Global Warming is Happening

Kevin Trenberth

National Center for Atmospheric Research[1]
P. O. Box 3000
Boulder, CO 80307

[1]The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Kevin E. Trenberth may be contacted via the above *Corresponding Author Address* or via:

email: trenbert@cgd.ucar.edu
voice: (303) 497 1318
fax: (303) 497 1333

Summary
The latest 2001 Intergovernmental Panel on Climate Change (IPCC) report reaffirms in much stronger language that the climate is changing and the major cause is from human effects on changing the composition of the atmosphere through use of fossil fuels and deforestation. The long lifetime of several greenhouse gases (carbon dioxide lasts for over a century) suggests that we can not stop the changes, but we can slow them down. Moreover, the slow response of the oceans to warming, means that we have not yet seen all of the climate change the planet is already committed to. Major climate changes are projected under all likely scenarios of the future and the rates of change are much greater than occur naturally, and so are likely to be very disruptive.

The IPCC
The IPCC is a United Nations body that was set up jointly under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. Its mandate is to provide policy makers with an objective assessment of the scientific, technical and socio-economic information available about climate change, its environmental and socio-economic impacts, and possible response options. The IPCC carries out major assessments of the state of knowledge and understanding about every five years, the first in 1990, the second in 1995, and the third was completed in early 2001. There are three major working groups under the IPCC. Working Group (WG) I deals with the science of climate change, WG II deals with impacts of climate change and options for adaptation to such changes, and WG III deals with options for mitigating and slowing the climate change, including possible policy options.

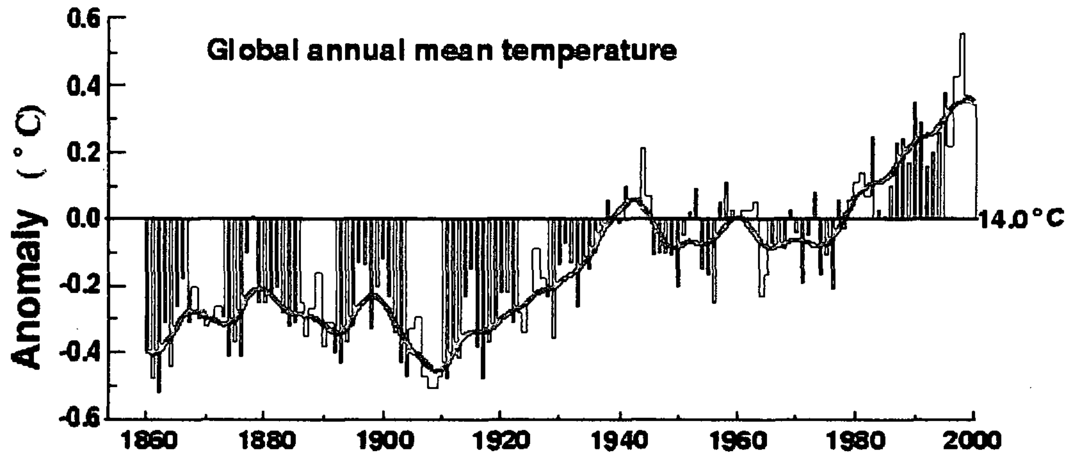
Each WG is made up of participants from all the UN countries, and for the Third Assessment, WG I consisted of 123 lead authors, 516 contributors, 21 review editors, and over 700 reviewers. The resulting report (IPCC 2001) is about 1000 pages long and involves 14 chapters. There is a Technical Summary and a short Summary for Policy Makers. The latter is approved line by line by all the governments in a major meeting, which in this case took place in Shanghai, China, in January 2001. The argument here is that the scientists determine what can said, but the governments determine how it can best be said.

