Understanding and Quantifying Glacier Ice Dynamics for Improved Sea Level Projections.

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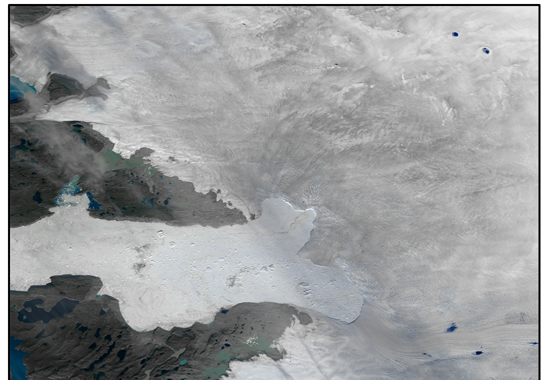

Figure 1: Landsat-8 image of the calving front of Jakobshavn Isbrae, Greenland, which has rapidly retreated since 2002 and is now calving 18 km inland into a 2-km deep canyon, with a 0.5-m global sea level rise potential. Tracking fracturing mechanisms is important to reduce uncertainties of projections of ice sheet evolution.

Sea level rise is a problem of considerable societal and scientific importance. Projections of sea level rise by year 2100, however, are affected by considerable uncertainty (Fig. 1), with values ranging from 20 cm to as much as 2 m, and sea level rising faster after 2100. A rise of 2 m would displace about 200 million people globally (Willis and Church, 2012).

Physical models of the Earth used by the Intergovernmental Panel on Climate Change Report (IPCC AR5) project a global sea level rise of 20 to 60 cm by 2100, but these projections do not include contributions from accelerated flow and/or rapid fracture of ice sheets into the ocean (e.g., Pollard et al., 2014) or catastrophic break up of ice shelves (MacAyeal et al., 2003)

Upper bounds on sea level from ice sheets have been estimated from kinematic constraints on glacier flow (Pfeffer et al., 2008) and paleoclimate analogs (Dutton et al., 2015). Paleoclimate records indicate that during the Eemian period (130,000 to 115,000 years ago), mean temperatures were similar to present (1-2^{o}C warmer than pre-industrial temperatures), global sea level was 6 to 9 m higher, and parts of Greenland and West Antarctica Ice Sheets had melted away (Dutton et al., 2015). The rate of sea level change during the Eemian is not well constrained.

Several marine-based sectors of the Greenland Ice Sheet totaling 1.1 m sea level equivalent are retreating rapidly (Mouginot et al., 2015) at present and the Amundsen Sea sector of West Antarctica is in a state of irreversible retreat with a potential global sea level rise equivalent of 1.2 m (Joughin et al., 2014; Rignot et al. 2014). In East Antarctica, the marine-based Wilkes Land sector holds a multi-meter sea level equivalent, with several of its glaciers thinning, but projections are limited by a lack of ocean observations.

As marine-based glaciers start retreating inland, the dominant process of ablation will be ice calving off big walls, but this process is not well understood at present (e.g., Pollard et al., 2014).

While historical missions considerably advanced our knowledge of ice dynamics and their role in ice sheet mass balance, no prior space missions were designed to make ice-sheet dynamics the prime focus. NISAR will be the first mission of its kind to offer this capability but its nominal duration is 3 years. Beyond NISAR, we need to continue measurements with greater observation frequency to observe rapid changes such as seasonal speed up and slow down, large iceberg calving events, rapid calving from embayed, retreating ice cliffs, and accelerating ice discharge. Understanding of these processes, along with ice-ocean interaction, is critical to improve the reliability of sea level projections from melting land ice.

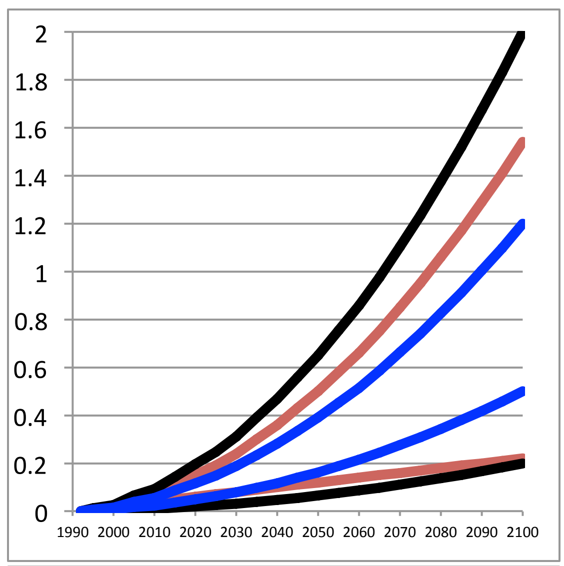

Figure 2. Projections of global sea level rise from USACE (red), NOAA (black), and IPCC AR5 (blue) with lowest and highest scenarios by year 2100. Most ice sheet experts, however, agree that the lower projections are too conservative.

Table 1: Ice dynamics processes, in priority order, including the amount of existing observations, models and additional space-based observations required to improve sea level predictions.

