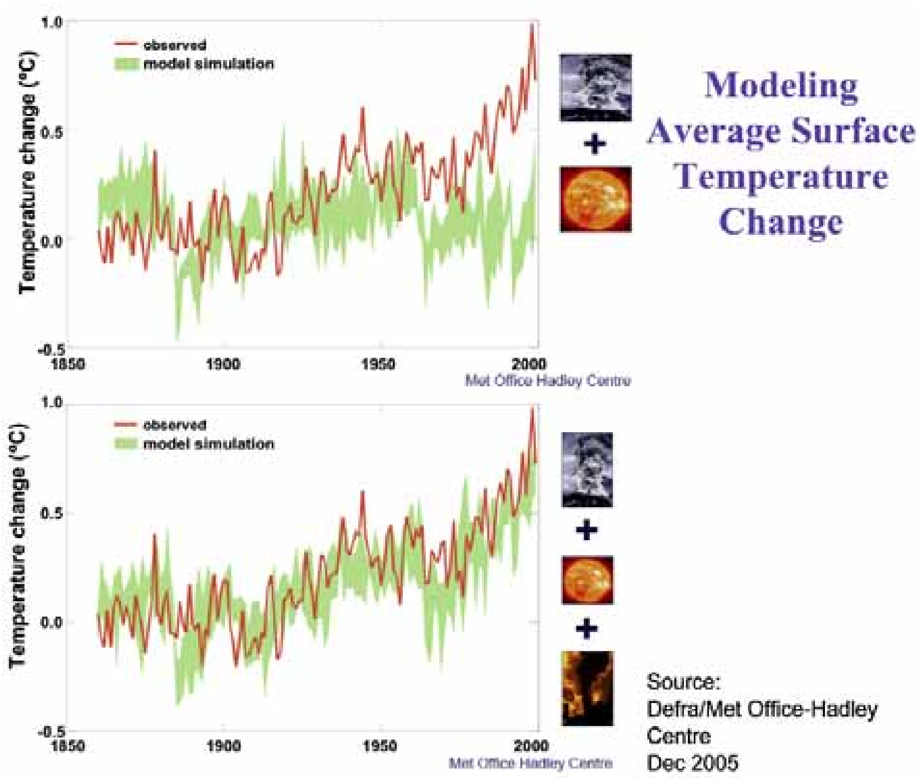

Modeling
Average Surface
Temperature
Change
observed
model simulation
Temperature change (ºC)
1.0
0.5
0.0
-0.5
1850
1900
1950
2000
Met Office Hadley Centre
Source:
Defra/Met Office-Hadley
Centre
Dec 2005

Figure 6.

