Basic Science and Physics of Climate Change

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Chairman Baird and members of the Subcommittee on Energy and Environment, thank you for the opportunity to participate in your hearing today. I will address the basic science and physics of climate change and how climate change happens. In addition, I will describe the role of the National Academy of Sciences in advancing the science and informing the public on this topic.

Climate Change in the Past

Earth's climate shapes the conditions for life and it has done so over geological history as it does now. The kinds of plant and animal species that can survive are determined or are strongly influenced by climate as are the locations and kinds of human installations and settlements such as agricultural areas and routes of transportation on rivers and oceans.

We have records of many past climate changes from sea-level changes, from deposits of soils and rocks, and from fossils and other debris from plant and animal life, big and small, and from chemical traces such as abundances of elements and their isotopes. There is such evidence of periodic Ice Ages when glaciers extended over the northern half of North America, for example, and of intervening warm periods. The mapping of many of these historical climate changes is imprecise, that is, we do not know exactly how big were the geographical regions that experience the changes. Yet, some patterns are clear. For example, there is a 100,000-year cycle of Ice Ages in the past. These repeated events were probably triggered by changes in the non-circularity (eccentricity) of the earth's orbit around the sun. Earth's orbit is not circular but more like an elipse and just how non-circular the orbit is, changes slowly. Also, Earth's tilt angle of the access of its rotation changes periodically and its access of rotation wobbles a bit over tens of thousands of years. These astronomical changes lead to small changes in the amount of sunlight received by earth and to the geographical distribution of sunlight. While no one has yet been able to predict exactly how Ice Ages are brought on or how earth exits them, and how quickly, the principles of our understanding are sound. Volcanoes of certain types have also caused climate changes in the past. Regions of the earth or even the entire earth can experience cooling due to volcano injection of reflective matter that floats in the upper atmosphere (stratosphere). For a year or a few years, such coolings have been observed, for example, following the June 1991 explosive eruption of Mt. Pinatubo (in the Philippines). Our ability to calculate the amount of cooling is very high if the volcanic cloud material amounts and types are measured well.

Earth's Energy Balance and Climate Change Today

These kinds of natural climate changes are likely to occur in the future although their timing and sizes are not predictable. The main reason that we are here in this hearing today is that humans are capable of causing earth's climate change. The underlying mechanism is the greenhouse effect and the leverage that it exerts is worth understanding. In fact, many people are not yet aware of how large this leverage is, or how it arises.

The key scientific principles can be seen by considering the energy balance of the Earth. The Earth receives energy from the sun and it sends energy back to space. Every physical body that is warmer than its surroundings loses energy to its surroundings. Because of the temperature of the sun, the form of energy that escapes it is mostly visible light while the temperature of the Earth causes most of the energy sent away from the Earth to be in the form of infrared wavelengths. If you have ever done any infrared photography such as on a cold winter night looking at an inhabited house from outside on a cold winter night you can see where the hot spots are. Also, some infrared detector devices for military purposes also operate in infrared wavelengths. The Earth's energy balance is such that we receive approximately 237 watts per square meter from the sun as visible light, averaged over day and night, over the entire surface of the Earth. A watt is a rate of energy flow of one Joule per second. Approximately, the same amount of energy leaves the Earth, 237 watts per square meter, but as infrared waves. One of the earliest scientific instruments ever orbited around Earth saw the wavelength matter and distribution of Earth's planetary radiation to space (IRIS instrument), thus demonstrating the greenhouse effect. Many more recent instruments and measurements have led to the numbers that I just quoted.

The greenhouse effect is a natural phenomenon that has been active over the history of the Earth. This fact can be demonstrated by calculating the temperatures of various planets using the energy-balance framework and the principles that I just outlined. When we calculate the temperature of Mars from the amount of sunlight that reaches it and its reflectivity, we obtain very close to the right answer as compared to actual measurements. When we calculate the temperatures of Earth or of Venus using the same framework with appropriate numbers, we arrive at too low a temperature. We calculate that the average temperature of Earth is approximately 15 degrees below zero centigrade which is perhaps 30 degrees centigrade too low and we calculate a temperature of Venus which is far below what is actually measured. These errors indicate that something is missing from the calculation and it is easily demonstrated that inclusion of the natural greenhouse effect enables one to get much closer to the actual observed temperature in a revised calculation.

Greenhouse Gases

The key ingredients in the greenhouse effect are greenhouse gases and clouds which when in the atmosphere surrounding the planet can absorb outgoing planetary infrared radiation. Mars has a very thin atmosphere with not much gas at all. Venus has a very thick high-pressure carbon dioxide atmosphere with many clouds and Earth has the atmosphere which we have measured and experienced with significance amounts of natural greenhouse gases, carbon dioxide, water vapor, methane, and several others. The signature of a greenhouse gas is the selectivity in how it absorbs infrared radiation at different wavelengths. This signature is measured in laboratory experiments using each gas and the signature of individual greenhouse gases can be seen by Earth-orbiting instruments or even from some other vantage point in space.

