Greenland ice sheet surface mass balance simulated by the NASA GISS ModelE2 GCM

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Including an accurate simulation of ice sheet mass balance in General Circulation Models (GCMs) is important for understanding feedbacks between ice sheet mass loss and global climate change. Here we evaluate and test improvements to the simulation of Greenland Ice Sheet (GrIS) surface mass balance (SMB) in the NASA GISS ModelE2 GCM. ModelE2 SMB and SMB components are compared with Modèle Atmosphérique Régional regional climate model (MAR RCM) outputs. A control simulation with ModelE2 captures average GrIS SMB as simulated by MAR and general patterns of GrIS SMB spatial variability. There are larger discrepancies in SMB components (e.g. ~50% less melt in ModelE2, compensated for by a lack of refreezing). Adding a surface elevation class scheme for which the surface model is run at multiple elevation classes reduces local differences relative to MAR, but has a relatively small impact (~6%) on overall SMB. Replacing ModelE2 fixed albedo with satellite-derived albedo from the Moderate Resolution Imaging Spectroradiometer (MODIS) increases ModelE2 melt by ~100%, bringing ModelE2 closer to MAR. Improvements under development include a multilayer snow model that incorporates meltwater percolation and refreezing, physically-based surface albedo scheme, and corrections to the parameterization of surface roughness length.
Visco-Elastic Response of Shear Weakening Due to Periodic Drainage of Water-Filled Crevasses

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The impacts of surface melt water on ice dynamics via supraglacial lake drainage and runoff have been well documented. However, little attention has been focused on the impact of direct melt water injection into the shear margins of fast flowing, marine-terminating outlet glaciers or on present modeling capabilities ability to address such processes. Even less attention has sought to quantify the viscoelastic response of ice sheets to rapid injection of surface melt water to the base. It is possible that injection of surface melt water produces a rapid impulse response in ice flow before returning to its base flow state that would likely be undetected by most satellite imagery due to the short time scales required. Here, the pulsed response nature of this process is considered by applying an idealized version of drainage perturbations for the summers between May 2007 and September 2015 to a viscoelastic model. We use the model to rapidly increase subglacial water pressurization caused by drainage of 7 water-filled crevasses along the Jakobshavn Isbrae shear margin and trace the dynamical response along four, 10 km long flow lines on the southern margins of the ice stream. This works seeks to quantify the ice dynamical response to surface melt drainage and the anticipated length of time such perturbations can be expected to affect ice flow. This work will also assist in understanding how future ice flow will be affected by prolonged duration of water-filled crevasses due to global warming.
Quantifying Water Retention Within the Greenland Ice Sheet using Airborne Radar Sounder

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Each year, surface ablation generates substantial meltwater along the ablation zone of the Greenland Ice Sheet. Surface streams carry some of this meltwater to the edges of the ice sheet where water runoff into the oceans. However, earlier studies have speculated that some of the meltwater is likely retained within the ice sheet instead of flowing out to the margins. Currently, there is little information on how much of surface meltwater is retained and the relative amount stored in the englacial and the subglacial water systems. Here we develop a new technique to quantify and constrain the amount and spatial distribution of water retention beneath the Southwestern and Western coast of Greenland. We examine radar bed echo strengths and develop metrics to calibrate these echoes to indicate the area of subglacial water storage. We show how to apply this technique to partition the relative importance of subglacial and englacial storage in water retention for Russell Glacier, Isunnguata Sermia and Store Glacier.
Ice-sheet discharge from PROMICE airborne surveys

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The Program for Monitoring of the Greenland Ice Sheet (PROMICE), has been surveying the Greenland ice sheet since 2007. Bedrock elevations surveyed around the PROMICE perimeter provide 5400 km of independent validation of the BEDMACHINE product. There has been no discernible change in ice flux across a PROMICE perimeter at c. 1700 elevation over this survey period. Combining altimetry and surface mass balance simulations with this ice flux in the context of historical observations provide an observationally-constrained estimate of the ice sheet's theoretical balance iceberg discharge. While the ice-sheet discharge assessed during 1995-2015 is consistent with previous studies, our observationally-constrained balance discharge is substantially lower than previous studies, meaning that the proportion of iceberg discharge we consign to sea-level rise is substantially higher than previous studies.
Meltwater storage in near-surface low-density bare ice in the Greenland Ice Sheet ablation zone

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On the surface of an ablating glacier, a layer of porous ice termed “weathering crust” forms when the depth of subsurface melting owing to penetration of shortwave radiation exceeds surface lowering. Subsequent drainage of subsurface meltwater through the permeable crust to supraglacial channels reduces near-surface ice density, by remove mass with no detectable change in glacier surface height. As such, mass change during periods of weathering crust development or removal cannot be resolved solely from ice surface elevation changes (for example as measured by ablation stakes or altimetric elevation retrievals) without knowledge of the sub-surface depth-density profile (Fig. 1). We document the density and hydrologic properties of near-surface, bare, ablating ice in a mid-elevation (1215 m a.s.l.) supraglacial catchment in the Kangerlussuaq sector of the western Greenland Ice Sheet. We find water-saturated, low-density ($\mu=0.69$ g cm$^{-3}$) ice to at least 1.1 m depth below the ice sheet surface. Ice density data from 10 shallow (0.9–1.1 m) ice cores along an 800 m transect suggest an average 14–18 cm of specific meltwater storage within this low-density ice.

Fig. 1. (a) Conceptual diagram of weathering crust structure, highlighting the porous ice layers, cryoconite holes, and saturated water table (adapted from Irvine-Fynn and Edwards, 2014 and Müller and Keeler, 1969). (b) Theoretical sub-surface depth-density profile showing the non-linear increase in ice density from the highly porous, low-density near-surface ice to a higher density substrate (adapted from LaChapelle, 1959).
Subglacial roughness of the Greenland Ice Sheet: relationship with contemporary ice velocity and geology

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The subglacial environment of the Greenland Ice Sheet (GrIS) is poorly constrained, both in its bulk (e.g. geology, sediment and presence of water) and interfacial properties (e.g. roughness and geotechnical bed properties). There is, therefore, limited understanding of how spatially heterogenous subglacial properties relate to ice-sheet motion. Here, via analysis of two decades worth of CReSIS radio-echo sounding data, we present a new systematic analysis of subglacial roughness beneath the GrIS. We use two independent methods to quantify subglacial roughness. First, we use the variability of along-track topography (enabling assessment of roughness anisotropy), and second, we infer roughness from bed-echo scattering (enabling assessment of finer-scale information).

