Program for Arctic Regional Climate Assessment (PARCA) 2020 Meeting

ABSTRACTS

Capturing Greenland ice sheet sub-grid-scale albedo variability in the NASA GISS ModelE GCM: Impact on simulated surface mass balance

Patrick Alexander, Lamont-Doherty Earth Observatory, Columbia University, pma2107@ldeo.columbia.edu
Marco Tedesco, Allegra N. LeGrande, Shujie Wang, Elizabeth Fischer, Xavier Fettweis, Mark Flanner, Maxwell Kelley, Raf Antwerpen, Sophie M. J. Nowicki, and Gavin Schmidt

Surface albedo variability plays an important role in regulating surface melt and runoff from the Greenland Ice Sheet (GrIS). It is therefore a key factor in general circulation models (GCMs) capable of simulating future changes in ice sheet contribution to sea level rise and ice sheet-earth system feedbacks. Recent studies have shown that variability in bare ice extent drives much of the variability in GrIS albedo. However, the coarse resolution of GCMs limits their ability to capture spatial variability in GrIS albedo and nonlinear feedbacks between albedo, melt, and snow depth. Here we show the impact of including sub-grid scale albedo variability on simulated Greenland Ice Sheet mass balance in the NASA Goddard Institute for Space Studies (GISS) ModelE2.1 GCM (GISS-E2.1). GISS-E2.1 includes an elevation class scheme that allows the GCM surface model to run at multiple elevations within a grid cell, enhancing the resolution of simulated SMB. We have introduced the capability of simulating surface albedo variability on the sub-grid scale. In simulations with a snow-age-dependent albedo scheme, and 20 elevation classes, we find that simulated melt increases by 34% in simulations where albedo is allowed to vary by elevation class. We also compare simulated albedo to albedo from the Moderate Resolution Imaging Spectroradiometer (MODIS) and examine the sensitivity of our results to the number of elevation classes, the albedo parameterization, and other factors such as snow model parameters and atmospheric circulation variability.

Modeling moulin evolution on the Greenland Ice Sheet

Lauren C. Andrews, NASA Goddard Space Flight Center, lauren.c.andrews@nasa.gov
Kristin Poinar

Nearly all proglacial water discharge from the Greenland Ice Sheet is routed englacially via moulins. Identification of these moulins in high-resolution imagery is a frequent topic of study, but the processes controlling how and where moulins form remain poorly understood. Because moulins may reasonably compose approximately 10-15% of the englacial-subglacial hydrologic system, the evolution and shape of moulins can alter both the timing and variability of meltwater inputs to the bed. This evolution can impact both the form of the subglacial hydrologic system and associated response of ice motion. Here, we develop a physical model of moulin formation and evolution to constrain the role of englacial processes in shaping the form and structure of the subglacial hydrologic system. Within this model, moulin geometry is controlled by a balance of viscous and elastic deformation and is dependent on that deformation, refreezing, and the dissipation of turbulent and sensible heat energy. All of which are dependent on the characteristics of the available supraglacial meltwater and the surrounding ice. We find moulin geometry is responsive to changes in these parameters over the course of hours to days, indicating that diurnal and multi-day variations in melt can substantially alter the geometry of a moulin and, consequently, the pressure-discharge relationship at the bed of the ice sheet. Therefore, there is no single moulin shape that can appropriately represent englacial storage across the Greenland Ice Sheet.

An analysis of the Greenland Ice Sheet bare ice extent and albedo using MAR and MODIS

Raf Antwerpen, Utrecht University, ra3063@columbia.edu
Marco Tedesco

Greenland's contribution to global sea-level rise through ice melt and liquid water runoff is becoming increasingly important. One of the key parameters controlling melt is albedo which controls the amount of absorption of solar radiation. The bare ice extent on Greenland encompasses a relatively small fraction (maximum ~25%) of the Greenland Ice Sheet (GrIS). However, because of its low albedo, bare ice is responsible for the majority of ice melt and liquid water runoff (~78%). It is therefore imperative to investigate the spatio-temporal variability of the bare ice extent and albedo of the GrIS as this may lead to more accurate simulations of meltwater production and more accurate projections of the contribution of Greenland to global sea-level rise. Currently, discrepancies exist between model output and remote sensing observations of the bare ice extent and albedo over the GrIS. This study aims at identifying and examining these discrepancies by comparing model output (MAR) and satellite data (MODIS) from 2000 to 2018. By studying characteristics as the maximum bare ice extent, onset of bare ice season and bare ice albedo and relating them to atmospheric and biological variables, causes for the model-data discrepancies may be inferred. These findings can subsequently be used as a basis for model improvement.

