Statement of
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Hearing on NASA's Earth Science Program

I thank Chairman Boehlert, Ranking Member Gordon, and the other Members of the Committee for the opportunity to speak with you today on NASA's role in the Earth Sciences. My name is Tim Killeen, and I am the Director of the National Center for Atmospheric Research (NCAR), which is sponsored by the National Science Foundation. I am also the President-Elect of the American Geophysical Union (AGU). My academic background is as an experimental space scientist who has participated in several NASA space science programs and a former professor at the University of Michigan, where I taught atmospheric, space, and Earth system sciences for many years.

The topic of this hearing is of tremendous importance to our understanding of the planet on which we live. I would like to make three fundamental points today, using examples of past and future contributions by NASA to the study of Earth:

- First, NASA plays a crucial role in this country's vibrant Earth sciences program. NASA is the dominant federal funding agency for U.S. scientists and engineers who address fundamental questions about our planet, provide practical knowledge about the way the Earth functions, and reveal how human activities affect the environment upon which all life depends. NASA funding for Earth science provides the intellectual capital and scientific infrastructure to produce work that is not just intellectually exciting but critical to human existence.

- Second, rapid advances in NASA Earth observing capabilities, coupled with revolutionary advances in information technology, have positioned us for an extraordinary new era in Earth science research – one in which we can quantitatively understand and predict the Earth *as a system*, with the temporal and spatial fidelity needed by decision makers at many levels of our society: local, regional, and global. This will lead directly to major societal benefits including:

    - improved national security
    - better weather forecasts and warnings
    - more targeted climate outlooks
    - better management of natural resources including water, agriculture, and energy

- more effective mitigation of natural disasters such as drought, floods, landslides, and volcanic eruptions.

- Third, the importance of Earth science and the central role of NASA in this field argue for careful, thorough, and deliberative assessment to inform program planning, especially when major changes are being considered. The current pace of budgetary and program change in NASA is inconsistent with such an approach and could result in irrevocable damage to programs and scientific teams that have taken decades and billions of tax dollars to build.

I fully understand that NASA faces many difficult choices arising from the pursuit of ambitious goals in a period of national budget constraints. However, I believe it important to proceed carefully when making decisions regarding important national assets and programs such as those represented within the NASA Earth Science effort.

A. The Importance of Earth Science and NASA's Role

It is clear after decades of pioneering satellite observations that Earth is a system of tightly coupled parts that interact in complex ways to produce the whole. The study of such interactions has become known as Earth system science, and has led to numerous insights about how the Earth functions and how it is evolving and changing over time. To understand how the atmosphere supports and protects life, for example, one must appreciate the complex and tightly coupled circulation dynamics, chemistry, interactions with the oceans, ice, biosphere, and land surface: all driven by solar radiation. And today, the natural system is clearly susceptible to changes due to human activity, creating still more complexity and variability over many scales of time and space. In any foreseeable future, we will have to understand this "system of systems" in order to help create, maintain, safeguard, and guide human societies. Earth system science, based on comprehensive and accurate ground- and space-based observations, is the toolkit that enables such investigation. Furthermore, the manner in which we explore other worlds will be informed by the understanding of our own.

Slide 1. Fully sunlit Earth photographed by Apollo 17 astronauts on route to the Moon.

For me personally, this "blue marble" photograph taken over 30 years ago by Apollo 17 astronauts on the way to the moon perfectly represents this complex system. You have all seen this incredible picture hundreds of times in advertisements, reports and public media. It is perhaps one of the most significant, but under-sung, societal icons we possess. At NCAR, it is featured in a wall mural.

