Statement of

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Introduction

I thank Chairman Markey, Ranking Member Sensenbrenner and the other Members of the Select Committee for the opportunity to speak with you today on observed and likely future changes in climate and the contribution from human activity to those changes. My name is James W. Hurrell. I am a Senior Scientist at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, where I currently serve as the Chief Scientist of the NCAR Community Climate System Modeling project. My personal research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability and climate change. I have authored or co-authored more than 80 peer-reviewed articles in leading scientific journals, numerous book chapters, and dozens of other planning documents and workshop papers. I have given more than 120 keynote and invited lectures worldwide, as well as many contributed presentations at national and international conferences on climate. I have also convened many national and international climate workshops, and I have served several national and international science-planning efforts. Currently, I am extensively involved in the World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR), and I serve as the co-chair of the Scientific Steering Group of International CLIVAR. I have been involved as an author in both national and international assessment activities on climate and climate change, including lead author on several chapters dealing with observed change in climate. I have also served on several National Research Council panels.

In today’s testimony I will address the observed changes to the climate system and the evidence that provides attribution of these changes to human activities. Indeed, significant advances in the scientific understanding of climate change now make it clear that there has been a change in climate that goes beyond the range of natural variability. The culprit is the astonishing rate at which greenhouse gas (GHG) concentrations are increasing in the atmosphere, mostly through the burning of fossil fuels and changes in land use, such as those associated with agriculture and deforestation. GHG are relatively transparent to incoming solar radiation while they absorb and reemit outgoing infrared radiation. The result is that more energy stays in the global climate system, raising not only temperature but also producing many other direct and indirect changes in the climate system.

In the sections that follow, I will briefly summarize major observed changes in climate, with a focus on changes in surface climate. I will then summarize how natural and anthropogenic drivers of climate change are assessed using climate models. After describing projections of future climate change by these models, I will conclude with remarks on a few anticipated impacts of climate change on the United States and the world.

Observed changes in climate

Surface Temperature

The globe is warming dramatically compared with natural historical rates of change. Global surface temperatures today are more than 0.75°C (1.4°F) warmer than at the beginning of the 20th century, and U.S. average temperature has risen by a comparable amount. Moreover, rates of temperature rise are greatest in recent decades (Figure 1). Over the last 50 years, the rate of warming is nearly double that of the 100-year trend, and 14 of the 15 warmest years in the global surface instrumental temperature record (beginning around 1850) have occurred since 1995. The period since 2001 is ~ 0.2°C (0.4°F) warmer than the 1991-2000 decade. Global land regions have warmed the most (0.7ºC or 1.3°F) since 1979, with the greatest warming in the boreal winter and spring months over the Northern Hemisphere continents.

There is a very high degree of confidence in the aforementioned global surface temperature values and the change estimates. The maximum difference, for instance, among three independent estimates of global surface temperature change since 1979 is 0.01ºC (0.018°F) per decade. Small differences that do exist relate to how missing data are treated, especially over the Arctic where major warming is clearly evident from sea ice melt. Two of the surface temperature data sets have 2005, and not 1998, as the warmest year in the instrumental record. Spatial coverage has improved, and daily temperature data for an increasing number of land stations have also become available, allowing more detailed assessments of extremes, as well as potential urban influences on large-scale temperature averages. It is well documented, for instance, that urban heat island effects are real, but very local, and they have been accounted for in the analyses: the urban heat island influence on continental, hemispheric and global average trends is at least an order of magnitude smaller than decadal and longer timescale trends, as cities make up less than 0.5% of global land areas.