Reducing uncertainties in sea level projections using statistical emulators

Andy Aschwanden, University of Alaska Fairbanks, aaschwanden@alaska.edu
Rachel Chen, and Doug Brinkerhoff

ABSTRACT TBD

Greenland Rising: Connecting Changing Ice and Changing Coastlines

Robin Bell, Lamont-Doherty Earth Observatory, Columbia University, robinb@ldeo.columbia.edu
Karl Zinglersen, Kirsty Tinto, Jacqueline Austermann, David F. Porter, Jonathan Kingslake, Margaret Turrin, Guy Paxman, Frank Nitsche, and Peter Lisager

While much of the work in Greenland is motivated by the potential for global sea level rise. In coastal Greenland, sea level will drop dramatically up to 2 meters by the year 2100, impacting key shallow environments and critical marine habitats will change. These sea level changes will be the combined response of the solid Earth (uplift or subsidence) and gravity field to changes in past, present, and futures glaciers and ice sheets. Communities around Greenland and around the globe will need to develop a framework for adapting to these changes that reflect their proximity to the changing ice and their local geologic setting. Due to the adjacent ice sheet, the signals of shallow water change in Greenland will be large - the Greenland GPS Network (GNET) has documented uplift rates up to 23 mm/yr and subsidence rates of 5 mm/year in the southwest. Given the large changes, together with the ongoing economic, mining, natural resources and infrastructure development occurring in Greenland, it is critical to provide Greenlandic communities with a comprehensive, quantitative framework for understanding how shallow water environments will change in coming decades. The goal of the NSF Funded Navigating the New Arctic Greenland Rising project is to bring together a convergent international team focusing for the first time on the natural, social, and built environment of Arctic communities proximal to a changing ice sheet. Working together, scientists from Lamont, GNIR and Asiaq will focus on four Greenlandic communities experiencing distinct responses to the changing ice, with differing natural, social, and built environmental needs to develop a framework of observation, modeling, and community involvement in data collection. This approach of linking changing ice and changing coastlines can be replicated around the Arctic. With a focus on these four communities, we will i) map shallow water environment and habitats ii) develop data-informed models and projections of how sea level has responded to changing ice in the past, present and future and iii) partner with local communities in both collecting the data needed to improve the sea level models and the baseline bathymetric mapping to identify hot spots for future change where new infrastructure, fisheries, and other marine use will be susceptible to change.

The Petermann Ice Shelf Estuary and its impact on ice-sheet stability

Alexandra Boghosian, Lamont-Doherty Earth Observatory, Columbia University, alb@ldeo.columbia.edu
Lincoln H. Pitcher, Laurence C. Smith, and Robin E. Bell