We depict the spatial distribution of subglacial roughness and quantify the relationship with ice velocity (magnitude and flow direction). In fast flowing regions ‘topographic roughness’ exhibits an exponential scaling relationship with ice velocity parallel, but not perpendicular, to flow direction. In many slow flowing regions both roughness methods indicate spatially coherent regions of smooth bed, which, combined with analyses for underlying geology and lithology, we conclude is likely due to the presence of a hard bed. In this vein, this study provides scope for a spatially variable hard bed/soft bed boundary constraint for ice-sheet models.
Improved SERAC fusion for seamless extraction of elevation time-series from altimetry and DEM data in preparation for ICESat-2

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Satellite and airborne remote sensing missions have provided a wealth of information about the elevation and thickness changes of ice sheets and glaciers over the last decades. However, the fusion of the elevation data obtained from altimetry measurement and stereo imagery is still a challenging task due to the different physical principles and sampling of the observations. Our Surface Elevation Reconstruction And Change detection (SERAC) approach uses simple surface shape models to facilitate multisensor fusion. This presentation will summarize the following improvements of SERAC implemented in preparation for the ICESat-2 mission: (1) modification of SERAC algorithm to handle ICESat-2 data; (2) inclusion of improved ASTER DEMs derived by the MMASTER algorithm (Girod et al., 2017); (3) analysis of ICESat Intermission Bias Corrections using extended SERAC time series; and (4) improved temporal modeling of elevation/thickness change time series using P-Spline fitting.
Recent (2015-2017) melt patterns over the Larsen C ice shelf from models and observations

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Surface melting has been implicated in the collapse of ice shelves on the Antarctic Peninsula (AP). In July of this year, a rift in the remaining Larsen C ice shelf broke away one of the largest icebergs ever recorded (iceberg A68). The northern Larsen C ice shelf is one of the most vulnerable regions in the AP, subject to both general atmospheric warming as well as the föhn winds which can result from strong westerly flow. Here, we discuss the frequency of surface melt patterns during the 1998-2017 period (assessed with passive microwave data) over the northern Larsen C ice shelf, differentiating melt which is a result of föhn flow in contrast to melt resulting from general warming. We place specific focus on the 2015-2016 and 2016-2017 melt seasons. During these periods, we compare modeled circulation patterns (assessed with AWS data), including föhn frequency, with the period average. We also examine the evolution of firn density and the depth of meltwater percolation over these two seasons during periods of intense surface melt.
Robot Towed SWIR Camera for Specific Surface Area Retrieval

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Optical grain size (OGS) and specific surface area (SSA) are key parameters for measuring the atmospheric interactions of snow, as well as tracking metamorphosis and allowing for the ground truthing of remote sensing data. We describe a device using a shortwave infrared camera with changeable optical bandpass filters (centered at 1300 nm and 1550 nm) that can be used to quickly measure the average SSA over an area of 0.25 m^2. The device and method are compared with calculations made from measurements taken with a field spectral radiometer. The instrument is designed to be towed and powered by a four wheeled autonomous ground vehicle, and is built to run and collect data for hours or days without human intervention.
18 Year Record of Surface Melt Impact on the Greenland Ice Sheet from MODIS - where and when firn was modified by melt

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Melt modifies the reflectance of snow by wetting the surface grains and saturating the snowpack, and leaves a record of increased grain size and ice crusts and lenses. By calculating a simple spectral index affected by these changes, we map the year-to-year variations in the impacts of melt across Greenland from 2000 to present using MODIS 500m bands. This record provides a spatial picture of where firn modifications occur in any given year, which can provide a check on region climate reconstructions over time and should contribute to our understanding of firn densification patterns relevant to altimetry time series. The normalized spectral index returns compatible results from Landsat, Sentinel 2, and MODIS; it is sensitive to even small amounts of surface melting, and can be used to delimit even the dry snow zone on an annual basis.
Glacier bed knickpoints limit inland thinning around the Greenland Ice Sheet

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The fastest observed rates of dynamic mass loss from the Greenland Ice Sheet occur near termini of marine-terminating glaciers. Here we show that, for these glaciers, terminus retreat initiates thinning that diffuses upglacier to steep portions of glacier beds. Theory predicts that, as glacier flow self-organizes into topographic lows, mountainous bed topography focuses ice flux into fjord-terminating tidewater glaciers, eroding knickpoints where the bed slope is steeper than up- and down-glacier of the knickpoint. These bed knickpoints occur where the bed goes below sea level and creates an ice sheet geometry that limits inland diffusion of terminus thinning. Our survey of 185 marine-terminating glaciers corroborates the theory; we find steeper knickpoint slopes in East Greenland, where topography is more mountainous than in Northwest Greenland. Some glaciers have inland thinning limits that extend beyond sea level because of gentler knickpoint slopes. These glaciers are thus able to contribute more to sea-level rise because the bed knickpoints are less capable of preventing the diffusion of terminus thinning from reaching deep into the interior of the ice sheet. Using inland thinning limits and ice flux, we rank each glacier by its susceptibility for future mass loss. Our ranking focuses future monitoring and modeling efforts on the most vulnerable parts of the ice sheet.
Airborne radar observations of Greenland firn aquifers

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In 2011, prior to seasonal melt, our research team drilled into an unknown firn aquifer system in Southeast Greenland. Since 2013, we have conducted four field seasons, complemented with modeling and remote sensing to gain knowledge regarding firn aquifers and surrounding snow/firn/ice. We aim to provide a more complete picture of the system including formation conditions, controlling mechanisms, spatial and temporal changes, and connections with the larger ice sheet hydrologic system. Our compilation of remote sensing measurements point to a dynamic and expanding aquifer system. We found that firn aquifers have existed at least since 1993 (dataset start) in the high melt and high accumulation region of the South Eastern Greenland ice sheet. Firn aquifers are now growing toward the interior related to the warming air temperatures in the Arctic and more intense melt during summers. These airborne radar observations and our associated in-situ measurements are required to validate improved ice sheet mass balance models that incorporate firn aquifers. They are also needed to further investigate the potential of firn aquifer discharge to the glacier bed via crevasse hydrofracturing influencing ice dynamics.
Cloud and boundary layer variability over Greenland observed from remote sensing and in-situ observations