There are many ways to illustrate the importance of NASA's role in supporting

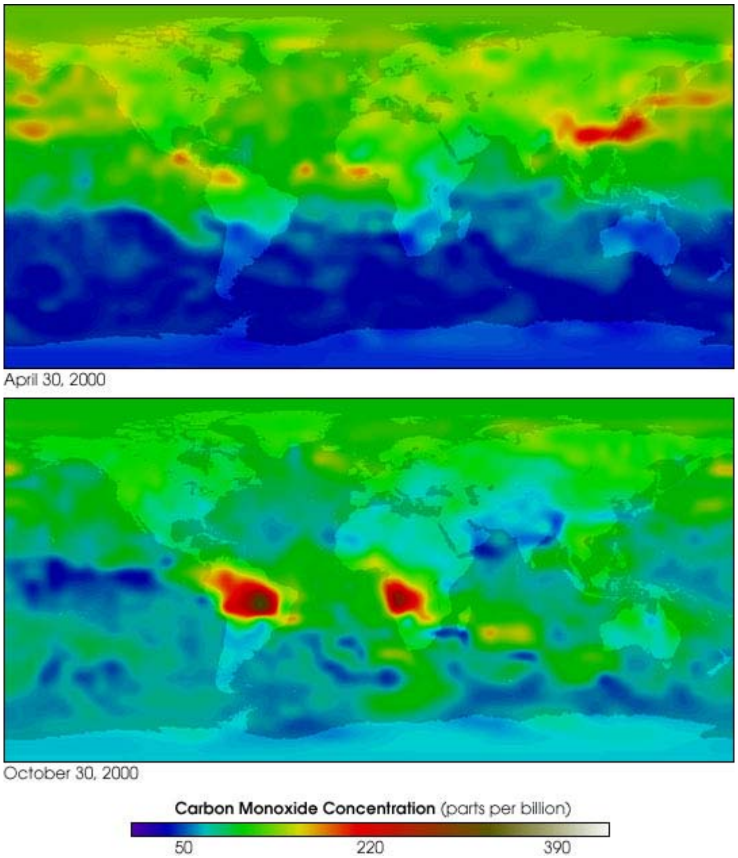
Earth system science in the U.S. In sheer budgetary terms, NASA is the single largest environmental science program supported by the federal government. The widely respected budget analyses of the American Association for the Advancement of Science (AAAS) indicate that NASA provided 34 percent of the total funding for the environmental sciences in 2004. Much of this spending is devoted to the design, development, and operation of scientific instruments, the spacecraft that carry them, and the data systems required to process, analyze, archive, and distribute data to the scientific community and other users. But it should also be remembered that NASA provides significant resources to university investigators through the research and analysis component of its program.

In fact, leaving spacecraft and data system costs aside, AAAS analyses show that NASA was the third largest provider of competitively awarded extramural funding for the university environmental science community in 2004, trailing only the National Science Foundation and the National Institutes of Health. Even small reductions in the NASA program have large effects in the university community. This matters both because research and analysis is the process by which useful information is derived from remote sensing systems, and because university-based research activities provide the human capital (undergraduates, graduate students, young researchers and engineers) that underpins the entire space program. The effects of funding perturbations reach far beyond the year in which they occur. The design and development of an Earth observation satellite takes a decade or more, and keeping young scientists and engineers engaged in such work requires some degree of steady ongoing support.

Another way of showing NASA's importance to this field is by looking at what has been accomplished. The scientific and practical results from NASA's Earth science program are much too extensive for me to catalogue here, but two examples can illustrate the unique contribution that NASA has made to our understanding of the Earth's atmosphere and its variations.

Example 1: Ozone depletions

The first example is probably well known to you. The ozone "holes" in the Antarctic and Arctic were monitored from space by various NASA satellite systems, including the Total Ozone Mapping Spectrometer (TOMS). The diagnosis of the physical and chemical mechanisms responsible for these dangerous changes to our protective ozone shield was made possible by the combination of observations, modeling, and theory supported by NASA. In fact, it was a NASA high-altitude aircraft that made the "smoking gun" measurements that convinced the scientific and policy communities that chlorine compounds produced by various human activities were centrally responsible for the observed ozone loss. Following these observations, international protocols were put in place that are beginning to ameliorate the global-scale ozone loss. The TOMS instrument has provided an ongoing source of data that permits us to track the level of ozone in the stratosphere, the annual opening and closing of the "ozone hole," and how this phenomenon is changing over time. These continuing measurements and analyses and the effective regulatory response have led, among other things, to a reduction in projected deaths from skin cancer worldwide.



