Statement of

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Mr. Chairman, Ranking Minority Member, and members of the committee: thank you for inviting me here to testify today. My name is Berrien Moore III, and I am the Executive Director of Climate Central in Princeton, New Jersey and Director Emeriti of the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire. I appear today as Chair of the Earth Studies Committee of the National Research Council's (NRC's) Space Studies Board. In addition, my colleague Dr. Anthes and I served as co-chairs of the NRC's Committee on Earth Science and Applications from Space, which completed the Decadal Survey in 2007.

As you know, the NRC is the unit of the National Academies that is responsible for organizing independent advisory studies for the federal government on science and technology. The NRC has been conducting decadal strategy surveys in astronomy for four decades, but this was the first decadal survey in Earth science and applications from space.

Before addressing the role of space-based observations for improving our understanding of the planet's climate, I must express my concern about realizing the recommended missions from the Decadal Study.

For the moment, I will focus upon NASA. The Decadal Study concluded that the recommended NASA program could be accomplished by restoring the Earth science budget in real terms to the levels of the late 1990s. What I have observed since 2007 is that even with the political momentum following the Study and even with modest near-term increases, there has never been an "out-year" commitment to actually accomplish the recommended program. In fact, it is worse than that; it does not appear that there is an adequate commitment of funds to accomplish even a third of the program by 2017. This lack of "out-year" commitment that has characterized the last two budgets may be different in the future. I hope so; it should be so, but when I read about the out-year funding for NASA as a whole, I fear that the future for these key measurements is not good.

Finally, compounding the inadequate funding is the cost growth of the missions currently in development as well as the early missions from the Decadal Study. We must find a better way to manage costs.

Let me turn to climate change.

The issue of Climate Change poses a *serious* societal problem: First, the consequences could well be dire if the major industrialized nations do not act aggressively to alter their use of fossil energy, and second, the changes in our energy systems that are needed are without historical precedent.

The issue of Climate Changes also poses an almost uniquely *difficult* scientific problem. The difficulties come essentially from two sources.

First, the climate system is exceptionally complex. The range of important time constants is broad: from years to decades to centuries and hence almost all parts of the Earth system become involved in understanding the future evolution of the planet's climate.

Second, scientists often like to have a control group—those that get the medicine and those that do not; comparisons can then be made to evaluate how well the predicted effectiveness compared to what is to be measured. With regards to the increase in greenhouse gases and the changes in the planet, we have no other planet on which to carry out the control study—we cannot compare the Earth's with and without the increase in greenhouse gases.

In such a situation, we are fundamentally dependent upon our ability to develop models built upon our understanding of the dynamics of the planet's atmosphere, biosphere, hydrosphere, cryosphere and how these subsystems interact in the overall Earth system.

Over the last several decades and aided by ever more powerful computers and an array of space-based and *in situ* observation, we have made remarkable progress in modeling the climate system.

It seems to me, that two fundamental questions must be answered:

1. Given a suite of energy futures, what are the expected climate changes?
2. How confident are we in our answer?

The first question sets the pace required to avoid unwelcomed or dangerous changes in climate. Given the centrality of fossil fuels in all economies, we need to get the pace of change right with some margin on the safe side. The question of how much margin is needed is governed, in part, by our ability to answer the second question.

Hence for better or worse, our very best tool for evaluating the risk of climate change are climate models such as those developed by NOAA's Geophysical Fluid Dynamics Laboratory, the National Center for Atmospheric Research, and within the Department of Energy's Lawrence Livermore National Laboratory.

Given the complexity of the climate system, we must have means of testing our understanding as expressed through these highly complex mathematical models. There need to be ways to evaluate the prognostic skill of any model and of understanding the characteristics of this skill. In the case of weather prediction, one can test the skill—we do this daily. One can even question the skill and perhaps fire the forecaster. But for climate the problem is fundamentally different. The question of predictability of climate is integral to understanding the physics behind the low frequency natural variability of climate and distinguishing the signal of climate change. In other words, there are the paired challenges of capturing "natural" variability of climate as well as detecting (and predicting) the emerging human-forced climate signal. This dual challenge is distinctively climatic in nature; as is the *longer-term* character of climate projections; these linked aspects of the climate problem and system are unavoidable and problematic.

Fortunately, there appear to be coherent modes of behavior (such as El Niño-Southern Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation) that not only support a sense of optimism in attacking the prediction problem, but that also may offer measurable prediction targets that can be used as benchmarks for evaluating our understanding of the climate system. Moreover, predicting these modes represents a valuable contribution in itself.

Such demonstrations and the insights gained in developing and making prognostic statements on climate modes frame an important area for further work. This success also clearly demonstrated the importance of space-based observations such as the Topex-Poisidon and Jason ocean topography data, sea surface winds from QuickScat and WindSat, and MODIS Sea Surface Temperature data. My concern about this set of measurements is that sea surface winds is not adequately addressed. The Decadal Study recommended flight by NOAA of a sea surface winds instrument. I am worried that budget challenges for NOAA are having a negative impact on realizing an ocean winds instrument. One path forward would be to proceed with a simpler instrument; namely fly a copy of QuickScat—we need to avoid having the perfect be the enemy of the good.