In a warming world, increased meltwater will form on Antarctica's ice shelves. The fate of this meltwater will be critical to future ice-shelf and ice-sheet stability. Two main observations define the current theoretical framework for understanding the influence of surface hydrology on ice-shelf stability. The first is the collapse West Antarctica's Larsen B Ice Shelf that was triggered by the formation of thousands of surface ponds atop the ice shelf. The second is the observation of a waterfall on the Nansen Ice Shelf, in East Antarctica, that is hypothesized to protect the ice shelf from hydrofracture by removing meltwater from the ice-shelf surface. We present a third process that couples ice-shelf hydrology to atmospheric and ocean forcing: the development of an ice-shelf estuary on the Petermann Ice Shelf in northwest Greenland. High-resolution imagery and digital elevation models (DEMs) shows that channelized surface meltwater on the Petermann Ice Shelf in northwest Greenland incises into underlying ice to form an estuary that propagates fractures along the ice shelf. The estuary at the front of the Petermann Ice Shelf is indicated by the convergence of sea ice at the river mouth, the upstream transport of sea ice in the channel as far as 460 m from the calving front, and the persistence of water in the channel following the end of seasonal surface melt. Between 2013 and 2018, the estuarine reach of the river tripled in width and a 1.5 km longitudinal crack propagated along the bottom of the channel. The Petermann Ice Shelf Estuary forms on top of a basal channel, where basal melting has led to ice-shelf thinning, and the creation of the linear surface depression in which the estuary forms. The Petermann Estuary may be the first of several ice-shelf estuaries to develop in a warming climate. Widespread surface melting on ice shelves in Greenland and Antarctica increases the urgency to determine the influence of surface hydrology on ice-shelf stability. We hypothesize that surface rivers may initially buffer ice shelves from collapse by terminating in waterfalls and preventing the formation of damaging lakes. However, with increased meltwater transport across ice shelves, channels can incise to sea level and establish estuaries. Once an estuary is established, estuarine weakening can lead to fracture propagation and enhanced calving, destabilizing ice-shelves, and increased ice-sheet mass loss.

GNET: A network with potential for more than just GNSS

Kelly M. Brunt, NASA Goddard Space Flight Center, kelly.m.brunt@nasa.gov
Robert L. Hawley

The Greenland Geodetic Network (GNET) consists of 58 global navigation satellite systems (GNSS) installed on the bedrock around the perimeter of the island. Much of the network was installed between 2007 and 2009, providing a long time series of GNSS data for much of Greenland. The network includes power and communication infrastructure; this infrastructure could potentially support new and innovative GNSS science. The network is currently owned and maintained by the Danish Agency for Data Supply and Efficiency (SDFE), while the National Science Foundation (NSF) provides support for data transport from the deep field. Here, we present information about the GNET infrastructure resource.

Variable basal channel evolution from high resolution surface elevation measurements

Allison Chartrand, Byrd Polar and Climate Research Center, Ohio State University, allisonchartrand@gmail.com
Ian M. Howat

The ICESat-2 mission, ArcticDEM, and the Reference Elevation Model of Antarctica (REMA) together provide unparalleled spatiotemporal resolution of surface elevation information over the Greenland and

Antarctic Ice Sheets. These data enable measurements of change over the most rapidly changing parts of the ice sheets, including their ice tongues and ice shelves. In the last decade, sub-ice shelf melt channels (basal channels) have become a focus of ice shelf research due to their prevalence on vulnerable Antarctic ice shelves. Basal channels are associated with zones of concentrated melt, but their short term behavior and impact on ice shelf stability is largely unknown. Using REMA and ArcticDEM digital elevation models (DEMs), ICESat-1 and ICESat-2 laser altimetry, and NASA Operation IceBridge laser altimetry and ice penetrating radar data, we characterized the recent evolution of basal channels on several West Antarctic ice shelves and on the Petermann Glacier ice tongue. The DEMs enable tracking of basal channel position, and both the DEMs and along-track data enable estimates of thinning rates due to the presence of surface depressions directly above the basal channels, which change in response to perturbations at the base of the floating ice. We find a variety of basal channel behaviors and morphologies throughout the ice shelves investigated, ranging from active incision and channel migration to no change over annual-decadal timescales. We aim to elucidate patterns in channel behavior and assess which channel characteristics warrant further scrutiny regarding their impact on ice shelf stability.