Slide 2. Global measurements of air pollution from NASA Terra satellite. Courtesy NASA/GSFC, University of Toronto and NCAR

Example 2: Air Pollution Observations

Last week, President Bush mentioned proposed rules to limit air pollution from coal-fired power plants. Air pollution is clearly an important concern. NASA has played a major role in the development of new technologies that can monitor the sources and circulation patterns of air pollution globally. It is another tremendous story of science serving society through innovation. In this case, through an international collaboration, NASA deployed a one-of-a-kind instrument designed to observe global carbon monoxide and its transport from the NASA Terra spacecraft. These animations show the first global observations of air pollution. Sources of carbon monoxide include industrial processes (see, for example, source regions in the Pacific Rim) and fires (for example in Amazonia). These global-scale data from space have helped change our understanding of the relationship between pollution and air quality – we now know that pollution is not solely or even primarily a local or regional problem. California's air quality is influenced by industrial activity in Asia, and Europe's air quality is influenced by activities here in America.

From such pioneering work, operational systems can now be designed to observe pollution events, the global distribution of chemicals and particulate matter in the atmosphere, and the ways in which these substances interact and affect the ability of the atmosphere to sustain life – such a system will undoubtedly underpin future efforts to understand, monitor, and manage air quality globally. Without NASA's commitment to innovation in the Earth sciences, it is hard to believe that such an incredible new capability would be available today.

B. The Promise of Earth Observations in the Next Decade

The achievements of the last several decades have laid the foundation for an unprecedented era of discovery and innovation in Earth system science. Advances in observing technologies have been accompanied by vast improvements in computing and data processing. When the Earth Observing System satellites were being designed, processing and archiving the data was a central challenge. The Terra satellite produces about 194 gigabytes of raw data per day, which seemed a daunting prospect at the time of its definition. Now laptop memories are measured in gigabytes, students can work with remote sensing datasets on their laptops, and a large data center like NCAR increases our data holdings by about 1000 gigabytes per day. The next generation of high performance computing systems, which will be deployed during the next five years or so, will be petascale systems, meaning that they will be able to process millions of gigabytes of data. The ongoing revolution in information technology has provided us with capabilities we could hardly conceive of when the current generation of Earth observing satellites was being developed. We have just begun to take advantage of the synergies between these technological areas. The U.S., through NASA, is uniquely positioned to take advantage of this technological opportunity.

Example 3: Weather Forecasting

Weather forecasting in the Southern Hemisphere has been dramatically improved through NASA's contributions, and this experience illustrates the power of remote sensing for further global improvements in weather prediction. The lack of surface-based data in the Southern Hemisphere once meant that predictive skill lagged considerably behind that achieved in the Northern Hemisphere. The improvement in the accuracy of Southern Hemisphere weather forecasting is well documented and almost entirely due to the increased use of remote-sensing data. But improvements in the quality of satellite data were not sufficient. Improvements in data assimilation—a family of techniques for integrating observational results into predictive models—were also necessary. The combination has resulted in rapid improvement in Southern Hemisphere forecasting, which is now nearly equal to that in northern regions. Data assimilation capabilities continue to advance rapidly.

One can now easily conceive of forecast systems that will fuse data from satellites, ground-based systems, databases, and models to provide predictions with unprecedented detail and accuracy – perhaps reaching natural limits of predictability. A new generation of weather forecast models with cloud-resolving spatial resolution is coming on line, and these models show significant promise for improving forecast skills across the board. Use of new NASA remote sensing data from upcoming missions such as Calipso (Cloud-Aerosol and Infrared Pathfinder Satellite) and CloudSat will be essential to fully validate and tune these new capabilities which will serve the nation in providing improved hurricane and severe storm prediction, and in the development of numerous decision support systems reliant on state-of-the-art numerical weather prediction capabilities.