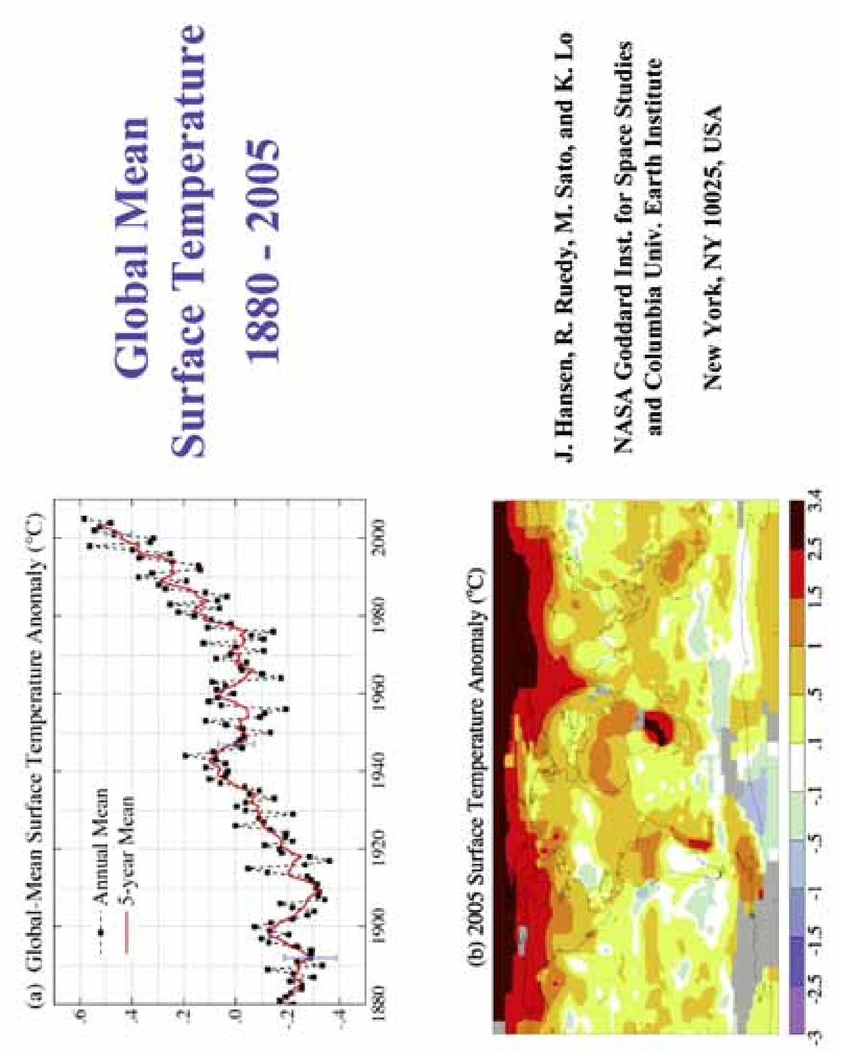

(a) Global-Mean Surface Temperature Anomaly (°C)
Annual Mean
5-year Mean
.6
.4
.2
.0
-.2
-.4
1880
1900
1920
1940
1960
1980
2000
Global Mean
Surface Temperature
1880 - 2005
(b) 2005 Surface Temperature Anomaly (°C)
-3
-2.5
-1.5
-1
-.5
-.1
.1
.5
1
1.5
2.5
3.4
J. Hansen, R. Ruedy, M. Sato, and K. Lo
NASA Goddard Inst. for Space Studies
and Columbia Univ. Earth Institute
New York, NY 10025, USA

Figure 7.

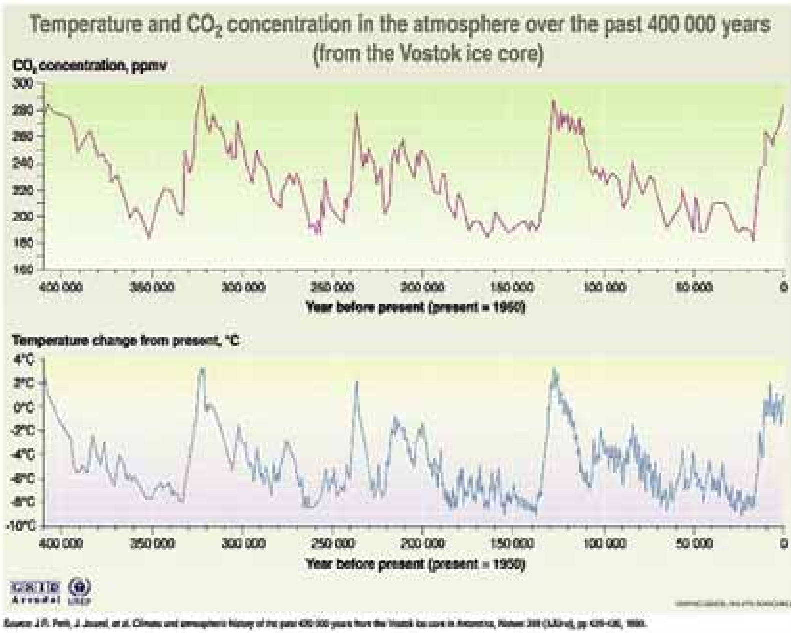


Figure 8.

