Chapter 4

How Warm? How Fast? Scientific Consensus and Debate

Where Lies Scientific Consensus? Where Uncertainty?

Journalists need facts. Editors and fact-checkers are constantly working to prove wrong something that a poor, overworked reporter has written (and it is a tribute to reporters that they succeed so rarely).

Understandably, reporters do not like uncertainty. In their search for absolute truth, journalists often run to scientists in a belief that scientists have the final answers.

But scientists, and particularly the most responsible scientists, are rarely certain of anything in an absolute and final sense. Virtually all scientific assumptions or theories are subject to further testing and confirmation — and it is this skepticism which has allowed modern science to make such progress. It is axiomatic that the final conclusion of any scientific study is that more scientific study is needed.

Journalists might do well to go to scientists for skepticism as well as for certainty.

In the arenas of politics and public policy debate, scientific uncertainty can be a two-edged sword. Each side in a debate can use scientific uncertainty to discredit the opposing view, or to support its own. This goes on in many fields of policy debate, and nowhere more often than in discussions of environmental and health issues. So often, reporters hear environmentalists say a chemical should be taken off the market if it can not be proven "safe." Just as often, reporters hear manufacturers of the same chemical say, in effect, that justice requires that it be demonstrated to be unsafe before their economic livelihood is taken away. So much depends not on the certainty of the answer, but rather on what question is asked, the way it is asked, and on which side bears the burden of proof.

It is no different with global warming. It sheds little light on the subject to ask whether scientists are certain about global warming or the greenhouse effect. Those questions are too broad and too hazy to mean much.

Are scientists certain that natural greenhouse warming is a real effect? The answer is: "Yes, there is strong scientific consensus on that one."

Are scientists certain of how much human-induced change to the atmosphere will cause how much warming over what period of time? The answers to those questions are: "No."

For a reporter thinking about global warming, it is most useful to do what scientists themselves have done — divide the many scientific issues into groups according to how strong the scientific certainty is on any particular question.

The area of strongest scientific consensus involves the basic physics which govern the greenhouse effect, such as the radiative properties of gases discussed in the previous chapter. A strong consensus among scientists — generally shared even by those scientists seen as being at odds on other greenhouse issues — holds basic greenhouse physics as a matter of fact. This is the area where it is often easiest to measure things, quantify them, and even prove them in the laboratory.

Ranges of Responsible Consensus, Debate

What matters more from the perspective of humans is not the greenhouse gases themselves, but the climate change that scientists believe will eventually come if humans continue indefinitely to increase greenhouse gas concentrations.

But climate prediction and details of greenhouse effect, timing, and scope are by no means an exact science — any more than weather prediction is. Will sea levels rise? By how much? Where? When? Will the regional incidence and severity of storms increase? By how much? How soon? Which regions? How will marine and terrestrial ecosystems respond? How will precipitation be affected? Where?

The questions abound, and easy answers often are impossible. Nonetheless climatologists (and weather forecasters) are constantly being asked to give their “best estimate” by people to whom the answers matter very much: farmers, builders, shippers, pilots, power companies, and, of course, journalists and policymakers. For people whose livelihoods and even lives are at stake, an informed, though admittedly imprecise, prediction or forecast may be better than no prediction at all. After all, we don’t stop checking the weather forecasts just because we know that they are not always right.

The climate system is enormous and complex. Heat, air, and moisture circulate worldwide, and only a worldwide view of the climate system is adequate to understand it. The physical bigness of the climate system tends to dwarf not only human understanding, but also the abilities of the largest and fastest computers built so far.

Moreover, the climate system, understood properly, consists of many more things than weather. Climate is a matter of much more than wind and clouds, rain and snow. That is only the beginning.

Climate involves just about all earth sciences. Changes in Earth’s orbital mechanics, for example, play a big role in influencing climate.

Changes in the thermonuclear processes inside the sun are also central to Earth's climate system, which is driven by the sun's energy. The vast oceans and polar icecaps are even more of a variable in climate prediction than they are in weather prediction — and much more of a scientific mystery than the weather that occurs in the atmosphere itself. Earth's living things and geological processes play central roles in setting and changing climate, although on long time scales we are not used to thinking about.

To arrive at most authoritative estimates, climatologists are used to relying on computer models, which in turn rely on scientists' knowledge of the natural world. Strengths and limits of what these models can tell us are discussed in Chapter 7.

At the outset, however, it is worth remembering that these models give us something short of precise "predictions" of what to expect over narrow time frames. Rather, they allow scientists to test "what if" propositions based on available knowledge of how climate works, and to come up with some idea of which outcomes are within the range of possibility. Computer models of climate change are large and complex enough to challenge the best available supercomputers. Still, the climate system itself is tremendously more complex than the models. Because the models greatly simplify reality, they remain a somewhat crude tool.

One simplification that is often used in modeling climate change is the starting assumption that, for the future climate being simulated, the carbon dioxide concentration in the atmosphere has doubled over its pre-industrial values.