Decadal changes in Greenland subglacial hydrology from airborne radar sounding

Winnie Chu, Stanford University, wchu28@stanford.edu
Saurabh Vijay, Michalea King, Dustin Schroeder, and Stephen Livingstone

NASA IceBridge has collected over two decades of remote sensing and geophysical observations across the Greenland Ice Sheet. The MCoRDS radar sounder, in particular, has provided critical constraints on the meltwater condition beneath the ice sheet subsurface. So far, these measurements have enabled us to map the spatial distribution of subglacial water. However, inter-catchment rerouting of subglacial water can occur, and this process of subglacial water piracy could potentially trigger a large-scale reorganization of ice flow. Here we analyze ~50,000 km of MCoRDS flight lines to investigate the temporal variations of subglacial meltwater in Greenland for the last two decades. We examine these hydrologic results along with observations of seasonal ice velocity on individual glaciers, derived from a combination of feature tracking algorithm and Sentinel-1 SAR. Results across western Greenland indicate evidence of subglacial water piracy, whereas most of the eastern glaciers display more persistent drainage flow paths. We find that Type-2 glaciers that have an in-sync, positive dynamic response to seasonal changes in surface melting are more likely to exhibit subglacial water piracy over time. We also compare these radar observations with surface altimetry records to investigate the relationship between ice sheet evolution and the long-term changes in subglacial hydrology. Together, these results highlight the importance of combining radar sounding and altimetry in understanding the long-term evolution of the Greenland Ice Sheet.

Surface melting trends analysis of the Greenland ice sheet from enhanced resolution passive microwave brightness temperatures

Paolo Colosio, University of Brescia, p.colosio002@unibs.it
Marco Tedesco, Roberto Ranzi, and Xavier Fettweis

Surface melting is a major component of Greenland ice sheet surface mass balance, affecting ice dynamics and hydrological processes, supraglacially, englacially and subglacially. Passive microwave (PMW) brightness temperature observations, because of their long temporal coverage (1979-2018) and high temporal resolution (at worst every other day), are of paramount importance in studying long-term climate and large-scale earth surface processes. However, a major limitation of PMW datasets has been the relatively coarse spatial resolution. Here, we use an enhanced spatial resolution passive microwave dataset (37 GHz, horizontal polarization) recently made available through the NASA MeASUREs program to produce high spatial resolution (3.125 km) maps over both the Greenland ice sheet. We show the progresses and results of our work aimed at studying long term trends and melting season variability using the enhanced resolution product. Specifically, we present trends of melt duration, melting index, onset and end dates, maximum melting surface extent obtained by applying threshold-based melt detection

algorithms to the Ka-band passive microwave brightness temperatures. The results have been assessed through the comparison with the outputs of MAR regional climate model.

Twenty-five years of Greenland elevation and mass changes from fusing NASA's laser altimetry record with SMB and FDM models

Beata Csatho, University at Buffalo, bcsatho@buffalo.edu
Prashant Shekhar, Brooke Medley, Tony Schenk, and Abani Patra

With the successful conclusion of NASA's Operation IceBridge (OIB) airborne laser altimetry mission, a 25-year-long time series of Greenland Ice Sheet elevation changes has become available. In addition to observations for the OIB mission, the massive data set also includes airborne laser altimetry data from NASA's Program for Arctic Regional Climate Assessment (PARCA, 1993-2008) and satellite laser altimetry data from ICESat (2003-2009). We used our Surface Elevation Reconstruction And Change detection (SERAC) method to generate time series of ice sheet elevations changes at tens of thousands of locations. By retaining the original temporal resolution of the observations, these time series depict seasonal, annual, and interannual ice sheet elevation changes. After partitioning the time series into components due to Firn Densification, crustal deformation, and ice dynamics, we applied our Approximation by Localized Penalized Splines (ALPS) method to interpolate in the time domain. Spatial interpolation was achieved by extension of the ALPS framework to higher dimensions and larger datasets. Our workflow allows the estimation of ice sheet elevation, thickness, dynamic thickness, and mass changes and corresponding error estimates with different, user-defined spatiotemporal sampling, including unstructured meshes and regular grids. We will show elevation and mass change grids with annual and better temporal resolutions to highlight the unprecedented details of the new reconstruction. Derived parameters, such as elevation change gradients, will be used to detect and characterize regions of unusual behavior.

