An update on human-induced climate change

Testimony of

Dr. Kevin E. Trenberth[*]
National Center for Atmospheric Research[**]

before

The U. S. Senate Committee on Environment and Public Works
The United States Senate
Room 406 of the Dirksen Senate Building
Committee on Science and Technology
10:00 a.m., July 22, 2008

[*] Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the National Science Foundation.
[**] The National Center for Atmospheric Research (NCAR) is sponsored by the National Science Foundation.

Summary

In 2007 the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), known as AR4, clearly stated that "Warming of the climate system is unequivocal" and it is "very likely" due to human activities. Since the IPCC report, nature continues to provide evidence that it is under duress with impacts affecting people and animals. Increasing rates of carbon dioxide emissions raise the specter that future climate changes could be much larger and come much quicker than IPCC suggests.

The AR4 found that warming of the climate system is unequivocal based on an increasing body of evidence showing discernible physically consistent changes. These include increases in global average surface air temperature; atmospheric temperatures above the surface, surface and sub-surface ocean water temperature; widespread melting of snow; decreases in Arctic sea-ice extent and thickness; decreases in glacier and small ice cap extent and mass; and rising global mean sea level. The observed surface warming at global and continental scales is also consistent with reduced duration of freeze seasons; increased heat waves; increased atmospheric water vapor content and heavier precipitation events; changes in patterns of precipitation; increased drought; increases in intensity of hurricane activity, and changes in atmospheric winds. This wide variety of observations gives a very high degree of confidence to the overall findings. Because these changes are now simulated in climate models for the past 100 years to a reasonable degree, there is added confidence in future projections for more warming and increased impacts. Moreover, these changes in physical variables are reflected in changes in ecosystems and human health.

Carbon dioxide concentrations are increasing at rates beyond the highest of the IPCC scenarios, suggesting even bigger and faster climate change than IPCC projected. Warming is manifested in multiple ways, not just increases in temperatures. Most dramatic is the loss of Arctic sea ice in 2007, which affects surrounding areas and promotes changes in permafrost, as well as polar bears and other native species. Distinctive patterns of temperature and precipitation anomalies in the winter of 2007-08 were characteristic of the strong La Niña that had a signature over most of the world. In the first 6 months of 2008, record heavy rains and flooding in Iowa, Ohio, and Missouri, led to overtopped levees along the Cedar River in Iowa and the Mississippi, and point to the increases in intensity of rains associated with more water vapor in the atmosphere: a direct consequence of warming. The record breaking numbers of tornadoes and deaths in the U.S. in 2008 probably also have a global warming component from the warm moist air coming out of the Gulf of Mexico adding to instability of the atmosphere. Longer dry spells also accompany warming, as heat goes into evaporating moisture, drying and wilting vegetation, and thus increasing the risk of wild fire enormously. Wild fires in California early in 2008 and again this summer are evidence of the impacts. In 2007, for the first time, two category 5 hurricanes made landfall in Central America. Recent devastation from typhoon Nargis in Myanmar and typhoon Fengshen that hit the Philippines are signs of lack of adequate planning for consequences. In the Atlantic in July 2008, hurricane Bertha has broken several records for how early and how far east it formed, and it is the longest lasting July hurricane. Sea level rise, perhaps the best single indicator of a warming planet, continues at a rate of over a foot a century. Changes in ocean acidity accompany the buildup in carbon dioxide in the atmosphere with consequences for sea creatures, and bleaching of corals occurs in association with warming oceans. Melting permafrost exposes huge potential sources of methane and carbon dioxide that can amplify future climate change. Global warming is not just a threat for the future, it is already happening, endangering the health and welfare of the planet. There is a crisis of inaction in addressing and preparing for climate change.

Introduction

Thank you for the opportunity to appear before the Committee. My name is Kevin Trenberth. I am a senior scientist and the Head of the Climate Analysis Section at NCAR, the National Center for Atmospheric Research. I have authored over 400 publications in the area of climate, many highly cited, and given hundreds of talks on the subject. I am especially interested in global-scale climate dynamics; the observations, processes and modeling of climate changes from interannual to centennial time scales. I have particular expertise in El Niño, the hydrological and energy cycles, and hurricanes and climate change. I have served on many national and international committees including National Research Council/National

Academy of Science committees, panels and/or boards. I co-chaired the international Climate Variability and Predictability (CLIVAR) Scientific Steering Group of the World Climate Research Programme (WCRP) from 1996 to 1999 and I have served as a member and officer of the Joint Scientific Committee that oversees the WCRP as a whole from 1998 to 2006. I chair the WCRP Observations and Assimilation Panel. I have been extensively involved in the Intergovernmental Panel on Climate Change (IPCC) scientific assessment activity as a lead author of individual chapters, the Technical Summary, and Summary for Policy Makers (SPM) of Working Group (WG) I for the Second, Third and Fourth Assessment Reports (SAR, TAR and AR4; IPCC 1996, 2001, 2007a,b). I was Coordinating Lead Author of Chapter 3 of WG I of AR4 that deals with observations of the surface and atmospheric climate change.

The IPCC is a body of scientists from around the world convened by the United Nations jointly under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) and initiated in 1988. Its mandate is to provide policy makers with an objective assessment of the scientific and technical information available about climate change, its environmental and socio-economic impacts, and possible response options. The IPCC reports on the science of global climate and the effects of human activities on climate in particular. Major assessments were made in 1990, 1995, 2001, and 2007. Each new IPCC report reviews all the published literature over the previous 5 to 7 years, and assesses the state of knowledge, while trying to reconcile disparate claims and resolve discrepancies, and document uncertainties.

WG I deals with how the climate has changed and the possible causes. It considers how the climate system responds to various agents of change and our ability to model the processes involved as well as the performance of the whole system. It further seeks to attribute recent changes to the possible various causes, including the human influences, and thus it goes on to make projections for the future. WG II deals with impacts of climate change, vulnerability, 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 the United Nations countries, and for the 2007 assessment there were over 450 lead authors, 800 contributing authors, and over 2,500 reviewers from over 130 countries. The IPCC process is very open. Two major reviews were carried out in producing the report, and climate "skeptics" can and do participate, some as authors. All comments were responded to in writing and by changing the report. The process is overseen by two Review Editors for each chapter. The SPM were approved line by line by governments. The rationale is that the scientists determine what can be said, but the governments help determine how it can best be said. Negotiations occur over wording to ensure accuracy, balance, clarity of message, and relevance to understanding and policy. The strength is that it is a consensus report but the process also makes it a conservative report.