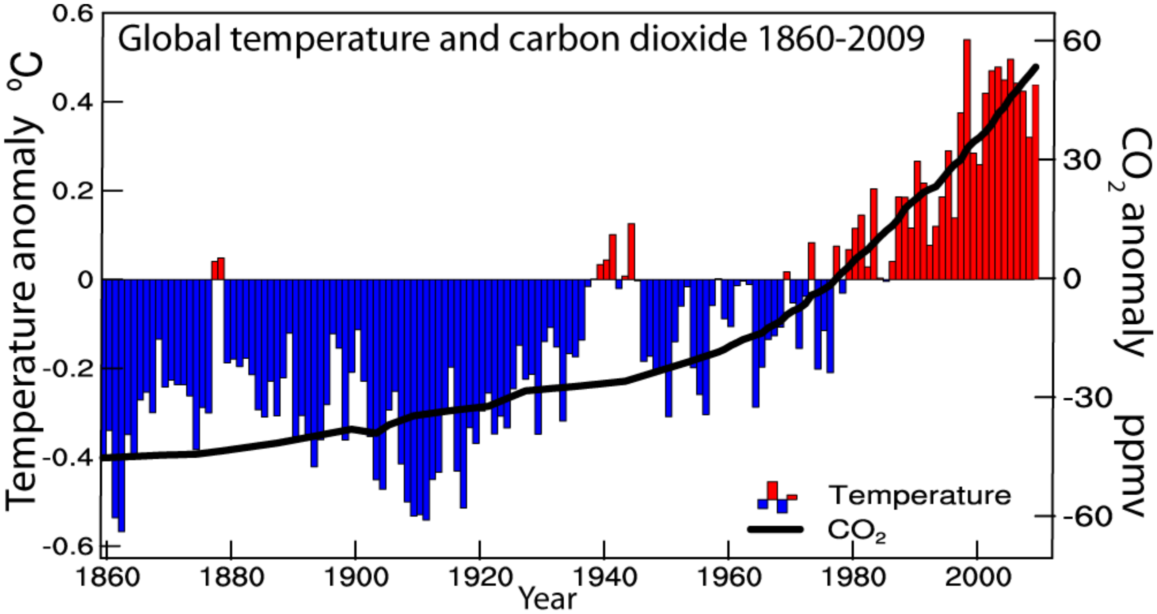

Figure 1. *Estimated changes in annual global mean surface temperatures (ºC, color bars) and CO_2 concentrations (thick black line) over the past 150 years. The changes are shown as differences (anomalies) from the 1961-1990 average values. Carbon dioxide concentrations since 1957 are from direct measurements at Mauna Loa, Hawaii, while earlier estimates are derived from ice core records. The scale for CO_2 concentrations is in parts per million (ppm) by volume, relative to a mean of 333.7 ppm, while the temperature anomalies are relative to a mean of 14ºC (57°F).*

Of course there is absolutely no urban heat effect (bias) in the global sea surface temperature (SST) record. Over the global oceans, surface temperatures have warmed 0.35ºC (0.63ºF) since 1979, and the warming is strongly evident at all latitudes over each of the ocean basins. Moreover, the warming is evident not only at the surface but deep in the ocean as well, indicating that the ocean is absorbing most of the heat being added to the climate system. Such changes in global average temperature do not imply, however, that changes are uniform around the globe. There are notable regional and seasonal variations, especially over relatively short time periods (year-to-year and even decade-to-decade). Regional differences in SST change arise, for instance, from natural variability. One example is the very strong warming of the central and eastern tropical Pacific Ocean that occurs during El Niño events typically every few years. These events also produce regional cooling over portions of the subtropical oceans and the tropical western Pacific. Over the Atlantic, the average basin-wide ocean warming is imposed on top of strong, natural variability on multi-decadal time scales. The level of natural variability, in contrast, is relatively small over the tropical Indian Ocean, where the surface warming has been steady and large over recent decades. These important differences in regional rates of surface ocean warming also affect the atmospheric circulation, producing changes in the atmospheric flow so that some regions warm more than others, while other regions cool, especially over periods of years or even decades.

A good example of the substantial role that natural climate variability plays over shorter periods of time is the strong La Niña conditions during the northern winters of 2007-08 and 2008-09. This cooling of the tropical Pacific SSTs contributed to relatively cooler conditions worldwide; moreover, starting from the record global warmth in 1998, some have argued global warming has ceased, ignoring the fact that the long-term trend is clearly upward (Figure 2) and, over the past decade, most years have remained close to the 1998 value. Because of such natural variations in the climate system, climate scientists have long recognized that a temporary slowdown in the rate of warming is possible even while GHG concentrations continue to increase. Climate models also predict such behavior.

Another example of the strong impact of natural variability occurred this past winter, when extraordinary conditions in the North Atlantic Oscillation (NAO) combined with a moderate-to-strong El Niño to produce very distinctive and strong weather patterns across portions of the Northern Hemisphere. In particular, it was unusually cold over parts of North America and Eurasia this past winter, even as the rest of the world was well above normal in temperature (e. g., March 2010 was the warmest March on record, and the 3-month season from January through March 2010 was the fourth warmest winter season on record). El Niño and NAO conditions also contributed to the record breaking snow storms in the Washington D.C. region as well as flooding heavy rain events in New

England this past winter. Such natural variations in climate are expected and will continue, even as the overall climate system warms.

