Glacier and ice sheet monitoring: Data needed for cutting edge science in the next decades.

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Introduction

In the last two decades, scientists and policy makers have become increasingly concerned about changes in the Earth's land ice (i.e., glaciers and ice sheets). This has been driven by a growing consensus that changes in glaciers and ice sheets are sufficiently large and rapid to cause significant changes in sea level, and by concerns about the future availability of water supplies for populated areas downstream of glacier catchments; both of these will have severe impacts on human activities. Recent independent satellite-derived estimates, using three techniques[1], show clear agreement of accelerated ice mass loss in Antarctica, Greenland, and glaciers worldwide, and have focused our attention on changes in the land ice. Loss of land ice is an example of the effects of a changing climate on large-scale earth systems. Current scientific consensus suggests that large losses in land ice will continue in the coming decades, likely with increasing magnitude and visibility.

This white paper addresses the needs of the scientific community for observations of glacier and ice-sheet, changes that are required for improved decadal- to centennial-scale estimates of land-ice change. The goals to be addressed are:

I. To measure the present rate of change of each component of land ice with sufficient spatial and temporal sampling required for attribution (atmosphere, ocean, or internal forcing?)

II. To use these data and improved understanding in glacier and ice-sheet models to estimate the sensitivity of land ice change to climate and ocean forcing.

Glaciers

[1] The three techniques for estimating mass loss are: 1) satellite altimetry which gives direct estimates of height/volume/mass changes; 2) satellite gravity which gives direct estimates of mass change; and 3) mass-flux method which uses InSAR-derived velocity and altimeter-derived ice thickness.

Mass loss from glaciers and ice sheets accounted for nearly two thirds of the sea-level rise observed between 2003 and 2009 (Shepherd and others, 2012, Gardner and others, 2013). Glaciers contain only a small fraction of land ice and the sea-level rise equivalent of the remaining glaciers is less than 0.41 m (Vaughan and others., IPCC AR5, 2014). Glaciers are, however, currently losing mass at a rate comparable to the ice sheets, and are expected to continue to do so for the next century and a little beyond (Marzeion and others, 2014) (Radić and others, 2013); therefore, they are of first-order importance to NASA's goal to better understand the roles and interactions of the ocean, atmosphere, land and ice in the climate system (NASA Science plan, 2014). Characterization of the causal processes controlling observed changes in glacier mass require temporally- and spatially-resolved estimates of glacier mass change. Knowledge of regional-scale glacier mass changes comes primarily from airborne and satellite geodetic assessments (changes in height and/or gravity) and numerical modeling efforts validated against *in situ* records (Gardner and others, 2011, Lenaerts and others, 2013).

Only within the last decade have near-global geodetic assessments of glacier change become possible, as a result of complementary height and gravity data collected by NASA's ICESat (Ice, Cloud, and land Elevation Satellite) and GRACE (Gravity Recovery and Climate Experiment) satellites, respectively (Gardner and others, 2013, Jacob and others, 2012). After the end of the ICESat mission in 2009, the GRACE satellites became the only NASA satellites to continue global-scale analysis of glacier mass changes until ICESat-2 and GRACE Follow On are launched in late 2017. GRACE is able to directly measure the redistribution of mass around the Earth but is limited by coarse spatial resolution (~300 km) and the requirement for detailed knowledge of non-glacier sources of near-surface mass variation, such as glacier isotactic adjustment and changes in terrestrial water storage. These limitations make the attribution of the processes responsible for the observed mass changes exceedingly challenging.

Measuring changes in subpolar glaciers with sufficient resolution to understand the processes and sensitivities in the coupled ice-atmosphere system requires an improvement in our capability for high-resolution geodetic measurements. In general, this requires two or more well-timed measurements of surface height per year for each glacier worldwide. While ICESat-2 will improve on estimates made using ICESat data, primarily by providing denser spatial coverage at sub-polar latitudes, it will still only give sparse repeat coverage for most small glaciers and ice caps such that glaciological studies based on these data will require ancillary reference heights. Currently, data of this type are available to US researchers from non-NASA sources including the Worldview satellites (coordinated through the Polar Geospatial Center at the University of Minnesota) and the German TanDEM-X satellite constellation; the former is not guaranteed to continue in the future, and the latter can be prohibitively costly for routine monitoring over large areas.

