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Statement of
Dr. Waleed Abdalati
Chief Scientist
National Aeronautics and Space Administration

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Mr. Chairman and members of the committee, it is my pleasure to appear before you today to discuss the topic of sea level rise. Sea level rise is one of the most readily recognizable manifestations of climate change, because it is directly observable without the aid of instrumentation, with very visible effects. Sea level rise is not as rapidly variable as many of the other indicators of climate change, such as temperature or precipitation. Rather it evolves relatively slowly and presents a clear expression of the integrated elements of our changing climate.

Since the late 19th century, measurements of sea level rise have been made using tide gauges in coastal regions. These gauges provide tremendously valuable information on local changes in ocean height relative to their adjacent land. However, they provide an incomplete picture of the absolute and global rates of sea level rise because (1) their measurement is relative to the ground surface in which they are mounted, so they do not account for the upward or downward movement of that surface itself, and (2) their distribution is limited, making sample measurements in a few places rather than over the global ocean. These gauges reflect a bias toward the regions in which they are located, grossly undersampling the global ocean; thus they do not offer a picture of sea level rise's considerable regional variability. Since 1993, NASA and its partners have been monitoring sea level continuously from space using satellite altimetry. Satellite altimetry has the advantage of being able to measure globally, for a more complete and representative sampling of the oceans. Moreover, it works in a global terrestrial reference frame rather than a local relative one, making its measurements independent of the local movement of the underlying surfaces.

Since the beginning of the satellite record in 1993, sea level is estimated to have been rising at a rate of 3.1 $\pm$ 0.4 mm/yr (see attached figure). Estimates based on tide gauges prior to 1993 are for rates of approximately half that amount.

These values represent global averages. Of greater concern to coastal managers and those who have to deal with the effects of sea level rise, are the regional values referred to earlier, which can vary significantly from place to place. Some ocean areas, including parts of the Eastern tropical Pacific, have experienced a lowering of sea level since 1993, while others, such as the Western Pacific, exhibit sea level rise rates several times greater than the global mean. This difference is related to: the rising or sinking of parts of the globe in response to the loss of the great ice sheets that blanketed much of North America roughly18,000 years ago; the global wind patterns, which distribute the water differently around the globe by pushing water toward land in some areas, and away from land in others; and the rotation of the Earth, which also changes the distribution of water. According to the U.S. Global Change Research Program report *Global Climate Change Impacts in the US (2009)*, "Approximately one-third of all Americans live in counties immediately bordering the nation's ocean coasts," and similar scenarios are true - often in greater proportions - for other nations. For this reason, it is very important to understand variations in sea level not just on a global scale, but on a regional scale as well.

Looking toward the future, the projections of sea level rise have large uncertainty as a result of our limited – but emerging – understanding of the factors that contribute to sea level rise. These projections range from a low of 0.2 meters by the end of the century to a high of 2 meters. Values near the low end of the range are less likely than others, since they do not account for some potentially significant contributions for the Greenland and Antarctic Ice Sheets. At the same time, the highest values are based on warmest of the temperature scenarios commonly considered for the remainder of the 21st century.

To understand the current state of sea level rise, and estimate the future rates, it is important to understand the elements that influence it. In the simplest terms, sea level is the combined effects of the following components:

- Ocean thermal expansion is the increase in ocean volume as it warms.
- Input from the world's glaciers and the Greenland and Antarctic ice sheets can either raise sea level, when the glaciers and ice sheets are shrinking and dumping their mass into the ocean, or it can lower sea level, when they are growing, and taking mass out of the ocean.
- Terrestrial storage in groundwater, dams and reservoirs, etc. can either raise or lower sea level.

Our current estimates indicate that about a third of the sea level rise over most of the last three decades is coming from the expansion of the warming ocean, while two thirds is derived from the world's shrinking glaciers and from the Greenland and Antarctic ice sheets. The amount attributable to terrestrial storage is currently negligible.