The success in El Niño forecasting and in unraveling the large-scale climate modes is first order. And yet, the range of uncertainty in climate forecasting remains a large problem.

Much of the uncertainty about climate change and the degree of warming centers on clouds.

It is generally accepted that the net effect of clouds on the radiative balance of the planet is currently negative and has an average magnitude of about 10-20 Wm^{-2}; in other words clouds have a cooling effect overall.

The effect of clouds on the radiative balance consists of a short-wave cooling (the albedo (reflectivity) effect) of about 40-50 Wm^{-2} and a long-wave warming of about 30 Wm^{-2}. Unfortunately, the size of the uncertainties in this budget is large when compared to the expected anthropogenic greenhouse forcing. Understanding the cloud-climate connection is a particularly challenging scientific problem because it involves processes covering a very wide range of space and time scales.

There are, however, hopeful signs.

The CloudSat and Calipso missions (launched in 2006), which fly in formation (in the A-Train) with the NASA Aqua Mission, are providing valuable profiles of cloud water content, optical depth, cloud type, and aerosol properties, and this information leads to understanding processes.

From an energy budget view point, there is also good news. The Clouds and the Earth's Radiant Energy System (CERES) that is flying on the NASA Terra spacecraft are providing new insights on clouds and the heat balance of the planet. The added good news is that it will now be flown on the NPOESS Preparatory Mission and on the first NPOESS spacecraft. The Total Solar Irradiance Sensor (TSIS), which provides detailed measurements of the energy from the sun, will fly on NASA's Glory mission and again on the first NPOESS spacecraft.

Given that it is likely that the concentration of greenhouses gases will continue to increase in the atmosphere for *at least* the next 30 years, and that this change will force a change in the Earth energy balance, then we must monitor that energy balance and the solar output, if we are going to be able to make credible climate statements including forecasts. Even if there were an extraordinary change and greenhouse gases were stabilized, there would still need to monitor the Earth's energy budget because of the pre-committed warming. This is the reason that the Decadal Study recommended the Climate Absolute Radiance and Refractory Observatory Mission (CLARREO), which will build upon the record of CERES and other Earth radiation budget measurements. It seems obvious to me that we will need to monitor this basic energy budget for the planet from now on.

One central reason is that while current evidence that the current effect of clouds is cooling (negative feedback), the nature of the *future* cloud feedback is not clear. Will it remain *negative*?

If the planet warms, then it is likely that evaporation will increase which probably implies that cloud water content will increase but the volume of clouds and the area they cover may not. What will be the effect and how will the effects be distributed in time and space? What will be the effect of changes in the distributions of aerosols? What is the effect of changes in the chemistry of the atmosphere? *We simply must understand the underlying processes and this requires observations.*

The cloud feedback problem is important since it affects the albedo (roughly the reflectivity) of the planet. There is another issue associated with the planet's albedo.

There is increasing evidence that there is a rapid (more rapid than any model predicted) decline in extent and thickness of Arctic sea ice in the summer. This decline appears to be connected with the observed recent Arctic warming. It is not known whether these changes reflect anthropogenic warming transmitted either from the atmosphere or the ocean or whether they mostly reflect a major mode of multi-decadal natural variability. Some of this pattern of warming has been attributed to recent trends in the Arctic Oscillation; however, how the anthropogenic signal is imprinted on the natural patterns of climate variability remains a central question.

What does seem clear is that the changes in Arctic sea ice are significant, and there is a positive feedback that could be triggered by declines in sea ice extent through changes in the planetary albedo. If the Arctic shifted from being a bright summer object to a less bright summer object—an open Arctic sea, then this would be an important positive feedback on a warming pattern. The shift could be rapid and dramatic.

There is another feedback loop through increased evaporation lending to increases in cloud formation and enhanced albedo. Which will win? Are we to have an open Arctic sea in summer? The issue and the uncertainty are disturbing. Knowledge of the planet's energy budget is fundamental as is knowledge of its cryosphere.

IceSAT, MODIS, GRACE, and radar data from international partners have provided important observations, but the problem of changes in the snow and ice cover of the planet are immense and the system is inadequately monitored and understood. This is one reason that ICESAT-II was recommended in the first tier of Decadal missions

In thinking about climate change, we may be paying too much attention to temperature—the term global warming may actually focus concentration on too restrictive a topic. After all, most people on the planet live in areas far warmer than New Hampshire. It may well be that changes in the water cycle (rainfall, soil moisture, river flow, and evaporation) are more significant—particularly when these changes are viewed against the backdrop of other changes including population growth.

I state the obvious: precipitation is absolutely key for human society. It is obviously tied up with the cloud feedback problem via atmospheric water vapor, temperature, and other state variables and processes in the climate system. In other words, this is an area where our ability to probe possible changes in the patterns of precipitation is far weaker than our ability to bracket patterns of temperature change.