Each new report reviews all the published literature over the previous 5 years or so, and assesses the state of knowledge, while trying to reconcile disparate claims and resolve discrepancies, and highlight uncertainties. The IPCC process is very open. Two major reviews are carried out in producing each report, and skeptics can and do participate in every phase. The strength is that the result is a consensus report. It is not necessarily the latest or greatest, but it does sort out what can be reliably stated. The weakness is that all chapters are written in parallel, and also the working groups operate in parallel. Several plenary sessions of all authors helps to cut down on conflicts, gaps, and duplication, but that some of those problems remain is almost inevitable.

Introduction to the Science of Climate Change
Climate changes have occurred in the past naturally, over decades to millennia for various reasons. However, humankind is performing a great geophysical experiment (Revelle and Suess, 1957). By modifying the Earth's environment in various ways, we are changing the climate. Legitimate debates go on about the extent and rate of these changes, and what, if anything, to do about them, but that the experiment is underway is not in doubt. The human-induced environmental changes of most relevance are in land use (e.g., farming, building cities), storage and use of water (dams, reservoirs, irrigation), generation of heat, and combustion of fossil fuels. The latter, in particular, pollutes the atmosphere and alters the balance of radiation on Earth through both visible particulate pollution (called aerosols) and gases that change the composition of the atmosphere. The latter are referred to as greenhouse gases because they are relatively transparent to incoming solar radiation, while they absorb and reemit outgoing infrared radiation, thus creating a blanketing effect which results in warming. Global warming and associated climate change are expected as a result.

The problem with this experiment is that if it turns out badly - however that is defined - we cannot undo it. We cannot even abruptly turn it off. Too many of the things we are doing now have long-term ramifications for centuries into the future. For instance, carbon dioxide has an atmospheric lifetime of greater than a century and simply stopping increases in emissions would still result in increases in atmospheric concentrations for many decades. The only way to reverse those trends is to reduce emissions to well below current levels. Even fully implementing the Kyoto protocol would merely slow the time of doubling of carbon dioxide concentrations in the atmosphere from pre-industrial values by perhaps 15 years (from 2060 to 2075) unless substantial further emissions reductions were to take place at some time in the future (Wigley 1998). Moreover, changes underway in the oceans would endure.

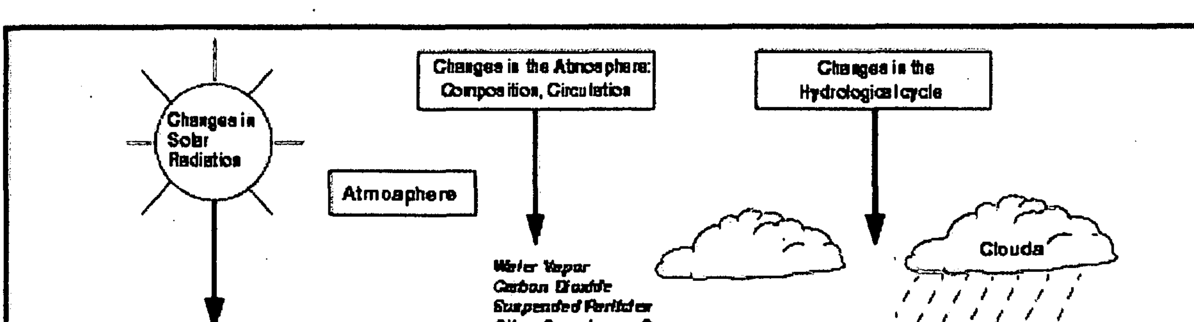
Observed Climate Change
Analysis of observations of surface temperature show that there has been a global mean warming of about 0.7°C over the past one hundred years; see Fig. 1 for the instrumental record of global mean temperatures. The warming became noticeable from the 1920s to the 1940s, leveled off from the 1950s to the 1970s and took off again in the late 1970s. The calendar year 1998 is by far the warmest on record, exceeding the previous record held by 1997. The year 2000 (not shown) is similar to 1999. The last ten years are the warmest decade on record. Information from tree-rings, corals and ice cores further indicates that these years are the warmest in at least the past 1000 years in the Northern Hemisphere, which is as far back as a hemispheric estimate of temperatures can be made (Mann et al. 1998, 1999). The melting of glaciers over most of the world and rising sea levels confirm the reality of the global temperature increases. There is good evidence for decadal changes in the atmospheric circulation and some evidence for ocean changes. Although precipitation is generally increasing at mid to high latitudes, changes in rainfall and other components of the hydrological cycle vary considerably geographically. Changes in climate variability and extremes are beginning to emerge.

