The importance of understanding and quantifying surface processes over the cryosphere for improved climate and sea level rise predictions

Figure 1: Melt ponds on sea ice modify the heat and energy budgets of the polar oceans through albedo-feedback mechanism yet, they remain poorly constrained in models. Monitoring their extent and volumes from space-based sensors would provide key data needed to improve sea ice predictions. Photo: Kathryn Hansen/NASA

Climate change and rising sea levels present economic, engineering, and societal challenges for current and future generations. Two-thirds of the world's cities have vulnerable populations of five million or more living in at-risk areas, less than 10 meters above sea level. Warming temperatures, amplified in the Arctic, are melting glaciers and ice sheets and diminishing Arctic sea ice extent and volume, creating feedback loops for further warming (**Figure 1**). For decades *US and international agencies have designed monitoring programs for the cryosphere*, supporting missions to monitor sea ice extent/concentration and land ice melt extent (e.g., DMSP), sea ice freeboard and ice sheet elevation changes (ICESat, Operation IceBridge (OIB), CryoSat-2 and the future ICESat-2), albedo variations (e.g., MODIS), total mass change from gravity (GRACE) and ice motion (e.g., RADARSAT, TerraSAR-X, Sentinel-1). *While historical missions advanced our knowledge of the cryosphere, they generally neglected measurements of crucial parameters driving surface processes (SP) such as melt water production, runoff, accumulation, and storage/retention, leaving models, constrained by limited in situ measurements, to estimate SP.* Though OIB monitors SP to a limited extent, as measurements of opportunity, *there are no future planned missions, either space-borne or suborbital, that will directly measure SP.*

1) Key challenges for basic research, applied research, applications, and operations in the coming decade

The key challenges for **surface processes** for land and sea ice for the coming decade are:

Basic Research:

1) Quantifying and reducing uncertainties of the spatio-temporal evolution of melt and melt volume over land and sea ice.
2) Quantifying fluxes and reducing uncertainties of the supraglacial hydrological system over the Greenland ice sheet (GrIS) especially for runoff and retention.
3) Assessing the contributions of feedback loops and processes connected to albedo (e.g. surface composition, presence of impurities and biota, and deposition processes).
4) Constraining snow accumulation and mass redistribution processes (e.g., blowing snow, snow depth) and their impacts on mass balance and on snow-atmosphere heat and chemical exchange from the ice sheet, sea ice, and ocean.
5) Understanding the relationships between SP and ice flow/dynamics, ocean freshening from runoff, and internal ice warming from retention/refreeze of melt.

Applied research:

1) Characterizing hydrological systems, improving albedo schemes, and improving accumulation and snow redistribution in land and sea ice models for improved sea level rise and climate predictions.

Operations:

1) Providing platforms capable of collecting data at the required spatial, spectral and temporal resolution to monitor SP, specifically for albedo, melt pond evolution and melt volume (**Table 1**).

2) Timeliness and Readiness

Though SP are important over the entire cryosphere, the contemporary behavior of the GrIS and Arctic sea ice punctuate the immediate need for space-based resources capable of capturing crucial processes that are currently poorly quantified. In the past two decades, the GrIS has quadrupled its annual mass loss and, in the past few years, it has undergone a paradigm shift, now losing the majority of its mass from surface runoff (**Figure 2**) rather than from ice dynamics (e.g., calving). Melt extent in 2012 covered ~97% of the ice sheet, with runoff over 2.5 standard deviations above the mean, causing proglacial rivers to swell. The destruction of a bridge near Kangerlussuaq, Greenland (**Figure 2**) epitomizes the exceptional runoff in 2012. Also in 2012, the Arctic sea ice minimum extent reached a new record low. The decline of Arctic sea ice is outpacing model predictions. *Despite the immediate global significance of GrIS meltwater to sea level rise and the feedback effects of melt processes on Arctic sea ice, they remain among the least understood hydrologic systems on Earth. The dynamic, fine scale processes of production, transport, storage/retention, and release of freshwater into the oceans are poorly understood and quantified.*

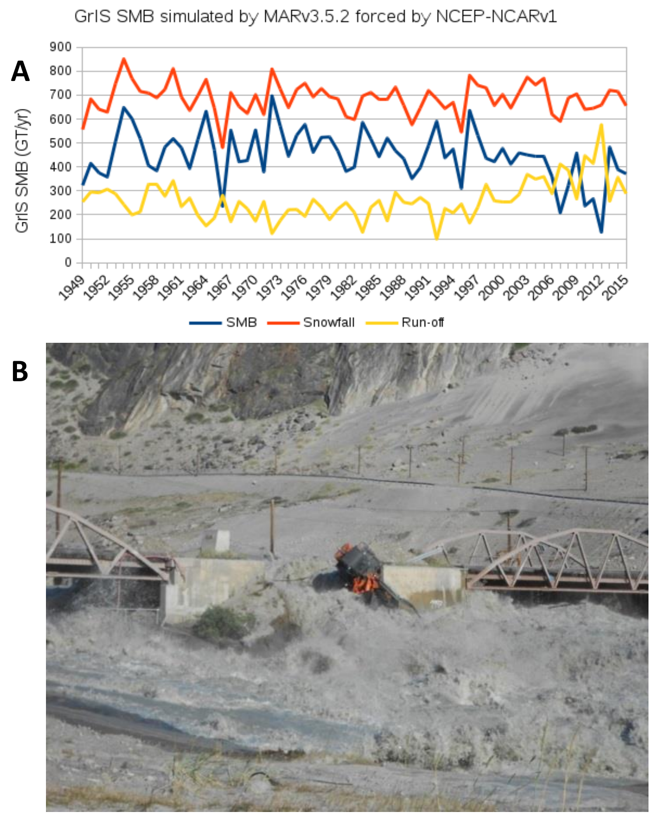

Figure 2: **A**) Time-series of modeled surface mass balance (blue) for the GrIS showing stable snowfall (red) and accelerating run-off (Yellow) since ~2000. (X. Fettweis) B) The impact of peak run-off in 2012 is illustrated by the swollen Watson River, near Kangerlussuaq, Greenland, overtaking and destroying a bridge. Photo: K. Choquette.