The natural greenhouse effect on Earth has been enhanced or amplified by the increased amounts of greenhouse gases in the air due to human activities. The human-enhanced greenhouse effect due to such increased atmospheric concentrations is now calculated to be 2.7 watts per square meter, or more than one percent of the incoming solar energy. And this increase has occurred in a period of a few decades, a very rapid change. The components of this increase listed in order starting with the largest is carbon dioxide, methane, nitrous oxide, a number of fluorine-containing chemicals, and ozone in the lower atmosphere, etc. When one attempts to calculate the impact on the climate of the earth, the way that wind motions are forced, and how temperatures and precipitation amounts change, one must include the additional forcing due to water-vapor changes caused by the original greenhouse-gas forcings. The climatic impact of these atmospheric greenhouse-gas increases is influenced by changes in atmospheric water vapor and clouds which are initiated by warming. As water warms, it evaporates faster, disproportionately faster than the amount of warming. Thus, water vapor is injected into the air. While some scientists continue to propose that water-vapor changes due to greenhouse forcing might not amplify the original warming, they are fighting against this fundamental fact of physics, the dependence of vapor pressure on temperature (Clausius-Clapeyron Effect).

As I said earlier, it is important to realize that this enhanced greenhouse effect represents leverage over Earth's energy balance and Earth's climate. If we look only at humans <u>direct</u> influence on Earth's energy budget, we find a smaller influence. In particular if we take all energy, all human energy usage today, all nuclear power, the burning of all fossil fuels, coal, petroleum, gasoline, natural gas, the burning of wood, the use of hydroelectric power, of geothermal power, tidal and solar and wind power, and we average it over the surface of the Earth, we find a number of 0.025 watts per square meter or barely 1/100th

of the enhanced greenhouse effect. Thus, we see that the greenhouse effect is exerting leverage of more than a factor of 100 over the impact on Earth's energy budget due only to human energy usage. This notion and these numbers are very important to understand. From the viewpoint of atmospheric chemistry, this leverage is not very surprising considering that chemical catalysis causes minute amounts of chemicals to be far more important than their small numbers might suggest. The chemical impact of catalysts can be enhanced by 100,000 to a million times through the mechanism of catalysis.

Less technically, one can appreciate this leverage by realizing that these changes on Earth in the amounts of greenhouse-gas concentrations in the changes observed over the last 30 years on the surface of the Earth and the air and oceans and the ice amounts on Earth, the changes that have been observed in the last decade, can all be seen from space looking back at Earth. In fact, that is how many of the data have been obtained, by looking at the Earth from space. So these changes are not small. One of the easiest tasks in foreseeing how climate change due to human activities will happen, is indeed evaluating the enhanced greenhouse effect. We know the properties of greenhouse gases that make them either more or less effective. For example, because the outgoing planetary radiation occurs mostly in a well-defined range of wavelengths, an ideal greenhouse gas is one that absorbs radiation in that same range and does so effectively. An ideal greenhouse gas is also one which can survive in the atmosphere without being broken apart and which can be distributed more or less uniformly on a global scale without being removed. Those properties are largely chemical and they can be measured through laboratory experiments, and they have been so measured, so that the calculations of the enhanced greenhouse effect due to a measured increase in the gas's concentration are very quantitative and reasonably precise today.

The concept of radiative forcing was first created and employed by scientists who created the first fluid dynamical models of the atmosphere. Bob Dickinson and I used the concept to permit a comparison of the effectiveness of greenhouse gases and their amounts in 1986. In the early and mid-1980s scientists had become aware that not only are the increased carbon dioxide amounts capable of influencing Earth's climate but a number of other chemicals also have this capability although in lesser amounts. Radiative forcing is a measure of how strongly substances in the atmosphere affect Earth's energy budget. The concept has been extended to materials which are less uniformly distributed such as aerosol particles from biomass burning, from sulfur pollution, from fossil-fuel burning, smoke particles, and the like. The impact of those less uniformly distributed substances is more difficult to estimate because the substance's geographical distributions are not as well known, so the estimates of such substances on Earth's energy budget are not as well defined.