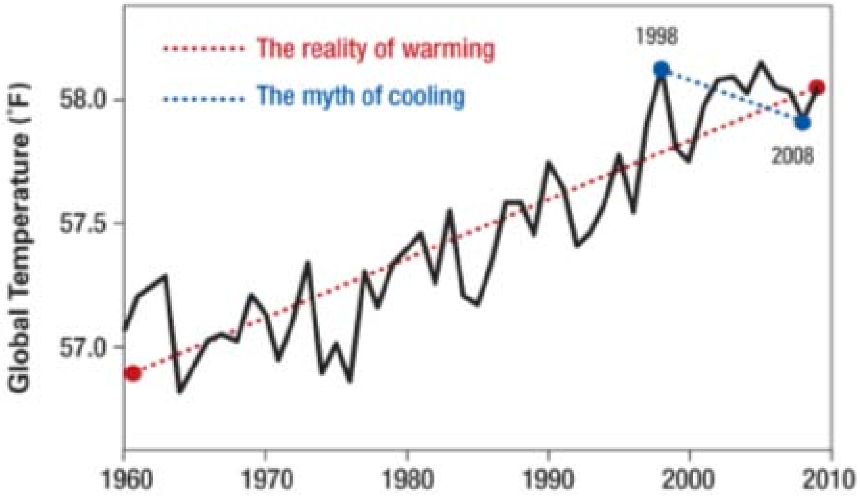

Figure 2. *Changes in annual global mean surface temperatures (ºF) since 1960. Note the record surface warmth in 1998 from the major El Niño. Moreover, trends over short periods of time (1998-2008, blue) do not accurately reflect the longer-term warming (red). From NOAA/NCDC*

Sea level

The warming ocean waters expand and, thus, contribute to sea level rise. Melting of glaciers on land as well as ice caps and ice sheets also contribute by adding water to the ocean. Instrumental measurements of sea level indicate that the global average has increased approximately 17 cm (6.7 inches) over the last century, and the increase has been 0.18 cm (0.07 inches) per year since 1961. The rate has been even faster recently (about 0.33 cm or 0.13 inches per year from 1993 through 2009), when truly global values have been measured from altimeters in space (Figure 3). Prior to 2004, about 60% of global sea level rise is from ocean warming and expansion, while 40% was from melting land ice adding to the ocean volume. Since 2004 melting ice sheets have contributed more.

The observation of consistent global 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. This is because sea level is a great integrator: it is not affected appreciably by a cold winter or two in Washington or London, a hot summer in

Kansas, or a hurricane like Katrina. A consequence of ocean warming and rising sea levels is increasing risk of coral bleaching and coastal storm surge flooding.