Observed Climate Change

The following includes a summary of aspects of the IPCC report, which mostly takes account of observations through 2005, but with updates on more recent changes and developments in the context of the IPCC findings.

Carbon dioxide concentrations in the atmosphere have increased such that current values of about 385 ppmv are over 36% higher than pre-industrial values of 280 ppmv and over half that increase has occurred since 1970 (Fig.1). Of particular note is the clear evidence that carbon dioxide concentrations are increasing at rates beyond the highest of the IPCC scenarios (Raupach et al., 2007) in spite of the Kyoto Protocol, suggesting that climate changes are apt to become larger than any IPCC projections. Although U.S. emissions continue to climb, large increases in emissions from China and India contribute to the acceleration, and in 2007 China supposedly surpassed the U.S. as leader in annual emissions. Carbon dioxide comes primarily from burning of fossil fuels in association with energy production and industrial activity (see the U.S. Energy Information Administration web pages for detailed data, e.g., http://www.eia.doe.gov/iea/environment.html.) There is no doubt that carbon dioxide is a greenhouse gas and causes warming, and it has a long lifetime which is why amounts are increasing in the atmosphere. Other greenhouse gases also contribute significantly to warming, while aerosols and dust more often cause cooling and regionalize some of the radiative forcing. A direct consequence of the escalating level of

carbon dioxide in the atmosphere is the world's ocean becoming more acidic, dramatically altering ocean chemistry and threatening corals and other marine organisms that secrete skeletal structures (e.g., Caldeira et al., 2007).

Since 1979, measurements from space have been made of changes in the sun and, as there are no changes of consequence during the period to date, changes in the sun are not responsible for the large changes observed in climate since the 1970s.

The iconic summary statement of the observations section of the IPCC (2007a) report is "**Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level."** The language was carefully chosen to reinforce the view that

1) There are multiple lines of evidence from many variables
2) There is a wide body of evidence and multiple analyses of each variable
3) The variables and evidence are physically consistent with warming
4) The human signal has clearly emerged from noise of natural variability, i.e., it is large.

This finding fundamentally changes the way we think about and approach climate change. Previously, we have always supposed (scientists refer to it as a null hypothesis) that the climate is not changing and the onus has been to prove that global warming is having an effect. Now this should switch to an underlying hypothesis that global warming is affecting all aspects of weather and climate, and the onus is on showing this is not the case. We are often asked, "Is a particular event caused by global warming or natural variability?" The answer is that it is always both.

a. Temperature

Instrumental observations over the past 158 years show that temperatures at the surface (Fig. 1) have risen globally, with important regional variations. For the global average, warming in the last century occurred in two phases, from the 1910s to the 1940s (0.35°C or 0.63ºF), and more strongly from the 1970s to the present (0.55°C or 1.0ºF) at a rate of about 0.16ºC (0.3ºF) per decade. An increasing rate of warming has taken place over the last 25 years, and 12 of the 13 warmest years on record have occurred in the past 13 years. The total warming since the 1800s is about 0.76ºC (1.4ºF). Globally, 2006 ranks 6th and was the second warmest on record in the United States (behind 1998), while 2007 ranks as 8th warmest. Sea surface temperatures (SSTs) are also increasing, however land areas are warming much faster than the oceans since 1970.

Two possible issues with the surface temperature record – urban heat island effects, and discrepancies with balloon-based and satellite measurements – were extensively studied in the IPCC (2007a) report. The urban heat island effects are real but local, and have been found to have a negligible influence on the overall surface temperature record. New analyses of balloon-borne and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to the surface temperature record and consistent within their respective uncertainties. The 2007 IPCC report essentially removes these two issues as serious sources of uncertainty for the global surface temperature record.

Regional temperature observations do not always track the global average warming because of atmospheric wave patterns, as well as increased natural variability at smaller geographic scales. For example, the eastern half of the United States has not warmed as much as other areas, especially during the daytime, owing to increases in cloud and precipitation associated with changes in atmospheric circulation as the climate changes. On the other hand, average Arctic temperatures increased at almost twice the global average rate in the past 100 years and also since 1960. However, Arctic temperatures have high decadal variability and a warm period was observed from 1925 to 1945, but that was focused in the North Atlantic and not global as in the recent warming.

Since 1950, the number of heat waves globally has increased and widespread increases have occurred in the numbers of warm nights. Cold days, cold nights and frost have generally become rarer.

For the United States (Fig. 2), the temperatures feature an especially warm period in the 1930s and it is only in the past decade that these values have been exceeded. Six of the 10 warmest years for the contiguous U.S. have occurred since 1998. In the summer half year, there is a strong negative correlation

between temperature and precipitation: it is either hot and dry or cool and wet, but not other combinations. Hence, the record heat in the 1930s was associated with the drought of the Dust Bowl years (see also the precipitation in Fig. 2). In contrast, the warming over the U.S. since about 1970 has taken place in spite of the exceptionally wet conditions that have generally prevailed, even as the year-to-year variations still tend to reflect changing precipitation. It is important to recognize this aspect of local variability: wetter conditions mean more cloud and less sunshine, and more heat goes into evaporation of surface water instead of increasing temperature. The change in the 1970s to much wetter and cloudier conditions across the United States, especially east of the Rockies, corresponds to a change in the atmospheric circulation and more El Niño-like conditions. The eastern U.S. is unique around the world in not having warmed by day in some areas during the 20th century. In 2007, this pattern broke down in association with the development of a La Niña event, and a substantial drought in the Southeast ensued, with major water shortages as a result. The eastern U.S. would be exceedingly vulnerable to such events if the atmospheric circulation were to return to pre-1970 patterns. Because of the nature of the changes over the past four decades, the U.S. is more vulnerable to large future warming and drought than many other areas.

b. Temperature related

The average atmospheric water vapor content has increased over land and ocean as well as in the upper troposphere, and over the global oceans this is estimated to be 4% since 1970. The increase is broadly consistent with the extra moisture that warmer air can hold and amounts to a fairly constant relative humidity. The added water vapor also adds to the greenhouse effect and roughly doubles that due to carbon dioxide, providing a powerful positive feedback to climate change.

