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I thank Chairman Boucher, Ranking Member Hastert and the Members of the Subcommittee for the opportunity to testify today, and I would like to also thank you for your leadership and interest in global warming. My name is Gabriele C. Hegerl. I recently had the pleasure of serving as a coordinating lead author on the U.N. Intergovernmental Panel of Climate Change's Fourth Assessment Report. Our report reflects a continued strengthening of the scientific evidence that human-caused global warming is occurring; we hope that it is helpful to policymakers seeking to address the issue.

First, a word on my background. I am a Research Professor at Duke University. I got my Ph.D. in applied mathematics at the Ludwig-Maximilians University in Munich, in a topic of numerical fluid dynamics. After that, I worked as Postdoctoral Scientist and then Research Scientist at the Max-Planck Institute for Meteorology in Hamburg, one of the world's leading climate modeling centers. I have since been a visiting scholar on a fellowship from the Alexander von Humboldt Association at the University of Washington, Seattle (1997-1999), a Research Scientist at Texas A&M (1999-2001) and have been a Research Professor at Duke since 2001. My scientific interest has been focused on understanding and determining the causes of observed climate change.

I have authored and coauthored about 50 scientific publications, and serve on a number of national and international committees, among them the National Research Council's Climate Research Committee, the National Center for Atmospheric Research (NCAR)'s advisory board for the Geophysical Statistics project, and the CLIVAR Joint Expert Team on Climate Change Detection and Indices. I have also served on the World Climate Research Program's (WCRP) Working Group on Coupled Modeling, 1999 to 2004.

I was a Lead Author of the Intergovernmental Panel on Climate Change (IPCC) Working Group I contribution to the Third Assessment Report, and am a Coordinating Lead Author of the Fourth Assessment Report that was just recently released. The chapter that I coordinated focuses on determining the causes of observed climate changes.

My testimony will answer three central questions: (1) Are global temperatures increasing? (2) are the increasing temperatures attributable to human activities? and (3) how do we expect future temperatures to be affected by continued human activity?

Key aspects of my answers are that there is unequivocal evidence that global temperatures are increasing. Secondly, a large body of scientific research shows that the observed changes in the global climate over the past half century strong reflect the “fingerprints” of greenhouse gas increases and other external influences on climate, leading the IPCC to conclude that most of the warming over the second half of the 20^{th} century has very likely been due to greenhouse gas increases. If greenhouse gases keep increasing, we will see substantially more warming than observed over the 20^{th} century. I attach a file with figures from my slide presentation to illustrate these key points. The figures are from the Summary for Policymakers or the Technical Summary for Working Group I of the IPCC Fourth Assessment Report.

1. Are global temperatures increasing?

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report concluded that “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”. This is a very strong statement, reflecting that the finding that warming is observed in many independent datasets, and that the observed changes are physically consistent with each other.

Direct measurements show that surface temperature warmed by 0.74^{o}C over the past century (1906 to 2005, 5-95% range 0.56-0.92^{o}C; this is a 1.3^{o}F warming with a range of 1.0-1.7^{o}F). This warming has been widespread, as seen in Figure 1. The largest amount of data is available during the second half of the century, when surface air temperatures, temperatures of the upper ocean, and temperatures of the lower atmosphere all increased and when most glaciers worldwide shrank. Therefore, evidence for warming is strong and comes from diverse parts of the climate system and many independent datasets.

2. If global temperatures are increasing, to what extent is the increase attributable to greenhouse gas emissions from human activity as opposed to natural variability or other causes?

Greenhouse gas increases caused very likely most of the warming over the second half of the 20^{th} century.

The observed warming, illustrated in figure 1, far exceeds the magnitude of warming or cooling that is expected from variability generated internally within the climate system. El Nino is one example of this so-called “natural variability” of the climate system. The fact that all major components of the climate system have gained heat supports the assessment that an external influence on the climate system is responsible, since such a significant change can only be plausibly explained by a change in the energy balance of the planet. Therefore, IPCC concluded that it is “extremely unlikely” (less than 1 chance in 20) that this warming was due to the internal variability of the climate system.