This is not a far-fetched assumption, if we remember that CO_2 has already increased by more than 30 percent in the industrial age. Actually, the combination of CO_2 and other greenhouse gases will bring about radiative forcing equivalent to a doubling of CO_2 well before CO_2 itself doubles. For CO_2 alone, the IPCC estimates a doubling (from about 280 ppmv before the industrial era) before the end of the 21st century.

Many climate change computer models start by doubling the CO_2 forcing abruptly. Modelers then watch the model climate change in response until it reaches a new equilibrium. These new climate conditions, and the amount of change from the previous equilibrium, are taken as an indication of how sensitive climate is to greenhouse forcing. Such analyses are often called "sensitivity" analyses. By noting the range of estimates given by different models under different conditions, scientists can get a sense of the range of possible or plausible outcomes. All this is instructive, because it tells us roughly how much climate change we could plausibly encounter.

We should remember, however, that such simulations aren't even trying to estimate how soon various levels of climate warming might come. Abruptly doubling greenhouse forcing is unrealistic, because in reality it would occur gradually. Moreover, there are important forces at work which will delay greenhouse warming such as the heat storage capacity of the ocean.

Other models try to simulate the warming-up process itself, with a realistic time scale, to estimate the timing of the so-called “transient” response of climate to greenhouse forcing. These models are more complex because they take more variables into account. Accounting for those variables means models include more uncertainties, so the results may be more uncertain. But for policy purposes it is important to make the effort to estimate how quickly climate could change.

Global Mean Precipitation Levels

All models studied by the IPCC in its 1990 *Scientific Assessment* report produced more precipitation in response to increases of greenhouse gases, and also more evaporation. These results held up in the 1995 IPCC Assessment even when aerosols (microscopic particles and droplets floating in the atmosphere) were cranked into the equation, although the increases were smaller.

The increased precipitation in the models fell in the high latitudes and the tropics throughout the year, and in the mid-latitudes during winter. The changes were small and indeterminate in the dry subtropical regions, but a little rainfall means a lot in those regions. The models differ considerably in the changes they depict on sub-continental scales, but most show more rain in the Southwest Asian monsoon.

Global Mean Sea Level Rise

Sea level rise — of a possibly cataclysmic scale — has been one of the most commonly featured highlights in media accounts of climate change. Scenarios of waves lapping at the steps of Washington’s monuments and of New York’s skyscrapers make great copy. Yet the size and speed of any potential sea level rise remain quite uncertain.

Any long-term climatic warming makes the level of the oceans rise. Two main mechanisms contribute: the melting of glaciers and icecaps, and the expansion of ocean water as it warms.

A few points are worth remembering. First, in quite recent Earth eras, sea levels have risen and fallen far more cataclysmically than our current worst-case scenarios anticipate. Since the end of the last ice age (after the time pre-Columbians arrived in the Americas), the oceans have probably risen by more than 300 feet (compared to a worst-case greenhouse scenario of less than 3 feet in the coming century). With the melting of the great continental ice sheets and the relative stabilization of climate in the current interglacial era, sea level rise appears to have slowed.

That's the good news. The bad news is that in the last few centuries human settlement and development along coastal areas have mushroomed. So small sea level rises will have much greater human impact — and human changes to the coastlines will probably magnify the ecological impact of sea level rise as well.

All the same, the oceans have probably been rising for the past 10,000 years or more. Anyone who predicts they will continue to rise stands a very good chance of being right.

It should be sobering to a journalist planning to report the imminent flooding of Miami to understand how much scientific uncertainty there is even about the current rate of sea level rise. We think we ought to be able to measure this directly with "modern" instruments like the tide gauge, but the more measurements scientists make, the more they are bothered by inconsistencies and errors. (As the ancient adage has it: A person with one watch knows what time it is; a person with two watches is never sure.) Future satellite-borne instruments may make measurements more precise. There are places in Scandinavia where the land is rising almost one hundred times faster than the sea (as the land rebounds from the weight of the melted ice sheet).

The IPCC scientists who reviewed the best sea level studies for the 1990 assessment would not even claim certainty that sea levels have been rising at all in the past 100 years. The best they could say was that it "is highly likely."

The 1995 IPCC Assessment spoke with greater confidence based on better analytic methods, which they said suggested "global mean sea level has risen 10-25 cm over the last 100 years." That's roughly 4-10 inches.

Another interesting 1995 IPCC Assessment finding: "There has been no detectable acceleration of sea level rise during this century. However, the average rise during the present [20th] century is significantly higher than the rate averaged over the last several thousand years... ."

Estimates of the *rate* of rise over the past century range from one-half to 3 millimeters a year, with most estimates in the range of 1.8 mm per year (about 0.07 inch per year).

It might be reasonable to take this as a "baseline" rate of sea level rise. It appears to have gone on at this slow rate for hundreds or thousands of years since the last ice age ended. There is some reason to think that much of this slow, steady rise is caused by interglacial warming.

