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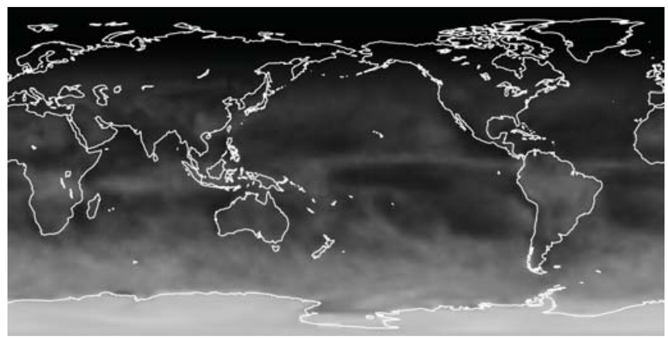
Global Warming

Twenty-five years ago if you made a trip to the local library and perused the periodical section for articles on global warming, you'd probably have come up with only a few abstracts from hard core science journals or maybe a blurb in some esoteric geopolitical magazine. As an Internet search on global warming now attests, the subject has become as rooted in our public consciousness as Madonna or microwave cooking.

Perhaps all this attention is deserved. With the possible exception of another world war, a giant asteroid, or an incurable plague, global warming may be the single largest threat to our planet. For decades human factories and cars have spewed billions of tons of greenhouse gases into the atmosphere, and the climate has begun to show some signs of warming. Many see this as a harbinger of what is to come. If we don't curb our greenhouse emissions, then low-lying nations could be awash in seawater, rain and drought patterns across the world could change, hurricanes could become more frequent, and El Niños could become more intense.

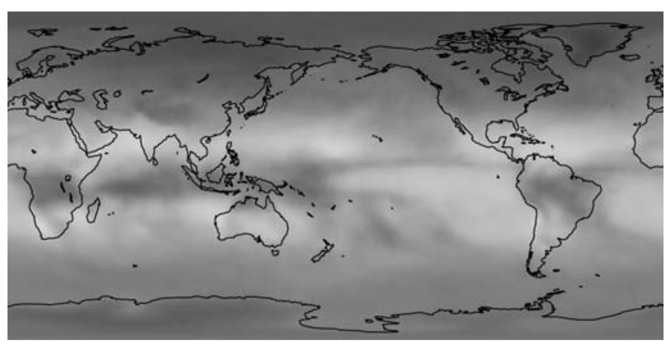
On the other hand, there are those, some of whom are scientists, who believe that global warming will result in little more than warmer winters and denser vegetation. They point to the flaws in scientists' measurements, the complexity of the climate, and the uncertainty in the climate models used to predict climate change. They claim that attempting to lower greenhouse emissions may do more damage to the world economy and human society than any amount of global warming.

In truth, the future probably fits somewhere between these two scenarios. But to gain an understanding of global warming, it is necessary to get to know the science behind the issue.



Reflected Solar Radiation (W/m^2)

0 — 425



Emitted Heat Radiation (W/m^2)

85 — 350

The two maps above show measurements from the Clouds and the Earth's Radiant Energy System (CERES) instrument in January 2002. The top map shows solar radiation reflected from the Earth by clouds, ice, and bright surfaces like desert. Dark, absorbing areas are dark gray, while bright, highly reflective areas are various shades of light gray. The bottom map shows heat radiated from the Earth. More energy is emitted by warmer surfaces, so tropical regions are radiating strongly except where there are high, cold clouds. The areas emitting the least energy are represented by darker shades of gray, while lighter shades of gray represent areas where more heat escapes.

Our Warming Planet

Global warming, or for that matter any substantial warming of the Earth's surface, begins with the sun. Except for relatively small fluctuations due to sunspot activity, the amount of radiation from the sun that reaches the Earth has been fairly constant from year to year and century to century. If you were to travel to the outer reaches of the atmosphere and hold up a flat surface perpendicular to the sun's rays for several years during the daylight hours, you'd find that about 1,368 Watts per square meter on average would hit that surface.

Not all of that energy would be absorbed by the Earth. Roughly 30 percent of the total solar energy that strikes the Earth is reflected back into space by clouds, atmospheric aerosols, reflective ground surfaces, and even ocean surf. The remaining 70 percent is absorbed by the land, air, and the oceans. The absorbed light is mostly in the form of ultraviolet, visible, and near-infrared solar radiation.