Ice sheets

The Greenland and Antarctic ice sheets have a combined sea-level rise potential of 66 m (Vaughan et al., IPCC AR5, 2014). We divide the ice sheets into three categories based on the different measurement requirements of each: coastal ice-sheets and outlet glaciers, ice sheet interiors, and Antarctic ice shelves.

Coastal ice-sheets and outlet glaciers

Ice loss from the coastal regions of ice sheets has outpaced modest changes occurring in their interiors since the late 1990s in Greenland and more recently in Antarctica (Krabill and others, 2000, Harig & Simons, 2015). This increasingly negative mass balance is due to processes related to surface mass balance and changes in ice discharge as glaciers react to changing environmental conditions (van den Broeke and others, 2009, Velicogna and others, 2014). Both melt-induced and dynamic mass losses exhibit rapid short-term fluctuations and large spatial variability, indicating the complexity of surface processes and the ice sheets' response to climate forcing (Csatho and others, 2014). Moreover, dynamic processes could lead to rapid collapses of large marine-based sectors of the ice sheets (Joughin and others, 2014).

Extrapolation of the current behavior into the future could yield erroneous long-term trends, because of our incomplete understanding of the complex interplay between the major earth systems (ice sheet, atmosphere, ocean, solid earth). Continued monitoring of ice sheet surface elevation and velocity with improved temporal and spatial resolution along the coastal regions of ice sheets are required to improve ice sheet and coupled ice-atmosphere-ocean models, which will lead to reduced uncertainties in sea-level predictions.

Ice-sheet interiors

One important challenge in the next decades will be to understand changes in the interior of the Greenland and Antarctic ice sheets. While ongoing changes are likely to be subtle compared to the meter-scale vertical changes measured near the coasts and in subpolar glaciers, the volume of ice and the area of its interface with the atmosphere are both large. For example, a 7 cm per year water-equivalent change in ice thickness distributed over the 14 million square km surface area of Antarctica would roughly equal the currently observed sea-level rise of 3 mm/yr. Geodetic estimates of ice-sheet change, particularly in combination with gravimetric estimates that measure changes in the mass of the ice sheet and the bedrock beneath it, can provide direct estimates of the contribution of the ice sheets to sea-level change.

Interpretation of measured changes in surface elevation are confounded by short term processes such as snow accumulation and subsequent densification to firn then to glacier ice, and, for grounded ice, by solid earth processes that act on continental scales, such as post-glacial rebound. While solid-earth processes induce a generally constant rate of height change over the timescale of an altimetry mission and are correlated over long spatial scales, surface mass balance processes induce height changes over timescales from hours to years and vary over spatial scales of hundreds of meters to hundreds of kilometers. Thus, they have a first-order contribution to height change measurements (Shepherd and others, 2012). As snow accumulates on glaciers and ice sheets, the surface height increases. In warmer regions of the ice sheets, this height increase is counterbalanced by episodic melting; in colder regions it is offset by the slow densification of snow into ice. This interplay between accumulation and densification is a function of the snow temperature profile and the snow accumulation rate. Consequently, conversion of height change estimates into mass balance estimates requires a robust characterization of the snow accumulation and surface temperature changes that drive height changes on short space and time scales. Any geodetic program must therefore combine well-calibrated height change measurements with state-of-the-art surface mass balance studies.

Estimates of ice-sheet mass balance spanning multiple decades may be less affected by fluctuations in the near-surface density than those that rely on short observation periods. Historical data span more than two decades and include satellite radar altimeters (RAs) aboard ESA's ERS-1 (1992-1996) and ERS-2 (2003) and Envisat (2002-2012), and laser altimetry from ICESat (2003-09). Current and planned missions include RA from Cryosat-2 (2010-present), altiKA (2013-) and Sentinel-3 (2015-), and laser altimetry from ICESat-2 (2017-), together with airborne laser altimetry from IceBridge and previous NASA missions (1992-). RA data have an unknown, potentially large (Nilsson et al., 2014), sensitivity to surface condition changes that is likely not consistent between missions, which limits their usability for measuring long-term changes; laser altimeter data offer a more precise estimate of surface height and a smaller sensitivity to surface changes, but, even at the end of the ICESat-2 mission, will have a shorter epoch. Improving our understanding of interior ice-sheet mass balance will require improved models of biases for historical radar altimetry data, as well as laser-altimetry missions that continue beyond the predicted lifetime of ICESat-2.