As to whether putative human-induced climate changes are yet causing a speed-up in sea level rise, the IPCC scientists say evidence leaves them skeptical. “There is no convincing evidence of an acceleration in global sea level rise during the twentieth century,” they reported in 1990 (They stuck to that finding in 1995). “For longer periods, however, there is weak evidence for an acceleration over the last two to three centuries.”

Several things can tend to slow sea level rise. Among them are glaciers and icecaps. The amount of water they keep out of the oceans makes a big difference in sea level, and big ice sheets change very slowly on a scale of hundreds or thousands of years. The behavior of ice sheets is less well understood, and therefore less predictable, than many other parts of the climate system. The other source of time lag is the heat-storing capacity of the immense volume of water in the oceans. It takes hundreds or thousands of years for this big reservoir of cool water to warm up. All this makes the timing of any anthropogenic sea level rise rather uncertain.

The time lag can be both good news and bad news. The good news is that we have time to anticipate, plan, adapt, move to dry ground, build different structures, or even partially avert any human-induced sea level rise. The bad news is that we may already be committed to some appreciable sea level rise brought about by human activities. Even worse, our inability to see it yet may lull us into a false sense of comfort and keep us from taking needed action.

Doomsday scenarios in recent decades have been fueled by scientists’ speculation about the stability of the West Antarctic ice sheet. Most of the Antarctic icecap, thousands of feet thick, sits on solid ground that is above sea level. The West Antarctic sheet fills a kind of bay, sitting on ground well below sea level. Some fear this arrangement would make it melt and break up much faster than the bigger main ice sheet (grounded above sea level) in the event of climate warming, making sea levels rise not gradually but suddenly.

There is no special reason to think that this could not happen, nor any overwhelming reason to think that it will. But fears have been eased some by studies in recent years strongly suggesting that climate warming will cause more evaporation and precipitation, more snow build-up on the Antarctic ice sheet. All by itself, the Antarctic ice sheet would consequently have a downward influence on sea levels (offset, remember, against the upward influence that ocean-warming would have on sea levels). The 1995 IPCC Assessment took this position. But IPCC scientists noted that there was “no firm evidence” that the Antarctic ice sheet in general, or the West Antarctic sheet in particular, had in the past exerted either an upward or downward push on sea levels.

After enumerating many such uncertainties, the IPCC scientists went ahead and made a “best guess” about possible sea level rise. The estimate came from a computer model which was itself based on other "best guess" assumptions. If human greenhouse emissions continue according to IPCC's "mid-range" scenario, they estimated, global sea level by the year 2100 would rise to about 50 cm (19.5 inches) above 1995 levels (about 25 percent lower than the 1990 IPCC estimate). They estimate that the most stringent controls would reduce this increase by only about a third — because much of the 21st-century rise has already been determined by past greenhouse emissions, but delayed by oceans and ice masses.

Global Mean Surface Temperature Outlook

The key questions about any human-induced global warming are "How Much?" and "How Fast?" — not just "Whether."

As background, remember that the human species has lived through a natural global warming over the past 18,000 years that was bigger than any that human-induced greenhouse changes is likely to produce in the next 100. If we continue "business as usual" over the next 200 years, the warming is estimated to be about the same as the warming since the coldest part of the last ice age. It is also worth remembering that the temperature on Earth has changed constantly on all the historical and geological time scales that can be measured. Fairly drastic warming and cooling has gone on since Earth was formed 4.6 billion years ago. Some of this change can be attributed to various natural causes and processes that are understood, and some appears to be random. All of it can be called "natural variability."

How big a climate change, if any, humans may have to confront largely depends on what time scale we are using. To a journalist or a politician or a farmer, tomorrow or next year may be a long time. To a climate scientist, 100,000 years may be a short time.

Climate has always changed; that it will continue doing so is quite certain. Few scientists doubt, as noted above, that if societies continue pumping greenhouse gases into the atmosphere fast enough, for long enough, the climate eventually will warm by some amount.

Computer models of "equilibrium" climate change help answer the "How Much?" question. The IPCC scientists in 1990 looked at more than 20 computer modeling studies and arrived at the estimate that, for doubled carbon dioxide, "near Earth's surface, the global average warming lies between +1.5°C and +4.5°C (2.7°F and 8.1°F), with a 'best guess' of 2.5°C (4.5°F)."

That number — Earth's global mean equilibrium surface temperature response to a CO_2 doubling — is often used as the measure of the climate system's "sensitivity" to CO_2 increase. The IPCC in 1995 did not fundamentally change its estimate of the system's sensitivity to CO_2; but it did crank new factors into its estimate. The most notable of these was the effect of human-induced aerosols (dust and smoke particles) in shading and cooling Earth's surface. Since this cooling effect partly offsets the warming effect of greenhouse gases, the IPCC in 1995 revised its warming projections for the year 2100 downward by about a third.

For the mid-range emissions scenario and climate sensitivity, the 1995 IPCC Assessment's estimate was that the global mean surface air temperature would increase by about 2ºC (3.6ºF) above 1990 levels by the year 2100. That warming would come on top of an estimated warming of 0.5°C (.9°F) from the dawn of the industrial age to 1990.