Now, obviously, if our concern is over changes to the net energy balance of the Earth, then a change in the amount of <u>sunlight</u> reaching the earth is also very important. In fact, any number of scientists have tried to focus on whether changes from the sun are causing contemporary climate change. But it is only in the last few years that we have had enough evidence to be able to say that the changes in climate that have been observed over the last several decades, are not due to changes in the output of the sun. It has been known in principle for a long time that the sun, like other stars, can change its luminosity over geological timescales but there is no evidence from other stars or any theory of stellar evolution that suggests that the sun's output could change by as much of the enhanced greenhouse effect has changed, that is, over one percent in say 50 years. A more solid kind of evidence has come from monitoring the sun itself. By stringing together the records of a series of satellites that have orbited the earth while observing the incoming sunlight, several scientists have shown that the amount of sunlight energy reaching the Earth has oscillated with an approximate 11-year cycle over the last 30 years, that is, the amount of solar energy reaching the Earth has not increased during the time of the observed climate changes. So we are left with the realization that the enhanced greenhouse effect is 15 or 20 times larger than the difference between solar maximum and solar minimum in the output of the sun. Moreover, the enhanced greenhouse effect is not oscillating, it is simply continuing to rise, so the evidence today rules out any significant role for solar changes in causing the observed climate changes of the last several decades.

I have alluded to increased concentrations of greenhouse gases that have been observed worldwide that demonstrate human impact. In the case of carbon dioxide, our data are of extremely high quality, measurements are taken frequently from many locations on the surface of the Earth, from aircraft, satellites, and from dated ice cores extending back over hundreds and thousands of years. The evidence that the increase in carbon dioxide worldwide amounts from approximately 280 parts per million in the late 19th century to approximately 390 parts per million this year is very strong and that the increases due to human activities is also clear. The lines of evidence that one uses in attributing the carbon dioxide increase to human activities includes the rate of the concentration increase compared to the rate of release of carbon dioxide from fossil-fuel usage, the isotopic content of the carbon dioxide, the carbon dioxide patterns geographically compared to the places where carbon dioxide is being released by human activity, by oceanic amounts, and by known patterns of movement of atmospheric chemicals. There is a contribution to this increase from human-caused deforestation. This contribution is approximately 15 percent of the total while fossil-fuel usage is approximately 85 percent of the total. The release of carbon dioxide from deforestation is due both to the direct burning of wood and the decay of exposed soil organic matter.

Methane as a greenhouse gas has also risen rapidly since the late 19th century as evidenced by surface measurements made at many sites around the world, by satellite measurements and by the amounts of methane extracted from dated ice cores. The list and sizes of methane sources for the atmosphere is complicated and it includes rice agriculture, the domestication of cattle, the use and transmission of natural gas, of the decay of landfill of organic matter placed in landfills, and many other sources. Nitrous oxide, another greenhouse gas, also has an array of processes that injected it into the atmosphere, mostly traceable to the increased human usage of synthetic nitrogen fertilizer for agriculture. Several classes of chemical gases containing fluorine also contribute to the enhanced greenhouse effect. The chlorofluorocarbons whose usage was regulated and banned due to the Montreal Protocol and later amendments to it, still reside in the atmosphere. Several kinds of replacement chemicals for the chlorofluorocarbons, namely, hydrochlorofluorocarbons and hydrofluorocarbons are observed to be increasing in concentration worldwide along with measured increases of perfluorinated chemicals such as carbon tetrafluoride and perfluoroethane along with sulfur hexafluoride. The increases observed in the concentrations of all of these gases are clearly attributed to human activities. While the enhanced greenhouse effect due to all of these greenhouse gases has been an inadvertent consequence of human activities, this force, led by carbon dioxide emissions, continues to grow with larger consequences for future climate.

Observed Climate Changes

A number of meaningful changes to Earth's climate have been measured since 1980 or the late 1970s. These include globally averaged surface temperatures, both of air and of water. Large data sets covering almost all of the world are available from at least three climate centers around the world, one from NASA, one from NOAA, and one from the University of East Anglia. These data sets are generally similar although they consist of somewhat different entries with more or less weighting from individual continents and the Arctic and they employ somewhat different methods to adjust for potential biases such as the encroachment of urban areas and the urban heat-island effect on thermometer stations which were at one time far from urban areas. As an example, the data sets use slightly different time periods of comparison but they all show a warming of the earth in all regions. The globally averaged warming since 1980 is approximately one degree F. Stronger warmings have been measured in the Arctic region with, of course, differences season-by-season and locality-by-locality. Just as one example, the calendar year 2009 was significantly warmer than the long-term average of the Northern Hemisphere but it was cooler than several of the previous years while the temperatures in the Southern Hemisphere in 2009 were at an all-time record high. Further, temperature rises are higher over land areas than over oceans.

The data on the temperatures and heat content of the upper layers of the ocean are very important as a measure of global climate change yet these data are more difficult to obtain with the density of stations that we would desire because the oceans are not as well monitored as the atmosphere. Nonetheless, in the last several years, new data sets have materialized which show an upward trend with time over the last 40 or 50 years with the amount of heat stored in the upper layers of the ocean rising, roughly in accord with calculations of the enhanced greenhouse effect.