While sea level is simple to conceptualize, it is difficult to predict, as major contributing factors involved are very complex and not well understood. The biggest wild-card in the sea level equation is the Earth's great ice sheets. With the equivalent of about 7 meters of sea level in Greenland, and 60 meters in Antarctica, their potential for contributing to sea level rise is large. To understand how ice sheets contribute to sea level rise, one first has to understand their mass budget. As with sea level rise, the budget is the difference between the mass *input* to the ice sheet, which comes mainly from snow accumulation, and the *output*, which is mainly a combination of melting, discharge or calving of icebergs, and sublimation (direct transition from snow to water vapor). If global average air temperatures continue to increase along the trends observed over the last 100 years, all of these components – accumulation, melting, and discharge rates – are expected to increase.

Analysis of satellite, aircraft and in situ observations, coupled with models of the accumulation and precipitation, make clear that the Greenland ice sheet has been losing mass at a rate that contributes about 0.6 $\pm$ 0.01 mm/yr to sea level rise, and Antarctica is losing ice that translates to the equivalent of 0.45 $\pm$ 0.2 mm/yr of sea level rise. What has the attention of the scientific community, however, is that a number of key glaciers in both Greenland and Antarctica have dramatically accelerated their flow to the sea in recent years. Some have more than doubled their speed in just a few years. This is in response to the warming of surrounding seas, which causes the floating ice at the ends of the outlet glaciers that drain the ice sheet to melt, which then reduces their restraining force on the glaciers upstream, causing the ice to accelerate. In the simplest terms, the warmer the seawater gets, the less resistance to flow there is in the outlet glaciers, and the more rapidly they dump their ice into the sea.

This phenomenon is of particular concern in the West Antarctic ice sheet (WAIS), an area about the size of the states of Texas and Oklahoma combined. WAIS contains the equivalent of 3.3 m of sea level, and all that ice rests on a soft-bed that lies below sea level. In this configuration, as warm seawater melts the floating ice shelves, causing them to retreat and the glaciers that feed them to speed up, there is no mechanism to stop the retreat and associated discharge, if warming continues. Thus the WAIS exhibits great potential for substantial and relatively rapid contributions to sea level rise.

In Greenland, the situation is not as dramatic, since the bed that underlies most of the ice is not below sea level, and the potential for unabated retreat is limited to a few outlet glaciers. In Greenland, however, summer air temperatures are warmer and closer to ice's melting point, and we have observed widespread accumulation of meltwater in melt ponds on the ice sheet surface. The water from these melt ponds often drains rapidly to the bottom of the ice, where it lubricates the interface between the ice and the underlying bedrock, and causes a rapid acceleration of the ice toward the sea. Both the acceleration due to ice shelf retreat, and the acceleration due to meltwater penetration, represent potential instabilities and can lead to rapid sea level rise. To be clear, "rapid" in terms of sea level rise means on the order of about a meter or two in a century. There is evidence that during some periods over the last 18,000 years, oceans have risen by as much as 5 cm/yr (5 meters in a century), which is roughly fifteen times the current rate. Such rapid rates of sea level rise are a result of rapid discharge of ice from the Earth's great ice sheets, which, during the last glacial maximum, were much larger than today.

These past high rates amplify the importance of understanding the underlying mechanisms and their likely behavior in the future. The importance is underscored by the vulnerability of coastal populations and infrastructure. Unfortunately, while we have the ability to observe changes in ice sheets, sea level, and ocean characteristics, our ability to predict these phenomena is very limited, and requires a greater understanding of the physical processes at work.

The expansion of oceans in response to warming temperatures is fairly well understood, as are some aspects of ice sheet changes – specifically the loss of ice through melt, and the accumulation of ice through precipitation. But the motion of ice sheets, which control the rate of discharge to the surrounding seas, are not well understood and cannot at present, be predicted with confidence. The speed-up I described earlier may constitute a sustained, enhanced discharge keeping rates of sea level rise high; it may be a precursor to a more substantial discharge through increased acceleration; or it may be self-correcting, as these glaciers adjust to their new shapes in a way that reduces the forces that carry the ice out to the sea.