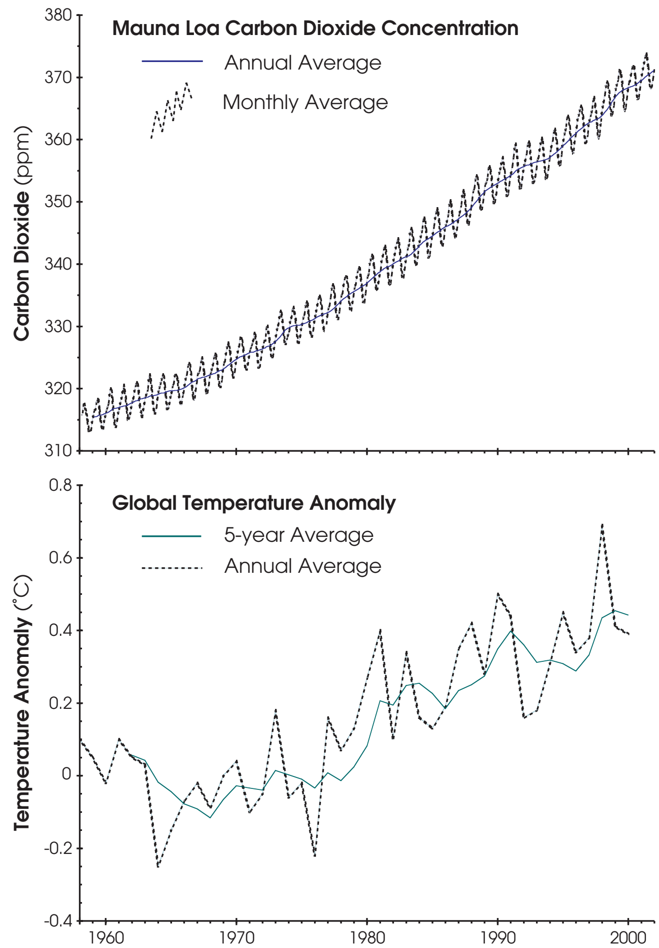
Absorption of solar energy heats up our planet's surface and atmosphere and makes life on Earth possible. The energy does not stay bound up in the Earth's environment forever. If it did, then the Earth would grow hotter and hotter until its temperature exceeded that of the sun. Instead, as the rocks, the air, and the sea heat, they emit thermal radiation. Much of this thermal radiation, which is largely in the form of longwave infrared energy, travels directly out into space, leaving the Earth and allowing it to cool. Such radiation is invisible to our eyes, but our hands can feel it radiating from a fire or a car engine.

Some of this outgoing longwave infrared radiation, however, is re-absorbed by water vapor, carbon dioxide, and other greenhouse gases in the atmosphere and is then re-radiated back toward the Earth's surface. On the whole this re-absorption process is good. If there were no greenhouse gases or clouds in the atmosphere, the Earth's average surface temperature would be a very chilly -18°C instead of the comfortable 15°C that it is today.

What has many people worried now is that over the past 250 years humans have been artificially raising the concentration of greenhouse gases in the atmosphere. Our factories, power plants, and cars burn coal and gasoline and spit out a seemingly endless stream of carbon dioxide. We produce millions of pounds of methane by allowing our trash to decompose in landfills and by breeding large herds of methane-belching cattle. Nitrogen-based fertilizers, which we use on nearly all our crops, release unnatural amounts of nitrogen oxide into the atmosphere.

Once these carbon-based greenhouse gases get into the atmosphere, they stay there for decades or longer. According to the Intergovernmental Panel on Climate Change (IPCC), since the industrial revolution, carbon dioxide levels have increased 31 percent and methane levels have increased 151 percent. Paleoclimate readings taken from ice cores and fossil records have shown that these gases, two of the most abundant greenhouse gases, are at their highest levels in the past 420,000 years. Many fear that the increased concentrations of greenhouse gases have prevented additional thermal radiation from leaving the Earth. In essence, these gases are trapping excess heat in the Earth's atmosphere in much the same way that a windshield traps solar energy that enters a car.