Physical Processes	Existing Observations	Space-based Observational Need	Priority/Justification
Ice flow (ice sheets, glaciers and ice caps).	**Space-based:** *Limited* – Int'l SAR limited by cost/acquisition (Cosmo Skymed, TerraSAR-X, TanDEM-X, RADARSAT-1/2, ALOS-PALSAR-1/2) acquisition (Sentinel-1a/b, Landsat-8). ICESAT-2, CryoSat. **Suborbital /Field:** *Limited*- OMG/GLISTIN.	**Instrument:** InSAR, Landsat time series. **Spatial/Temporal Resolution:** 1 m - 10 m Daily to weekly.	**Very High**- Space-based technologies and algorithms are in place, but there is no dedicated mission for monitoring ice dynamics beyond NISAR (3-yr mission). Probably requires a constellation of satellites or a tandem NISAR mission.
Ice fracture at margin	**Space-based***:* *Limited*- Except for largely unavailable commercial missions, no existing SAR offers temporal repeats < 11 days. **Suborbital/Field:** *Very limited*- OIB and OMG visit once a year.	**Instrument:** InSAR **Spatial/Temporal Resolution:** 1m/ daily	**Very High**- Space-based technologies and algorithms exist, but no space mission offers frequent repeat.
Surface mass balance	**Space-based:** *GRACE* at low resolution (400km) combined with ice dynamics derived from InSAR and ICESAT-2. **Suborbital /Field:** *Limited- OIB* multi-seasonal deployments.	**Instrument:** GRACE follow-on, 3D InSAR **Spatial/Temporal Resolution:** 1 cm/mo. **Model**: RCM	**High**- Space-based technologies and algorithm exist, improvements in spatio-temporal resolution are required to document surface mass balance processes.
Sea ice dynamics (polynea).	**Space-based:** *High* - Existing SARs provide some coverage, including Sentinel-1a/b.	**Instrument:** Frequent-repeat SAR	**High:** Space-based technologies and algorithms exist.
Ice shelf melt	**Space-based:** *Limited* **-** Int'l SAR limited by cost/acquisition (see ice flow row). Laser altimetry limited (ICESat-1/OIB/ICESat-2). Terra, Aqua, Landsat time series. **Suborbital:** Radar sounders. **Model:** Regional climate model (RCM)	**Instrument:** InSAR with frequent repeat to detect grounding lines, ICESat-2 laser altimetry mission (laser). Landsat time series. **Suborbital:** Sustained radar sounders OIB. **Model:** RCM	**Very High**- Space-based technologies and algorithms are in place, but there is no dedicated mission for monitoring ice dynamics beyond NISAR (3-yr mission).

1) Key challenges for ice flow dynamics in terms of basic research, applied research, and operations in the coming decades.

Basic Research:

1) Quantifying changes in ice flow regime of ice sheets at high-enough temporal and spatial resolutions to reduce uncertainties in sea level rise reconstruction.
2) Quantifying ice fluxes into the ocean to reconstruct sea level fingerprints.
3) Quantifying the feedback between ice-ocean interaction and ice dynamics.
4) Providing adequate observational constraints for ice sheet numerical models to capture rapidly evolving component of ice sheets: seasonal acceleration and slow down, iceberg calving, grounding line migration.
5) Improved understanding of glacier calving dynamics.

Applied research:

1) Building up big-data assimilation techniques for ice sheet numerical models to incorporate information about ice dynamics (and also surface mass balance).

Operations:

1) Providing space-based platforms capable of measuring ice flow dynamics accurately, uniformly and frequently over ice sheets, glaciers and ice caps (**Table 1**), including in 3 dimensions, which requires the ability to routinely image to the left and right of the orbit track (which is also required for pole-to-pole coverage).

2) Timeliness and Readiness

Many major glaciers in Greenland and Antarctica have opened up their respective floodgates and started a possibly irreversible retreat inland, with decades to centuries of future sea level rise. *Despite their global significance, the mechanics of glacier flow, ice fracture into icebergs, and ice-ocean interaction (including ice shelf melt into the ocean) are the least-well understood components of sea level rise for decades to centuries to come.*

3) Fundamental aspects of space-based observations in addressing key surface process questions

The technologies for the requested sensors exist. Monitoring ice dynamics from space requires multiple sensors, including time series of InSAR data, ICESAT-2, and Landsat follow-on. CubeSat constellation and suborbital assets (Operation IceBridge) would increase the temporal resolution for key measurements. These resources would have additional applications for sea ice monitoring, solid earth science and ecology (aka NISAR).

Space-based observations (Table 1) can address key scientific questions and societal needs by providing the spatio-temporal resolution required to characterize ice dynamics across glaciers and ice sheets worldwide.

Table 1 provides a list of measurements needed to overcome existing limitations and subsequently contribute to improve sea level projections. Table 1 provides a general assessment of readiness for space-based applications.

4) Scientific Community Involvement

There is broad support in the scientific community for comprehensive space-based measurements of ice flow dynamics. We expect additional white papers highlighting the need for improved understanding of ice dynamics. For instance, Straneo et al., 2012 as part of Greenland CLIVAR; Fernandez-Pietro et al., 2012 as part of a meeting organized by ESA, CliC, WCRP, and EGU.

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