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In this study, we compare the seasonal and climatological distribution of surface-based inversions (SBIs) and cloud fraction over Greenland using 8 years of COSMIC RO and CALIPSO/CloudSAT observations, respectively. The SBI frequency and low-cloud fraction appear to be negatively correlated in the given spatiotemporal framework. In order to investigate further, we examine the relationship between surface temperature, saturation, and boundary layer stability using in-situ surface and upper-air observations over Summit. In lieu of cloud observations, we use profiles of minimum dewpoint depression for estimating saturated layers in the lower troposphere. Thermodynamic instability appears to be the dominant factor influencing the boundary layer stability. The two-way feedbacks between surface and saturated layers is examined with an aim of separating cause-and-effect mechanisms, viz., the influence of cloud longwave forcing on surface temperatures and boundary layer mixing versus the influence of thermodynamic instability on boundary layer mixing and cloud formation.
Development of automated methods for terminus picking of the Greenland ice sheet from Landsat imagery

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A better understanding of the changes at the outlet glacier termini over seasonal/sub-seasonal timescales may reveal information on how glaciers adjust to climatic changes over a range of time scales. The NASA Landsat missions have provided a record of continuous, multispectral satellite imagery for 45 years with repeat observations every 16-18 days and with two Landsat satellites currently in orbit and one preparing for launch in 2020, a method to extract terminus position as data are collected would provide a way to continuously monitor the changes to the Greenland ice sheet in near real-time. Currently, all glacier termini are picked manually or semi-automatically, but this is labor intensive and places limits the detail of observations that can be made. Here we propose a technique to develop an automated image segmentation algorithm that will enable the identification of masks in individual Landsat scenes over glaciated terrain. Segmentation takes advantage of multiple differences between ice, water, snow, rock, and clouds (e.g. spectral, textural, geometrical, etc.) and allows the development of image masks classified by ground type. Using edge-detection algorithms we are able to extract out the curvilinear boundaries between ground types that enable terminus identification. Our plan is to examine a range of glacier termini from easier-to-detect termini (steep-cliffed, water/ice boundaries) to harder-to-detect termini (gently sloped, melange/ice boundaries) in order to develop a robust terminus picking tool. We will then compare our automatically-picked glacier termini with handpicked termini to examine the robustness of the autopicker.
Greenland ice sheet facies identification using Landsat spectra with airborne multi-channel, photon counting lidar and VSWIR spectroscopy

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Over the past several decades, surface melting of the Greenland Ice Sheet has been amplified in response to regional climate warming. Surface melting promotes increased water runoff to the surrounding ocean, and infiltration into the subsurface. We are establishing a method to interpret and map seven ice sheet surface facies (e.g., dry and saturated snow, firn with and without the presence of shallow surface water, deeper bodies of water and clean and dirty ice) from a specialized set of airborne data acquired in 2015 as well as Landsat reflectance images. Mapping will be accomplished using a time series stack of Landsat imagery corrected for sensor and solar incidence angle and slope, and screened for clouds and cloud shadows. The Landsat spectra are classified using a unique combination of training data: SIMPL 8-channel, photon-counting lidar data (polarimetric, green and near infrared, laser and solar reflectance), profiling visible-to-shortwave infrared spectroscopy, and high-resolution, color camera images. These results will aid the interpretation of ICESat-2 green laser and solar reflectance altimetry data, and enable Landsat-based Greenland Ice Sheet facies mapping during the mission and on historical timescales.
Changes in Greenland and Alaska Ice Surface Roughness and Relationships to Glacial Acceleration — Analyses Using Altimeter Data from ICESat, CryoSat-2 and ICESat-2 Simulator Instruments

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Spatial ice surface roughness is an indicator of many processes that affect the ice surface, including glacial acceleration, ice deformation, crevassing, snowfall, melting, and wind deposition and erosion. We derive ice-surface roughness from satellite and airborne observations and investigate the relationships of surface roughness and its changes to glacial acceleration as one of the main manifestations of climate-induced changes in the Greenland Ice sheet. Comparing the situation around the Greenland margin and its glaciers with the situation of the recent surge of the Bering Bagley Glacier System, different acceleration types are classified.

The analysis is based on ICESat GLAS data (2003-2009), CryoSat-2 SIRAL data (from 2010), data collected during four NSF-supported flight campaigns in Alaska (2011-2013) and data from ICESat2 simulator instruments MABEL and SIMPL (2014, 2015). Our approach uses a spatial statistical concept of generalized spatial surface roughness and characteristic parameters, which are mathematically related to physical concepts including crevassing, deformation and aerodynamic roughness length. To derive micro-topographic and roughness information from MABEL and SIMPL data, the Density-Dimension Approach (DDA) is introduced. Results demonstrate the expected capabilities of NASA’s future ICESat-2 mission to map spatially complex ice-surface topography with unprecedented resolution and accuracy. The remote-sensing data analysis lays the foundation for applied case studies. Roughness and elevation changes in Ilulissat Ice Stream and other outlet glaciers are analyzed to investigate links between glacial acceleration and its causes. The study is rounded off with numerical modeling experiments. Results are relevant for assessment of the sea-level rise through mass loss from the Greenland ice sheet and for understanding relationships between observations and physical processes.
The Ultra-Wideband Software-Defined Radiometer (UWBRAD) for Ice Sheet Internal Temperature Sensing: Results from the September 2017 Campaign

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The ultra-wideband software-defined radiometer (UWBRAD) provides measurements of ice sheet thermal emission over the frequency range 0.5-2 GHz for the purpose of remotely sensing internal ice sheet temperature information. UWBRAD was deployed in a September 2017 campaign in Greenland, and observed brightness temperatures of the ice sheet as well as firn aquifers, sea ice, the ocean surface, and land regions during the transit to and from Calgary, Canada (the aircraft base of operations). Because the instrument operates in unprotected portion of the spectrum, RFI detection and mitigation algorithms are included to filter the data in real time. The presentation will review the campaign and datasets collected, as well as the observed spectral features of thermal emissions from the ice sheet and other geophysical regions. The use of the results to retrieve internal ice sheet temperature information and for remotely sensing sea ice and sea salinity properties will also be reviewed and discussed.
A constraint upon the basal water distribution and thermal state of the Greenland Ice Sheet from radar bed-echoes

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There is widespread, but often indirect, evidence that a significant fraction of the Greenland Ice Sheet is thawed at the bed. However, the ice-sheet-wide distribution of basal water is poorly constrained by existing observations. Here we introduce a new radio-echo sounding diagnostic for basal water that is associated with wet-dry transitions in bed material: bed-echo reflectivity variability. Importantly, this technique is demonstrated to be insensitive to signal attenuation, and it enables combined analysis of over a decade’s worth of CReSIS airborne survey data.