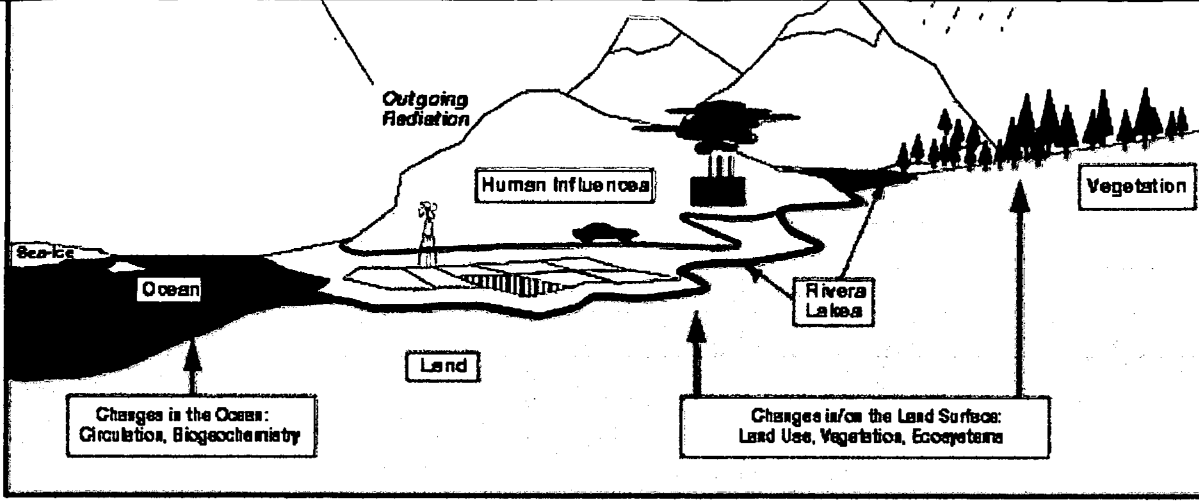


Because of the land/ocean contrasts and obstacles such as mountain ranges, the mid-latitude westerly winds and the embedded jet stream in each hemisphere contain planetary-scale waves. These waves are usually geographically anchored but change with time as heating patterns change in the atmosphere. A consequence is that extensive regions of both above and below normal surface temperatures are found in different places at any time. The recent warming has been largest over most of the northern continents, much less over the eastern half of the United States, and with cooling over the North and South Pacific and North Atlantic. These changes are dominant in the northern winter and are associated with changes in El Niño.