Antarctic ice shelves

Antarctica's ice shelves provide mechanical support that 'buttresses' the seaward flow of grounded ice, so that ice-shelf thinning and retreat result in enhanced ice loss to the ocean (Rignot and others, 2004, Scambos and others, 2004). Accelerated ice-shelf thinning and grounding line retreat over the past two decades raises concerns about future loss of grounded ice and resulting sea level rise. All of the regions of large grounded-ice height changes seen from satellite altimetry (Zwally and others, 2005, Shepherd and others, 2012, Pritchard and others, 2009) are associated with shrinking or disintegrated ice shelves. If present climate forcing is sustained, we expect there will be a significant reduction in floating-ice at decadal-to-century time scales, leading to the loss of buttressing and to increases in grounded-ice loss and grounding-line retreat. An 18-year time series of ice-shelf thickness estimates constructed from ERS-1, ERS-2 and Envisat RA height data (Paolo and others, 2015) demonstrates that the thickness varies on annual and decadal timescales, implying that results from single satellite missions over a few years are insufficient to draw conclusions about long-term ice-shelf changes.

Understanding ice-shelf change requires observations at ~km spatial scales relevant to ice shelf processes and on temporal scales that are sufficient to capture seasonal and annual changes. Geodetic change monitoring on ice shelves is rendered more difficult than that for grounded ice, because ice shelves are floating, and so the surface height changes by approximately 10 cm for every ice-equivalent meter of mass gained or lost. Further, the motion of km-scale features that move with the ice-shelf surface can also lead to apparent surface-height changes, whose effects can best be corrected if contemporaneous surface-velocity data are available (Moholdt and others, 2014). This implies that the ice shelves need to be continuously monitored at fine spatial resolution and that future altimetry missions should be planned so that they overlap. It also suggests that ice-shelf height change measurements must be made at decimeter precision, and that corrections need to be developed for changes in the firn column, which can introduce large biases into ice-shelf melt-rate estimates.

Summary

The largest unknown contribution to future global mean sea-level change likely will come from changes in land ice, in response to atmospheric, oceanic and internal forcing. A better understanding of ice-mass loss processes and forcing mechanisms is required for improving models that project future changes in sea level and availability of water resources. One way forward is to observe land-ice change over long time periods and then empirically relate observations to ocean and atmospheric variability. This requires repeat measurements of surface elevation on temporal and spatial scales that can only be accomplished through space observations. Satellite altimetry is the only technique that has the spatial and temporal resolution required to more fully understand the processes leading to the mass change. Satellite gravity data provide important independent data to identify which regions are losing mass.

We recommend that NASA's portfolio missions over the next decade include:

--Temporally continuous or overlapping satellite laser altimetry that cover glaciers and both ice sheets

-- Temporally continuous or overlapping and satellite gravimetry missions that that cover glaciers and both ice sheets

--High-resolution photogrammetry and/or synthetic-aperture radar missions to measure velocity and geometry changes in glaciers, ice shelves, and ice-sheet margins.

To fully recognize the explanatory power of satellite altimetry, we further recommend additional investments need to be made not only in the satellite instruments but also into understanding firn and surface-mass-balance processes. This will require continued NASA investment into in situ monitoring of surface processes. and subsequent improvement/development of physically-based model frameworks that can provide robust estimates of between repeat elevation measurements. These studies would help reduce the uncertainty in ice-sheet and ice-shelf mass balance due to accumulation and firn-compaction variability, and due to mission-to-mission biases in historical radar data.

	Measurement goals	**Unique challenges**	**Measurement priorities**
Glaciers	-Current trend magnitudes -Process model constraints	Small spatial scales Strong atmospheric signals need downscaled data	-Fine-scale altimetry / photogrammetry -Understanding of SMB processes such as surface reflectance
Coastal ice sheets and outlet glaciers	-Process-based modeling -Ablation rates	-Processes operate on short temporal and spatial scales	-Altimetry / photogrammetry with sub-seasonal temporal resolution -Seasonal velocity measurements
Interior ice sheets	-Estimating present and recent-past mass balance -Inland propagation of coastal changes	-High precision requirements -Large signals due to accumulation and densification variability	-Long-term laser-altimetry measurements -Accurate firn and SMB modeling -Mission-to-mission radar altimetry calibration
Ice shelves	-Estimates of ocean and atmospheric forcing -Changes in marginal forcing	-Hydrostatic compensation reduces signal -Large sensitivity to firn-model processes -Advection of small-scale features	-Long-term altimetry time series -Accurate firn and SMB modeling -Velocity mapping

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