There is less certainty about many aspects of how the warming would be distributed geographically. All of the above estimates are of atmospheric temperature at Earth's surface. The temperature of the stratosphere would become cooler.

Those estimates also represent annually averaged global means. By themselves, they say little about how any temperature increase would be distributed in time or space. Some scientists think, for example, that much of the temperature increase would come at night, when re-radiation of heat absorbed by Earth during the day is the main force heating the atmosphere. Warming at night generally involves lower temperatures than warming during the day — and therefore raises fewer concerns.

The 1995 IPCC Assessment expressed confidence about some details of how the warming would play out. They summarized:

> "All model simulations, whether they were forced with increased concentrations of greenhouse gases and aerosols or with increased concentrations of greenhouse gases alone, show the following features: greater surface warming of the land than of the sea in winter; a maximum surface warming in high northern latitudes in winter, little surface warming over the Arctic in summer; an enhanced global mean hydrological cycle, and increased precipitation and soil moisture in high latitudes in winter. All these changes are associated with identifiable physical mechanisms."

High-Latitude Climate Change

At high latitudes (nearer the poles), all of the equilibrium models came up with warming higher than the global means in late autumn and winter. This warming results from various effects of sea ice and snow cover, according to the IPCC.

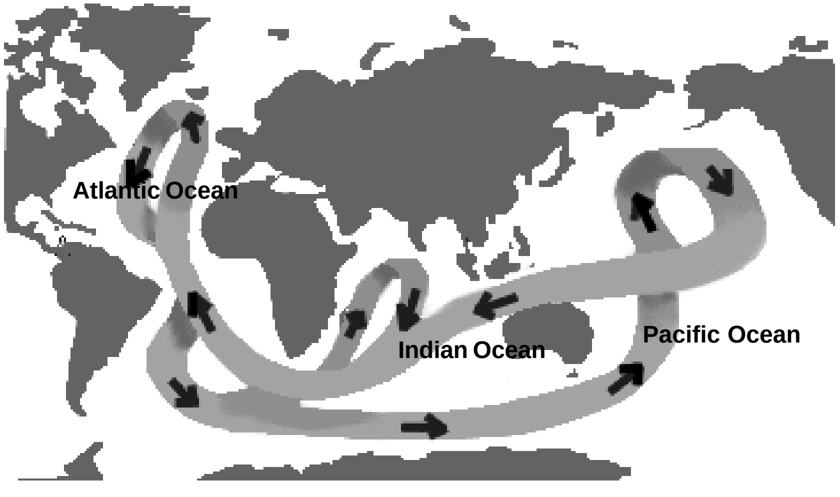
Sea ice, because it is white, reflects more light than does the sea surface. Because it reflects short-wavelength sunlight directly back to space, rather than letting it heat the sea surface, sea ice cools the climate. But, in the warmer climate system of a human-induced greenhouse, sea ice would form later in the year, retarding this natural cooling effect. Moreover, sea ice "insulates" the atmosphere in winter from heat stored in the sea. A similar effect occurs with snow cover in northern lands. These processes form a "feedback" cycle that intensifies itself: warmer air leads to less snow and ice, which in turn leads to warmer air.

In the tropics (nearer the Equator) models studied by the IPCC showed less warming than the global mean, because more of Earth's heat went into evaporating water rather than raising air temperature.

Although some models concentrate exclusively on the atmosphere, climatologists can create more sophisticated models of climate by coupling atmospheric circulation models to models of ocean circulation and sea ice. The use of coupled atmosphere-ocean models was one of the main advances which the 1995 IPCC Assessment made over the 1990 one. These efforts are among the most challenging frontiers of climate study, calling for more knowledge and more computer power. Even though coupled models raise as many questions as they answer, they help illuminate some features likely to play a strong part in any human-induced climate warming.

One of the most noticeable and well-understood aspects of ocean circulation is a powerful downward flow (or circulation) in the upper North

Figure 11. Great Ocean Conveyor Belt



Source: University of Michigan's Space Physics Research Laboratory, http://www.sprl.umich.edu/GCL/paper_to_html/blue_planet.html

Atlantic (i.e., the Labrador, Norwegian, and Greenland Seas). It illustrates an effect involving both the saltiness and temperature of sea water, known as thermohaline circulation. Saltier and colder water, more dense than normal sea water, tends to sink. The water in the North Atlantic tends to be extra salty for several reasons. It arrives in currents from the tropical oceans and the Mediterranean Sea, where excess evaporation makes water saltier (see Figure 11). Another factor is seasonal ice formation, which takes up fresh water, leaving saltier water behind. As this salty water is chilled by the naturally cold atmosphere of the North Atlantic, it becomes much denser and sinks. As it sinks, it pulls in warmer surface water from other parts of the Atlantic, working as a powerful pump.