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

*Space-based observations (**Table 1**) can address key scientific questions and societal needs by providing the spatio-temporal resolutions required to characterize SP across the cryosphere.* **Table 1** provides a list of the measurements needed to overcome the existing limitations and, hence, improve sea level and climate predictions. **Table 1** provides a general assessment of readiness for space-based applications and a brief assessment of space-based algorithms, existing field measurements and model estimates. While some space-based instruments/technologies currently monitor SP, they are either in sub-optimal orbits (e.g., GPM, TRIMM), have a coarser spatial and spectral resolution than what is required to resolve the physical processes (e.g., MODIS), and/or have a coarser temporal resolution than the physical processes (e.g., WorldView, Landsat, ASTER).

Although we focus here on the scientific measurements, the technologies already exist for the requested sensors. Monitoring key SP from space will require multiple sensors, including a multispectral/hyperspectral sensor and a bathymetric lidar for water depths. Using a CubeSat constellation and/or suborbital assets, like UASs, could increase the temporal resolution for key measurements. These resources would constrain the highest priority SP (**Table 1**) and have additional applications for hydrology, oceanography and ecology. The success of an SP mission will be judged by the quantifiable improvements to process understanding, modeled estimates and data integration into wider system's research.

4) Scientific Community Involvement

There is broad support in the scientific community for comprehensive space-based measurements of SP over the cryosphere. We expect, and support, additional white papers from other cryospheric scientists highlighting different scientific foci and instrumentation that will improve our understanding of SP. This white paper predominantly focuses on Arctic applications, derived from meeting notes from the SUMup 2012 and PARCA 2014/215 meetings compiled by the NASA SUMup (Surface Mass Balance and Snow on Sea Ice) Working Group whom has coordinated the SP community and consolidated in situ data to improve SP models since 2012. This white paper was broadly distributed and has 22 coauthors.

Table 1: Surface processes, in priority order with justification, including an assessment of the amount of existing observations and models and the space-based observations required to improve climate and sea level predictions

Surface Process	Existing Observations/Models	Space-based Observational Need	Priority/Justification
Melt	**Space-based:** *Limited* - melt extent is well characterized at low spatial resolution by microwave sensors, melt volume is poorly constrained from multi/hyperspectral imagery and empirically-derived algorithms **Suborbital /Field:** *Limited*- multi/hyperspectral imagers, Weather station spectrometers, some **Models:** RCM	**Instrument:** Multi/ Hyperspectral imagery, Bathymetric Lidar (vertical precision of 10 cm) **Spatial/Temporal Resolution:** 1 m/ daily during melt season	**Very High**- Space-based technologies and algorithms exist, improvement in spatio-temporal resolution are realistic and required to monitor melt processes, limited in situ measurements, models differ significantly over the GrIS (~38% variance), required for modeling Arctic sea ice decline
Runoff / Outflow	**Space-based***:* *Limited*- water depths and stream velocities from multi/hyperspectral imagery and empirically-derived algorithms **Suborbital/Field:** *Extremely limited*- Supra- and proglacial stream mapping and discharge estimation, proglacial gauging stations and cameras. **Models:** RCM	**Instrument:** Multi/ Hyperspectral imagery, Bathymetric Lidar (vertical precision of 10 cm) **Spatial/Temporal Resolution:** 1m/ daily during melt season	**Very High**- Space-based technologies and algorithms exist, improvements in spatio-temporal resolution are realistic, an improved quantification of runoff/outflow will directly improve SLR estimates, very few in situ measurements can be sustained, models differ significantly over the GrIS (~42% variance)

Surface Process	**Existing Observations/Models**	**Space-based Observational Need**	**Priority/Justification**
Albedo	**Space-based:** *Well sampled*- low spatial resolutions (e.g., MODIS) and low temporal resolutions (e.g., Landsat, ASTER). **Suborbital /Field:** *Limited*- multi/hyperspectral imagers, Weather station spectrometers **Models:** RCM and GCM	**Instrument:** Multi/ Hyperspectral imagery **Spatial/Temporal Resolution:** 1 m/ daily during melt season	**High**- Space-based technologies and algorithms exist, improvements in spatio-temporal resolutions are realistic and required to monitor melt processes, limited in situ measurements
Accumulation/ Snow Redistribution	**Space-based:** *Limited*- long-term averages from microwave sensors **Suborbital/Field:** *Moderately sampled*- airborne and in situ radars, stakes, ice cores and snowpits **Models:** RCM and GCM	**Instrument:** Large-bandwidth radar altimeter similar to OIB Snow or Accumulation Radar **Spatial/Temporal Resolution:** 10 km/ weekly	**Medium**-Suborbital radars are capable of measuring accumulation, redistribution difficult to measure near sea ice pressure ridges, models have reasonable agreement over GrIS accumulation (~20% variance), redistribution mass loss is small over ice sheets compared to melt and calving
Retention	**Space-based:** *Extremely limited*- experimental algorithms from radar backscatter **Suborbital/Field:** *Limited***-** OIB accumulation radar, ice cores **Models:** RCM	**Instrument:** Radar **Spatial/Temporal Resolution:** 10 km/ monthly	**Low**-Limited return monitoring from space as algorithms are experimental, a better course of action, at this time, is to monitor from in situ measurements or existing suborbital instruments