We also know that influences outside the climate system, that is, external forcing, can cause variations in climate. For example, it is well documented that explosive volcanic eruptions, which eject sulfate aerosols into the upper atmosphere, cause a worldwide cooling during the few years following such events. This happens because the aerosols ejected by volcanoes into the upper atmosphere reflect some incoming solar radiation back to space. The cooling that occurs after such eruptions is visible in the modern instrumental temperature record (e.g., temperatures fell after the eruption of Mount Pinatubo in 1991, visible in figure 2). It is also visible in reconstructions of temperatures in the Northern Hemisphere over the last several centuries in conjunction with reconstructions of past volcanic activity from ice cores and historical records. In fact, multiple volcanic eruptions appear to have contributed substantially, for example, to the cool conditions of the Little Ice Age (~1450-1850).

Changes in solar radiation over time can also influence climate, but variations in solar radiation measured by satellite over the last 2-3 decades have been small in recent decades and can not explain the temperature increase over the same period. Based on statistical studies, we also concluded that the warming over the recent fifty years is very unlikely to have been due to natural causes alone.

By far the strongest influence on the energy budget of the planet (called “radiative forcing”) since preindustrial times is the warming effect of the increase in greenhouse gases such as CO_2 and methane, and the partially offsetting cooling effect from sulfate aerosols. In the Fourth Assessment report, changes in the energy budget of the planet due to changes in solar radiation are estimated to be about a tenth of the total human-induced change in the energy balance of the planet, with non-overlapping uncertainty ranges. Changes in land cover and land use (e.g., replacement of forest with agricultural land) could have contributed to some regional temperature changes over the historical period. Changes in land surface characteristics are estimated to have caused a small cooling effect globally. Some recent model simulations have included the effect of land use change and find it very small on temperature averages over larger spatial scales.

When trying to explain observed temperature changes over the 20th century, it is important to consider all important external influences on climate, such as changes in solar radiation and volcanic eruptions as well as the increase in greenhouse gases, aerosols, and changes in ozone in the lower and upper atmosphere. Climate models integrate our understanding of the physics of climate, and simulate the changes in the climate system that are expected in response to external forcing. Climate models are evaluated extensively by their ability to simulate seasonal and short-term climate variations, and also to simulate conditions of past climate such as the Last Glacial Maximum or the mid-Holocene, a time when climate was quite different from today.

For the Fourth Assessment report, a very large number of such simulations from dozens of climate models worldwide has been available to study past and future climate. The second figure illustrates that climate models, when including all important external influences, reproduce the observed evolution of global mean temperature over the 20th century very well (top diagram). They reproduce the observed episodes of warming and the cooling following volcanic eruptions (indicated by vertical bars). The range that is covered by these simulations indicates the effect of variability internal to the climate system. Individual simulations are very similar in appearance to the observed record. In contrast, if anthropogenic greenhouse gas and aerosol influence is not included in the models, they cannot reproduce the warming, particularly in the second half of the 20th century, as is illustrated in the bottom panel.

However, we do not rely just on such an agreement to attribute observed climate change to causes. Instead, we use rigorous signal detection techniques to estimate the contribution of greenhouse gas increases to observed temperature changes, and rely on a careful examination of all plausible explanations of the observed warming including variability generated within the climate system. This is done by utilizing statistical methods to analyze the *observed* pattern of warming in space and time. Climate models are an important tool since they provide information about the "fingerprint" that different external influences are expected to have on climate. For example, volcanic eruptions are expected to cause short-term cooling. Changes in solar radiation cause warming throughout the lower and upper atmosphere, and follow the 11-year cycle of solar variability. Changes in greenhouse gases cause global warming, with greater warming over land than oceans, warming in the lower atmosphere, and cooling in the stratosphere. Sulfate aerosol and other anthropogenic influences cause cooling which is strongest over industrialized regions. Incorporating these effects into climate models enables one to develop a "fingerprint" of external influences on climate, and the statistical methodologies allow us to quantify the presence of such fingerprints in observations. Such studies allow for the possibility that the response to a forcing may be larger or smaller in observations than simulated in the models.

Based on many studies it was found that the best explanation of the observed warming over the recent 50 years involves substantial greenhouse warming, some of which was counteracted by cooling influences from other anthropogenic sources, and a small influence of natural forcing such as changes in solar radiation and volcanism. We also concluded that it is very likely that greenhouse gases caused more warming over the recent 50 years than solar forcing. This assessment does not consider the fact that solar forcing is estimated to be much smaller, but only relies on the observed pattern of changes.