This replacement of cold surface water with warm water has the effect of "warming" the surface of the North Atlantic, like a heat pump. Coupled ocean-atmosphere models suggest that human-induced greenhouse warming might slow this pump down, cooling the North Atlantic and causing it to help delay global warming. (A similar effect occurs in the Antarctic Sea.) Still, overall, the models continue to show high-latitude warming.

Summer Mid-Latitude Continental Dryness

The IPCC discusses in its 1990 assessment another potentially important consequence of global warming brought about by human activities — an intensification of summer droughts in mid-latitude continental expanses like the U.S. midwestern grain belt.

This effect seems paradoxical, in light of the high confidence of modelers that human-induced warming would bring more precipitation on a global average. Drought, as understood by climatologists, however, involves more than just lack of rain. It involves soil moisture low enough to harm plants, upsetting a balance between precipitation and evaporation. Some climate models suggest that warming would increase evaporation even more than precipitation over mid-latitude continents. In fact, many of these areas already experience late summer drought in the current "normal" climate, so it seems plausible that further warming could intensify it. The problem is that some models do not show this effect, and scientists generally are less confident of it than they are of some other consequences of warming.

Still, the prospects for such an effect are worth considering given that mid-latitude continental breadbaskets in the United States and other countries produce much of the world's food.

Local Impacts of Climate Change

Journalists are trained to look for the "local angle" to any story, especially one as sweeping as global warming, because editors and readers and viewers demand it. They want to know how any story affects real people. Good copy is made of the concrete and specific.

It is no different with the climate change story. The issue takes on more life and importance only when readers and viewers hear of the real impacts. What wakes up fishermen in a coastal Maine or Louisiana town are the effects on fishing. What wakes up Iowa farmers are pictures of dead, drought-stricken cornstalks. What wakes up a Floridian are memories of past hurricanes.

Inquiries into the local angle on climate change, however, can raise as many problems as they solve. The reason: climate models get worse at depicting potential change as they try to zoom in on the local scale. These may be the issues our readers are most interested in, but they are also the ones involving much more uncertainty.

One reason climate models are less reliable at predicting local and regional effects is built into the models themselves. They simulate reality by dividing the atmosphere into a three-dimensional grid, calculating the climate physics for each “box” in the grid. Today’s models use boxes ranging from 250 km to 700 km (about 155 to 435 miles) on a side horizontally. This is much like a newspaper printer making a photograph into a screened half-tone. When the detail you are trying to see in a half-tone gets as small as one of the dots (say, about 1/120 of an inch), you no longer can see it. Actually, it takes more than one dot just to make an image, so the meaningful “resolution” of a half-tone or a climate model is really larger than a grid square. Climate models get fuzzy about details smaller than 1,000,000 square kilometers (about 390,000 square miles).

While regional climate change predictions may be a shaky foundation for a journalist’s story, regional impacts indeed matter. Climate modelers and statisticians in recent years have devised new methods for looking at regional impacts, with encouraging results.

Incidence of Severe Storms

When Hurricane Gilbert thrashed the southeastern United States in 1988, the media were abuzz with speculation that global warming could cause an upsurge in such “super-hurricanes.”

Such speculation by some scientists and environmentalists was not entirely idle. Hurricanes (scientists call them “tropical cyclones”) and other large storms get their energy from warm sea surface water. It seems logical to expect that warmer climate might breed larger storms.

Several theoretical studies suggest that the maximum intensity of tropical storms is determined by sea surface temperature. But others note that there may be mechanisms keeping storms from reaching such maximum intensities. Most global circulation models do not have sufficient resolution to portray hurricanes at all.

The IPCC scientists took this idea seriously. They noted in 1990: “There is some evidence from model simulations and empirical considerations that the frequency per year, intensity and area of occurrence of tropical disturbances may increase, though it is not yet compelling.”

The 1995 Assessment did not really resolve this question much further. Their bottom line: “In conclusion, it is not possible to say whether the frequency, area of occurrence, time of occurrence, mean intensity or maximum intensity of tropical cyclones will change.”

Some climatologists are concerned that global warming could increase climate variability in other ways (e.g., floods and droughts) that could harm humans.

Has a Period of Global Warming Been Detected?

Most scientists who have studied the matter were quite strongly convinced even in 1990 that there has been a definite increase in global average surface temperature since the late 19th century. The IPCC estimates the increase at 0.45°C ± 0.15°C. (That’s 0.81°F ± 0.27°F.)

Has that warming been caused by increases in greenhouse gases caused by human activities? In 1990, IPCC scientists were not yet ready to say that it was. The big news in the 1995 assessment was that the IPCC finally found “discernible human influence” on climate. This is discussed further in Chapter 8.

The data on which a history of global average surface temperature can be based is far from perfect, although scientists exercise great ingenuity in compensating for its imperfections. It is worth remembering that the thermometer was invented no more than four centuries ago, and that there are few systematic records of thermometer readings more than a century old.

Most of us think of reading the temperature as a simple and straightforward process: just look out the window at the thermometer. But if we were trying to come up with an average annual temperature, we would have to take a lot more readings in order to systematically average out the differences from hour to hour, day to day, and season to season. And if we were trying to come up with a global average, we would need a lot more thermometers, and a system for distributing them around the hot, cold, wet, and dry places on the planet. This is the type of problem that can greatly excite statisticians.