The predicted basal water distribution is compared with existing analyses for the thermal state and geothermal heat flux. In addition to the generally thawed ice-sheet margins, we demonstrate widespread water storage in the Northern and Eastern interior. Notably, we observe a quasi-linear ‘corridor’ of basal water extending from NorthGRIP to Petermann glacier that spatially correlates with elevated heat flux predicted by a recent magnetic model. With a general aim to stimulate future regional and process specific investigations, the basal water distribution is compared with bed topography, predicted subglacial flow paths, and ice-sheet motion. The basal water distribution (and its relationship with the basal thermal regime) provides a new constraint for ice-sheet and hydrological models.
Greenland Ice Mapping Project: Measuring rapid ice flow

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Numerous recent studies have revealed rapid change in ice discharge from Greenland, as many of the ice sheet’s outlet glaciers have accelerated dramatically over the last decade. These observations are significant in that they show Greenland’s mass balance can fluctuate rapidly and unpredictably. Despite the large magnitudes of these changes, we do not yet understand the underlying processes controlling fast flow well enough to determine their long-term impact on sea level. Improving such predictions and gaining a firm understanding of the dynamics that drive mass balance requires annual to sub-annual observations of outlet glacier variability (velocity and ice front position) to avoid aliasing of this rapidly varying signal. Since 2009 TerraSAR-X and later TanDEM-X have regularly imaged many of Greenland’s fast-moving glaciers. This record is now in the process of being extended using C-band Sentinel 1 (6-day repeat) and in an effort to measure change in flow speed and geometry. In 2015, the Copernicus Sentinel 1 series of SARs had been imaging Greenland regularly. In addition, Landsat 8 has been collecting optical data since 2014. The technology for measuring velocity in Greenland is mature and, under the ongoing Greenland Ice Mapping Project (GIMP), we are merging these various sources of data to produce consistent time series of glacier flow speed and geometry. Here we summarize some of the large changes that have occurred on Greenland’s outlet glaciers over this period.
Decoding the Impacts of Hydrologic Shear Weakening on Jakobshavn Isbræ Regional Ice Flow: Insights from Measurements and Modeling

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The impact of surface melt water on ice dynamics via supraglacial lake drainage and runoff has been well documented. Little attention has been focused on direct injection of surface melt water into the shear margins of fast flowing, marine-terminating outlet glaciers. Our initial work was the first to characterize water-filled crevasse ponds within the shear margins of Jakobshavn Isbræ and assessment the volume of infiltrated melt water potentially reaching the bed. In the intervening years since this seminal work, we have utilized satellite observations and numerical models to decode the impact of hydrologic shear weakening due to melt water injection from these structures. We have constrained the theoretical impact of hydrologic shear weakening on extra-marginal ice flow using diagnostic models and provide projections for flow enhancement under future warming scenarios. For select seasons, we assessed relationships between extra-marginal, summer-time ice velocities and drainage of water-filled crevasses. We are starting to understand factors that drive how these crevasse systems fill and drain. Lastly, we have characterized the spatial and temporal variability of these structures over a 16 year period. Insights gained from these various efforts are starting to produce a comprehensive assessment of how supraglacial hydrology can influence the dynamics of marine-terminating outlet glacier systems.
Changes in OLR over Arctic as Depicted by AIRS, CERES, MERRA-2, and TOVS

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In this presentation, we compare the temporal and spatial characteristics of monthly mean level-3 anomaly time series of Outgoing Longwave Radiation (OLR) contained in the AIRS Version-6 with those in the CERES Edition 4 and MERRA-2 data sets over the 14 year period September 2002 through August 2016. Fourteen year global mean OLR average rates of change (ARCs) of AIRS and CERES data sets show slightly positive trends. However, the increases of Arctic OLR and clear sky OLR over Barents-Kara Seas and Canadian Archipelago during last decade are noteworthy. The ARCs over Barents-Kara Seas are larger than 0.4W/m²/yr. The clear sky OLR changes more rapidly with surface warming, since it is more sensitive to surface skin temperature than the OLR. The recent arctic OLR changes are more than twice of those shown by TOVS observation during 1978-2002. AIRS and CERES OLR time series agree extremely well in this aspect. This agreement validates the results of both data sets. Agreement of AIRS OLR with CERES also validates to some degree the AIRS retrieved geophysical parameters, which are used to calculate the AIRS OLR. Analogous results are shown with regard to the MERRA-2 OLR data set. Some aspects of the MERRA-2 OLR data set perform reasonably well.
Spatial Heterogeneity of Bed Processes in Supraglacial Streams

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Supraglacial streams are pervasive on ice sheets and disproportionately affect albedo (Smith et al. 2015, Ryan et al. 2016, Kingslake et al. 2017). Future warming may cause supraglacial streams to expand contributing to a positive feedback loop for melting. Supraglacial streams may also cause seasonal speedups of the ice sheet and worsen hydrofracturing exacerbating calving (Palmer et al. 2011). Understanding the flow dynamics of supraglacial streams is therefore vital for predicting future ice sheet contributions to sea level rise. Such predictions though require knowledge of how the hydrologic parameters that dictate routing vary along the flow path. During the summer of 2017, high resolution GPS measurements of the stream bed, stream velocity measurements, and sediment samples were collected on a supraglacial stream near Russell Glacier in southwest Greenland. These measurements allow for a detailed investigation of the spatial variability of bed incision and relate it to changes in bed friction, radiative melting, and sediment distribution. The evidence points to a potential velocity threshold in supraglacial streams in which a sediment heavy, radiative melting dominated system switches to a smoothed bed, frictional melting dominated regime. This complicates the idea of a steady decrease in albedo with higher flows as increased meltwater supply might flush out dark sediment-laden stream beds. These stream dynamics will likely play an important role in dictating future albedo changes on the Greenland ice sheet and will help predict time lags between meltwater production and peak runoff.
Preliminary assessment of the Modèle Atmosphérique Régionale (MAR) regional climate model over High Mountain Asia

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The lack of ground measurements has made the use of remote sensing, atmospheric reanalysis and modelling tools over the High Mountain Asia (HMA) pivotal for understanding the impact of climate change on the hydrological cycle and on the cryosphere. Due to the diverse climate systems in the HMA region, it is extremely important to assess these tools. Here, we show the results of the analysis of the assessment of the outputs of Modèle Atmosphérique Régionale (MAR) model RCM over the HMA region as part of the NASA- project ‘Understanding and forecasting changes in High Mountain Asia snow hydrology via a novel Bayesian reanalysis and modeling approach’.