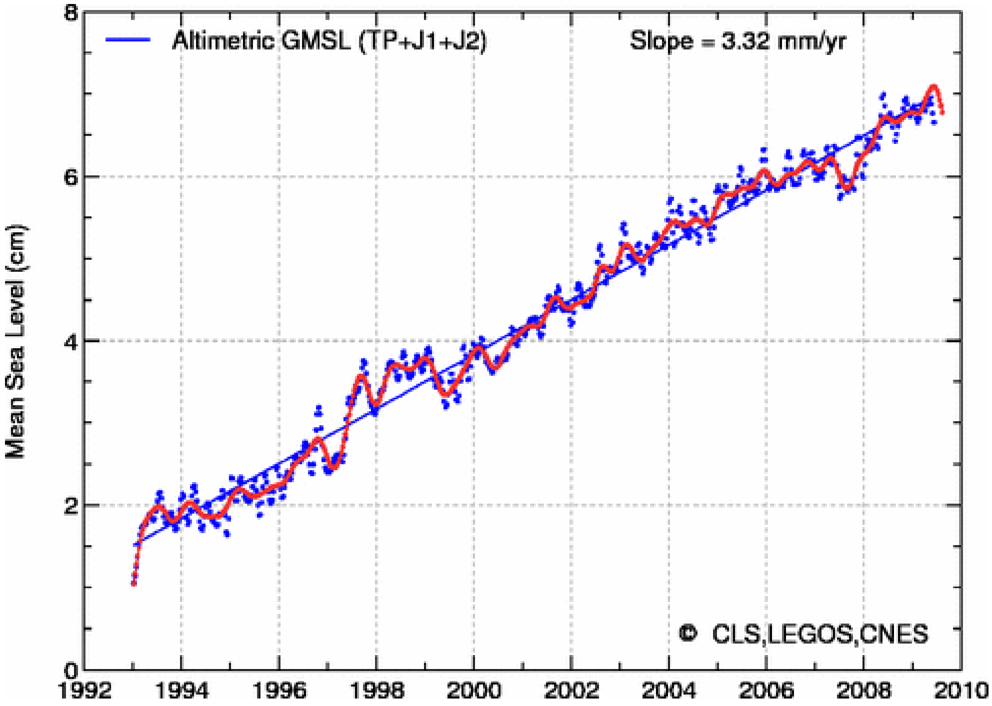

Figure 3. *This figure shows a steady rise in average global sea level since 1993 when satellite data became available using a technique called radar altimetry. Radar altimetry uses a radar on a satellite to precisely measure the distance between the sea surface and the satellite. Courtesy of www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/, where one may also obtain the raw data that produced the figure. Other independent groups have also computed sea level rise (e.g. NOAA, http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/ , and the results are very similar to this one.)*

Snow cover, sea and land ice

The observed increases in surface temperature are consistent with nearly worldwide reductions 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 temperature 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 those at higher latitudes and have shown declines in recent decades. Decreases in glaciers and ice caps contributed to global sea level rise by 0.05 cm (0.02 inches) per year from 1961 to 2003, and 0.08 cm (0.03 inches) per year from 1993 to 2003. Taken together, shrinkage of the ice sheets of Greenland and Antarctica contributed 0.04 cm (0.016 inches) per year to sea level rise over 1993 to 2003. Since then evidence suggests increased melting of both Greenland and Antarctica, whereby they contribute about 0.1 cm (0.04 inches) per year to sea level rise, about equally.

Snow cover has decreased in many Northern Hemisphere regions, particularly in the spring season, and this is consistent with greater increases in spring than autumn surface temperatures in middle latitude regions. Sea-ice extents have decreased in the Arctic, particularly in the spring and summer seasons (7.4% per decade decrease from 1978 through 2005), and this is consistent with the fact that the average annual Arctic temperature has increased at almost twice the global average rate, although changes in winds are also a major factor. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) included data only through 2005 when sea-ice extents were at record low values, which was also the warmest year since records began in 1850 for the Arctic north of 65°N. This record was smashed in 2007 when Arctic sea ice dropped to over 20% below the 2005 value. There have also been decreases in sea-ice thickness. With an unprecedented amount of first-year ice in the Arctic that is very vulnerable to melting, 2008 ranks slightly higher in terms of sea-ice extent than 2007, and 2009 ranks third, but still lower than 2005. The total peak summer time decrease in Arctic sea ice is about 40% of the 1970s values. Temperatures at the top of the permafrost layer in the Arctic have increased since the 1980s (up to 6°F locally), and the maximum area covered by seasonally frozen ground has decreased by about 7% in the NH since 1900, with an even greater decrease (15%) in the boreal spring. There has been a reduction of about two weeks in the annual duration of northern lake and river ice cover.

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 been observed, 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. Antarctic conditions are uniquely influenced greatly by the ozone hole, which alters the atmospheric circulation over the southern regions.

Extremes

For changes in mean temperature, there is likely to be an amplified change in extremes. Extreme events, such as heat waves, are exceedingly important to both natural systems and human systems and infrastructure. People and ecosystems are adapted to a range of natural weather variations, but it is the extremes of weather and climate that exceed tolerances. Widespread changes in temperature extremes have been observed over the last 50 years. In particular, the number of heat waves globally has increased, and there have been widespread increases in the numbers of warm nights. Cold days, cold nights and days with frost have become rarer.

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. Recent community consensus is that heavy rains in tropical storms and hurricanes have increased by 6 to 8% as a result of higher SSTs and more water vapor in the atmosphere, and that hurricane intensity may be increasing.

Precipitation and drought

Changes are also 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, 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 on average. 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.

Long-term (since 1900) trends 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 Earth’s water cycle, with freshening at high latitudes and increased salinity in the subtropics.

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.

In summary, there are an increasing number of many independent surface observations that give a consistent picture of a warming world. Such multiple lines of evidence, the physical consistency among them, and the consistency of findings among multiple, independent analyses form the basis for the iconic phrase from the AR4 of IPCC that the “warming of the climate system is unequivocal”.