Patterns of precipitation set the stage for, and are partially determined by, evapotranspiration and the resulting distribution of soil moisture. Soil moisture is an important determinant of ecosystem structure and hence a principal means by which climate regulates (and is partially regulated by) ecosystem distribution. It is also central for agriculture. Our inability to bracket adequately changes in precipitation translates into a similar weakness in handling soil moisture, and soil moisture is dead central for terrestrial ecosystems and agriculture.

Returning to precipitation, the Tropical Rainfall Monitoring Mission has contributed significantly to our understanding of this central feature of our planet—for this we can be thankful. Unfortunately, the news is not always good—the Global Precipitation Mission continues to suffer cost growth and delay, and I am worried that the Soil Moisture Active and Passive (SMAP) mission faces a similar fate.

I would like to close with some thoughts about CO_2 and climate and human behavior.

The carbon dioxide problem is a big problem. The Ozone Hole was a big problem and not easily addressed even though CFCs were not in the center of the global economy. Fossil fuels are in the center of the global economy. Furthermore, the CO_2-Climate interaction has a very challenging dynamic.

Three Facts must be stressed:

1. To stabilize the concentration of carbon dioxide in the atmosphere, we must drastically reduce (cut by more than 80%) the global consumption of fossil fuels as well as manage the biosphere far better. In other words, stabilizing the atmospheric concentration of CO_2 requires far more than simply stabilizing emissions—if we could wave a magic wand and instantly stabilize CO_2 emissions today, the atmospheric concentration would continue to increase almost indefinitely with stable emissions.
2. To stabilize the global mean temperature below levels of harm *requires* that we acknowledge that global temperature increases lag the increases in the atmospheric concentration of carbon dioxide. Consequently temperature continues to increase globally well after the stabilization (in the atmosphere) of human induced greenhouse gases (e.g., principally carbon dioxide).
3. Finally, we are far from stabilizing the emissions of CO_2. More than 15 years have elapsed since the Climate Convention in 1992, and in the mean time, global CO_2 emissions from fossil fuels have increased by roughly 40%. The current trend in the CO_2 concentration in the atmosphere is above any of the IPCC Scenarios that were devised to explore future climates. We need to alter course.

I also think that we need to understand better the Carbon Cycle—where is CO_2 coming from; how much and where is it taken up by terrestrial biota; what is being released (net) by vegetation and through landuse, and how much and where is it absorbed into the oceans. How do these patters of sources and sinks vary with climate and weather patterns?

Understanding and perhaps managing carbon sinks (and other carbon sources) will be important as will having independent knowledge of fossil fuels sources.

Direct oceanic and terrestrial measurements of carbon and/or the flux of carbon dioxide are resource-intensive and hence sparse, and difficult to extrapolate in space and time. The problem of source-sink determination of CO_2 will be aided greatly by such surface measurements and studies, but it will not be resolved by this approach.

There is, however, a different complementary approach, and this is what the Orbiting Carbon Observatory (OCO) was to pursue. The geographical distribution of CO_2 in the atmosphere and its temporal evolution can be used to quantify surface fluxes. In other words, by measuring carefully the differences in CO_2 concentrations in the atmosphere, one can "work backwards" to the terrestrial and oceanic sources and sinks of CO_2.

Unfortunately, there was a launch failure and OCO did not achieve orbit.

Fortunately, the Japanese Greenhouse gases Observing Satellite is on orbit and other instruments (NASA's Atmospheric Infrared Sounder (AIRS) and the European Infrared Atmospheric Sounding Interferometer (IASI)) can help. Also, the Decadal Study has recommended an active laser-based mission, ASCENDS, to produce a highly precise global dataset for atmospheric CO_2 column measurements without seasonal, latitudinal, or diurnal bias.

The coupling of this high-precision, high-volume datastream with atmospheric inversion, data assimilation, and coupled atmospheric, terrestrial and ocean carbon modeling will enable us to quantify the sources and sinks at unprecedented space and time resolution. The final scientific outcome will be both greatly advanced understanding of the global carbon cycle as well as the essential scientific foundation for making reasoned future projections of atmospheric concentrations of carbon dioxide.

In sum, we are in need of knowledge of the Earth. We know that the planet's environment is changing on all spatial scales including global, and change is rapid, likely more rapid than at any time in human history. Many of these changes are occurring because of human activity. These human-induced changes are over and above the stresses imposed by the natural variability of a dynamic planet.

The changes cascade through the Earth's environment in ways that are difficult to understand and often impossible to predict. At the least, these human-driven changes in the global environment will require that societies develop a multitude of creative responses including strategies for mitigation and adaptation. The linked challenges of confronting and coping with global environmental changes and addressing and securing a sustainable future is daunting and immediate, but they are not insurmountable. The challenges can be met, but only with a new and even more vigorous approach to observe and understanding our changing planet.