We compared the MAR outputs with reanalysis data from ERA-Interim over the region bounded by the following coordinates: 66°E to 89°E and 21°N to 39°N. In particular, we evaluated the following parameters: surface pressure, snow depth, total cloud cover, two-meter temperature, horizontal wind speed, vertical wind speed, wind speed, surface new solar radiation, skin temperature, surface sensible heat flux, and surface latent heat flux. The level of agreement between the RCM outputs and the reanalysis highly depend on the specific parameters. For example, in case of surface pressure the maximum percentage error is 13.24% while the 2-m air temperature has a maximum percentage error of 340.62%. We also compare the outputs of the MAR model when forced with two different re-analysis datasets (e.g., ERA-INTERIM and MARRA-2). Our results indicate that large differences between the outputs exist in the case of snow depth and wind speed.

Lastly, we report results concerning the assessment of MAR surface albedo and surface temperature over the region through MODIS products. Next steps are to continue the assessment through in-situ datasets and determine whether RCMs and reanalysis datasets are effective at capturing snow and snowmelt runoff processes. This will help determine what refinements are necessary to improve RCM outputs.
Local Variability in Firn Layering and Compaction Rates Using GPR Data, Depth-Density Profiles, and In-Situ Reflectors in the Dry Snow Zone Near Summit Station, Greenland

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Understanding the surface mass balance (SMB) of the Greenland ice sheet is critical to evaluating its response to a changing climate. A key factor in translating satellite and airborne elevation measurements of the ice sheet to SMB is understanding natural variability of firn layer depth and the relative compaction rate of these layers. A site near Summit Station, Greenland was chosen to investigate the variation in layering across a 100m by 100m grid using a 900 MHz and a 2.6 GHz ground penetrating radar (GPR) antenna. These radargrams were ground truthed by taking depth density profiles of five 2m snow pits and five ~5m firn cores within the 100m by 100m grid. Combining these measurements with the accumulation data from the nearby ICECAPS weekly bamboo forest measurements, it’s possible to see how the snow deposition from individual storm events can vary over a small area. Five metal reflectors were also placed on the surface of the snow in the bounds of the grid to serve as reference reflectors for similar measurements that will be taken in the 2018 field season at Summit Station. This will assist in understanding how one year of accumulation in the dry snow zone impacts compaction and how this rate can vary over a small area.
The Effects of Low-Permeability Ice Slabs on Altimetry-Based Mass Balance Estimates of the Greenland Ice Sheet

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As melt increases across the Greenland ice sheet, multi-meter thick low-permeability ice slabs (LPISs) are forming in the near-surface firn of the lower-accumulation zone, blocking percolation and causing runoff in warm summers. Measurements from IceBridge radar show LPISs have already increased the area of Greenland’s runoff zone by ~24% since 1990, and are likely to increase it by another 50-300% by the year 2100 as Greenland’s climate continues to warm. Ice slabs complicate altimetry-based estimates of ice sheet mass balance by creating a new “hybrid facies” of the ice sheet where both runoff and firn compaction affect elevation simultaneously. Using FirnCover compaction measurements and Regional Climate Models, we present estimates of how ice slabs change the thermal and hydrological regime of Greenland’s percolation zone and discuss the importance of quantifying LPISs when interpreting Greenland’s mass balance from altimetry in a future warming climate.
A new high resolution geothermal heat flux distribution for Greenland derived from magnetic anomalies

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The Greenland Ice Sheet is the second largest reservoir of fresh water on Earth and ~80% of its surface is covered by ice. The study of the subglacial thermal conditions, geology and lithospheric structure of the continental interior largely requires indirect methods because it is only near the coast rock that outcrops are accessible. We use the World Digital Magnetic Anomaly Map v2 to derive a new map of the geothermal heat flux of Greenland and Ellesmere Island. This map shows significantly higher spatial variability than earlier maps, especially in north-central Greenland, yet lower overall amplitude. It also demonstrates a better overall agreement with previously inferred local values - primarily at deep ice-core locations.

Our geothermal heat flux map provides a new boundary condition for numerical models of the Greenland Ice Sheet. It will enable a revised assessment of the basal temperature field, geothermal control upon basal melt water production, and the influence of thermal conditions upon ice-sheet dynamics.
Southeast Greenland has been one of the largest contributors to ice mass loss in Greenland in part because of significant changes in glacier dynamics. The glaciers response has been observed to vary significantly from one fjord to the next, but until now there was not enough data to understand or interpret these changes. We employ NASA’s Operation IceBridge (OIB) high-resolution airborne gravity from 2016, NASA’s Ocean Melting Greenland (OMG) bathymetry from 2015, ice thickness from Operation IceBridge (OIB) from 2010-2015, and BedMachine v3 (BM3) to study 20 major southeast Greenland glaciers. The results reveal deep channels hundreds of meters deeper than estimated previously that provide natural pathways for AW. Our approach is validated using the misfit on the inversion, radar sounder data and a re-estimation of ice fluxes. Glaciers that have been stable or that stopped retreated stand on shallow sills or have met higher ground, away from AW. Conversely, a pattern of fast retreat is found in areas with retrograde slopes. In 2016-2017, several glaciers experienced renewed retreat along retrograde beds and we project that these glaciers will continue retreating for several years.
We utilize a harmonic mascon approach to process GRACE data regionally with a set of locally optimized spherical caps to study the mass balance of Totten and Moscow University glaciers. We obtain a trend of $-14.59\pm3.97\text{Gt/yr}$ for the two glaciers for the period April 2002 to August 2016 using the Ivins et al. (2013) GIA model (errors include leakage, GIA, and regression errors). Our results agree well with independent Mass Budget Method (MBM) estimates, providing confidence in our basin-scale estimates in these hard to measure areas. In addition, we use the results to evaluate surface mass balance models in this area. We calculate the MBM time-series within the area covered by our mascons using RACMO2.3 and MAR3.6.4. RACMO2.3 shows much better agreement with the GRACE estimates. Furthermore, we extend the study to the drainage basin of the Getz ice shelf, the third largest ice shelf in West Antarctica after Ronne and Ross West ice shelves. We find a trend of $-19.83\pm6.06\text{Gt/yr}$ with an acceleration of $-1.75\pm2.06\text{Gt/yr}^2$ for the period April 2002 to August 2016. The MBM trends obtained from both RACMO2.3 and MAR3.6.4 are in agreement with the GRACE estimates in this region.
Constraining components of surface height change in Southeast Greenland

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Meltwater, produced from recent warming across the Arctic, has changed the landscape’s surface and subsurface. Changes in the height of an ice sheet is controlled by the velocity, or dynamic behavior, of glaciers and densification within the firn column. Both are affected by increased meltwater. We explore velocity and density measurements around southeast Greenland, specifically in the Helheim Glacier catchment, to verify where in situ and remote sensing data can constrain or quantify the effect of each component in surface height change. This research will help identify where future ICESat2 altimetry data can be used to gain a better understanding of surface height change due to meltwater.
Monitoring supraglacial streams for three months in southwest Greenland