A climate variable of great importance especially in the longer term is sea level. Since 1992, sea level has been measured by Earth-orbiting instruments on satellites which are capable of measuring sea level nearly worldwide and frequently so that the trend of rising sea levels has now been measured more accurately and more precisely in more places than had been possible before 1992. There is now evidence of a rate of sea-level rise since 1992 which is approximately twice as fast as the sea-level rise observed from the late 19th century to 1992 with far more primitive and fewer instruments in coastal environments.

The amounts of ice residing on land formations in Greenland and Antarctica are now being measured by independent instruments, vertical ranging devices on Earth-orbiting satellites, as well as instruments which measure the deviations of the Earth's gravitational field from that of a perfect sphere and the rate at which those deviations are changing. In other words, the data from this instrument can be used to infer the rate of change of ice mass over those continents. Both kinds of data now show that over the last perhaps seven or eight years, that is the entire record of the measurements, that the masses of ice lodged on Greenland and Antarctica are both decreasing with time with a possibly accelerating rate. When combined with the inferred amount of ice lost from continental glaciers and the rate at which sea level is rising due to thermal expansion, due to the increased temperatures, one can now calculate how fast sea level is rising and find agreement with the sea-level rise that is actually measured independently. So this kind of evidence is new and rather compelling.

Many other important measures of climate change are being gathered, measures of variables which are directly important to human animal and plant life, but which are inherently more variable spatially, that is, geographically and with time such as the rate of flows of various streams and rivers, the amounts and kinds of cloudiness, the frequency and duration of droughts and of storms in many locations, and the length of growing season and the frequency of new high-temperature settings and of new low-temperature settings. Continued research on these variables and many others is essential for us to gauge and predict climate changes that are underway and how effective human responses might be.

Efforts to predict more detailed evolution of future climate change begin with mathematical expressions of the laws that govern the motion of fluids and their temperatures and of ice amounts. These equations are of the type which cannot be solved with paper and pencil and with neat mathematical expressions. Instead, they can only be solved by numerical computations, computations that are becoming more rigorous and more understood. Other witnesses will describe more of the actuality and the details of these efforts, but I do want to emphasize several kinds of inputs to these mathematical models which require continued scientific effort. One is the specification of the role of aerosol particles and of clouds in the atmosphere and another is the need to specify the rate at which fossil-fuel burning will be used discharging carbon dioxide into the atmosphere, which rate depends on growing human population, human activities and energy technology.

The National Academy of Sciences has been active in our national efforts to detect, understand and predict climatic change. Most of our analyses are conducted through our operating arm, the National Research Council, which co-administered by the National Academy of Sciences and the National Academy of Engineering. And we often obtain help from our own Institute of Medicine. There are, of course, many other nations that are active in climate research and are attempting to mitigate climate change and/or to adapt to it. And some of these nations not only conduct research but perform their own nationally based assessments. In addition, there are international bodies performing analyses of climate change such as the Intergovernmental Panel on Climate Change which is a creature of the World Meteorological Organization and of the United Nations Environmental Program.

Our NAS/NRC reports have been issued more frequently and they have grown in size over the last 30 years with one of the first major reports being released in the last 1970s followed by another in 1983, another series in 1991-92, and then a large number in the early part of this decade. In the past year, we have written and released a series of reports entitled, *America's Climate Choices*, in response to a Congressional request from the House Subcommittee on Commerce, Justice, Science and Related Agencies under Chairman Mollohan. This series of reports examined the state of climate science, what we know, and what we believe we still must learn along with the state of strategies for climate mitigation and climate adaptation as well as an analysis of how to communicate with decision makers and the general public. Another recent report on climate from the National Research Council is on how to estimate the emissions of greenhouse gases with regard to any international agreement that might be adopted and on how well we could determine compliance with any international agreement. On a completely separate topic, the National Research Council issued a report recently on what impacts could be expected by stabilizing the atmosphere at various target levels of greenhouse gas concentrations. We have also been asked in the last several years, both by Congress and by Federal agencies, to examine the effectiveness of the United States Climate Change Science Program under President Bush, both its plans and its achievements. All of our reports have been clear that there is much to learn about future climate change and that the potential of future disruptions is large.

The Congressional Charter under President Lincoln that created the National Academy of Sciences in 1863, charges us to be responsive to request from the Federal Government for analyses of topics involving science. Our analyses are conducted by leading American experts occasionally augmented by talent from other countries. Each of our reports is peer reviewed by participants who did not engage in the study itself but whose evaluations and analyses are used so as to suggest revisions or corrections to the early draft versions of our reports. This method and the high standards which we attempt to employ assure that our reports will be of value as our government, our businesses, and our citizens continue to gauge how to respond to the challenges which we face today and in the future concerning human-caused climate change.

Thank you, Mr. Chairman.