Human and natural drivers of climate change

The scientific consensus is that most of the observed global temperature increase of the past 50 years is due to human activity. This conclusion is based on studies that assess the causes of climate change, taking into account all possible agents of climate change (forcings), both natural and from human activities.

Forcings are external to the climate system and may arise, for instance, from changes in the sun or from changes in atmospheric composition associated with explosive volcanic eruptions. These phenomena occur naturally. Human activities that generate heat or which change the atmospheric composition are also external to the climate system but do not occur naturally. In contrast, many feedbacks occur through interactions among the components of the climate system: the atmosphere, ocean, land and cryosphere (which includes sea, lake and river ice, snow cover, glaciers, ice caps, ice sheets, and frozen ground). Some amplify the original changes producing a positive feedback, while others diminish them: a negative feedback. Feedbacks considerably complicate the climate system, and the physical processes involved are depicted in climate models. Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it.

The capability of climate models to simulate the past climate has been comprehensively assessed in the peer-reviewed scientific literature. Given good replications of the past, the forcings can be removed one by one to disassemble their effects and allow attribution of the observed climate change to the different forcings. Therefore, climate models are a key tool to evaluate the role of various forcings in producing the observed changes in temperature and other climate variables.

The best climate 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. Uncertainties arise, however, from shortcomings in the understanding and how to best represent complex processes in models. Yet, in spite of these uncertainties, today's best climate models are able to reproduce the climate of the past century, and simulations of the evolution of global surface temperature over the past millennium are consistent with paleoclimate reconstructions.

As a result, climate modelers are able to test the role of various forcings in producing observed changes in climate. Human activities increase long-lived GHG, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other traces gases. They also increase aerosol concentrations in the atmosphere, mainly through the injection of sulfur dioxide (SO_2) from power stations and through biomass burning. A direct effect of sulfate aerosols is the reflection of a fraction of solar radiation back to space, which tends to cool the Earth's surface. Other aerosols (like soot) directly absorb solar radiation leading to local heating of the atmosphere, and some absorb and emit infrared 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 and the lifetime of the cloud. The precise nature of aerosol/cloud interactions and how they interact with the water cycle remains a major uncertainty in our understanding of climate processes. Because man-made aerosols are mostly introduced near the Earth's surface, they are washed out of the atmosphere by rain in typically a few days. They thus remain mostly concentrated near their sources and affect climate with a very strong regional pattern, usually producing cooling.

In contrast, GHG such as CO_2 and CH_4 have lifetimes of decades or much longer. As a result, they are globally mixed and concentrations build up over time. GHG concentrations in the atmosphere have increased markedly as a result of human activities since 1750, and they are now higher than at any time in at least the last 650,000 years. It took at least 10,000 years from the end of the last ice age (18,000 years ago) for levels of CO_2 to increase 100 parts per million (ppm) by volume to 280 ppm, but that same increase has occurred over only the past 150 years to current values in excess of 385 ppm (Figure 1). About half of that increase has occurred over the last 35 years, owing mainly to combustion of fossil fuels and changes in land use. The CO_2 concentration growth-rate was larger during the last decade than it has been since the beginning of continuous direct measurements in the late 1950s. In the absence of controls, future projections are that the rate of increase in CO_2 amount may accelerate, and concentrations could double from pre-industrial values within the next 50 to 100 years.

Methane is the second most important anthropogenic GHG. Owing predominantly to agriculture and fossil fuel use, the global atmospheric concentration of CH_4 has increased from a pre-industrial value of 715 part per billion (ppb) by volume to 1774 ppb in 2005, although growth rates have declined since the early 1990s, consistent with total emissions (natural and anthropogenic sources) being nearly constant over this period. Global N_2O concentrations have increased significantly from pre-industrial values as well. Together, the combined radiative forcing from these three GHG is +2.3 Watts per square meter (W m^{-2}), relative to 1750, which dominates the total net anthropogenic forcing (+1.6 W m^{-2}). The total net anthropogenic forcing includes contributions from aerosols (a negative forcing) and several other sources, such as tropospheric ozone and halocarbons.