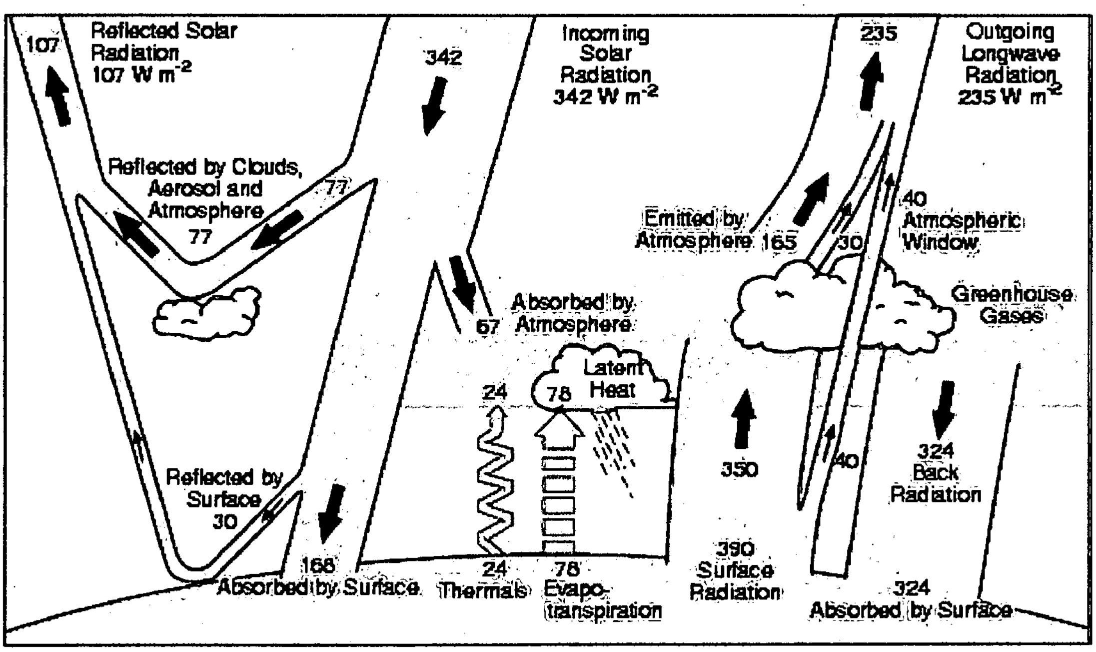
The Climate System and its Driving Forces

Because humans live in and breathe the atmosphere it is natural to focus on the atmospheric changes. Climate involves variations in which the atmosphere is influenced by and interacts with other parts of the climate system, and "external" forcings (Fig. 2). The internal interactive components in the climate system include the atmosphere, the oceans, sea ice, the land and its features (including the vegetation, albedo, biomass, and ecosystems), snow cover, land ice, and hydrology (including rivers, lakes and surface and subsurface water). The components normally regarded as external to the system include the sun and its output, the Earth's rotation, sun-Earth geometry and the slowly changing orbit, the physical components of the Earth system such as the distribution of land and ocean, the geographic features on the land, the ocean bottom topography and basin configurations, and the mass and basic composition of the atmosphere and ocean. These components determine the mean climate, which may vary from natural causes. A change in the average net radiation at the top of the atmosphere due to perturbations in the incident solar radiation or the emergent infrared radiation leads to what is known as radiative forcing of the system. Changes in the incident radiation energy from the sun or changes in atmospheric composition due to natural events like volcanoes are possible examples. Other external forcings may occur as a result of human activities.





The source of energy which drives the climate is the radiation from the sun. About 31% is scattered or reflected back to space by molecules, tiny airborne particles (known as aerosols) and clouds in the atmosphere, or by the Earth's surface. To balance the incoming energy, the Earth itself must radiate on average the same amount of energy back to space (Fig. 3). It does this by emitting thermal "long-wave" radiation in the infrared part of the spectrum. The radiation emitted by the Earth to space corresponds to a temperature of about -19° C, much colder the annual average global mean temperature of about 14°C.



The reason is because the bulk of the Earth's radiation to space is intercepted by the atmosphere and re-emitted both up and down. The emissions to space occur either from the tops of clouds at different atmospheric levels (which are almost always colder than the surface), or by gases present in the atmosphere which absorb and emit infrared radiation. Water vapor, carbon dioxide and some other minor gases present in the atmosphere absorb some of the thermal radiation leaving the surface and emit radiation from much higher and colder levels out to space. The blanketing is known as the natural greenhouse effect. Water vapor gives rise to about 60% of the current greenhouse while CO2 accounts for about 26% (Kiehl and Trenberth 1997). Clouds also absorb and emit thermal radiation and have a blanketing effect similar to that of the greenhouse gases. But clouds are also bright reflectors of solar radiation and thus also act to cool the surface. While on average there is strong cancellation between the two opposing effects, the net global effect of clouds in our current climate, as determined by space-based measurements, is a small cooling of the surface.