Much of the available climate data appears to back these fears. Temperature data gathered from many different sources all



Carbon Dioxide concentration in the atmosphere has been increasing since measurements began in 1958 on Mauna Loa in Hawaii. Simultaneously, global temperatures have been rising. The graphs above compare Carbon Dioxide concentration to temperature anomaly (the difference between annual temperatures and a long-term average temperature). Note the decrease of Carbon Dioxide during each Northern Hemisphere summer, which is caused by plant respiration. Graphs based on data from the NOAA Climate Monitoring & Diagnostics Laboratory (top) and the Goddard Institute for Space Studies (lower).

across the globe have shown that over the last 100 years the surface temperature of the Earth, which includes the lower atmosphere and the surface of the ocean, has risen dramatically over the past century. The IPCC estimates the increase has been between 0.4°C and 0.8°C. Worldwide measurements of sea level have shown a rise of 0.1 to 0.2 meters over the last century. Readings gathered from glaciers reveal a steady recession of the world's continental glaciers. Taken together, all of these data suggest that over the last century the planet has experienced the largest increase in surface temperature in 1,000 years.

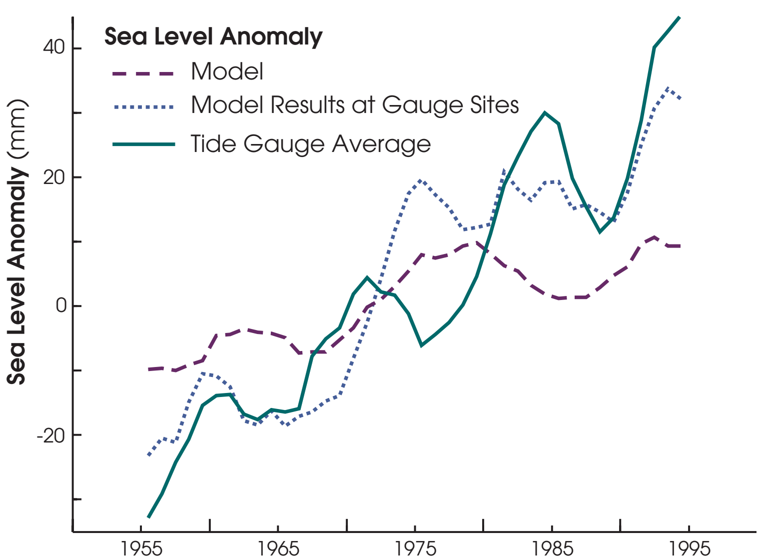
As of now, greenhouse gases afford a plausible explanation for such changes. Paleoclimate readings back this hypothesis up. In the Earth's past, drastic increases in carbon dioxide nearly always coincide with large increases in Earth surface temperatures. Conversely, ice ages are almost always accompanied by a decrease in carbon dioxide.

Logic dictates that, as third world nations develop their economies and first world nations consume more energy, greenhouse gas concentrations will continue to rise. Though scientists have not reached a consensus, most leading researchers and organizations purport that the average surface temperature of the Earth will increase along with increasing emissions. According to the IPCC, the surface temperature could rise by between 1.4 °C and 5.8 °C by the end of the century. Scientists at Goddard Institute for Space Studies, NASA's division spearheading climate modeling efforts, report that we should expect between 0.5 °C and 1 °C over the next fifty years.

At first glance, these numbers probably do not seem threatening. After all, temperatures typically change a few degrees whenever a storm front moves through. Such temperature changes, however, represent day-to-day regional fluctuations. When surface temperatures are averaged over the entire globe for extended periods of time, it turns out that the average is remarkably stable. Rarely in the Earth's history has the average surface temperature changed as dramatically as the changes that scientists are predicting for the next century. During the last ice age 20,000 years ago, for instance, the Earth was roughly 5 °C cooler than it is today. Since then it has warmed up, although not steadily, to present levels. That's an increase of roughly 1 °C every 4,000 years. Current global warming scenarios predict this bare minimum increase over the next century.

Potential Effects of Global Warming

How all of this warming will alter the weather is more uncertain. It's much easier for scientists to forecast the Earth's average surface temperature than it is to forecast how much rain will fall in, say, Boise, Idaho, during the next in 50 years. So far scientists have not been able to pinpoint with certainty any changes in weather due to global warming over the last century. Most of that "weird" weather we've been experiencing–that unusually warm fall or that particularly wet winter–is due to normal, regional changes in the weather. Some scientists believe that global warming will continue to have relatively little impact on the day-to-day climate conditions. Others purport that future changes will likely be subtle, and they will spread over large areas of the globe from decade to decade and creep up on us like old age. Still others hypothesize that when the Earth's surface temperature reaches some critical threshold, the heat will trigger relatively drastic changes to the atmosphere and the oceans and transform the Earth's weather patterns in a matter of years.