Firn Density in Greenland's Dry Snow Zone from Operation IceBridge Radar Sounding Data

Riley Culberg, Stanford University, culberg@stanford.edu
Dustin Schroeder

The depth, density, and heterogeneity of polar firn are important controls on near-surface hydrology and can significantly influence the interpretation and uncertainty of altimeter measurements and their translation to changes in ice sheet mass balance. Observations of these variables are mostly limited to field or laboratory measurements of firn cores, which are inherently point measurements in both space and time. Firn models, coupled to regional climate models, can fill many of these gaps, but at limited spatial resolution and dependent on the completeness of the physics or parameterizations used in the models. Remote sensing observations would offer the capability to assess firn structure at local to continental scales over at least the last decade and provide an important expanded baseline for model tuning, validation, and downscaling. We present an empirical method that leverages Accumulation Radar and Multi-Channel Coherent Depth Sounder data from Operation IceBridge to derive mean depth-density profiles down to the firn-ice transition in Greenland's dry snow zone. Our results are in good agreement with firn core measurements and show spatial trends consistent with those predicted by both the Herron and Langway model and the IMAU Firn Densification Model. Additionally, our method can resolve local variations in firn structure such as those related to feedbacks between surface morphology and accumulation. Bordering the percolation zone, where this method begins to break down, we also demonstrate the use of a radar simulator and statistical firn density model to explore the spatial evolution of density variability, to include detecting refrozen ice layers likely linked to recent anomalous melt seasons. Altogether, our results suggest that there are strong prospects for studying Greenland's local firn structure with the OIB radar sounding record.

Evolving Centennial-Scale Snow Accumulation Rates Across Greenland from Operation IceBridge Accumulation Radar

Indrani Das, Lamont-Doherty Earth Observatory, Columbia University, indrani@ldeo.columbia.edu
Joseph A. MacGregor, Nicole Schlegel, Eric Larour, Kristin Poinar, Brice Noel and Patrick Alexander

The accumulation rate of snow over ice sheets is an important climate parameter in assessing their overall health, and it is the largest component of surface mass balance for the Greenland Ice Sheet. This accumulation rate is also difficult to constrain across the entire ice sheet because direct observations are sparse, challenging validation of regional climate models. Continent-wide estimates of paleo accumulations rates are also very sparse making it difficult to assess historical accumulation rate patterns across regions. Here we use airborne accumulation radar data from NASA's Operation Ice Bridge to derive centennial-scale accumulation rates through the past ~1200 years. We use density profiles from an ensemble of firn cores from all of Greenland to convert the radar depths to accumulation rates. The firn cores across Greenland are grouped based on regions to derive radar-based regional accumulation rates for ~1200 years. At depths where the density reaches the density of ice, we correct the radar-derived accumulation rates for strain-induced thickness change using strain rates from MeASURES ice velocity and ISSM simulated strain rates. The pattern of the radar-derived accumulation rates agrees well with historical accumulation rates from ice cores. Comparison with regional climate models RACMO and MAR indicate that the both of these climate models underestimate accumulation rates in low accumulation regions such as the North-East Greenland and overestimate accumulation rates in the South-East.

Estimating Meltwater Volume over Western Greenland During the 2019 Melt Season, Using a Fusion of ICESat-2, Planet SkySat and MAR Model Outputs

Tri Datta, NASA Goddard Space Flight Center/University of Maryland, rajashree.datta@nasa.gov
Mahsa Moussavi, David Shean, Xavier Fettweis, and Brooke Medley

Over the summer of 2019, Greenland has experienced an intense melt season. Following an early melt onset in May, maximum melt extent reached 712,000 km2 in June, and continued with another burst of melt at the end of July following record temperatures in both the Arctic and Europe. Here, we discuss a new dataset that articulates the effects of intense melt on the evolution of surface meltwater in western Greenland, introducing a method for estimating melt pond volume using ICESat-2 laser altimetry and high-resolution commercial imagery. The method for estimating meltwater volume is tested and refined using representative sections along the flowline of Sermeq Kujalleq (Jakobshavn Isbræ glacier), one of the fastest-moving glaciers in Greenland. We use ICESat-2 laser altimetry to estimate lake depth from dual interface returns (air-water and water-ice). These estimates of depth are used to build a spectrally driven depth estimate from Planet SkySat imagery (at a 1-m resolution), which is used to estimate meltwater volume over the full image. We will also discuss initial development of a method using spectral signatures alone, although the development of the atmospheric correction process is still in progress. Imagery was collected at least once a week over the full melt season (May – September). The high spatial resolution of this imagery allows for the detection of small stream features and different bottom surface types while the high temporal frequency provides for a dense timeseries of meltwater evolution over the entire melt season. The full dataset can potentially be used for model validation and parameterizations for the filling and drainage of lakes. Additionally, the simultaneous collection of imagery with ICESat-2 at various points in the melt season can be used to hone an algorithm to detect melt pond depth over a variety of surface types using ICESat-2 alone. Finally, we use the findings of this dataset to discuss the effects of this season's intense melt on Western Greenland in the context of the historical record, comparing this observational dataset to modeled outputs from the MAR regional climate model.