Human Influences

The amount of carbon dioxide in the atmosphere has increased by about 31% since the beginning of the industrial revolution about 250 years ago, owing mainly to combustion of fossil fuels and the removal of forests. In the absence of controls, future projections are that the rate of increase in carbon dioxide amount may accelerate and concentrations could double from pre-industrial values within the next 50 to 100 years. Several other greenhouse gases are also increasing in concentration in the atmosphere from human activities (especially biomass burning, agriculture, animal husbandry, fossil fuel use and industry, and through creation of landfills and rice paddies). These include methane, nitrous oxide, the chlorofluorocarbons (CFCs) and tropospheric ozone, and they tend to reinforce the changes from increased carbon dioxide. However, the observed decreases in lower stratospheric ozone since the 1970s, caused principally by human-introduced CFCs and halons, contribute to a small cooling.

Human activities also affect the amount of aerosol in the atmosphere, which influences climate in other ways. A direct effect of some aerosols is the scattering of some solar radiation back to space, which tends to cool the Earth's surface. Other aerosols directly absorb solar radiation leading to local heating of the atmosphere and some absorb and emit thermal radiation. A further influence of aerosols is that many act as nuclei on which cloud droplets condense, affecting the number and size of droplets in a cloud and hence altering the reflection and the absorption of solar radiation by the cloud.

Aerosols occur in the atmosphere from natural causes; for instance, they are blown off the surface of deserts or dry regions. The eruption of Mt. Pinatubo in the Philippines in June 1991 added considerable amounts of aerosol to the stratosphere which, for about two years, scattered solar radiation leading to a loss of radiation at the surface and a cooling (see Fig. 1). Human activities contribute to aerosol particle formation mainly through injection of sulfur dioxide into the atmosphere (which contributes to acid rain) particularly from power stations and through biomass burning. Because man-made aerosols are mostly introduced near the Earth's surface where they can be washed out of the atmosphere by rain, they typically remain in the atmosphere for only a few days and they tend to be concentrated near their sources such as industrial regions. The changed heating therefore possesses a very strong regional pattern, and the presence of aerosols can help mask any global warming arising from increased greenhouse gases.

The increases in greenhouse gases in the atmosphere and changes in aerosol content produce a change in the heating. The determination of the climatic response to this change is complicated by feedbacks. Some of these can amplify the original warming (positive feedback) while others serve to reduce it (negative feedback). If, for instance, the amount of carbon dioxide in the atmosphere were suddenly doubled, but with other things remaining the same, the outgoing long-wave radiation would be reduced and instead trapped in the atmosphere. To restore the radiative balance, the atmosphere must warm up and, in the absence of other changes, the warming at the surface and throughout the troposphere would be about 1.2° C. In reality, many other factors will change, and various feedbacks come into play, so that the best estimate of the average global warming for doubled carbon dioxide is 2.5° C (IPCC, 1996). In other words the net effect of the feedbacks is positive and roughly doubles the response otherwise expected.

Prediction and Modeling of Climate Change
To quantify the response of the climate system to changes in forcing it is essential to account for all the complex interactions and feedbacks among the climate system components and this is done using numerical models of the climate system based upon sound well-established physical principles. Global climate models include representations of all processes indicated in Fig. 2. With comprehensive climate models, experiments can be run with and without increases in greenhouse gases and also other influences, such as changes in aerosols. The best models encapsulate the current understanding of the physical processes involved in the climate system, the interactions, and the performance of the system as a whole. They have been extensively tested and evaluated using observations. They are exceedingly useful tools for carrying out numerical climate experiments, but they are not perfect, and so have to be used carefully (see Trenberth 1997).

