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BEFORE THE
SUBCOMMITTEE ON COMMERCE, JUSTICE, SCIENCE,
AND RELATED AGENCIES
COMMITTEE ON APPROPRIATIONS
U.S. HOUSE OF REPRESENTATIVES

MARCH 17, 2009

I thank Chairperson Mollohan, Ranking Member Wolf, and the other Members of the Subcommittee for the opportunity to speak with you today on the state of climate change science. My name is Susan Solomon and I am a Senior Scientist at NOAA's Earth System Research Laboratory in Boulder, Colorado. I've been a scientist at NOAA for more than 28 years. My work has focused on understanding both ozone depletion and climate change. In 2000, I received this nation's highest scientific award, the National Medal of Science. I've also been honored with membership in the U. S. National Academy of Sciences and I am a foreign associate of the French Academy of Sciences, the Royal Society of London, and the Acadamiae Europaea. I'm the author or co-author of more than 150 scientific publications. I've served as an author on various reports of the Intergovernmental Panel on Climate Change (IPCC) beginning in 1992 and as co-chair of IPCC's fourth major climate science assessment report released in 2007.

I would like to summarize some aspects of the process and primary findings of IPCC's 2007 reports, and to describe my view of key advances in understanding that have occurred since the reports were issued. I'll identify key findings that can be considered well understood on the basis of both observations of climate change and physical understanding of the processes involved. I'll also identify aspects of climate change science that are not as well observed or understood, and are therefore subject to larger uncertainties.

Since its inception about 20 years ago, IPCC has produced assessments of the state of understanding of (i) the science of climate change, (ii) the impacts of climate change and climate change vulnerability, and (iii) mitigation of climate change. Each of these areas is the subject of a separate scientific assessment, and there is also a synthesis summarizing findings across all three. The IPCC does not carry out or manage research. The mandate of the IPCC is to evaluate information that must be independently documented, primarily as peer-reviewed literature. IPCC's reports have become the gold standard for authoritative scientific information on climate change because of the rigorous way in which they are prepared, reviewed, and approved. The 2007 IPCC climate science assessment was prepared by 152 leading scientists from around the world who served as its authors. It was then reviewed and re-reviewed by more than 600 experts and dozens of governments. All of the review comments and responses have been made publicly available. The comprehensiveness of the literature considered, the scope of the evaluation, as well as the robustness of the findings were all subject to extensive review. Completion of an IPCC assessment report requires a demanding line-by-line approval of its summary that is critical for its value to policy-makers, and must also be acceptable to the authors involved. This process ensures that key conclusions are scientifically accurate. It also ensures that findings are accepted by all governments and expressed in language that is useful to policy.

Among the key conclusions and updates to IPCC's 2007 report are the following:

Warming is unequivocal, as is evident in independent sets of observations all attesting to long-term changes to our planet's climate. Among these are increases in global average surface air and ocean temperatures, widespread losses of snow and ice cover, and rising global average sea level. The finding that warming is unequivocal is one that the authors chose to express in unusually strong terms, which stems from the diverse sets of independent data documenting changes in many different observables. Climate may be defined as the weather averaged over a period of about 20-30 years. Globally averaged, today's temperatures are about 0.75°C or about 1.3°F warmer than they were 100 years ago. In a world that is warmer on average there is still variability from year to year or season to season. Since the 2007 IPCC report, it's been noted that a La Nina event contributed to making global temperatures in 2008 slightly cooler than some other recent years, but it was nonetheless much warmer than La Nina years that occurred in the early part of the 20^{th} century. Indeed, despite the presence of a La Nina, 2008 is estimated to be the tenth warmest year since systematic global thermometer records began about 150 years ago, showing that global warming remains apparent.

IPCC's 2007 report noted the observation of increases in water vapor in association with the observed global warming. This occurs because warmer air can hold more water vapor. Multiple scientific studies have continued to support and extend those observations since the 2007 report appeared. While water vapor is a very important greenhouse gas, it responds to and amplifies climate change rather than being an independent driver of climate change. It is a feedback to climate changes forced by other factors but is not a significant forcing agent.

It is clear that the primary driver of climate change is increased carbon dioxide produced by fossil fuel burning, and to a lesser degree by deforestation. Today's levels of carbon dioxide are about 385 parts per million parts of air, and this is unprecedented in more than half a million years of data from ice cores. Carbon dioxide has increased by about 30% compared to observations prior to the industrial era, and in the past few years the rate of increase of carbon dioxide has been faster than ever observed in the instrumental record. This is due to increased global fossil fuel use. These changes in carbon dioxide have increased the acidity of the global surface ocean through well-understood sea water chemistry. It is well understood that a substantial portion of the carbon dioxide remains in our atmosphere for a very long time even after emissions stop:

about 20% of today's emitted carbon will remain present in the atmosphere for more than a thousand years and will therefore alter the Earth's climate for many human generations. Other greenhouse gas forcing agents including methane, nitrous oxide, and halocarbons have also made significant but lesser contributions to global warming.