Example 4: Earth System Models

Data from NASA missions are central to constructing more comprehensive and detailed models that will more realistically represent the complexity of the Earth system. Cloud observations from MODIS (the Moderate Resolution Imaging Spectroradiometer) and precipitation measurements from GPM (the Global Precipitation Mission), for example, are critical to improving the representation of clouds and the water cycle in such models. Observations from MODIS and Landsat are fundamental to the development of more sophisticated representation of marine and terrestrial ecosystems and atmosphere–land surface interactions. The inclusion of this detail will help in the creation of true Earth system models that will enable detailed investigation of the interactions of Earth system processes and multiple environmental stresses within physically consistent simulated systems.

In general terms, Earth system observations represent the only means of validating Earth system model predictions. Our confidence in short-term, regional-scale weather predictions is based on how closely they match observed regional conditions. Assessing the performance of global-scale, longer-term model predictions likewise depends on comparing model results with observational records. Scientific confidence in the ability of general circulation models to represent Earth's climate has been greatly enhanced by comparing model results for the last century with the observational records from that period. At the same time, the sparse and uneven nature of past observational records is an ongoing source of uncertainty in the evaluation of model results. The existence of much more comprehensive and consistent global measurements from space—such as the data from the NASA Terra, Aqua, and Aura satellites—is a giant step forward in this regard, and, if maintained, will enable much more rigorous evaluation of model performance in the future.

In summary, Earth system models, with increasing temporal and spatial resolutions and validated predictive capabilities, will be used by industry and governmental decision makers across a host of domains into the foreseeable future. This knowledge base will drive new economies and efficiencies within our society. I believe that requirements flowing from the needs and capabilities of sophisticated Earth system models will be very useful for NASA in developing strategic roadmaps for future missions.

C. The Importance of Careful Planning

The central role of NASA in supporting Earth system science, the demonstrated success and impact of previous and current NASA missions, and the promise of continued advances in scientific understanding and societal benefits all argue for a careful, analytical approach to major modifications in the NASA Earth science program.

As noted above, the development of space systems is a time-consuming and difficult process. Today's actions and plans will have long-term consequences for our nation's capabilities in this area.

The link between plans and actions is one of the most important points I want to address today. From the outside, the interagency planning process seems to be experiencing substantial difficulties in maintaining this link. The NASA Earth science program is part of two major Presidential initiatives, the Climate Change Science Program (CCSP) and the Global Earth Observation System of Systems (GEOSS). With regard to the CCSP, it is not apparent that the strategies and plans developed through the interagency process are having much impact on NASA decision-making. In January 2004, then-Administrator of NASA, Sean O'Keefe, called for acceleration of the NASA Glory mission because of the direct relevance of the mission to understanding the roles of aerosols in the climate system, which is one of the highest-priority science questions defined in the CCSP research strategy. NASA is now proposing cancellation of the mission. As I have emphasized throughout this testimony, the progress of and benefits from Earth system science research are contingent upon close coordination between research, modeling, and observations. The close coordination of program planning among the agencies that support these activities is also a necessity. This coordination currently appears to be fragile.

The effect of significant redirections in NASA and reduction in NASA's Earth science effort are equally worrisome in the case of the Administration's GEOSS initiative, which is focused on improving the international coordination of environmental observing systems. Both NASA and NOAA satellite programs are vital to this effort. The science community is very supportive of the GEOSS concept and goals. There are over 100 space-based remote-sensing systems that are either operating or planned by various nations for the next decade. Collaboration among space systems, between space- and ground-based systems, and between suppliers and users of observational data is critical to avoiding duplication of effort and to getting the most out of the investments in observing technology. The tragic example of the Indian Ocean Tsunami demonstrates the need for such coordination. The tsunami was detected and observed before hitting land, but the absence of effective communication links prevented warnings from reaching those who needed them in time. A functioning GEOSS could lead to major improvements in the rapid availability of data and warnings, and the U.S. is right to make development of such a system a priority. But U.S. credibility and leadership of this initiative will be called into question if our nation is unable or unwilling to coordinate and maintain the U.S. programs that make up the core of our proposed contribution.

D. Answers to Questions Posed by the Committee

My testimony to this point has outlined my views on a series of key issues for the NASA Earth science program. Much of the text found above is relevant to consideration of the specific questions posed by the Committee in its letter of invitation. In this section, I provide more direct answers to these questions to the extent possible and appropriate.