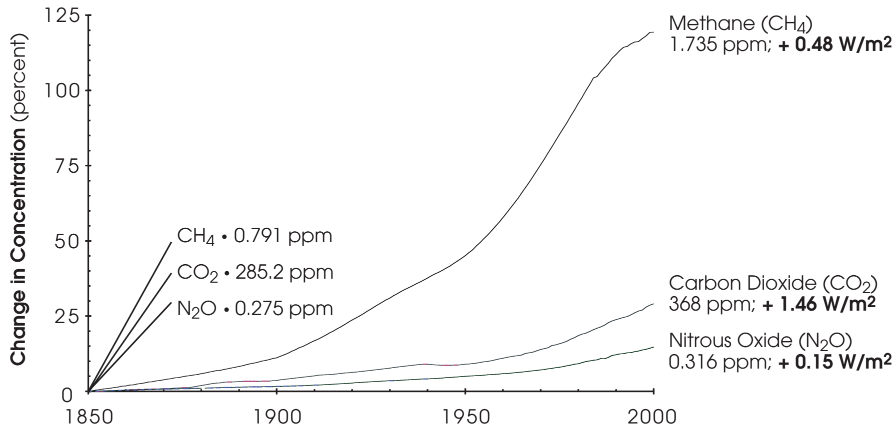


Sea-level rise is one of the most widely discussed effects of global warming. The graph above shows real-world tidal gauge measurements (solid line) compared with a model of global average sea level (dashed line), and model calculations at the locations of the real-world gauges (dotted line). Models can both help predict future change (so scientists can estimate the effects of global warming) and evaluate the accuracy of instrumental measurements. (Graph adapted from Cabanes, C. et. al., Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations, Science, October 26, 2001, Vol 294, pp. 840-842.)

Not surprisingly, many scientists speculate that such changes in the climate will probably result in more hot days and fewer cool days. According to the IPCC, land surface areas will increase in temperature over the summer months much more than the ocean. The mid-latitude to high-latitude regions in the Northern Hemisphere–areas such as the Continental United States, Canada, and Siberia–will likely warm the most. These regions could exceed mean global warming by as much as 40 percent.

Forecasts for precipitation and weather are cloudier. Right now the IPCC reports that the amount of precipitation, especially in the mid-latitude to high-latitude regions of the Northern Hemisphere, will likely increase. They believe, however, that it will come in the form of bigger, wetter storms, rather than in the form of more rainy days. So it's more probable that the increase in rain will only serve to tax our drainage systems rather than benefit vegetation or replenish natural, underground aquifers. As to larger more destructive weather patterns, hurricanes will likely increase in intensity due to warmer ocean surface temperatures. And researchers speculate that El Niño events may increase in intensity for the same reason.

The outlook for rising sea levels is nothing like the deluge portrayed in Hollywood. The statue of liberty won't be up to her neck in water, and we won't all be living on flotillas on an endless sea. According to the IPCC, over the next century, sea levels are likely to rise between 0.09 and 0.88 meters. The rise will mainly be due to seawater expanding from the increased ocean temperatures and run-off from the melting of continental glaciers and a slight melting of the Greenland Ice Sheet. For now, the West Antarctic Ice Sheet, which could raise our sea levels dramatically, will probably stay in place. It may even gain more mass due to an increase in precipitation over the next century. But, if somehow the entire Greenland Ice Sheet melted and the West Antarctic Ice Sheet fell into the sea, the sea level would rise roughly 10 meters. This is probably impossible over the next century, but there is the danger that global warming could initiate ice sheet changes that will continue to develop over future centuries.