Decreases are found in the length of the freeze season of river and lake ice. Temperature at the top of the permafrost layer has increased by up to 3°C since the 1980s in the Arctic. The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900 and this value is up to 15% in spring.

The average temperature of global ocean water from the surface to a depth of 700 m increased significantly from 1961 to 2003, indicating that the ocean is absorbing most of the heat being added to the climate system. This causes seawater to expand and is estimated to have contributed 0.42 mm per yr to the average sea level rise from 1961 to 2003, and 1.8 mm per yr from 1993 to 2003.

Sea-ice extents have decreased in the Arctic since 1978, particularly in spring and summer (7.4% per decade through 2005), and patterns of the changes are consistent with regions showing a temperature increase, although changes in winds are also a major factor. The AR4 only included data through 2005 and sea-ice extents were at record low values in 2005, which was also the warmest year since records began in 1850 for the Arctic north of 65°N. This record has since been smashed in 2007 when Arctic sea ice dropped to over 20% below the 2005 value. There have also been decreases in sea-ice thickness. The result in 2008 is that there is an unprecedented amount of first year ice in the Arctic that is very vulnerable to melting.

In contrast to the Arctic, Antarctic sea ice did not exhibit any significant trend from the end of the 1970s through 2006, which is consistent with the lack of trend in surface temperature south of 65°S over that period. However, along the Antarctic Peninsula, where significant warming has occurred, progressive break up of ice shelves occurred beginning in the late 1980s, culminating in the break up of the Larsen-B ice shelf in 2002. In 2008 there was a marked expansion of Antarctic sea ice in association with changes in atmospheric winds.

The observed surface temperature increases are consistent with the observed nearly worldwide reduction in glacier and small ice cap mass and extent in the 20th century. In addition, flow speed has recently increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior, and melting of Greenland and West Antarctica has increased after about 2000. Critical changes (not well measured) are occurring in the ocean and ice shelves that buttress the flow of glaciers into the ocean. Glaciers and ice caps respond not only to temperatures but also to changes in precipitation, and both winter accumulation and summer melting have increased over the last half century in association with temperature increases. In some regions moderately increased accumulation observed in recent decades is consistent with changes in atmospheric circulation and associated increases in winter precipitation (e.g., southwestern Norway, parts of coastal Alaska, Patagonia, and the South Island of New Zealand) even though increased

ablation has led to marked declines in mass balances in Alaska and Patagonia. Tropical glacier changes are synchronous with higher latitude ones and all have shown declines in recent decades. Decreases in glaciers and ice caps contributed to sea level rise by 0.5 mm per yr from 1961 to 2003 and 0.8 mm per yr from 1993 to 2003. Taken together, shrinkage of the ice sheets of Greenland and Antarctica contributed 0.4 mm per yr to sea level rise over 1993 to 2003.

Global average sea level rose at an average rate of 1.8 mm per year from 1961 to 2003. The rate was faster after 1992 (Fig. 3), when truly global values have been measured from altimeters in space, at about 3.2 mm per yr from 1993 to early 2008. About 60% of this is from ocean warming and expansion, and 40% is from melting land ice, adding to the ocean volume. The observation of consistent sea level rise over several decades, and also an increasing rate of sea level rise in the last decade or so, is probably the single best metric of the cumulative global warming that we have experienced to date. There is really no explanation other than global warming for the observed sea level rise. A consequence is increasing risk of coral bleaching and coastal storm surge flooding.

In the northern winter of 2007-08, a strong La Niña event dominated the patterns of weather especially around the Pacific and had major influences across the United States. It also affected sea ice in the southern oceans. The cooling of the tropical Pacific Ocean amounts to a redistribution of heat within the ocean and it affects the jet stream and tracks of cyclones around the world. Only in northern Europe and Asia was the weather pattern not identified with La Niña, and the pattern called the North Atlantic Oscillation played a role there in making conditions much warmer than normal. The net result was a very snowy winter and above normal snow cover in North America, but much below normal snow cover for Eurasia, and much below for the hemisphere as a whole. Even sea level rise leveled off after mid-2007 (Fig. 3), suggesting a loss of heat from the ocean and/or a slowing of melting of glaciers and the ice sheets. This is exactly as expected and a counter example is in 1997/98 (Fig. 3) when a major El Niño occurred. Such natural variability is to be expected: global warming does not mean relentless warming at every place and time.

The observed surface warming at global and continental scales is consistent with observed changes in sub-surface ocean water temperature; decreases in sea-ice extent and thickness; decreases in glacier and small ice cap extent and mass; sea-level rise; reduced duration of freeze seasons, increased heat waves; and increased atmospheric water vapor content. Hence the Earth is warming, and major components of the Earth's climate system are already responding to that warming. This wide variety of observations gives a very high degree of confidence to the overall findings.

c. Precipitation and related

The IPCC (2007a) report finds that changes are occurring in the amount, intensity, frequency, and type of precipitation in ways that are also consistent with a warming planet. These aspects of precipitation generally exhibit large natural variability (compared to temperature trends), and El Niño and changes in atmospheric circulation patterns have a substantial influence, making it harder to detect trends in the observational record.

A key ingredient in changes in character of precipitation is the observed increase in water vapor and thus the supply of atmospheric moisture to all storms, increasing the intensity of precipitation events. Indeed, widespread increases in heavy precipitation events and risk of flooding have been observed, even in places where total amounts have decreased. Hence the frequency of heavy rain events has increased in most places but so too has episodic heavy snowfall events that are thus associated with warming. Snow cover has decreased in many Northern Hemisphere regions, particularly in spring, and more precipitation is falling as rain instead of snow. These changes are consistent with changes in permafrost, noted above.