The actual data available fall far short of such a standard. There are big gaps and variations in geographic coverage, and many inconsistencies in observation schedules and methods. Finally, there is the “urban heat island” effect. Most people are aware that the night-time temperature in smoggy, asphalt-covered cities can be 5°F, or more, warmer than in the surrounding countryside. As urban areas have grown up in recent decades around the airports or stations where weather measurements are taken, thermometers have likely overestimated the global "average warming."

Still, by sorting out the available measurements, combining them with other indicators (such as the retreat of glaciers), and compensating for the known errors, climatologists have come up with estimates of the global average about which they are pretty confident. They think the urban heat island effect, once compensated for, has probably put warming estimates (0.45°C ± 0.15°C or 0.81°F ± 0.27°F, remember) off by no more than .05°C according to the IPCC.

Marine Ecosystems and Their Responses

Biologists have little doubt that plankton, the microscopic plants and animals that are the foundation of the marine food chain, would be distributed differently in a warmer world. The reduction of sea ice expected in a warmer world would deprive plankton and algae (and also some marine mammals) of habitat. The species that subsist on plankton, and others on up the food chain, could also be affected. The net effect is still unpredictable.

Marine ecosystems are themselves a significant part of the climate system. The ocean waters, creatures, and sediments make up the planet's largest active reservoir of carbon. Not only do the waters take up and release carbon dioxide, but the plankton themselves take up carbon. As they die, this carbon sinks to the bottom as sediment. This "biological pump" acts to lower atmospheric CO_2 levels. But other likely effects of warming, such as changes in currents and habitat, make it hard to predict the outcome.

Major Areas of Uncertainty and Time Frames for Resolving Uncertainty

Finally, scientists are quite uncertain about some important parts of the climate puzzle.

Role of Clouds

Clouds play a key role in determining the temperature at any one time and place on Earth's surface by reflecting or absorbing the incoming solar energy. At higher altitudes, clouds can cool down the "greenhouse" by protecting it with an "awning." At lower altitudes, they also can contribute to greenhouse warming by trapping outgoing longwave radiation.

Clouds are much smaller than the grid-scale of today's climate models, so it is difficult for models to simulate them. Moreover, not enough specifics are known about how clouds behave, and how they affect Earth's energy budget, for models to simulate them effectively. Climatologists are attempting to better understand the behavior of different kinds of clouds, with different particle sizes and water content, and at different altitudes.

Clouds are especially important to estimates of climate change and related greenhouse concerns because they could be involved in various feedback mechanisms, either speeding or slowing global warming. In most climate models, changes in clouds have been found to exert a positive feedback, enhancing global warming. But scientists remain uncertain about the size and direction of the actual feedback effect of clouds.

The World Climate Research Programme (WCRP) has undertaken the International Satellite Cloud Climatology Program to gather data on the global distribution of cloud types. Another WCRP effort, the Global Energy and Water Cycle Experiment (GEWEX), should help quantify effects that clouds have on Earth's energy budget. GEWEX instruments will fly on the advanced Earth Observing System (EOS) satellites, which are just being deployed. The National Oceanic and Atmospheric Administration (NOAA) and the Department of Energy are two of the U.S. Global Change Research Progam agencies playing a major role in these experiments.