Projections have been made of future global warming effects based upon model results to the year 2100. As the actions of humans are not predictable in any deterministic sense, future projections necessarily contain a "what if" emissions scenario. These scenarios factor in such things as population growth, economic wellbeing, use and development of technology, and equity among nations. In addition, for a given scenario, the rate of temperature increase depends on the model and how features such as clouds are depicted, so that a range of possible outcomes exists. The projections for a mid-range emissions scenario in which carbon dioxide concentrations double 1990 values by the year 2100 produces global mean temperature increases ranging from about 11/2° C to 5° C above 1990 values with a best estimate of about 2 to 3° C. Note that while these projections include crude estimates of the effects of sulfate aerosol they deliberately omit other possible human influences such as changes in land use. A major concern is that the rates of climate change as projected exceed anything seen in nature in the past 10,000 years.

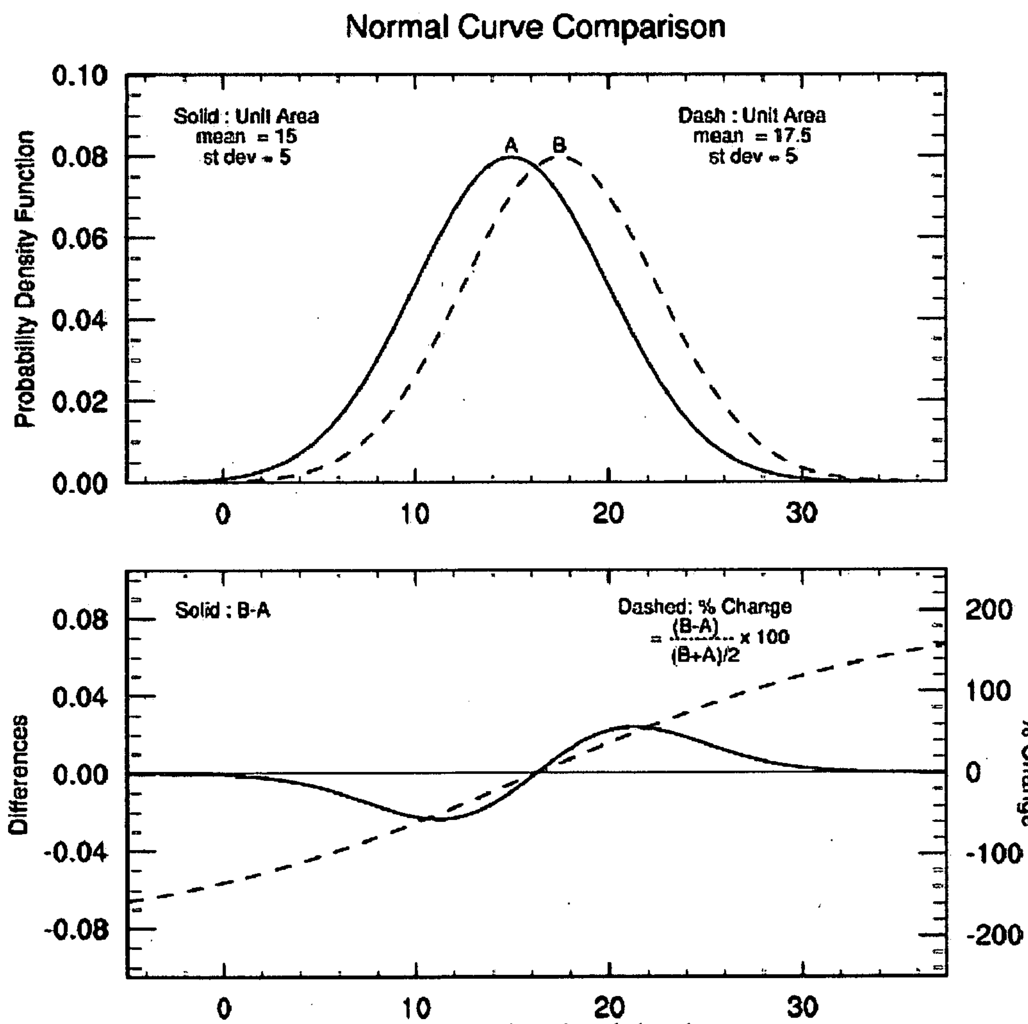
Increased heating leads naturally to expectations for increases in global mean temperatures (often mistakenly thought of as "global warming"), but other changes in weather are also important. Increases in greenhouse gases in the atmosphere produce global warming , and thus not only increase surface temperatures but also enhance the hydrological cycle as much of the heating at the surface goes into evaporating surface moisture. Global temperature increases signify that the water-holding capacity of the atmosphere increases and, together with enhanced evaporation, this means that the actual atmospheric moisture should increase. This is observed to be happening in many places, for example at a rate of about 5% per decade over the United States from 1973 to 1993 (Ross and Elliott, 1996). Because water vapor is a powerful greenhouse gas, this provides a strong positive feedback. Moreover, it leads to the expectation of enhanced rainfall or snowfall events and the result is that when it rains it pours harder than it would have under similar circumstances just a couple of decades ago (Trenberth 1998)! This also provides fuel for storms, which further enhances rainfall and snowfall intensity, increasing risk of flooding. Over many parts of the world, heavy rainfall events have been steadily increasing throughout this century giving the potential for more flooding. Precipitation does not increase uniformly but it should increase overall. In the United States, precipitation amounts have trended upwards by about 10% over the past century. Increased heat for drying means that naturally-occurring droughts are likely to be exacerbated. Thus droughts, such as those set up by El Niño, are likely to set in quicker, plants will wilt sooner, and the droughts may become more extensive and last longer with global warming. Once the land is dry then all the solar radiation goes into raising temperature, bringing on the sweltering heat waves.