Scientists study past trends to predict future changes. The graph above shows the increasing concentration of the three most significant greenhouse gases—methane, carbon dioxide, and nitrous oxide. Since 1850 the concentration of methane has increased 125%, carbon dioxide 30%, and nitrous oxide 15%—and the rate of increase is accelerating. The additional methane in the atmosphere has increased the energy trapped by the atmosphere (called radiative forcing) by 0.48 watts per meter squared, carbon dioxide 1.46 watts per meter squared, and nitrous oxide 0.15 watts per meter squared. (Graph based on data from the Goddard Institute for Space Studies)

Should global warming continue, many biologists envision the alteration of natural habitats. Some of this change may be for the better. Higher levels of CO_2 and warmer temperatures may cause forests to become more lush and vigorous. Warmer ocean waters on the open ocean could be beneficial to fish and algae on the high seas. Unfortunately, most changes will likely be for the worst. Plants and animals in mid-latitude regions, such as nut-bearing oaks in the midwestern United States, may find themselves in warmer environments where they cannot survive. Rising sea levels may inundate delicate coastal wetlands with brackish waters, which could drive out certain types of fish and kill wetland vegetation. Warmer ocean temperatures around the coast could overheat many types of coral, killing them and many of the animals that depend on them.

As far as human health is concerned, those hit hardest will probably be residents of poorer countries that do not have the funds to fend against changes in climate. A slight increase in heat and rain in equatorial regions would likely spark an increase in vector-borne diseases such as malaria. More intense rains and hurricanes could cause more severe flooding and more deaths in coastal regions and along riverbeds. Even a moderate rise in sea level could threaten the coastlines of low-lying islands such as the Maldives. All across the globe, hotter summers could lead to more cases of heat stroke and deaths among those who are vulnerable, such as older people with heart problems. The warmer temperatures may also lead to higher levels of near-surface ozone from cars and factories, which would likely cause more code red air quality days and hospital admissions for those with respiratory problems.

Making a Model of Global Warming

The severity of these environmental changes will be largely dependent on how much the Earth's surface warms over the next century. As the wide range of estimates for average global surface temperature suggests, researchers haven't exactly reached a consensus. The reason for the wide range simply comes down to the difficulty inherent in predicting the outcomes of current trends in both human society and the Earth's climate system.

To get their estimates for future warming, scientists must first discern how much human industry and expansion will impact the Earth over the next 100 years. Researchers typically review a wide range of socioeconomic data such as worldwide population trends and then come up with varying scenarios describing mankind's future. For the IPCC report, 16 such scenarios were developed. The worst case scenarios, typically known as the "business as usual" scenarios, go on the assumption that population growth in developing nations will proceed unabated and the entire world will continue to use more and more fossil fuel per capita. The best case scenarios envision a world in which environmentally friendly technologies such as fuel cells and solar panels replace much of today's fossil fuel combustion and the population increase is halted by an improved standard of living worldwide. Using these projections, researchers arrive at estimates for how much carbon dioxide, soot, ozone and other pollutants people will put into the air over the next 100 years. Obviously, the "business as usual" scenarios have people producing the most pollution, and the eco-friendly scenarios have people producing the least pollution.

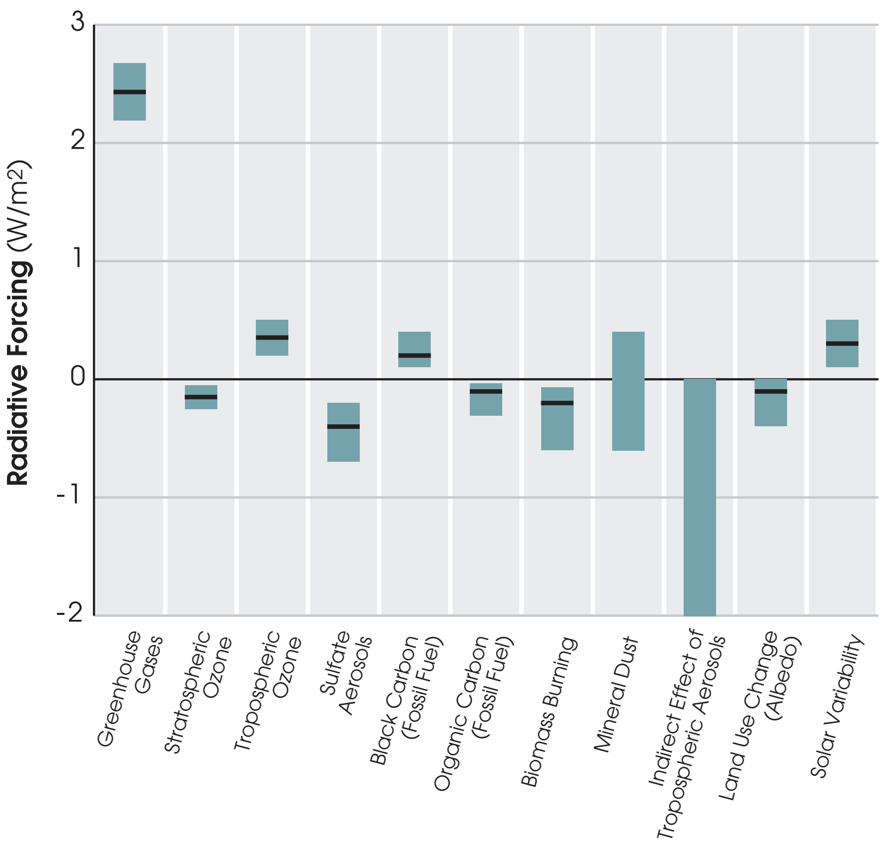
But projections of greenhouse gas concentrations alone cannot tell scientists how much the Earth's surface will warm or the climate will change. To make forecasts, they must employ climate models, which are essentially computer simulations of the climate. These models are a bit like those computer programs detectives use to envision what missing persons would look like ten years after their disappearance. But instead of being constructed on the knowledge and data on how people's faces age, these models are constructed on the knowledge and data of the Earth's climate. After inputting estimates for future greenhouse gas emissions, scientists run the models forward into many possible futures. Some of these models simply produce forecasts of the Earth's temperature, while others are built to predict other changes in the Earth's atmosphere and oceans.