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Supraglacial river networks are the most efficient conduits for evacuation of meltwater runoff produced on Greenland ice sheet. These rivers are prominent features on the ablation zone of southwest Greenland. However, little is known about the transport of meltwater through supraglacial stream network and most of the in-situ observations only capture a few days of streamflow. Here we report three months of observations of water level and discharge collected during summer of 2016, in two small supraglacial streams near the ice sheet margin in southwest Greenland. We also compare streamflow observations with meteorological data from a nearby automatic weather station. The two sites are very different, with the lower basin relatively steep, smooth and dark while the upper basin has rugged terrain and deeply incised stream channels. These catchment characteristics propagate to different relationships with meteorological parameters. For example, upper basin stream water levels show a strong covariance with surface temperature while the lower basin water levels do not. We also find differences in temporal variation of supraglacial stream water level, with the upper basin having two distinct peaks, in mid-June and mid-July, while the lower basin shows gradual decrease from June to August. Long-term supraglacial stream observations such as these will ultimately help assess how well surface mass balance models can simulate ice sheet runoff.
UNAVCO is a NSF funded, non-profit, university-governed consortium offering geodetic support to a diverse science community. Geodesy is the study of Earth’s shape, gravity field, and rotation. Geodetic research defines the terrestrial reference frame, and quantifies changes in the properties of Earth’s surface and subsurface, ice sheets and glaciers, and oceans and the atmosphere. UNAVCO Polar has maintained 120 permanent GPS stations in Greenland, Alaska, and Antarctica, some of which have continually gathered data for over a decade. With a rapid evolution in GPS-based science that now covers the hydrosphere, the atmosphere, the cryosphere and the ionosphere, UNAVCO support provided to the community has broadened significantly. This expanding support effort includes: precision GNSS instrumentation and technical support; 3D imaging from terrestrial LiDAR (TLS) and UAV Structure-from-Motion (SfM); GPS interferometric reflectometry; power and communications platforms capable of driving instruments through the heart of the polar winter; data archiving and access; and assistance with technical planning and community education and outreach.
Transient subglacial water storage and movement inferred at Helheim Glacier

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Helheim Glacier, a fast-flowing (> 7 km/yr) marine outlet glacier in southeast Greenland, exhibits complex elevation behavior controlled by processes not well-understood. Here, we fuse laser altimetry time series and surface Digital Elevation Models (DEMs) using the Surface Elevation Reconstruction And Change detection (SERAC) approach to correct DEM errors and reconstruct ice thickness changes due to dynamic processes. The spatiotemporal elevation change pattern indicates two separate dynamic processes. The overall spatial trend in the elevation record (1998-present) is a decrease in the magnitude of thinning with increasing distance from the terminus, likely a result of sustained calving front retreat during 2001-2005 propagating upglacier via diffusion. Additionally, dramatic short-term thinning and thickening events occurred in 2005, 2007, 2011, (2013), 2015, and 2016, a process akin to mini-surges. Mini-surge events are characterized by dynamic elevation changes of >20 m or < -20 m in <11 months, over deep troughs/cavities at the ice-bedrock interface, and at tributary boundaries. In annual DEM difference maps from 2003-2007 we observe over a dozen small regions (0.5 km² - 3.5 km²), or patches of ice, on the main trunk and tributaries that exhibit dynamic elevation changes (>20 m or <-20 m) multiple times in the observational record. In visible imagery from 2003-2007, we observe water-filled surface crevasses near these dynamic elevation patches (<700 m away) that fill, drain, and sometimes re-fill during a melt season. As meltwater channels are not observed at the ice surface, it is inferred that the water-filled crevasses fill and drain from below, and are likely connected to a complex hydrologic system. The improved elevation record, together with the water-filled crevasse histories, indicate water movement in the subglacial environment of one of the fastest flowing glaciers in the world. The upcoming ICESat-2 mission will be able to collect elevation measurements at the spatial and temporal resolutions needed to fully evaluate this dynamic subglacial process in space and time.
Role of bare ice extent for Greenland Ice Sheet albedo and melt variability

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The exceptional melt of the Greenland Ice Sheet since the mid-1990s has been primarily driven by rising air temperatures, increases in downward shortwave radiation, and a reduction of ice sheet albedo. Whilst our understanding of air temperatures and downward shortwave radiation are relatively well constrained, the controls on ice sheet albedo remain uncertain. Here, we develop a robust method to classify snow and ice pixels from MODIS surface reflectance products between 2000 and 2017. We use these classified maps to quantify changes in bare ice extent and investigate the role of bare ice and snow albedo in the reduction of ice sheet albedo since 2000. We find that bare ice has a mean extent of 232,395 km$^2$ in the summer, equivalent to 13% of the ice sheet, and displays substantial interannual and seasonal variability. During the same period, Greenland’s mean equilibrium line altitude was 1311 m and showed significant interannual and also regional variability.
A surface energy and mass balance model for the Ice Sheet System Model assimilation framework: integration and validation

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The Glacier Energy and Mass Balance (GEMB) software is a column surface model (1-D) that has been embedded as a module within the Ice Sheet System Model (ISSM) ice flow and uncertainty quantification framework. Uncertainties in the calculation of the surface radiation budget of the ice sheets exist, due to errors in estimates of surface parameters like albedo, surface emissivity, and cloud cover. Such uncertainties in the radiation budget affect model-derived temperature profiles, firn air content (FAC), and surface mass balance. Here, we evaluate ISSM-GEMB firn profiles for both Greenland and Antarctica, and take advantage of the ISSM uncertainty quantification framework to analyze the temporal evolution of FAC and its uncertainties. Quantification of uncertainties and model bias will allow us to better constrain local changes in ice mass when converting from altimetry-derived surface elevation changes. It will also allow us to characterize which surface forcings are most responsible for variations in surface elevation signals. This is a significant assessment for the assimilation of altimetry signals into historical reconstructions using ISSM; in the future, our analysis will aid in the reduction of the parameter space of surface forcings that must be weighted during reconstruction, and it will inform the assimilation with reasonable bounds for the surface forcings with the largest influence over surface elevation change.
Advances in time-series observations from ice penetrating radar sounding