Continuous measurements of firn-induced elevation changes and surface mass balance in the interior of Greenland and Antarctica in support for altimetry

Santiago de la Peña, The Ohio State University, delapenarodriguez.1@osu.edu
Ian Howat, Michalea King, Salvatore Candela, Darin Desilets, and Gary Womack

Short-term departures in surface elevation trends caused by fluctuations in the volume of the firn layer occur over most of the accumulation zone of the ice sheets of Greenland and Antarctica. Changes in the thickness of the firn column are influenced by variability in surface mass balance, firn compaction, and, in the case of Greenland, by abrupt seasonal densification near the surface caused by refreezing at depth of variable amounts of surface meltwater in the summer. These processes and dynamic thinning cannot be differentiated from each other by altimetry alone, yet measurements of snow accumulation and firn compaction remain sparse due in part to the remoteness, cold, and sheer size of the ice sheets. Until recently, nearly all information on snow density and surface mass balance over the firn layer of glaciers came from ice core and snow pit stratigraphy that provided annual rates with relatively large uncertainties. In an effort to obtain a continuous record of current surface mass balance for altimetry applications, semi-permanent stations have been installed in Greenland recording snow water-equivalent (s.w.e.) accumulation using sensors that measure the attenuation through snowpack of cosmic ray neutrons. More recently, a similar system was assembled over the Antarctic Plateau. The method directly quantifies changes in mass, not in volume, eliminating the reliance on snow density and yielding precise surface mass balance rates on a seasonal scale. The measurements also include firn compaction and relative surface elevation change (which yields snow density in combination with s.w.e.). Together, this information can be directly deconvoluted from altimetry measurements to isolate the dynamic thinning signal. These are the first direct, continuous measurements of surface mass balance over the accumulation zone of both Greenland and Antarctica.

Seasonal Elevation Timeseries of Alaskan Glaciers Constructed from ArcticDEM

William Durkin, Ohio State University, durkin.98@osu.edu
Ian Howat

The ArcticDEM dataset consists of a collection of high-resolution, time stamped digital elevation models (DEMs) for all regions above 60N. In this study, we explore the capabilities of the ArcticDEM dataset in constructing timeseries of seasonal elevation changes of glaciers in the St. Elias and Wrangell mountains of southern Alaska. We will present preliminary findings at the marine terminating Yahtse Glacier and the lake terminating, surge type Bering Glacier. During a period of quiescence, Bering Glacier thinned by 28m near its terminus between February and July of 2013 followed by thickening of 40m between July and December. Seasonal changes observed near the terminus of Yahtse are comparable but display thickening during February - July 2016 of 26m followed by 26m of thinning by the following December. At each glacier, the elevation timeseries evolve in synchrony with seasonal changes in the basal drainage systems inferred from velocity and cryoseismologic observations by previous studies, and we will use this combined dataset to investigate the processes driving these seasonal changes.