IPCC's 2007 report examined the distribution of temperature changes in time, latitude, longitude, and altitude, and compared these to physical understanding of the processes involved and to numerical model simulations that incorporate those processes. Land areas are warming more than oceanic regions, as expected from physical understanding and models. Higher latitudes in the Arctic are warming more than mid-latitudes. This is expected, because the process of snow and ice retreat decreases the reflectance of energy to space and allows more energy to be absorbed by the Earth's surface. This amplifies the high latitude warming. The Earth's surface and the atmosphere are warming globally up to about 10-15 km altitude, while temperatures are cooling at higher altitudes in the stratosphere, just as expected based on our understanding of greenhouse gases and ozone depletion. In contrast, larger warming would be expected in the upper atmosphere if increased levels of solar activity were responsible for the observed surface warming, so that is opposite to what is observed and suggests a small role for solar changes. Based on these and other patterns that represent fingerprints of the observed climate change, IPCC's 2007 report concluded that most of the global warming of the past half century was attributable to manmade increases in greenhouse gases at a 90% level of scientific certainty. Recent published work continues to support that conclusion. For example, IPCC carefully considered the possible contributions of changes in the sun's brightness to the observed warming. Direct high-quality observations of the brightness of the sun since 1979 show very small long-term changes in the sun over the period of the last three decades, when most of the global warming occurred. Since the 2007 IPCC report appeared, there have also been studies showing that cosmic rays have not increased significantly, providing direct evidence that solar cosmic ray/climate mechanisms don't account for a significant part of the current warming.

Among the key findings of IPCC's 2007 report was information not just about temperatures, but also about other changes in the climate system. IPCC's 2007 report presented observations and model simulations of changes in rainfall, and recent studies including the 2008 Climate Change Science Program (CCSP) assessment of weather and climate extremes have supported those conclusions. Among key robust conclusions is the finding that warming is associated with changes in rainfall patterns. In particular, the already-dry regions just outside the tropics are becoming drier, while wet regions at high latitudes are becoming wetter, and this is expected to worsen as the world continues to warm. There is also strong observational evidence that the frequency of heavy rainfall has increased and will continue to increase in the future, implying greater frequency of flooding.

I'd now like to briefly turn briefly to some robust aspects of climate change projections and impacts. By about the end of the 21st century, carbon dioxide concentrations could become as high as 1000 parts per million if emissions worldwide continue rising at a rate typical of the last decade, which is about 2% per year. The best current science implies that with a sustained level of 1000 ppmv of carbon dioxide, an average day would become about 10°F warmer than today, which corresponds to a greatly changed climate. Heat waves as bad or worse than the worst current heat waves (such as the one in Europe in 2003 that led to the deaths of more than 10000 people) would become common. There is now increased confidence that decreased rainfall can be expected as the world warms in parts of southwestern North America, west Australia, southern Europe, and both northern and southern Africa. Droughts comparable to the dust bowl can be expected to occur in the future not just occasionally in limited regions, but in all of these places and at the same time. Many of the world's most desolate deserts would expand as semi-arid soils dry out. Glaciers and snowpack that provide water to at least a billion people would disappear. Fires would become more common in these dry regions, and fire frequency is also expected to increase in many locations that are dependent upon snowpack for their water supply, such as much of California. Insect pests would become more common, with attendant damage to crops and forests. All of these impacts are based on physical processes that are well understood, and represent aspects of the science for which confidence is very high.

The amount of carbon dioxide in the atmosphere is sometimes usefully compared to the water level in a bathtub for the purpose of illustration. We are currently pouring carbon into the system, providing a tap at a rate much bigger than the drain can take it away (that drain is mainly absorption into the ocean and biosphere). The water level in the bathtub will keep rising unless the amount of water coming in equal to or less than what is removed, so the emission required to balance the carbon removal is important. If the world chooses to stop carbon dioxide increases and the attendant global warming at any level: 2°F, 4°F, or something else, this would require a reduction in global carbon emissions by at least 80%. *When* we cut emissions would affect how much total warming occurs, so decisions and actions on timing are important in determining the extent of the human-induced climate change that we can expect. But the drain has to ultimately match the tap if carbon dioxide is to be stabilized at any point, and this illustrates why mitigating climate change is a very substantial challenge.

I will now turn to key uncertainties. Society is clearly facing a vast array of decisions about climate change. Decision-makers ranging from national, state, and local levels as well as businesses, and citizens are increasingly seeking more climate change information as input to their choices. Policy makers and citizens worldwide are seeking more information regarding the design of future actions under the United Nations Framework Convention on Climate Change and the Kyoto Protocol: how dangerous is climate change is a frequent question, what are options for actions, how fast is the climate expected to change, etc. I will provide some illustrative but far from comprehensive examples of the many ways in which more research is needed to better inform current and future choices about mitigation, adaptation, and some key fundamentals of climate change.

Some scientists have suggested geoengineering to remove the carbon dioxide or to actively cool the climate as an alternative approach to emissions reductions. I do not have the expertise to comment on the engineering aspects of these. However, many of these proposals have the potential for uncertain climate side effects that would require more research to ensure a firm foundation. For example, schemes to reflect sunlight could cool the climate, but they could also reduce evaporation of surface water and affect the water cycle and rainfall. More research is needed before such approaches can be considered safe to present as options.