Long-term trends from 1900 to 2005 have been observed in total precipitation amounts over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally. Robust long term trends have not been observed for other large regions. The pattern of precipitation change is one of increases generally at higher northern latitudes (because as the atmosphere warms it holds more moisture) and drying in the tropics and subtropics over land. Basin-scale changes in

ocean salinity provide further evidence of changes in the Earth's water cycle, with freshening at high latitudes and increased salinity in the subtropics. Continental U.S. changes are given in Fig. 2.

More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying due to higher temperatures and decreased precipitation have contributed to these changes, with the latter the dominant factor. The regions where droughts have occurred are determined largely by changes in SST, especially in the tropics (such as during El Niño), through changes in the atmospheric circulation and precipitation. In the western United States, diminishing snow pack and subsequent summer soil moisture reductions have also been a factor. In Australia and Europe, direct links to warming have been inferred through the extreme nature of high temperatures and heat waves accompanying drought.

Satellite records suggest a global trend towards more intense and longer lasting tropical cyclones (including hurricanes and typhoons) since about 1970, correlated with observed warming of tropical SSTs. There is no clear trend in the annual number of tropical cyclones globally although a substantial increase has occurred in the North Atlantic after 1994. There are concerns about the quality of tropical cyclone data, particularly before the satellite era. Further, strong multi-decadal variability is observed and complicates detection of long term trends in tropical cyclone activity. In the Atlantic, many records were broken in the 2004 and 2005 hurricane seasons, with unprecedented damage in Katrina. It has been estimated that heavy rains in tropical storms and hurricanes (including Katrina) have increased by 6 to 8% as a result of higher SSTs and more water vapor in the atmosphere (Trenberth et al., 2007). In 2007, a record number of two category 5 hurricanes made landfall in the Americas, both hitting Central America. Widespread damage has also occurred in 2008 from typhoons in Myanmar (Nargis) and Fengshen in the Philippines. In the Atlantic, Bertha has broken several records for how early and how far east it formed, and it has also been the longest-lasting July tropical storm.

In the U.S., not only are precipitation amounts generally up since the 1970s (Fig. 2), but heavy rains are up much more: the top 0.3% are up 27% in the 40 years from 1967 to 2006 (Groisman and Knight, 2008). The same study also shows that dry spells of one or two months have also increased in most places, as the warm season has increased by 5 to 6 days in length. Easterling et al. (2007) show that drought would have been much more common and widespread if it were not for the increases in precipitation after the 1970s (Fig. 2). Temperatures would also have been much higher and with more heat waves.

d. Synthesis across variables

In summary, global mean temperatures have increased since the 19th century, especially since the mid-1970s. Temperatures have increased nearly everywhere over land, and SSTs have also increased, reinforcing the evidence from land. However, global warming does not mean that temperatures increase steadily or uniformly, indeed temperatures have increased neither monotonically, nor in a spatially uniform manner, especially over shorter time intervals. The atmospheric circulation has also changed: in particular increasing westerly wind flow is observed in most seasons in both hemispheres. In the Northern Hemisphere this brought milder maritime air into Europe and much of high-latitude Asia from the North Atlantic in winter, enhancing warming there. In the Southern Hemisphere, where the ozone hole has played a role, it has resulted in cooling since 1971 for parts of the interior of Antarctica but large warming in the Antarctic Peninsula region and Patagonia. Temperatures generally have risen more than average where flow has become more poleward, and less than average or even cooled where flow has become more equatorward, reflecting atmospheric patterns of variability.

Over land in low latitudes and in summer more generally, there is a strong tendency for either hot and dry or cool and wet. Hence areas that have become wetter, such as the eastern United States and Argentina, have not warmed as much as other land areas. Increased precipitation is associated with increases in cloud and surface wetness. Thus more heat goes into increased evapotranspiration and less into raising temperature at the surface in wetter conditions.

The three main ocean basins are unique and contain very different wind systems, SST patterns and ocean currents, leading to vastly different variability associated, for instance, with El Niño/La Niña in the Pacific, and the ocean currents including the Gulf Stream in the Atlantic. Consequently the oceans have not warmed uniformly, especially at depth. SSTs in the tropics have warmed at different rates and help drive,

through coupling with tropical convection and winds, distinctive wave patterns known as teleconnections around the world. This has changed the atmospheric circulation and the monsoons. Another consequence is increases in ocean acidity that accompany the buildup in carbon dioxide in the atmosphere with consequences for sea creatures. Changes in precipitation and storm tracks are not as well documented but clearly respond to these changes on interannual and decadal timescales. When precipitation increases over the ocean, as it has in recent years in the tropics, it decreases over land, although it has increased over land at higher latitudes. Droughts have increased over many tropical and mid-latitude land areas, in part because of decreased precipitation over land since the 1970s but also from increased drying arising from increased atmospheric demand associated with warming.

Warming promotes increases in both drought and temperature. Changes in both come as the heat goes into raising temperature or drying (evaporation) and, as the temperatures increase, the water holding capacity of the atmosphere goes up at 4% per deg F. Hence warmer temperatures have the effect of drawing moisture out of plants and soils. In the U.S., even as rains have become heavier (more intense), so dry spells have also become longer. The two go hand in hand and relate to how precipitation changes: more intense but less frequent, and the amount changes less. After a certain point where the ground is dry and the plants have reached wilting point, all the heat goes into raising temperature and creating heat waves, and then wild fire risk goes up substantially. The West has warmed more than the East (east of Rockies) and the latter region has become noticeably wetter in general, while drought has become more common in the West. All of this indeed promotes wildfire risk, and "dry lightning" is disastrous, especially in areas where trees are damaged such as by bark beetle. Wild fires in California early in 2008 and again this summer are direct evidence of the impacts. As of June 30, more than 2.1 million acres have burned this year according to the National Interagency Fire Center, the third highest on record after 2006 and 2002. Of course the risk of wild fire does not necessarily translate into a wild fire if care has been taken in managing the risk by building wild fire breaks, cutting down on litter, removing diseased and dead trees and vegetation near buildings, etc. A key question in recognizing that global warming is happening, is whether adequate preparation for the changes (whether heavy rains, drought, or wild fire risk) has been made?