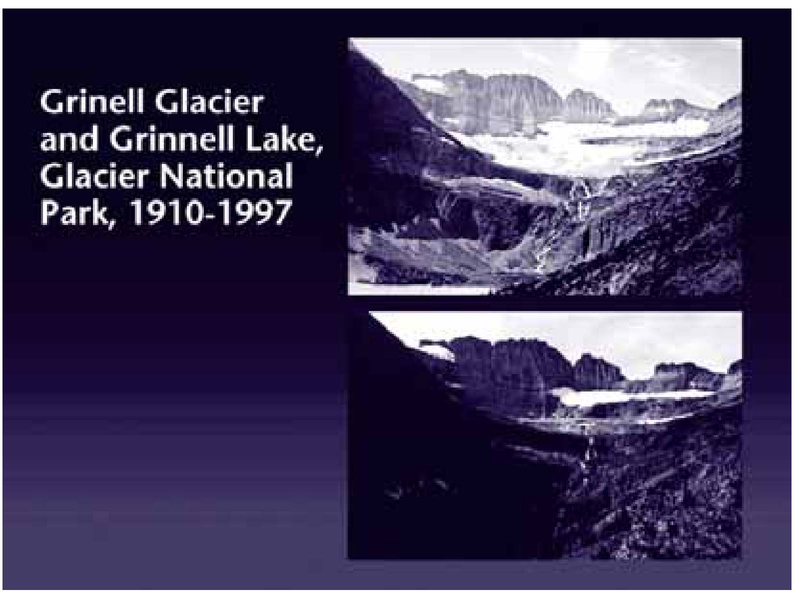


Figure 9.

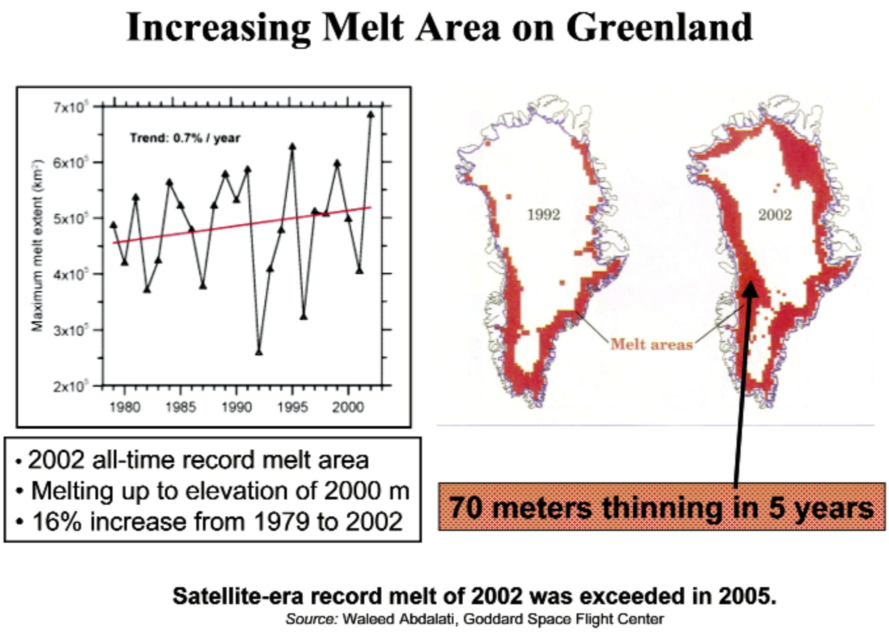


Figure 10.

Figure 11.

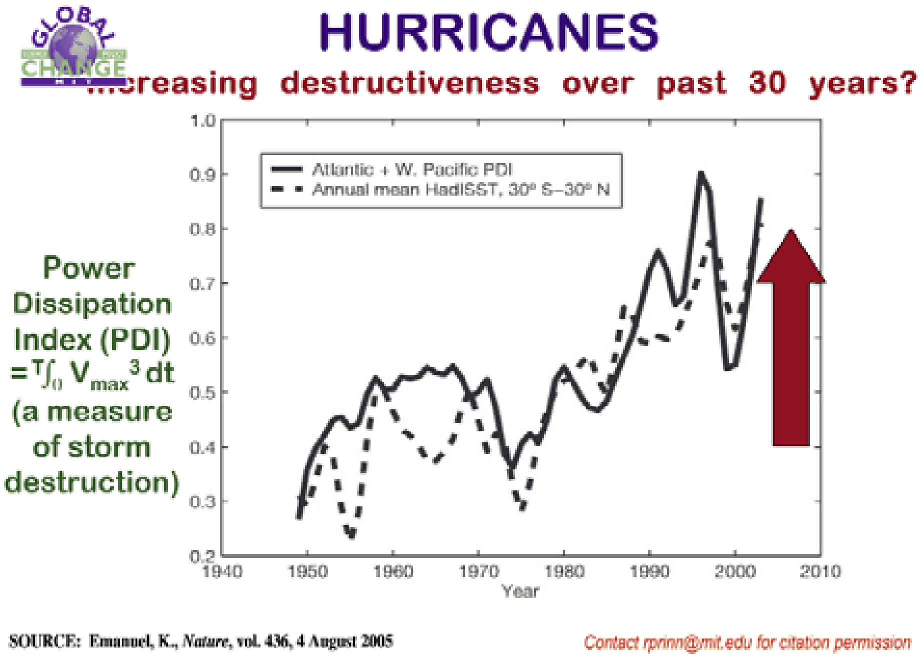


Figure 12.