With the development of satellite and airborne remote sensing capabilities, coupled with ever-advancing field measurements and modeling efforts, we are beginning to understand current changes and gain insights into what the future may hold for the Greenland and Antarctic ice sheets. Our satellite and airborne capabilities are providing observations of glacier flow rates, ice topography (which is indicative of the underlying processes that affect change), mass change, and depth and topography of the bedrock that lies beneath the ice. This last point is particularly important because it is the geometry of the bed, in conjunction with surface elevations, that determine the extent to which glaciers will continue to accelerate or will slow down.

Current and planned investments in missions such as the Ice, Cloud and Land Elevation Satellite 2 (ICESat-2 -- measuring elevation change) and the Gravity Recovery and Climate Experiment (GRACE) follow-on (measuring mass change) and airborne observations of ice topography bed geometries provide insights into the underlying mechanisms of ice sheet changes. NASA also works with data from its international partners to examine the variations in flow rates of outlet glaciers, tracking the magnitude and character of their acceleration. The information gained from all of these projects is incorporated into ice sheet models designed to predict how ice sheets will contribute to sea level rise in the next one or two centuries. The modeling activity is an integrated effort jointly carried out by NASA, the National Science Foundation, and the Department of Energy (DOE). NSF also invests in basic observations and process studies that are either directly coordinated with or are complementary to NASA's activities, and DOE is building dynamical models of Greenland and Antarctica, where future sea level rise projections take advantage of observations provided by NASA and NSF. Through these investments and activities, the scientific community is making progress toward addressing the wild-card of the sea level rise equation, but we are still a ways off from a level of understanding that would allow us to predict future changes accurately.

Sustained observations of ocean elevation from satellites, in particular with the Jason satellite series operated by NOAA in collaboration with our European partners, combined with tide gauges will provide an ongoing measurement of current rates of sea level rise. Continued observations of ice sheets and glaciers will provide necessary insights into the physical processes that govern their contributions to sea level rise. Ongoing measurements of ocean characteristics will continue to inform our assessments of temperature and circulation characteristics, which affect the rate of expansion. Continued observations of the movement of water throughout the Earth will provide important insights into the characteristics of land-water storage. All of these data are critical inputs used to inform models and improve our understanding of the physics, carrying us closer to a more complete and robust sea level rise prediction.

A complementary method for predicting future sea level rise is to compare past temperatures to past sea levels reconstructed from the geological record of Earth's climate history. There is a fairly robust relationship between the two, and by using this relationship or correlation, one can predict values of sea level rise for estimated values of future temperatures. This method is a statistical, rather than a physical approach, and when applied to future warming scenarios, this method provides the highest estimates (2 meters of globally-averaged sea level rise) for the end of the century. It has the advantage of not requiring a detailed understanding of the complex physics in order to make a prediction, and it produces results consistent with recent history. However, because it does not directly incorporate underlying physical processes, this method provides limited insight into mechanisms and characteristics of future sea level rise.

In summary, we can say with confidence that sea levels have been rising at a rate of approximately 3.1 mm/yr over the last 30 years. About a third of this rise is attributed to thermal expansion and about two thirds comes from the melting, retreat, etc. of glaciers and ice caps. The projections for the future are very uncertain, and range from a low of 0.2 meters by the end of the century to a high of 2 meters. This large uncertainty is a result of our currently limited understanding of instabilities in flow rates of outlet glaciers on the Greenland and Antarctic ice sheets. Moreover, some coastal areas will experience perhaps little or no rise in sea level, while others may experience rates that are far greater than this globally-averaged value. The consequences of a 1 meter rise in sea level by the end of this century would be very significant in terms of human well-being and economics, and potentially global socio-political stability.

Finally, because the ocean and in part the ice have a significant lag in response to temperature changes, the rise in temperatures over the last century has already set an inevitable course for this century. As a result, the effects of sea level rise in the coming decades should inform coastal, economic, and political planning today.

Figure Mean sea level anomaly from the satellite altimetry: Source: Nerem, et al., Marine Geodesy (2010);, *(updated at http://sealevel.colorado.edu)*.