Climate model simulations that account for such changes in forcings consistently show that global surface warming of recent decades is a response to the increased concentrations of GHG and sulfate aerosols in the atmosphere. When the models are run without these forcing changes, the remaining natural forcings and intrinsic natural variability fail to capture the almost linear increase in global surface temperatures over the past 40 years or so. But when the anthropogenic forcings are included, the models simulate the observed global temperature record with impressive fidelity (Figure 4). Changes in solar irradiance since 1750 are estimated to have caused a radiative forcing of +0.12 W m^{-2}, mainly in the first part of the 20th century. Prior to 1979, when direct observations of the sun from space began, changes in solar irradiance are more uncertain, but direct measurements show that the sun has not caused warming since 1979. Moreover, the models indicate that volcanic and anthropogenic aerosols have offset some of the additional warming that would have resulted from observed increases in GHG concentrations alone. For instance, since about 2000 the sunspot cycle went from a maximum to a minimum and a very quiet sun, decreasing total solar irradiance by 0.1%.

This has contributed a slight cooling component to the planet, perhaps offsetting about 10 to 15% of the recent warming.

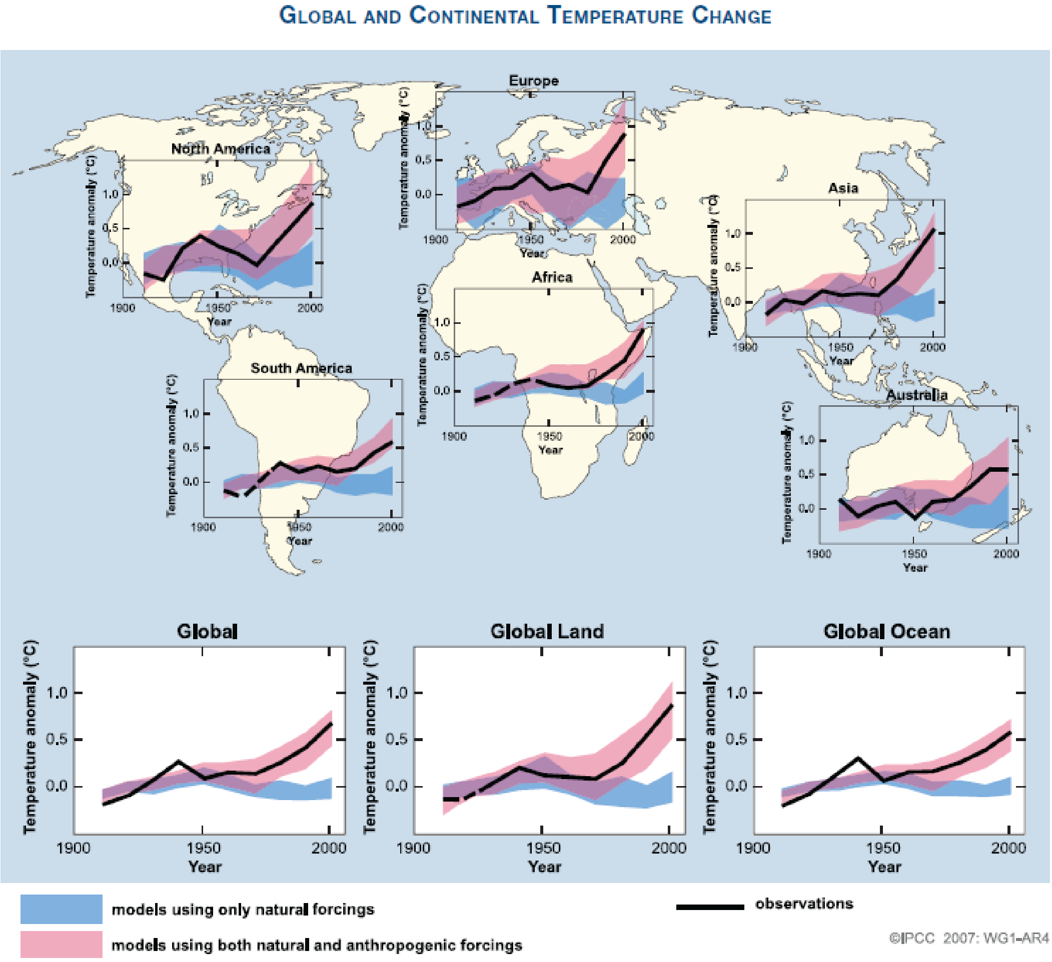

Figure 4. *Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for 1906–2005 (black line) plotted against the center of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. The figure is taken from the IPCC AR4 Working Group I Summary for Policymakers.*

A significant advancement is that a larger number of simulations available from a broader range of models allows for a more definitive evaluation of the role of various forcings in producing not only changes in global average temperature, but also changes in continental and ocean basin scale temperatures. The patterns of warming over each continent except Antarctica and each ocean basin over the past 50 years are only simulated by models that include anthropogenic forcing (Figure 4). Attribution studies have also demonstrated that many of the observed changes in indicators of climate extremes consistent with warming, including the annual number of frost days, warm and cold days, and warm and cold nights, have likely occurred as a result of increased anthropogenic forcing. In other words, many of the recently observed changes in climate are now being simulated in models.