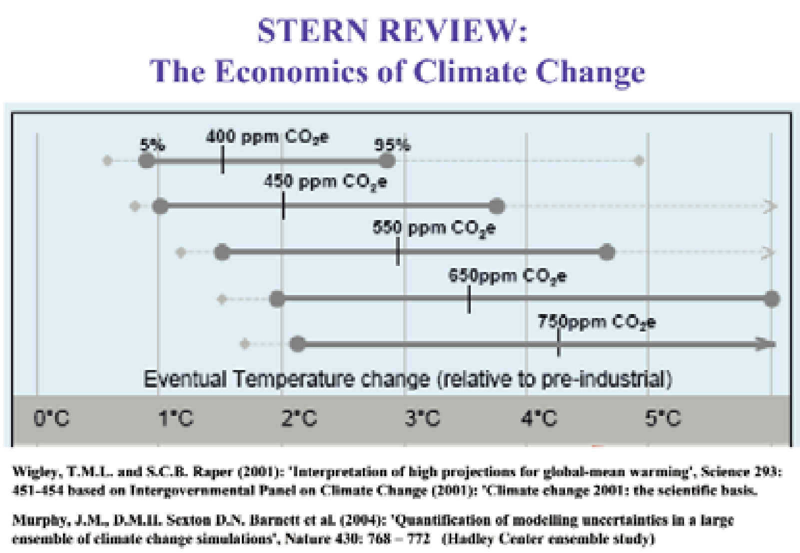
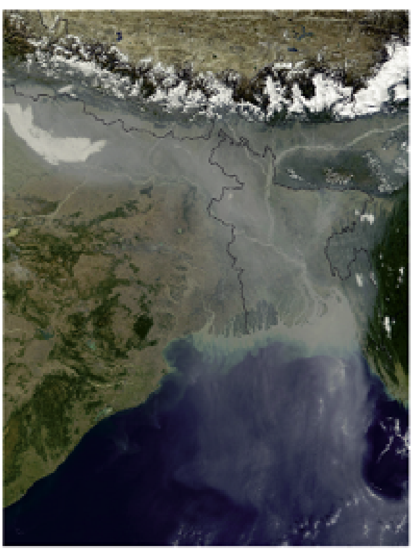


Figure 13.

Satellite photo of smoke from S California wildfires, October 2003

Figure 14.

Outflow of Aerosol, Northern India



The skies over Northern India are filled with aerosol particles all along the southern edge of the Himalayan Mountains, and streaming southward over Bangladesh and the Bay of Bengal.

Figure 15.

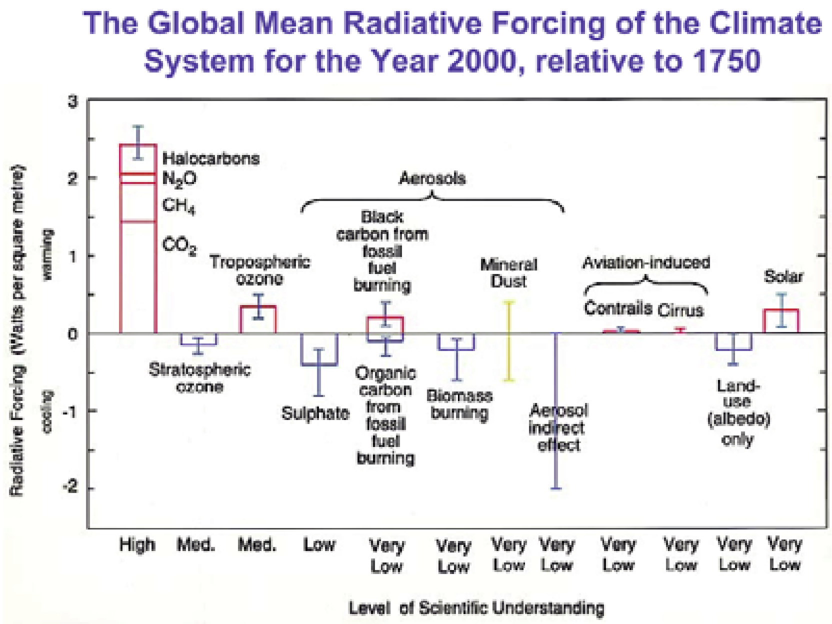


Figure 16.