As the world warms, land and ocean uptake of atmospheric carbon dioxide decreases, increasing the fraction of anthropogenic emissions that remain in the atmosphere and enhancing the warming per pound of gas emitted. There is also some evidence that large amounts of carbon could be released from melting permafrost in the Arctic as the world warms. These feedback processes are very uncertain but have the potential to substantially enhance future carbon levels. Their effects could become large enough to make it much more difficult to stabilize carbon dioxide concentrations should we choose to do so. There is hence a need for much better understanding of the cycling of carbon and the ways in which climate change affects it.

As already noted, carbon dioxide is not the only agent causing our climate to change, although it is the largest one. Other anthropogenic greenhouse gases and some aerosols provide additional opportunities for climate change mitigation. Some of these, such as reductions in soot, could have important co-benefits for air quality and related health effects. Other options include improved containment or substitution for hydrofluorocarbons in, for example, automobile air conditioners, and some of those emissions reductions may be relatively easy to achieve. There is a potential for trading in a basket of such choices among climate change agents, but there is limited information on factors such as the effectiveness of such trades over time, and more research is needed to ensure that the broadest range of practical climate change mitigation options are considered.

As alternative sources of energy are sought such as biofuels, wind or solar energy, new questions arise regarding those options, such as how local climate changes may influence the availability of the water required to produce biofuel, or how a large solar or wind array might modify local climates. There is very limited information now available to guide key choices between such mitigation alternatives, and increasing demands for such information.

Critical questions are being raised regarding how best to adapt to climate change, through such measures as coastal infrastructure choices, changes in water management, farming practices, and much more. But information about local climate changes at the required spatial and temporal scales is currently subject to very large uncertainties in many cases. Improved numerical simulations at smaller scales is a pressing issue in research.

Climate change is not limited to warmer temperatures but extends to water, storms, sea level rise, heat waves, flooding, fire, ecosystem feedbacks, and much more. While there is an emerging understanding of all of these scientific topics, improvements in numerical modeling, process studies and analysis, and monitoring will all be needed to provide the kind of information required for many decisions. I have already referred to the probable loss of water supplies in certain parts of the US such as the southwest and California, and while this is understood in broad terms much more information is needed to assist local water management choices. In other regions of the US, our ability to project rainfall changes with warming is generally much less clear but no less important. Similarly, there are many questions regarding how hurricanes could be affected by climate change. Although there is some evidence for increases in the intensity but not the number of the most intense storms, much more research is needed. Whether and how the intensity and frequency of El Ninos and La Ninas could be affected by climate change remains a research question, one that has large implications for many aspects of our climate. Networks to monitor how these and other aspects of climate are changing are generally considered to be barely adequate and some are in danger of being lost altogether. Sustained observations are essential to ensure that key records are not lost; better and broader observations and systematic analysis would help us to ensure that we are aware of climate changes as they evolve and can better understand and characterize them. Measurements of rain, snow, clouds, humidity, tropical and mid-latitude storms, solar radiation, aerosols, and many greenhouse gases are all examples of the key areas for monitoring.

Observations demonstrate that Arctic sea ice extent reached record low levels in the late summers of both 2007 and 2008. It is very likely that the Arctic sea ice retreat is driven at least in part by global warming, but the extreme reductions of 2007 and 2008 are not fully understood. There is some evidence that unusual wind patterns played a role along with warming. Similarly, the changes in Antarctic sea ice appear to be driven in large part by changes in wind patterns. So while changes in polar sea ice are well documented, and there is important evidence for human contributions to those changes, other factors are also likely to play some role and future projections are hence uncertain.

While ocean acidification is evident and is controlled by well-established chemistry, it is less clear how the acidity increases will impact life in the ocean. Increasing acidity of the world's oceans has the potential for vast effects on marine life and ocean ecosystems, but the degree to which various organisms may be capable of adapting to a more acidic environment is uncertain, and more research is badly needed.

Sea level rose by about 6 inches in the 20th century. How much further it will rise in the future is not well understood. It is well established that water expands when heated, and this is an important source of sea level rise. It is also clear that small glaciers worldwide have lost mass as the world has warmed, supplying more liquid water to the ocean and contributing to sea level rise. These two processes are well understand and can be expected to produce up to 3 feet of sea level rise within about the next two to three centuries if carbon dioxide continues to increase. Three feet of sea level rise would inundate many small islands and low lying coastal regions, such as Florida, and this is already becoming part of coastal planning in many regions. A third process may be very important but is very poorly understood, rapid flow on the great ice sheets of Antarctica and Greenland. There is evidence for locally rapid ice flows, but it is not yet possible to integrate this contribution over larger areas as would be needed to quantify the total contribution to sea level rise. The potential contribution could be on the order of a few meters over centuries, but is very uncertain.

These are but a few of the questions facing the nation and the world as the climate continues to change. There is much that we do know. There is also much that we don't yet know that is especially important to particular mitigation and adaptation decisions.

Thank you again for the opportunity to provide this testimony.