A consequence of these findings is that what were once 500 year flood events are now more like 30 or 50 year events. A particular example has been seen in the central U.S in the first 6 months of 2008 as record heavy rains have occurred in Iowa, Ohio, and Missouri, with associated flooding through overtopped levees along the Cedar River in Iowa and the Mississippi. This follows from similar flooding in 1993, just 15 years ago. The record breaking numbers of tornadoes and deaths in the U.S. in 2008 probably also has a modest global warming component. Tornadoes are most common in the spring and early summer in weather systems moving across the U.S. that bring warm moist low-level air flowing from the Gulf of Mexico into the storms, while drier westerly winds aloft create wind shear that leads to rotation and thus tornadic thunderstorms. Because the Gulf air is warmer and moister than it would otherwise have been 30 or more years ago, the instability of these storms is enhanced. The effect is not measurable owing to the nature of tornado statistics which mainly reflect increasing numbers of people in more places.

Consequences of the physical changes in climate in terms of public health are addressed extensively in WG II of IPCC (2007b), and see also Haines et al. (2007). Datasets are not as good or as long as for physical variables, and autonomous adaptation occurs to changing conditions to some degree. Climate change effects occur amidst increases in life expectancy in most places, and are thus hard to sort out. However, evidence already exists for changes in infectious disease vectors and allergenic pollens. Direct effects include those given above from changes in heat, cold, storms (including hurricanes and tornadoes), drought, and wild fires. In 2008 preliminary counts through June are that 119 people have died in tornadoes in the United States. The drought-related heat wave in Europe in summer 2003 killed as many as 35,000 people. On the other hand fewer cold waves reduce mortality. Safe drinking water is jeopardized by more intense rains and runoff which can lead to contamination and increased microbial loading, sometimes overwhelming water treatment plants (if they exist). Hence water-borne diseases have been observed to increase. Also drought and observed earlier snow melt and runoff jeopardize water supplies, especially in summer. Changes in temperatures, humidity and precipitation also affect the environment for pests and disease, and have increased risk of certain problems in plants, animals and humans. Changes in phenology, reproduction, and geographic range are occurring, disrupting predator-prey relationships. Some species have

become extinct. For instance, pine beetle that has devastated huge tracts of lodge-pine forest in the West has climate dependencies and flourishes and spreads in warmer temperatures. Evidence of climate change effects is also evident in fish, such as salmon. Air quality is also changing from pollution, and ground level ozone and particulate matter are increasing in most regions, with increased hospital admissions for respiratory disease. The capacity to adapt to these changes varies greatly regionally, but all of these problems or changes are evident in North America. Particular human health problems have occurred with spread of West Nile virus, which requires warmer temperatures to survive. Similarly, Lyme disease, borne by ticks, is associated with temperature and precipitation.

Modeling climate change and projections

Many of the above observed changes are now simulated in climate models run for the past 100 years, adding confidence to understanding of the relationship with the agents that alter the climate, and human-induced changes in atmospheric composition. In particular, when anthropogenic forcings are included, the models simulate the observed global and continental-scale temperature records with impressive fidelity. The models can then be used to simulate the record without anthropogenic forcings, and the results are similar up till about 1970, and it is only since then that the human influence has emerged above the levels of natural variability. Also, the models indicate that volcanic and anthropogenic aerosols have offset some of the additional warming that would have resulted from observed increases in greenhouse gas concentrations alone.

A climate model is a tool; often a very sophisticated tool that encapsulates much of our understanding about the complex climate system. But it is still a model that makes assumptions and approximations, and is a grossly simplified version of the real world. Faster computers that can permit much higher resolution are required, for one thing, to merely capture our current understanding about the role of currently unresolved phenomena such as hurricanes. Adding more processes and complexity could also allow progress to be made. The main way models have been used is to examine the change in response to some new forcing. This avoids worrying about specifying the initial state. But it means the result is not a prediction. It is referred to as a projection based on a "what-if" scenario of future emissions and forcing.

Climate models have crude representation of aerosols and their forcing, and clouds are the biggest source of uncertainty. Climate models have some systematic errors in placement of precipitation, in the diurnal cycle of precipitation, and in phenomena such as El Niño. George Box is credited with saying *"All models are wrong, some are useful*". It applies to climate models especially well. No-one should base a decision on a climate model and its output without proper evaluation as to whether it is in the useful category. In fact models are used to guide decisions every day: weather forecasts, seasonal forecasts, and so on. But they should not be used as a "black box". IPCC (2007a) evaluates the utility of climate models and uses them in their projections.

The climate is changing and the past is no longer a good guide to the future. So what should we use for guidance? Any decision involves a model: whether it is a model of no change (which is surely wrong), a back-of-the-envelope or heuristic model perhaps based on someone's limited experience, a simple energy balance model, or a full blown global climate model that requires a super computer to run. At least the latter includes many of the feedbacks and nonlinearities that we know are so important. But it does not include them all. For instance, carbon cycle feedbacks are not included in models used by IPCC. Warming promotes permafrost melt and also decay of soil vegetable matter generating methane (if a wet anaerobic environment) or carbon dioxide (if a dry aerobic environment). It also promotes out-gassing of carbon dioxide from the oceans as the oceans warm. These are likely to amplify the climate changes that have been projected from IPCC in the decades ahead.

Some of the major results from AR4 models, with some updates and commentary, include:

- Owing to the long lifetime of carbon dioxide and other greenhouse gases, even if no further emissions occurred into the atmosphere we are guaranteed to have further warming of the planet, amounting to about 1°F according to IPCC, but possibly quite a bit larger if feedbacks not accounted for in models kick in (such as with the carbon cycle noted above).