Even the simplest of these models can be exceedingly complex. When piecing together models to estimate the Earth's average surface temperature, scientists must take into account everything on the Earth that blocks outgoing thermal radiation or reflects sunlight into space as well as possible changes in the radiation emitted by the sun itself. There are, in fact, a myriad of unnatural and natural factors in addition to greenhouse gases that could sway global surface temperatures one way or the other in the future. Some of these influences are human made and some are natural. Some directly impact the amount of radiation absorbed by the Earth, and scientists expect others will be triggered as the climate heats up.

One example of a cooling influence that may counter the greenhouse effect is sulfate aerosols. When fossil fuels burn, they not only release greenhouse gases, but also sulfur dioxide. The sulfur dioxide gets into the air and mixes with oxygen to create sulfate aerosol particles, which reflect sunlight. Though these aerosols don't stay in the air as long as most greenhouse gases, they may cool regions of the world where their emissions are heavy, such as the eastern United States, China, and the Indian sub-continent.

Changes in clouds due to the warming of the atmosphere, on the other hand, could greatly add to the warming effect. As the Earth heats up, the cloud composition in the atmosphere could change dramatically. Low lying clouds could evaporate during the daytime hours and more high flying cirrus clouds could form as surface heat causes the air to rise. Since low lying clouds tend to reflect sunlight and higher clouds absorb heat radiation, the overall effect of these changes would be an increase in the amount of energy trapped in the atmosphere. On the other hand, the response of clouds to global warming is so uncertain that changes in clouds might act to reduce, not increase, the amount of surface warming over the next century.

As if these warming and cooling influences weren't enough to keep track of, some evidence has shown global warming may have a delay built into it. Given the level of carbon dioxide in the atmosphere now, a number of Earth scientists calculate that the Earth should be 0.5°C warmer than it is today. Temperature readings obtained from several hundred meters below the ocean's surface suggest that this extra energy could be lurking down there. The theory is that as the Earth has



The above chart shows the current scientific understanding of radiative forcing (how different phenomena affect the Earth's energy balance). Postive numbers represent forcing that will warm the Earth, negative numbers are cooling effects. The height of each bar represents the uncertainty, and the black line is a central estimate. The effects of mineral dust and the indirect effect of tropospheric aerosols are so uncertain that there is no central estimate. Scientists and policy makers who are skeptical of climate change emphasize the cooling effects, and propose feedback mechanisms that help stabilize Earth's climate. (Graph adapted from Climate Change 2001, The Scientific Basis) warmed, much of the excess energy has gone into heating the upper layers of the ocean, giving rise to a temperature imbalance between the surface waters and the deep waters. It is thought that convection currents in the ocean may have transported some of this excess heat in the surface waters down deep, effectively removing it from the surface of our planet. Were this process to continue, the temperatures of the lower layers of the ocean would eventually increase until they are once again in balance with the surface waters. At this point, the excess heat in the upper layers would no longer be drawn down, and the Earth would warm to a higher level. So even if we drastically lower our emissions today, we could still be in for a 0.5°C additional warming.