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Recent and planned airborne radar sounding of Antarctica and Greenland are providing repeat coverage of previous survey lines, enabling direct observation of temporal variation in ice sheet basal boundary conditions. Additionally, the earliest radar sounding data – recorded on optical film in the 1960s and 70s – are being digitized, extending the baseline for such comparisons by decades. In parallel, stationary active radar sounders are providing an exciting new tool to geophysical glaciology. Finally, passive radio sounding approaches under development for planetary exploration are being adapted to the observation of terrestrial ice sheets and glaciers. These advances in time-series observation of subglacial conditions as well as the technical and interpretative challenges they face are presented in the context of glaciological processes and conditions they make it possible to observe.
Pine Island Glacier Under the Midnight Sun

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A series of Landsat 8 image acquisitions in mid-December 2017 shows the fragments of Iceberg B-44 adjacent to the new front of Pine Island Glacier separated by a large area of open seawater called a polynya. The Thermal Infrared Sensor (TIRS) Band 10 data enables insights on temperature variations within the open water area and also across the sea ice to the northwest of the iceberg as well as across the much colder glacier front and the iceberg’s fragments. The Operational Land Imager (OLI) Band 8 data shows the polynya as open water with only a few small ice fragments within it and provides additional insight on the sea ice cover. This area of ice-free water suggests that the front of this large outlet glacier is floating in a pool of warm water as noted previously by Bindschadler et al. (2011).

Besides the evident polynya, the panchromatic imagery details an incomplete new rift up-glacier from the September 22, 2017 calving front. This rift was not visible in Landsat imagery acquired November 1st and lies about 2 km (1.25 mi) up-glacier and suggests additional calving and retreat may happen this austral summer.

Because the Landsat 8 pass on December 15 was acquired on an ascending pass (Path 157 Row 131) at 7:03 UTC, the acquisition was near midnight local time at 100°W longitude. With the austral summer solstice only a few days away, the sun elevation was 8.05° when the imagery was acquired. As a result, the topography in the area, including Evans Knoll to the northeast of Pine Island Glacier, casts very distinct shadows in the OLI imagery and the ice edges facing south are strongly illuminated. This work will detail how iceberg and ice front elevations were derived from this and other Landsat 8 data after Scambos et al. (2009), Bindschadler et al. (2011) and Lambrecht et al. (2007).
Calibrating and validating firn-densification and regional-climate modeling using altimetry and radar data

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Repeat altimetry records measure a combination of ice-dynamic imbalance, SMB variations, and firn-densification variations. Untangling the effects of the three processes can help us understand the processes driving ice-sheet change, and the most promising techniques now available to do this involve firn-densification models driven by climate-model output. We have begun a project to test the SMB and firn-densification estimates from the MAR regional climate model against ice-bridge altimetry and snow-radar data, with the goal of helping to adjust model parameters to improve accuracy of model output. We present preliminary data-vs-model comparisons, and discuss the statistical power of each type of measurement as a test of model FDM and SMB results.
Direct measurements of meltwater runoff on the Greenland Ice Sheet

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Meltwater runoff from the Greenland ice sheet surface influences surface mass balance (SMB), ice dynamics, and global sea level rise, but is estimated with climate models and thus difficult to validate. We present a way to measure ice surface runoff directly, from hourly in situ supraglacial river discharge measurements and simultaneous remote sensing of upstream fluvial catchment area. Field observations quantify how large, fluvial supraglacial catchments attenuate the magnitude and timing of runoff delivered to moulins and hence the bed. The data are used to calibrate classical fluvial hydrology equations to improve meltwater runoff models, and show how broad-scale surface water drainage patterns that form on the ice surface powerfully alter the magnitude and timing of meltwater penetration into the ice sheet.
Only skin deep? Evaluating the utility of Landsat sea surface temperatures in Sermilik Fjord

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Remotely sensed sea surface temperature (SST) have been widely unused in studies of glacial fjords and may hold clues to fjord circulation and ice-ocean interactions that occurred before rapid change began at the turn of the century. In this study, we compare Landsat SSTs to in situ ocean and atmosphere measurements near Helheim Glacier in Sermilik Fjord to determine the utility of SSTs for studying polar fjord waters. SSTs are derived from Landsat 7 and 8 thermal infrared imagery to produce a time series of the fjord surface since 2010. We find that Sermilik SSTs frequently give temperatures 0.2-0.8°C cooler than adjacent shipboard surface ocean measurements taken during annual summer cruises. SSTs across the fjord surface closely track air temperatures. However, SSTs closest to the glacier tend to cool rapidly in mid-summer before air temperatures begin to fall. Initial results suggest the early SST cooling corresponds to reduced surface ocean salinity driven by a large influx of freshwater into the fjord during peak summer glacial melt. The influx produces a relatively cool and fresh meltwater lens at the fjord surface downstream of the glacier, which then drives SSTs down. Our results suggest that Landsat SSTs may be able to give insight into the timing and magnitude of glacial melt near Helheim Glacier. Continued work at the Sermilik and other fjords around Greenland will help to determine further linkages between SSTs and the fjord water column, and how that relationship varies from one glacier system to the next.
Subglacial Hydrology as Kinetic Transient Interplay in the Ice Sheet System Model

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Subglacial hydrology has a significant influence on ice sheet dynamics, but is not yet entirely understood. A clear tradition has been established in the subglacial hydrology modeling literature of distinguishing between channelized (efficient) and distributed (inefficient) drainage systems or components. Imposing a distinction that changes the governing physics under different flow regimes, however, may not allow for the full array of drainage characteristics to arise. In our subglacial hydrology model formulation, a single set of equations is applied over the entire domain, with a transmissivity that allows for transition between turbulent and laminar flow, and the geometry of each element is allowed to evolve accordingly to form sheet and "channel" configurations. This model is implemented as a solution in the Ice Sheet System Model (ISSM). We will present steady state and transient examples to demonstrate features and capabilities of the model, including experiments from the Subglacial Hydrology Model Intercomparison Project (SHMIP) and current efforts involving application to Store Gletscher, a tidewater glacier in west Greenland.
Self-Consistent Ice Mass Balance and Regional Sea Level from GRACE

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Changes in glacier and ice sheet mass produce patterns of sea level change that vary significantly from a uniform average. The induced sea level change can affect gravimetrically determined estimates of ice mass change and represents between 3 and 5% of the total signal when averaged over the entire ice sheet. We use measurements of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) mission to determine changes in mass of the Earth’s glacial regions and their impact on regional and global sea levels over 2002–2016. We use a least-squares mascon technique combined with solutions to the sea level equation to iteratively correct the GRACE data for the induced sea level change on a monthly basis. We find that the Greenland ice sheet is changing mass at a rate of \(-262 \pm 19\) Gt/yr with an acceleration of \(-11 \pm 3\) Gt/yr\(^2\). The estimated mass change from the Antarctic ice sheet is dependent on the correction for Glacial Isostatic Adjustment, but ranges between \(-105 \pm 34\) Gt/yr and \(-136 \pm 45\) Gt/yr with an acceleration of \(-17 \pm 4\) Gt/yr\(^2\). We find that the mass losses from both ice sheets have contributed 14.8 ± 0.7 mm to global sea levels since 2002.
Understanding and quantifying spatio-temporal variability of refreezing in southwest Greenland through fieldwork, regional climate model outputs and remote sensing tools