- Over the next two decades, all models produce similar warming trends in global surface temperatures, regardless of the emissions scenario. The rate of the projected warming is near 0.2°C per decade.
- Decadal-average warming over each inhabited continent by 2030 is insensitive to the emission scenario; but by the middle of the 21st Century the choice of scenario becomes more important for the magnitude of surface warming, and by the end of the 21st Century there are clear consequences for which scenario is followed. The best estimate of the global surface temperature change from today to the end of the century is +1.8°C (with a likely range of +1.1°C to +2.9°C) for the low emission scenario (corresponding to a carbon dioxide equivalent concentration of 600 ppm by 2100) and +4.0°C (+2.4°C to +6.4°C) for the highest emission scenario (corresponding to 1,550 ppm). This result highlights the long lead times required before measures taken are effective in reducing the threat of global warming.
- Geographical patterns of warming show greatest temperature increases at high northern latitudes and over land, with less warming over the southern oceans and North Atlantic, as has been observed in recent decades. In spite of a slowdown of the meridional overturning circulation and changes in the Gulf Stream in the ocean across models, there is still warming over the North Atlantic and Europe due to the overwhelming effects of the increased concentrations of greenhouse gases.
- Sea ice coverage is projected to shrink in polar regions. In 2006 a model suggested that there are real prospects for the Arctic becoming ice free in late summer by about the 2040s (Holland et al., 2006) and the record low Arctic sea ice observed in 2007 suggest that this may be happening a lot faster than most models suggest. The IPCC models fail to capture these dramatic changes.
- Snow cover is projected to contract, with widespread increases in thaw depth over most permafrost regions. Another recent study (Lawrence et al, 2008) with a climate model suggests that permafrost may melt much faster than previously thought partly as a consequence of the diminishing sea ice, with consequences for the carbon cycle.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.
- It is likely that tropical storms and hurricanes will become more intense and with much heavier rainfalls, and thus risk of flooding.
- The observed patterns of precipitation change in recent decades is projected to continue, with increases over northern continents but decreases over subtropical regions, increasing risk of drought. At the same time, dry spells are expected to increase everywhere. Water resources will be a major issue and perhaps the biggest source of stress on society.
- Projections of sea level rise by the end of the century in IPCC range from 30 to 40 cm, but do not include possible ice sheet collapse. These climate models have very primitive modeling of ice sheets and the role of buttressing ice shelves (e.g., Shepherd and Wingham, 2007; Rignot et al., 2008), leading to considerable uncertainty in possible future sea level rise. The IPCC estimates of future sea level rise could be low by a factor of 2 or more.
- Consequences of these physical changes in climate are addressed extensively in WG II of IPCC (2007b) (see above for observed changes), and projections are based on many case studies of relationships of impacts with weather and climate. Increasing risk occurs especially with direct effects of heat and extreme weather events (including tornadoes, hurricanes, thunderstorms, and extratropical cyclones), air quality, spread of water-, food- and vector-borne diseases, disruptions to forests and also agriculture, resulting in food scarcity, fresh water shortages, changes in biological systems and disruptions in predator-prey relationships, and public health effects (e.g., Haines et al., 2007). The effects and vulnerability vary greatly by region, but even the U.S. is at risk for adverse impacts in many of these areas.

Models can be exceedingly useful if used wisely. Observed climate changes are now sufficiently large, and models in IPCC have now improved to the point that they simulate many of the observed changes going on. As shown by recent sea ice and ice sheet changes, the IPCC conclusions are quite conservative. We very much need to improve models and have access to faster bigger computers.

Some implications

The scientific understanding of climate change is now sufficiently clear to show that specific global and regional changes resulting from global warming are already happening, possibly faster than IPCC has projected. Uncertainties remain, and new efforts at reprocessing past satellite records for phenomena such as hurricanes are required, but the 2007 IPCC report definitively shows that the climate is changing. "Warming is unequivocal" and it is "very likely" caused by human activities.

In my personal opinion as a climate scientist, there is a need for a three pronged approach of mitigation, adaptation, and maintaining and improving climate observing and information systems.

While there are uncertainties (although these cut both ways) and some changes arising from global warming may be benign or even beneficial, at least in some places and in the short run, the IPCC report shows that the rate of change as projected exceeds anything seen in nature in the past 10,000 years. Moreover, the inertia of the climate system and the long life of carbon dioxide in the atmosphere mean that we are already committed to a significant level of climate change. I believe that mitigation actions are certainly needed to significantly reduce the build-up of greenhouse gases in the atmosphere and lessen the magnitude and rate of climate change. Action taken now to reduce significantly the build-up of greenhouse gases in the atmosphere will lessen the magnitude and rates of climate change. In fact I believe there is a crisis of lack of adequate action in this regard.

At the same time, the 2007 IPCC report makes clear that even aggressive mitigation would yield benefits decades in the future, and that no amount of mitigation can avoid significant climate change. It is apt to be disruptive in many ways. Hence it is also vital to plan to cope with the changes, such as enhanced droughts, heat waves and wild fires, and stronger downpours and risk of flooding. Managing water resources will be a major challenge in the future. Adapting to climate change and reducing vulnerability is essential. This means that we should adapt to climate change by planning for it and making better predictions of likely outcomes on several time horizons.

Finally, although not reported by the IPCC, my experience in working with observations of climate change has led me to urge the Committee to address the considerable shortcomings in our observing systems. Weather observing systems are continually used for climate purposes for which they were not designed. Moreover, weather stations come and go and changes are made without regard to the effect on the climate record. Changes in observing systems, especially from satellites, as new satellites and instruments are launched, create artifacts in the climate record. Loss of Earth observing satellites is also of concern, as documented in the National Research Council (2007) decadal survey. Ground based observations are not being adequately kept up in many countries. Calibration of climate records is critical. Small changes over long times are characteristic of climate change but they occur in the midst of large variations associated with weather and natural climate variations such as El Niño. Yet the climate is changing and an imperative is to track the changes and the causes as they occur. We need to build a system based on these observations to inform decision makers on what is happening, and why, and what the predictions are for the future on several time horizons.

In summary, global warming is coming, ready or not.

I appreciate the opportunity to address the Committee concerning the science of global climate change, and look forward to answering any questions you may have today or in the future.

References and some bibliography

Caldeira, K., et al. (2007), Comment on "Modern-age buildup of CO_2 and its effects on seawater acidity and salinity" by Hugo A. Loáiciga, *Geophys. Res. Lett.*, 34, L18608, doi:10.1029/2006GL027288.