Climate modelers must consider dozens of such factors, boil them down into equation form, and pack them into their models. Not all models are built alike. There is quite a lot of disagreement among Earth scientists as to how much of a role factors such as aerosols and clouds will play in heating the Earth and how they should be incorporated into the models. For instance, NASA climate modelers at GISS have evidence that black carbon aerosol particles (soot) contributes significantly to warming of the lower atmosphere, since they absorb incoming radiation. The IPCC, on the other hand, estimates that black soot plays only a very small role in warming. Each research group or agency builds its models accordingly, and the choices made influence the forecasts derived from the models. Even when modelers do agree on the mechanisms involved, many of these factors have a great deal of uncertainty associated with them.

The Skeptics

While the general consensus among scientists is that global warming is real and its overall effects are detrimental, there are still some prominent scientists who feel that the threat of global warming has been greatly exaggerated. Skeptics take issue with the basic temperature data that demonstrate the Earth's temperature has increased over the last century. Most of the pre-satellite, pre-1970 data were collected in urban areas using many types of thermometers that were spread far apart. Such measurements are subject to human error and do not give a clear depiction of ocean temperatures. Until satellite data are collected for several more decades, some researchers feel that the temperature data remain too unreliable to take at face value.

Another point of contention is that no one has ever proven outside of the laboratory whether global warming occurs as a result of carbon dioxide. Scientists have ample fossil evidence that shows that carbon dioxide levels in the atmosphere have risen as the Earth grows warmer, but no one has yet shown that a rise in carbon is responsible for the past temperature increases. It is still possible that the warming in the distant past could have triggered the rise in carbon dioxide.

As far as forecasts of future warming are concerned, skeptics point to the uncertainties inherent in the models researchers are using. There are a couple of dozen models currently in use that forecast everything from the average surface warming of the planet to complex interactions global warming will have with the Earth's atmosphere and weather systems. As mentioned, each of these models can generate a different answer depending on projections for future human emissions, the uncertainty in how the climate will respond, and what scientists decide to include in the models. Many feel there is still too much we do not understand about the climate or human society to take stock in any forecasts as of yet.

NASA's Missions to Study Climate Change

But perhaps the one aspect of global warming research that nearly everyone agrees on is that more has to be done. NASA's Earth Science Enterprise is involved in a number of projects that aim to monitor and analyze climate change. A number of Earth Observing System (EOS) satellite missions have either already been launched or are slated to be launched over the next several years. Instruments aboard these satellites will take unprecedented measurements of the Earth and the sun that are relevant to climate change. The EOS Terra satellite, which was launched in 1999, retrieves global readings of land surface temperatures, snow cover, atmospheric aerosol levels, cloud properties, methane, vegetation density, and a host of other variables that influence climate on a global scale. The measurements are taken over the entire globe once a day, often taken at resolutions of 1 km or less. Taking measurements by satellite is much more efficient, consistent, and timely than taking measurements *in situ* on the planet's surface.

Since the early 1970s, researchers at GISS have been constructing climate models with the data and knowledge gathered in part from satellite readings. They've constructed a number of radiative forcing models to try to understand the manner in which the Earth absorbs and reflects solar radiation. Such models could be used to make forecasts of the temperature of the Earth's surface and atmosphere. In addition, GISS researchers are working on several more comprehensive atmospheric and oceanic models in an effort to understand and forecast long-term changes in precipitation, air pressure, and wind currents. Were the scientists able to perfect these ocean-atmosphere models, they could get a better handle on how rainfall and cloud cover will change if the Earth warms due to greenhouse gases.

Though data collection and modeling efforts have come a long way in the last 25 years, NASA and other agencies dealing with global warming are still a long way off from forecasting the future with certainty. But this new generation of satellite remote sensors are far more sophisticated than their predecessors. Their measurements are more precise and made more frequently over the entire globe every day. Moreover, they can measure a wider range of the Earth's vital signs, enabling scientists to better quantify the key cause-and-effect relationships that drive our climate. Each year dozens of discoveries are made that add to scientists' body of knowledge of how the climate works. Ultimately, the goal is to determine which climate changes are natural in origin, and which are due to human influences.