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Recent and planned intensive monitoring missions operating radar and lidar spaceborne (Cryosat-2, Sentinel, ICesat, ICESat-2) and airborne (Operation IceBridge, Lamont IcePod) sensors have become crucial for measuring the spatial distribution of elevation changes around the Greenland ice sheet, providing an alternative to mass gravity and mass budget measurements. In order, to properly convert elevation changes to mass changes, snow/firn density vertical profiles must be known and compare lidar and microwave radar estimated elevation changes, snow/firn density must be known, so that corrections due to the different penetration depths can be properly accounted for. Validation in this regard is crucial and the problem is exacerbated by the lack of in-situ data, associated logistical issues and increased recent melting over the Greenland ice sheet. The increasing volume of meltwater produced during summer at higher elevations is promoting the formation of impenetrable ice lenses in firn once refreezing occurs. This not only impacts the vertical and horizontal redistribution of surface runoff, but also the penetration depth of the electromagnetic signal used to estimate elevation changes.

In this talk, we report preliminary analysis and results of in-situ measurements carried out within the framework of two projects (sponsored by the U.S. National Science Foundation and NASA) of firn core (20 m), in-situ radar data and model outputs collected in May 2017 over the southwest portion of the Greenland ice sheet, in proximity of the Dye-2 camp, at elevations between 1963 and 2355 m.a.s.l. During this fieldwork three automatic weather stations were also outfitted with surface energy balance sensors and 20 m deep thermistor strings, over 300 km of ground penetrating radar data were collected, and five 20-26 m deep firn cores were collected. Data collected within this project, together with other existing databases (e.g., SUMup,) are crucial validation tools for current and future remote sensing missions focusing on mass losses over Greenland and Antarctica.
Aerogravity is widely used across the cryosphere to map the bathymetry in inaccessible regions: hard-to-access fjords, broad regions of the Greenlandic continental shelf seasonally covered by sea ice, and underneath floating ice shelves and tongues. NASA Cryosphere continues to make advances in aerogravity by supporting airborne surveys as well as new instrument development and testing.

New airborne gravity-derived bathymetry models from the Oceans Melting Greenland surveys reveal pathways and connections between the glacially-carved troughs that traverse the Greenlandic continental shelf. Models incorporate a diverse range of measurements - from ship-based swath bathymetry to point measurements of minimum depth from OMG AXCTD surveys and Narwhal monitoring.

The 2017 Operation IceBridge spring campaign based out of Thule, Greenland included a new hybrid gravimeter system incorporating a traditional stabilized platform meter flown alongside a strap-down system. We compare free-air anomalies from this season against previously flown data and report on the development of new processing techniques, including new methods to increase signal-to-noise ratio, for modelling temperature effects, and to integrate conterminous data from multiple gravimeters.
Glacier mass balance and evaluation of surface mass balance with laser altimetry and other data

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We employ time series of laser altimetry combining pre-IceBridge (ATM), ICESat-1, IceBridge (ATM, LVIS) to evaluate glacier mass balance at the basin scale and to evaluate runoff output products from surface mass balance models. We compare the results with other techniques including GRACE and the mass budget method. We used time series of elevation change in slow moving areas of the ablation zone of Greenland to evaluate the runoff output products RACMO and MAR models. The results indicate a precision of about 20% +/- 10%, with the larger errors in north Greenland. At the basin scale, in East Antarctica, West Antarctica, South-West Greenland and for Jakobshavn Isbrae, we compare the three techniques and discuss the implications for the analysis of ICESAT-2 data in conjunction with ICESAT-1, pre-IceBridge and IceBridge data.
On the ocean-induced retreat of northwest Greenland glaciers: insights from Oceans Melting Greenland (OMG) bathymetric mapping in 2017

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Over the past 30 years, the tidewater glaciers of northwest Greenland have exhibited widespread retreat, yet we observe different behaviors from one glacier to the next, sometimes within the same fjord. This retreat has been synchronous with oceanic warming in Baffin Bay and increased runoff on the periphery of the ice sheet. Here, we estimate the ocean-induced melt rate on a collection of marine-terminating glaciers in this sector of the Greenland Ice Sheet from simulations employing the MITgcm ocean model, with bathymetry from NASA’s EVS-2 mission “Oceans Melting Greenland” (OMG). In particular, we focus on new areas mapped during the summer of 2017 using a multi-beam echo sounder mounted to the stern of the S/Y Ivilia. We illustrate the importance of accurate bathymetry in quantifying the ocean melting on glacier termini and the assessment of its impact on the glacier retreat. For example, our calculated melt rates are 2-fold higher at Nordenskiold Glacier as calculated with our new bathymetry in comparison to that from Bed Machine version 3. These results further illustrate the sensitivity of glaciers to changes in oceanic forcing and the modulating effect of bathymetry on their timing and magnitude of retreat. This work was carried out under a grant with the NASA Cryosphere Program and for the EVS-2 Ocean Melting Greenland (OMG) mission.
Interannual Oscillations of Summer Arctic TOA Radiation Fluxes

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The 18-yr Clouds and the Earth’s Radiant Energy System (CERES) data are analyzed to characterize interannual variabilities of the top-of-atmosphere (TOA) radiation in the summer Northern Hemisphere (NH). Coherent variabilities between 60°N-85°N latitude exists, showing equatorward progress of the Arctic flux oscillations with a period of ~4 years. The shortwave (SW), longwave (LW) and net TOA flux perturbations are further decomposed into poleward and equatorward propagating components. The Arctic TOA flux fluctuations in June-September are dominated by the SW flux and by the equatorward component. Both CERES and Multiangle Imaging SpectroRadiometer (MISR) TOA albedo measurements provide a consistent SW fluctuation pattern, showing more intensified oscillations after 2009. Two centers of action are identified through the empirical orthogonal function (EOF) analysis of the summer TOA fluxes over the Arctic, Queen Elizabeth Islands (QEI) and the Barents-Kara Sea (BKS). These regions are subjected to strong interannual variations of snow cover and sea ice extent. The observed large oscillations between excessive and deficient TOA energy have profound impacts on mid-latitude weather and climate at intra-seasonal and interannual scales.