Easterling, D. R., T. W. R. Wallis, J. H. Lawrimore, and R. R. Heim Jr., 2007: Effects of temperature and precipitation trends on U.S. drought, *Geophys. Res. Lett.*, **34**, L20709, doi:10.1029/2007GL031541.

Groisman, P.Ya., and R. W. Knight, 2008: Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years. *J. Climate*, **21**, 1850-1862.

Haines, A., R.S. Kovats, D. Campbell-Lendrum and C. Corvalan, 2007 : Climate change and human health : Impacts, vulnerability and public health. *Public Health*, **120**, 585-596.

Holland, M.M., C.M. Bitz, and B. Tremblay, 2006: Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters*, **33,** L23503, doi:10.1029/2006GL028024

IPCC (Intergovernmental Panel on Climate Change), 1996: *Climate Change 1995: The Science of Climate Change*. Eds. J. T. Houghton et al., Cambridge University Press, Cambridge, U.K. 572 pp.

IPCC, 2001: *Climate Change 2001: The Scientific Basis*. Eds. J. T. Houghton, et al., Cambridge University Press, Cambridge, U.K. 881 pp.

IPCC, 2007a: *Climate Change 2007. The Physical Science Basis*. S. Solomon, et al. Eds. Cambridge University Press. Cambridge, U. K., 996pp.

IPCC, 2007b: Climate Change 2007: Impacts, Adaptation and Vulnerability, M.L. Parry, et al., Eds., Cambridge University Press, Cambridge, UK, 976pp.

Karl, T. R., and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302**, 1719–1723.

Karl, T. R., and K. E. Trenberth, 2006: Modern global climate change. *Science Magazine's State of the Planet*, Donald Kennedy and the editors of *Science* magazine, Eds., Island Press, 88–98.

Lawrence, D. M., A. G. Slater, R. A. Tomas, M. M. Holland, and C. Deser, 2008: Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss, *Geophys. Res. Lett.*, **35**, L11506, doi:10.1029/2008GL033985.

National Research Council, 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The National Academies Press.

Raupach, M. R., G. Marland, P. Ciais, C. Le Quéré, J. G. Canadell, G. Klepper, and C.B. Field, 2007: Global and regional drivers of accelerating CO_2 emissions. PNAS. doi_10.1073_pnas.0700609104.

Rignot, E., J.L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W.J. van de Berg, E. van Meijgaard, 2008: Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, – *Nature Geoscience*, doi:10.1038/ngeo102.

Shepherd, A., and D. Wingham, 2007: Recent sea-level contributions of the Antarctic and Greenland Ice Sheets. *Science*, **315**, 1529–1532.

Trenberth, K. E., 2001: Stronger evidence for human influences on climate: The 2001 IPCC Assessment. *Environment*, **43**, 4(May), 8–19.

Trenberth, K. E., 2005: Uncertainty in hurricanes and global warming. *Science*, **308**, 1753-1754.

Trenberth, K. E., 2007: Warmer oceans, stronger hurricanes. *Scientific American*, July, 2007, 45–51.

Trenberth, K. E., 2008: The impact of climate change and variability on heavy precipitation, floods and droughts. *Encyclopedia of Hydrological Sciences.* M. H. Anderson (Ed.) J. Wiley and Sons, Ltd. Chichester, UK. Doi: 10.1002/0470848944.hsa211.

Trenberth, K. E., and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.*, **33**, L12704, doi:10.1029/2006GL026894.

Trenberth, K. E., T. R. Karl and T. W. Spence, 2002: The need for a systems approach to climate observations. *Bull. Amer. Meteor. Soc.*, **83**, 1593–1602.

Trenberth, K. E., C. A. Davis and J. Fasullo, 2007: Water and energy budgets of hurricanes: Case studies of Ivan and Katrina. *J. Geophys. Res.*, **112**, D23106, doi:10.1029/2006JD008303.

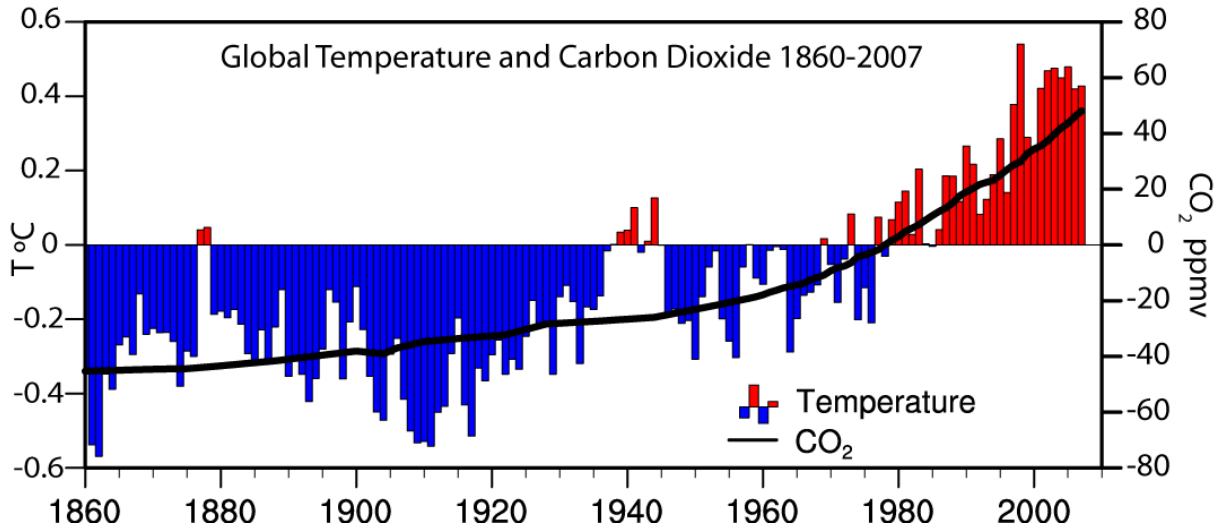

Figure 1. Time series of annual global mean temperature departures for 1861-2007 from a 1961-90 mean (bars), left scale, and the annual mean carbon dioxide from Mauna Loa after 1957 linked to values from bubbles of air in ice cores prior to then. The zero value for 1961-90 for temperature corresponds to 14ºC and for carbon dioxide 334 parts per million by volume (ppmv). Updated from Karl and Trenberth (2003); original data from HADCRUv3 http://www.cru.uea.ac.uk/cru/data/temperature/#datdow, and http://www.esrl.noaa.gov/gmd/ccgg/trends/.