The ability of climate models to simulate the temperature evolution on continental scales, and the detection of anthropogenic effects on each continent except Antarctica, provides very strong evidence of human influence on the global climate. No climate model that has used natural forcing only has reproduced either the observed global mean warming trend or the continental mean warming trends. Attribution of temperature change on smaller than continental scales and over time scales of less than 50 years or so is more difficult because of the much larger signal of natural variability on smaller space and time scales.

Projected future climate change

The ability of climate models to closely simulate the past climate record gives us increased confidence in their ability to simulate the future. We can now look back at projections from earlier climate change assessments and see that the observed rate of global warming since 1990 (about 0.36°F per decade) is within the projected range (0.27°F– 0.54°F). Moreover, the attribution of the recent climate change to increased concentrations of GHG in the atmosphere has direct implications for the future. Because of the long lifetime of CO_2 and the slow equilibration of the oceans, there is a substantial future commitment to further global climate change even in the absence of further emissions of GHG into the atmosphere. Several of the more recent climate model experiments explored the concept of climate change commitment. For instance, if concentrations of GHG were held constant at year 2000 levels (implying a very large reduction in emissions), a further warming trend would occur over the next 20 years at a rate of about 0.2°F per decade, with a smaller warming rate continuing after that. Such committed climate change is due to (1) the long lifetime of CO_2 and other GHG; and (2) the long time it takes for warmth to penetrate into the oceans. Under the aforementioned scenario, the associated sea level rise commitment is much longer term, due to the effects of thermal expansion on sea level. Water has the physical property of expanding as it warms; therefore, as the warming penetrates deeper into the ocean, an ever increasing volume of water expands and contributes to ongoing sea level rise. Since it would take centuries for the entire volume of the ocean to warm in response to the effects of GHG already in the air, sea level rise would continue for centuries. Further glacial melt is also likely.

The 16 climate modeling groups (from 11 countries) contributing to the AR4 produced the most extensive internationally coordinated climate change analysis ever performed. In total, 23 global coupled climate models were used to perform simulations of the 20th century climate, three scenarios of the 21st century (based on low, medium and high emission scenarios), and three idealized stabilization experiments. Some of the major results include:

- Over the next two decades, all models produce similar warming trends in global surface temperatures, regardless of the scenario. The rate of the projected warming is near 0.36°F per decade, or about twice that of the "commitment" runs.
- Decadal-average warming over each inhabited continent over the next decade or two is relatively insensitive to the emission scenario; moreover, the temperature change is very likely to exceed the model generated natural temperature variability by at least a factor of two. By the middle of the 21st century, however, 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 +3.2°F (with a likely range of +2.0°F to +5.2°F) for the low emission scenario (B1, corresponding to a CO_2 equivalent concentration of 600 ppm by 2100) and +7.2°F (+4.3°F to +11.5°F) for the highest emission scenario (A1F1, corresponding to 1,550 ppm). Recent emissions exceed even the A1F1 scenario owing especially to development in China, although very recently the global recession has slowed emissions somewhat.
- 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 GHG.

- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions.
- Sea ice coverage is projected to shrink. Large parts of the Arctic Ocean are expected to no longer have year-round ice cover by the middle of the 21st century. In AR4 the results were more suggestive of such changes by the end of the 21st century, but recent changes and new model results suggest that late-summer sea ice could disappear almost completely in just a few decades.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent. It is likely that hurricane intensity will increase. Models also project a 50 to 100% decline in the frequency of cold air outbreaks in most regions of the winter Northern Hemisphere. Related decreases in frost days contribute to longer growing seasons.
- Projections of sea level rise by the end of the century are similar to previous estimates, ranging from 30 to 40 cm (12 to 16 inches), but do not include possible ice sheet collapse.
- About 60-70% of the projected sea level rise is due to thermal expansion of sea water. There is less certainty of the future contributions from other sources. For instance, the projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed over the past decade, but how these flow rates might change in the future is not known.
- Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions, continuing recent trends.
- SLP is projected to increase over the subtropics and middle latitudes, and decrease over high latitudes. Consequently, storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns outside the tropics, continuing the pattern of observed trends over the last few decades.