Other even more important changes may be in the offing. The 1997-98 El Niño is the biggest recorded event by several measures. The last two decades have been marked by unusual El Niño activity

(Trenberth and Hoar 1996, 1997). A key question is how is global warming influencing El Niño? Because El Niño is involved with movement of heat in the tropical Pacific Ocean, it is conceptually easy to see how increased heating from the build up of greenhouse gases can interfere. Climate models certainly show changes with global warming, but none simulate El Niño with sufficient fidelity to have confidence in the results. So the question of how El Niño may change with global warming is a research topic.

Why Extremes are Important

For any change in mean climate, there is likely to be an amplified change in extremes. Figure 4 shows this for a simple case where the bell-shaped distribution of anomalies of temperature is shifted to correspond to a warmer climate. If the mean temperature is 15° C and the standard deviation is 5° C, then 95% of the values fall within plus or minus two standard deviations (5° to 25° C) on a given day and which value occurs depends on the weather. If the mean is increased by 2.5° C but with the same variability, then there is a small change in occurrence near the mean. The biggest percentage change is for the extremes: the frequency of occurrence of temperatures above 27° C increases by well over 100% while similar decreases occur for temperatures below 3° C. The wide range of natural variability associated with day-to-day weather means that we are unlikely to notice most small climate changes except for the extremes.



Temperature

Extremes are exceedingly important to both natural systems and human systems and infrastructure, as we are adapted to a range of natural weather variations, and it is these extremes that exceed tolerances and cause nonlinear effects: the so-called "straw that breaks the camel's back". For instance, floods that used to have an expected return period of 100 years may now recur in 50 or 30 years. In practice, this effect may be experienced in floods through dams or levees that break, inundating the surrounding countryside and urban areas, resulting in drownings, water damage, and more subtle effects such as polluted drinking waters. Yangtze River flooding in 1998 and 1999 is a case in point, but the same has also happened in the United States, in California in early 1997, in the Red River valley in the Dakotas in spring 1997, and in the Upper Mississippi Basin in 1993, as just three examples. Insect and disease outbreaks often follow.