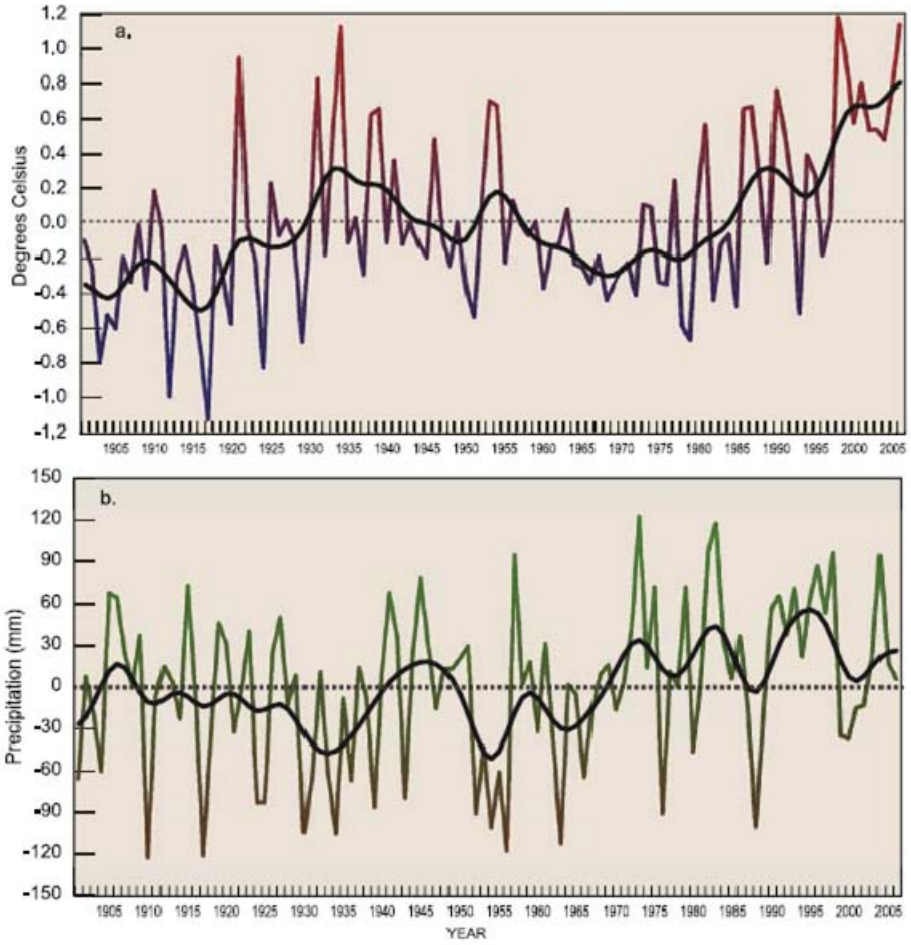

Figure 2. Changes from 1901 to 2006 in the continental US temperatures (top) and precipitation amounts (bottom): annual and smoothed decadal values; from Easterling et al. (2007)

.

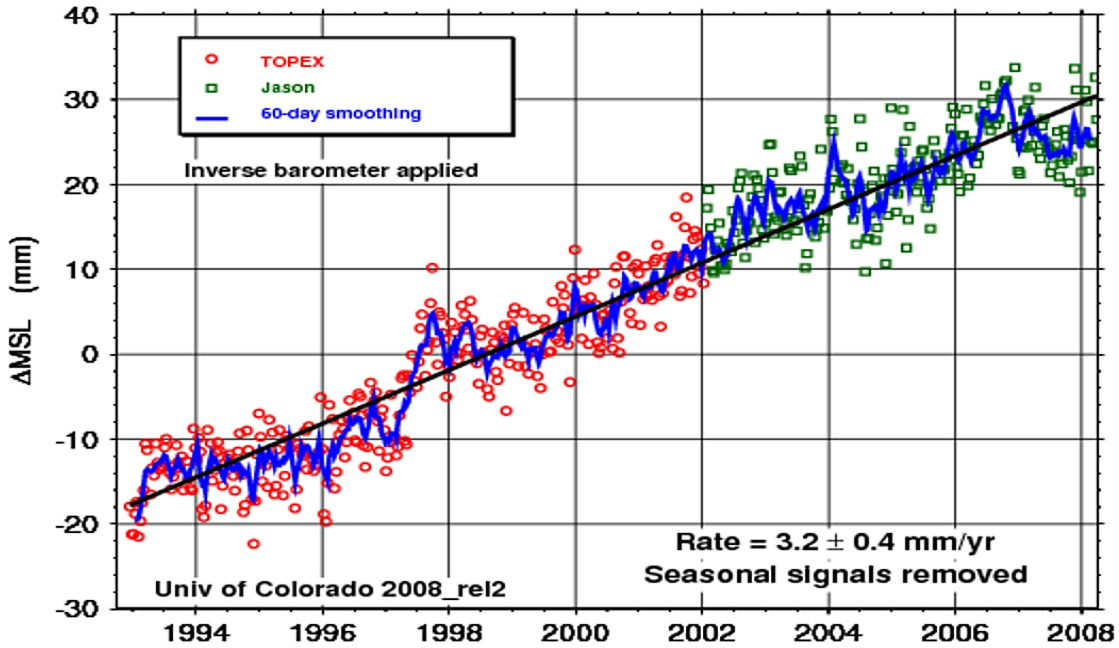

Figure 3. Sea level changes based on altimetry from space from the TOPEX/Poseidon and Jason measurements, processed to remove the mean annual cycle and with an inverse barometer correction applied (to account for changing sea level pressure over the oceans). From Univ. Colorado http://sealevel.colorado.edu/current/sl_ib_ns_global.jpg courtesy Steve Nerem.