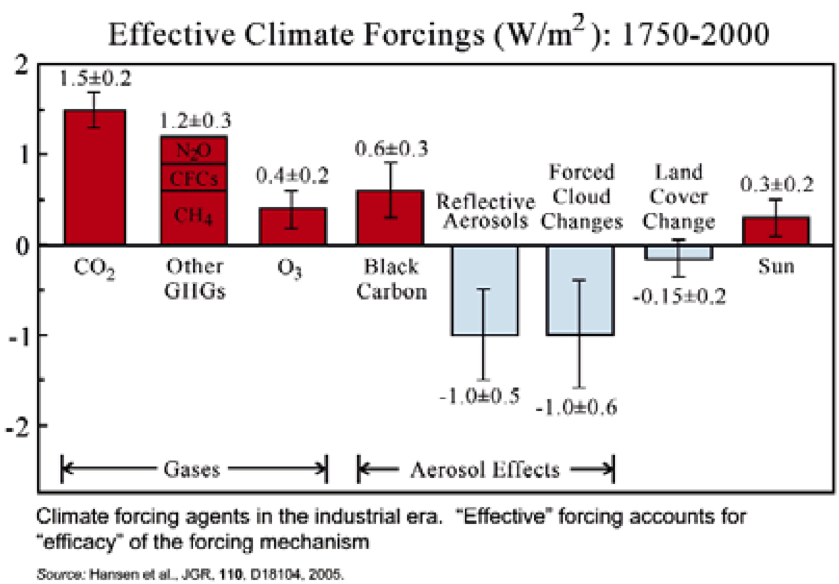


Figure 17.

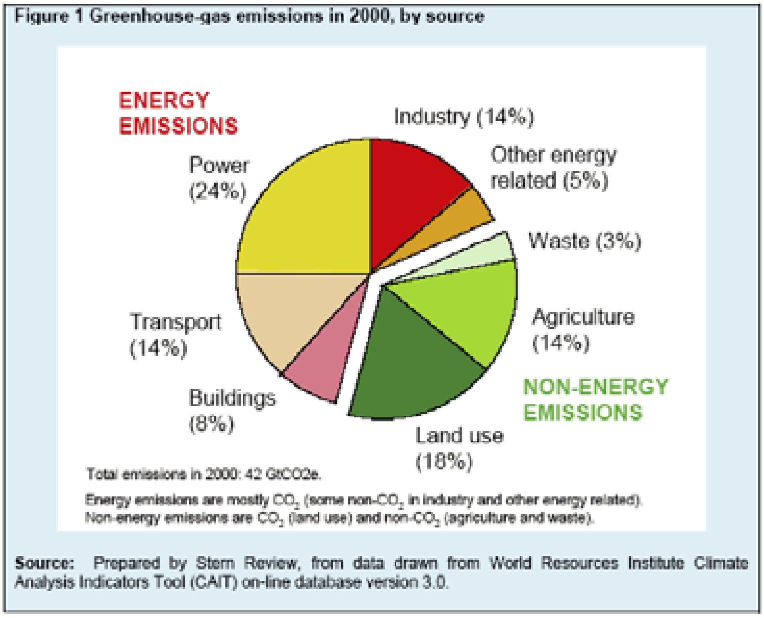


Figure 18.

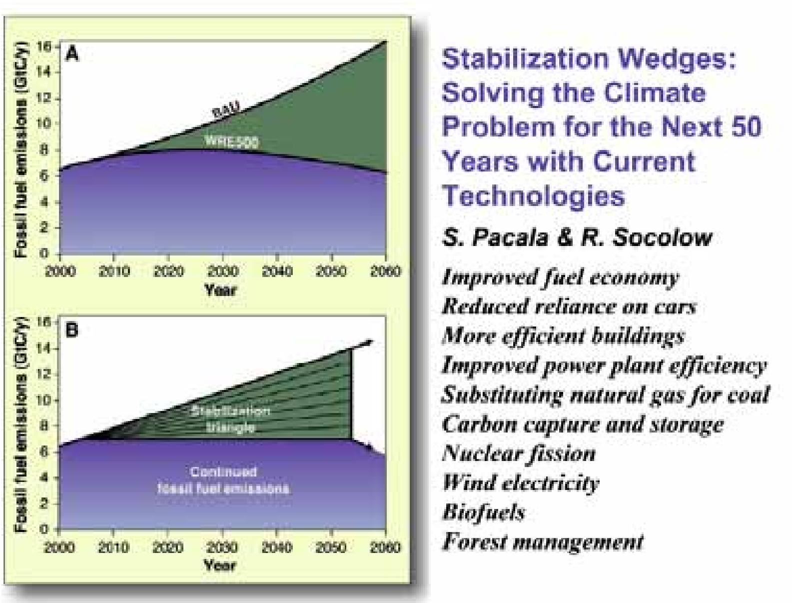


Figure 19.