How should NASA prioritize currently planned and future missions? What criteria should NASA use in doing so?

I believe that NASA should work with the scientific and technical community and its partner agencies to define a NASA Earth science plan that is fully compatible with the overall CCSP and GEOSS science strategies. In my view, the interaction with the scientific and technical community should include both input from and review by the National Research Council (NRC) and direct interaction with the strong national community of Earth science investigators and the aerospace industry who are very familiar with NASA capabilities and developing technological opportunities. Competitive peer review processes should be used appropriately in assessing the merit of competing approaches and in key decision-making. I believe NASA should also find a means of involving users and potential users of NASA-generated data in this process, perhaps through public comment periods or a series of workshops. Sufficient time should be allotted to this process for a careful and deliberative evaluation of options. This science plan should then guide the process of setting mission priorities.

Defining criteria to use in comparing and deciding upon potential missions would be an important part of this planning exercise. I would recommend consideration of a set of criteria that include:

- compatibility with science priorities in the CCSP and GEOSS science plans
- potential scientific return from mission
- technological risk
- direct and indirect societal benefits
- cost.

I believe that the decadal planning activity underway at the NRC in response to a request from NASA and NOAA is a valuable step in this process.

What are the highest priority unaddressed or unanswered questions in Earth science observations from space?

I believe this question is most appropriately addressed through the community process suggested above. There are many important Earth science questions, and prioritizing among them is best done in a deliberative and transparent process that involves extensive input from and discussion by the science community. I would personally cite soil moisture, three-dimensional cloud characteristics, global vector tropospheric winds, pollutant characteristics and transport, carbon fluxes, and aerosol distributions as all high priority measurements to make on a global scale.

What have been the most important contributions to society that have come from NASA Earth sciences over the last decade (or two)?

NASA Earth science programs have played a key role in developing our understanding of the Earth as a coupled system of inter-related parts, and in the identification and documentation of a series of global-scale changes in the Earth's environment, including ozone depletion, land use and land cover change, loss of biodiversity, and climate change. Other examples of societal contributions include improved weather forecasting, improved understanding of the large-scale climate variations, such as the El Nino-Southern Oscillation and the North Atlantic Oscillation that alter seasonal patterns of rainfall, and improved understanding of the status of and changes in marine and terrestrial ecosystems that contributes to more effective management of natural resources.

What future benefits to the nation (societal applications) are possible that NASA Earth sciences could provide? What gaps in our knowledge must we fill before those future benefits are possible?

In a broad sense, NASA Earth science activities are part of developing a global Earth information system that can provide ongoing and accurate information about the status of and changes in the atmosphere, oceans, and marine and terrestrial ecosystems that sustain life, including the impact of human activities. The continued development of observation systems, sophisticated Earth system models, data assimilation methods, and information technologies holds the promise of much improved predictions of weather and climate variations and much more effective prediction and warning of natural hazards. Much has already been accomplished to lay the groundwork for such a system, but many important questions remain. Some of the most important have to do with the functioning and human alteration of the Earth's carbon, nitrogen, and water cycles, and how these cycles interact; the regional manifestation of global scale climate change; and the reactions of ecosystems to simultaneous multiple stresses.

Summary

In closing, I hope that my short list of examples suffices to emphasize the fact that it is not possible to conceive of a vigorous and healthy Earth system science effort in the United States without a strong ongoing NASA program. The scientific community is in the initial stages of a knowledge revolution enabled by the vast increases in the capabilities of, and synergy between, observation and information technologies. The advances in Earth system science that are being enabled by these capabilities are critical for understanding the Earth system and how it is changing. Such understanding is an important contribution to natural resource management, natural-hazard mitigation, and sustainable economic growth. I understand that NASA faces many difficult choices arising from pursuit of ambitious goals in a period of budget constraints, but I urge you to take account of the unique and central role of NASA observing programs in our nation's climate, weather, and Earth system science efforts as you oversee development of the plans and strategies that will guide NASA in the coming decade and beyond.