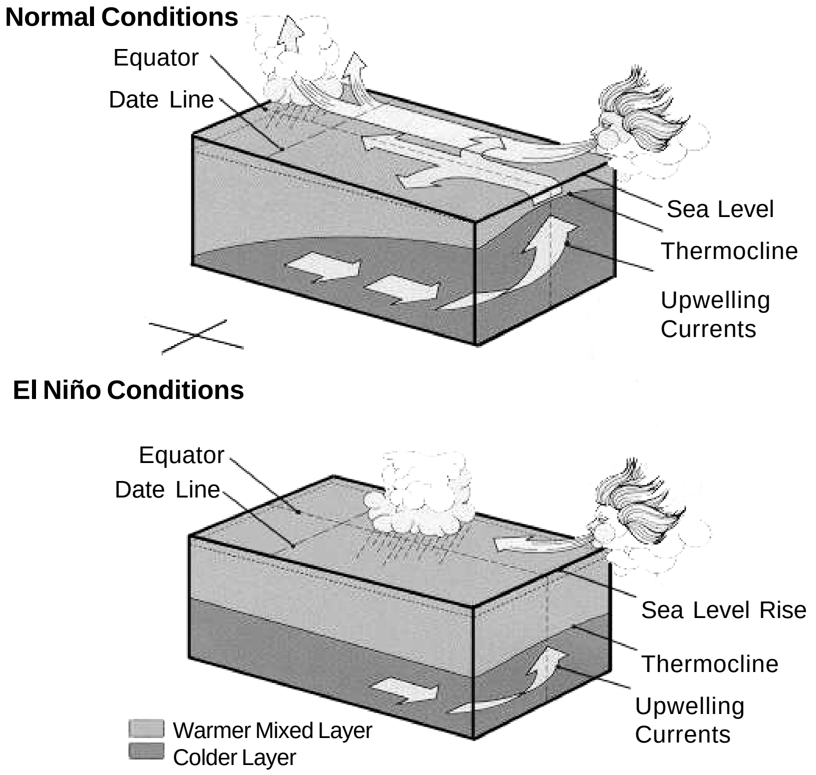
Atmospheric-Ocean Coupling

Another critical area of uncertainty involves how the oceans and atmosphere work together as a climate system. The oceans certainly will have important effects on climate change. For one thing, their enormous ability to absorb heat may delay any human-induced greenhouse warming for decades.

Atmospheric circulation models are more advanced than ocean models, partly because there are relatively fewer subsurface oceanic observations to provide basic understanding. Understanding ocean circulation is essential to understanding how oceans take up heat from the atmosphere (the downward "heat pump" in the North Atlantic is an example). Special problems arise, however, from the fact that ocean currents are so much slower than atmospheric currents. Some estimate that water turnover in one of the deep ocean currents may take 500 to 1,000 years. When atmospheric models are coupled to ocean circulation models, they must be run forward for hundreds of years to keep pace with simple ocean changes. That takes a lot of computer power.

Much has been written in recent years about the "El Niño" Southern Oscillation (ENSO) pattern that causes drastic weather changes in parts of

Figure 12. Normal and El Niño Conditions



Source: Jet Propulsion Laboratory, California Institute of Technology , http://airsea-www.jpl.nasa.gov/ENSO/welcome.html

the globe on an irregular 2- to 7-year cycle (see Figure 12). This phenomenon is another example of ocean-atmosphere coupling. Regular wind currents cause upwelling in parts of the oceans (e.g., in the Pacific off the coast of Peru). Upwelling cold water, in turn, causes changes in sea surface temperature. The El Niño is an irregular stalling of the upwelling of colder waters (i.e., upwelling still occurs but, because of change in the internal temperature of the ocean, warmer water wells up). This causes major changes in wind currents, ocean currents, temperatures, and precipitation to ripple across much of the globe.

To understand more about the basics of such phenomena, the WCRP in 1985 began its decade-long Tropical Ocean-Global Atmosphere (TOGA) program under NOAA leadership, with a full-scale set of oceanographic and atmospheric instruments, studies, and models. Another WCRP study, the World Ocean Circulation Experiment (WOCE), running from 1990 to 1995, deployed a wide array of instruments and tracers to understand in more depth and detail the global ocean currents. Given the global nature of the issue, these experiments involve the international cooperation of many governments and academic institutions. Various U.S. agencies are actively involved.

Sources — and Sinks — of CO_2 and Other Air Pollutants

When we consider how important the key greenhouse gases may be to our future, it is astonishing how little we really know about them — where they come from and where they go.

Without much more precise quantitative information about sources and sinks of carbon dioxide, methane, and nitrous oxide, it will be hard to

Technical/Scientific Issues Surrounding Controls: Lessons for Earth ... from Mars and Venus

If there's any doubt about the reality of the natural greenhouse described in Chapter 3, there are plenty of real-life examples that confirm the theoretical physics.

We can't put a planet in a test tube, but we can look at some of Earth's close neighbors to see how the principles apply there.

Unmanned space probes to the planet Mars, beginning with Mariner 9 in 1971, have shown that Mars has virtually no gaseous atmosphere, and its pressure is less than one percent of the atmospheric pressure on Earth. This gives Mars little ability to trap heat through a greenhouse effect and warm the planet's surface.

Largely as a result, Mars is a frozen wasteland, unable to support life in forms we recognize. Temperatures at Mars' poles often reach -180ºF, so cold that the ice at the poles is dry ice, or frozen carbon dioxide. Mars has plenty of carbon dioxide, in fact carbon dioxide is the main component of its atmosphere. But the fact that so little of it is in gaseous form dooms the planet to eternal cold.

Venus, on the other hand, has an atmosphere around 100 times more dense than Earth's, and Venus' primary constituent is the greenhouse gas carbon dioxide. Not surprisingly, given this dense atmosphere and the nearness of Venus to the sun, the temperature on the surface of Venus is a scorching 840ºF. It, too, seems lifeless.

The contrast between Mars and Venus is often cited in writings about climate change on Earth to drive home the important lesson that predict their buildup, and harder yet to control them.

Carbon dioxide is just one example. The human-induced changes in carbon going into the atmosphere are dwarfed by the amounts flowing through natural processes among the atmosphere, oceans, soil, geological sediments, and living things on both land and sea. Yet we have only the roughest estimates of the amounts of carbon involved in these processes.

The situation is even worse with methane and nitrous oxide. Work in these areas is quite preliminary. Termites, for example, were considered a big source of methane in the late 1980s, but today the estimates are lower. Uncertainty prevails, and estimates of how much methane termites put into the atmosphere vary ten-fold.