Today’s climate models have better and more complete representations of many physical processes. But as our knowledge of the different components of the climate system and their interactions increases, so does the complexity of climate models. Historical changes in land use and changes in the distribution of continental water due to dams and irrigation, for instance, need to be considered. Future projected land cover changes due to human land uses are also likely to significantly affect climate, especially locally, and these effects are only just now being included in climate models.

One of the major advances in climate modeling in recent years has been the introduction of coupled climate-carbon models. Climate change is expected to influence the capacities of the land and oceans to act as repositories for anthropogenic CO_2, and hence provide a feedback to climate change. Though fewer global climate models include the complex processes involved with modeling the carbon cycle, this feedback is positive (adding to more warming) in all models so far considered. Therefore, the addition of carbon cycle feedbacks increases the fraction of anthropogenic emissions that remain in the atmosphere, thereby giving higher values on the warm end of the uncertainty ranges.

Impacts

Consequences of the physical changes in climate are numerous and are only briefly mentioned in this written testimony. Considerable evidence suggests that recent warming is affecting human health, water supply, agriculture, coastal areas, and many other aspects of society and the natural environment. For instance, impacts on terrestrial biological systems include earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying, and poleward and upward shifts in ranges in plant and animal species. Moreover, the resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g., flooding, drought, wildfire, insects, ocean acidification), and other human effects such as land use and change, pollution, and over-exploitation of resources.

An unmistakable sign of climate change in my part of the country, for instance, is not only earlier spring snowmelt, which alters the timing and amount of water supplies, but also the extremely large clusters of dead pine trees from the southern Rockies into vast parts of Canada and Alaska. Forest managers throughout the North American West have called the diebacks “catastrophic” and “unprecedented”. The area affected is 50 times larger than the area affected by forest fire with an economic impact nearly five times as great. The trees are succumbing to the relentless attack of the mountain pine beetle. Warming temperatures have not only removed the natural line of defense against such infestations, namely sufficiently cold temperatures in winter, but they are speeding up the life cycle of the beetle. In contiguous USA, for example, warmer summer temperatures are enabling the beetle to produce two generations in a year, when previously they reproduced once a year.

Global warming promotes increases in both drought through drying (evaporation) and temperature increases. With warmer air more moisture is drawn out of plants and the soil, and the water holding capacity of the atmosphere increases as well. Thus, in many places even as rains have become more intense, so too have dry spells become longer. A consequence of more intense but less frequent precipitation events is that what were once 500 year flood events are now more like 30 or 50 year events. After a certain point where the ground is dry and plants have reached wilting point, all of the heat goes into raising temperature and creating heat waves, and then wild fire risk goes up substantially. "Dry lightning" can then be disastrous, especially in areas where trees are damaged such as by bark beetles. 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, and removing diseased and dead trees and vegetation near buildings.

For humans, 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. Direct effects are nonetheless evident from changes in heat, cold, storms (including hurricanes and tornadoes), drought, and wild fires. The drought-related heat wave in Europe in summer 2003, for instance, killed tens of thousands of 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. 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. Air quality is changing from pollution, and ground level ozone and particulate matter are increasing in most regions, with increased hospital admissions for respiratory disease. Particular human health problems have occurred with spread of West Nile virus, which requires warmer temperatures to survive.

Concluding comments

The reality of anthropogenic climate change can no longer be debated on scientific grounds, a fact widely recognized by international science academies and professional scientific organizations. For instance, the American Association for the Advancement of Science states “The scientific evidence is clear: global climate change caused by human activities is occurring now, and it is a growing threat to society”. The imperative is to act aggressively to reduce carbon emissions and dependency on fossil fuels, creating instead a sustainable and clean energy future. Although mitigation actions taken now mainly have benefits 50 years and beyond because of the huge inertia in the climate system, earlier cuts in emissions of carbon dioxide would have a greater effect in reducing climate change than comparable reductions made later. Still, society will have to adapt to climate change, including its many adverse effects on human health and ecosystems. The projected rate of change far exceeds anything seen in nature in the past 10,000 years and is therefore apt to be disruptive in many ways.

This opportunity to address the Select Committee concerning the science of global climate change is a distinct honor and privilege. I look forward to answering your questions.