Based on a large body of such work, the IPCC chapter I coordinated, together with Dr. Zwiers (Director of the Climate Research Division of Environment Canada), concluded that “most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in greenhouse gas concentrations.” The term “very likely” indicates an expert judgment, based on strong statistical evidence and physical understanding, and indicates that that there is more than a 9-in-10 chance that the statement is correct[1]. This assessment conservatively accounts for remaining uncertainties, such as observational uncertainty, uncertainty in some external forcings and uncertainty in the estimates of the expected responses to external forcing. We also find that it is likely that greenhouse gas forcing alone would have caused more warming than observed because volcanic and anthropogenic aerosols have offset some warming that would have otherwise taken place.

Such work on attributing observed changes to causes has been carried over to warming over individual continents with similar conclusions (Figure 3). Only model simulations with greenhouse gas forcing reproduce the observed warming over each continent (there was insufficient data to make such an assessment over Antarctica). The figure also indicates that over each continent, average temperatures are far from where they would be without greenhouse gas influences. The successful simulation of the different warming rates over different continents and land and ocean provides strong evidence for a human influence on climate.

3. How do you expect future global temperatures to be affected by greenhouse gas emissions from human activity?

Global temperatures will continue to increase, both due to the warming that is already “in the pipeline” and with further increases in greenhouse gases.

Predictions of future warming are made using climate models that are forced with scenarios of future emissions. The predictions from the first two assessment reports, 1990 and 1996, can now be directly compared against actual observed temperature changes, and have proven to be quite realistic. Confidence in simulations is further enhanced by the very convincing simulation of 20th century temperature change in the ensemble of climate model simulations, as seen in figures 2 and 3 of my presentation.

Future warming will not be small, since we have now more confident estimates of the equilibrium climate sensitivity, which is the eventual warming that would be expected to occur in response to a doubling of CO_2 in the atmosphere. It has been long believed, based on climate models, that this sensitivity is between 1.5

[1] The IPCC uses calibrated language to describe the uncertainty on its assessments. For example, an assessment of “very likely” indicates a judgment, based on strong statistical evidence and physical understanding, that there are better than 9 chances in 10 that the assessed statement is correct.

and 4.5^{o}C (2.7 to 8.1^{o}F). We now have data from observations that confirm this range. The observed estimate comes from the climate response to volcanic eruptions, the range of climate sensitivity in climate models that makes these models skillful at simulating climate change for present day conditions and the Last Glacial Maximum, and, most importantly, from a comparison between simulated and observed changes over the 20th century. The most confident IPCC AR4 conclusion from this work is that the "climate sensitivity is very unlikely below 1.5^{o}C (2.7^{o}F)". The most likely value was found to be about 3^{o}C (5.4^{o}F), and the likely range of climate sensitivity (i.e., the range that is expected to be correct with a probability of 66% or greater) is 2-4.5^{o}C (3.6 to 8.1^{o}F). This essentially rules out very small temperature changes in response to further increases in greenhouse gases.

Future warming, particularly later in the 21rst century, depends on how CO_2 and other radiative forcings develop in the future. For the lowest emission scenario considered, warming ranges between 1.1 and 2.9^{o}C (2.0 to 5.2^{o}F) by the end of the 21rst century, which is about 1.5 to 4 times the observed warming from 1906-2005 of 0.74^{o}C. For a high emission scenario, the future warming is expected to be about 3-9 times the warming observed in the past 100 years. Note that the emission scenarios considered by the IPCC report do not include mitigation policies.

Thus, I would like to summarize that direct observations find that global temperatures have warmed, that anthropogenic greenhouse gas increases have caused a very large part of this warming, and that we expect continued warming. We are very confident that the sensitivity of the climate system to greenhouse gas increases is not small. The amount of future warming depends on the emission path chosen by societies, and extends to a further warming that is much larger than the one we have already observed.

On behalf of Duke University, I also want to communicate our willingness to work with you as you struggle with all of the hard issues associated with global warming. In the Nicholas Institute, we are building a one-of-a-kind conduit between the University and policymakers like you in collaboration with Duke faculty involved in all issues relating to climate change.