Some of these questions about sources and sinks for greenhouse gases are being addressed in the Joint Global Ocean Flux Study (JGOFS), an important part of the International Geosphere-Biosphere Programme.

Earthlings can't and shouldn't take their climatic paradise for granted.

The Mars-Venus parable, however, is sometimes overdone in media interpretations, if only because the planets provide such exotic footage. Some accounts warn of the possibility or likelihood of a "runaway" greenhouse warming, which would transform Earth into a scalding desert like Venus. In fact, this outcome is extremely unlikely, if not impossible, on Earth. The Mars-Venus analogy is hardly an adequate basis for predicting a runaway greenhouse on Earth.

The scenario simplifies and ignores some of the complexities of planetary climate systems. One reason Venus is "too hot" is that it is closer to the sun than Earth; one reason Mars is "too cold" is that it is farther from the sun. (Distance from the sun, of itself, is not nearly enough to explain all of the temperature difference.) Mars is often portrayed as a planet lacking carbon dioxide, but the real problem is that its carbon dioxide is too cold to do it any good. A chicken-and-egg question of cause and effect arises: is Mars too cold because it lacks carbon dioxide, or does it lack carbon dioxide because it is too cold? We must remember also that Mars is too small to hold a substantial atmosphere with gravity. Mars has more CO_2 than Earth, but lacks water vapor, the most important greenhouse gas.

Many other conditions on Mars and Venus are drastically different from conditions on Earth. It is wise not to draw too many conclusions without knowing more.

Reporters pointing to the Mars and Venus "lessons" for Earth should do so only with numerous qualifications and caveats ... if at all.

These studies are organized by the International Council of Scientific Unions (ICSU), with U.S. agencies playing a leadership role.

Rate of Change

Better estimates of the rate of climate change and greenhouse effect attributable to human activity will ultimately be the product of many studies of air, land, and sea processes.

In the shorter term, however, climatologists will work to develop more realistic models of a coupled ocean-atmosphere system. This effort is already well under way at places like National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory, and the National Aeronautics and Space Administration's (NASA's) Goddard Institute of Space Studies.

Uncertainties in this area may be somewhat narrowed in coming years. Still better answers will come when new generations of supercomputers are applied to an improved understanding of ocean processes.

Additional Sources of Climate Forcing (Sulfate Aerosols, Solar Variability)

Greenhouse gases resulting from human activities are not the only force that may be changing climate, by a long shot. For example, it is fairly well established that various periodic stretches in Earth's orbit and tilts and wobbles in its axis of spin cause the coming and going of ice ages. Any effort to anticipate climate change must take all of these forces into account. Many of them are not yet well understood.

Just to take one example, the many microscopic particles and droplets floating in the atmosphere have a major influence on weather and climate. Scientists call these particles aerosols (the mists produced by spray cans are aerosols, in science jargon, hence the name "aerosol spray cans"). They come from both natural and manufactured or artificial sources. Most abundant in the atmosphere are particles of mineral dust, sulfuric acid, ammonium sulfate, biological material-like pollens, and carbon or soot. They may be dry, wet, or dissolved in droplets. Aerosols provide the nuclei, or "seeds," on which larger drops of water can condense, promoting cloud formation and precipitation. They can also absorb and reflect energy radiated from the sun or Earth, altering the "greenhouse" balance. Because they can have so many effects, it is not known for sure whether the net effect is to warm or cool Earth.

Ironically, the same sulfate aerosols which harm the environment as acid rain may also benefit the environment by partially or regionally inhibiting greenhouse warming. These aerosols can come from natural sources like volcanoes, but in many regions the dominant sources are the smokestacks of factories and powerplants. The smokestacks emit sulfur dioxide, which is changed in a complex series of chemical reactions in the atmosphere to sulfate particles and sulfuric acid droplets. Sulfur aerosols are found both in the troposphere and the stratosphere. They do not stay in the atmosphere as long as some greenhouse gases, but their effects may be multiplied by cloud formation.

As has been mentioned, the 1995 IPCC Assessment made strides in quantifying this effect. They estimated the negative forcing (cooling effect) from aerosols at about 0.5 Watts per square meter (W/m^2), compared to the positive (warming) forcing from all the long-lived greenhouse gases of about 2.45 W/m^2. Much more needs to be learned about the role aerosols play in climate.

One possibly more imminent force changing climate is solar variability. The sun is the main force driving the climate system, and even small changes in its energy output could have big consequences for Earth's climate. For many years, scientists believed that the intensity of the sun's radiation was quite steady. Better observations, in the age of satellite instruments, have called that belief into question.

Solar radiation increases and decreases over the 11-year (or, some say 22-year) sunspot cycle. The influence of these fluctuations on climate is believed to be far less than that of increases in greenhouse gases resulting from human activities, however. There may be other important solar cycles. To assess them requires making consistent measurements of solar activity and studying the paleoclimate of past centuries and millenia for clear signs of solar-climate interaction.