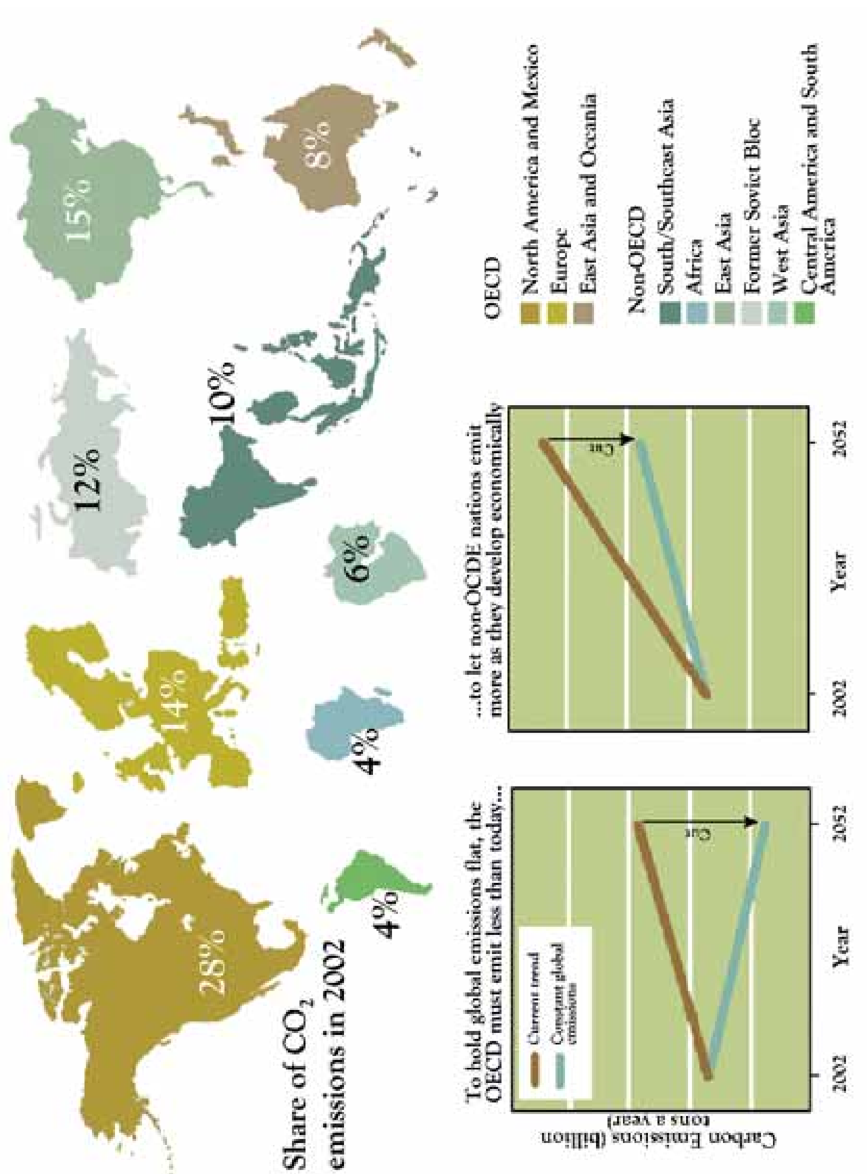

Share of CO_2 emissions in 2002
28%
4%
14%
4%
12%
6%
10%
15%
8%
OECD
North America and Mexico
Europe
East Asia and Oceania
Non-OECD
South/Southeast Asia
Africa
East Asia
Former Soviet Bloc
West Asia
Central America and South America
To hold global emissions flat, the OECD must emit less than today...
...to let non-OCDE nations emit more as they develop economically
Carbon Emissions (billion tons a year)
Current trend
Constant global emissions
Cut
Year
2002
2052

Figure 20.