Concluding remarks

In evaluating weather events, it is important to have 1) a global picture, 2) a comprehensive picture over several months to allow patterns to be discerned, and 3) a perspective that encompasses all aspects of the weather. In particular, it is insufficient to just consider temperatures when dealing with effects of global warming. The "air conditioning" effects of moisture are extremely important and the fact that the warm regions are often separate from the wet regions is an important part of the picture.

In 1995 the IPCC assessment concluded that "the balance of evidence suggests that there is a discernible human influence on global climate". Since then the evidence has become much stronger --- from the recent record warmth, the improved paleo-record that provides context and estimates of natural variability, improved modeling and simulation of the past climate, and improved statistical analysis. The best assessment of the global warming contribution is that the signals emerged from the noise of background variability in the late 1970s, and have biggest impact especially by making the extremes more extreme that they otherwise would have been. While some changes arising from global warming are benign or even beneficial, the economic effects of the weather extremes are substantial and clearly warrant further attention in policy debates.

While increasing forested regions helps, IPCC estimates that restoring vegetation to natural states, would reduce carbon dioxide in 2100 by only 5 to 10%. Consequently, there is a strong case for slowing down the projected rates of climate change from human influences. Any climate change scenario is fraught with uncertainties, and so slowing down provides time for researchers to proved better projections of how the climate may change and the impacts of those changes. Slowing down climate change also allows adaptation to changes as they come along and better planning. Natural systems and human systems, many of which have long amortization lifetimes (e.g., power stations, dams, buildings) are less likely to be dislocated. Increasing use of renewable resources, such as solar power, and increased energy efficiency are clearly key steps toward slowing the rate of climate change as well as a more sustainable world.

References

IPCC (Intergovernmental Panel of Climate Change), 1996: Climate Change 1995: The Science of Climate Change. Eds. J. T. Houghton, F. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge Univ. Press, Cambridge, U.K. 572 pp.

IPCC, 2001: Climate Change 2001. The scientific basis. Eds. J. T. Houghton, Y. Ding, M. Nogua, D. Griggs, P. Vander Linden, K. Maskell, Cambridge Univ. Press., Cambridge, U.K., (in press).

Kiehl, J. T., and K. E. Trenberth, 1997: Earth's annual global mean energy budget. *Bull. Am. Met. Soc.*, **78**, 197-208.

Mann, M. E., R. S. Bradley and M. K. Hughes, 1998: Global-scale temperature patterns and climate forcing over the past 6 centuries. *Nature*, **392**, 779-787.

Mann, M. E., R. S. Bradley and M. K. Hughes, 1999: Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophys. Res. Lttrs.*, **26**, 759-762.

Revelle, R. and H. E. Suess, 1957: Carbon dioxide exchange between atmosphere and ocean and question of an increase of atmospheric CO2 during the past decades. *Tellus*, **9**, 18-27.

Ross, R. J., and W. P. Elliott, 1996: Tropospheric water vapor climatology and trends over North America: 1973-93. *J. Climate*, **9**, 3561-3574.

Trenberth, K. E., 1997: The use and abuse of climate models in climate change research. *Nature*, **386**, 131-133.

Trenberth, K. E., 1998: Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change. *Climatic Change*, **39**, 667-694.

Trenberth, K. E., and T. J. Hoar, 1996: The 1990-1995 El Niño-Southern Oscillation Event: Longest on record. *Geophys. Res. Lttr.*, **23**, 57-60.

Trenberth, K. E., and T. J. Hoar, 1997: El Niño and climate change. *Geophys. Res. Lttr.*, **24**, 3057-3060.

Wigley, T. M. L., 1998: The Kyoto protocol: CO2, CH4 and climate implications. *Geophys. Res. Lttr.*, **25**, 2285-2288.

Go to List of CAS Papers