Calibrating Greenland's future contribution to sea-level rise using NASA satellite observations

Denis Felikson, NASA Goddard Space Flight Center/USRA, denis.felikson@nasa.gov
Sophie Nowicki, Isabel Nias, Bea Csatho, Erika Simon

Projections of both the magnitude and uncertainty in sea-level rise over the coming century are critical for planning and policy making. Mass loss from the ice sheets is expected to account for 27-38% of total global mean sea-level rise in years 2081-2100 relative to 1986-2005 (Oppenheimer et al., 2019). Estimates of ice sheet response to future climate forcing come from numerical models and uncertainty in the model projections can be quantified by creating ensembles that include a hindcast and comparing the hindcast with observations. Bayesian calibration is one approach for quantifying uncertainty, and this approach has been used to create probability distributions of the sea-level rise contributions of Antarctica, constrained by mass change observations from the Gravity Recovery and Climate Experiment (GRACE) mission. Here, we calibrate sea-level rise projections from Greenland Ice Sheet simulations using surface elevation change measurements from NASA's spaceborne and airborne laser altimetry record, as well as digital elevation models. We create probability distributions of Greenland's contribution to sea-level rise over the coming century and we explore how results differ when the observations are surface elevation changes versus mass changes.

An Energy-Conserving Coupling of Atmosphere and Ice Sheets: Challenges and Perspectives

Elizabeth Fischer, NASA Goddard Space Flight Center, elizabeth.fischer@columbia.edu
Sophie Nowicki

Modeling the long-term evolution of the Greenland Ice Sheet requires that processes of surface mass balance and dynamic ice flow are incorporated into global climate models (GCM) such as GISS ModelE. Dynamic ice sheet models (PISM, ISSM, etc) model dynamic ice flow for a single glacier or ice sheet. Since 2010, a handful of groups have coupled such models into GCMs in order to create a "two-way" coupling that incorporates feedback effects of a changing ice sheet on climate, as well as effects of a changing climate on ice sheets. However, efforts to date have failed to conserve energy, thereby throwing into doubt any long-term conclusions involving dynamic ice flow. A new energy-conserving two-way coupling of GISS ModelE and the PISM dynamic ice model is presented. The presentation will focus on how it works, the challenges involved, and ways it can be used to answer critical questions regarding future climate and ice sheets.

Characterizing buoyant conditions in West Greenland glaciers

Sophie Goliber, University of Texas at Austin, sgoliber@utexas.edu
Ginny Catania

Two major styles of calving have been identified for West Greenland glaciers through remote sensing of terminus change; full-thickness buoyant fracture and serac failure. The former is expected to happen at glaciers that are close to or at floatation. For these glaciers, basal crevasses form at the grounding line and propagate upward where they connect with surface crevasses as they are advected to the front of the glacier, promoting calving of large tabular icebergs. The latter style of calving results from undercutting of the glacier terminus, possibly through melt, which causes surface crevasses to weaken the ice resulting in serac failure. Here we present a time series of the spatial pattern of buoyancy conditions for several glaciers in central west Greenland using Polar Geospatial Center's ArcticDEM strips from 2012-2017 in order to highlight the differences in buoyant conditions between these two different calving types. Preliminary results confirm floating conditions for those glaciers that experience full-thickness calving events. Further, we use the height above buoyancy to determine the penetration height of basal crevasses in order to understand how these vary across different glaciers.

High Elevation Crevasses Coincide with Low-permeability Ice Slabs

Shane Grigsby, Colorado School of Mines, grigsby@mines.edu
Michael MacFerrin, Gabriel Lewis, and Waleed Abdalati

When comparing crevasse locations derived from the ICESat mission (years 2004 to 2006), and from optical imagery (2014 to 2016), we see evidence from both datasets of crevassing above the equilibrium line but below the dry snow zone. These crevassing observations correspond temporally and spatially with the substantial expansion of low permeability ice slabs, suggesting that multi-meter ice lensing within the firn column is providing a medium conducive to fracture. As surface melt continues to fill in pore space and expand these ice lenses and ice slabs to new areas of the ice sheet, there may be the potential for additional crevassing in these areas.

Remote Sensing of Sea Ice Thickness and Ice Sheet Internal Temperatures Using Ultra-Wideband Microwave Radiometry

Joel Johnson, Ohio State University, johnson.1374@osu.edu
Kenneth C. Jezek, Mark Andrews, Marco Brogioni, Giovanni Macelloni, Oguz Demir, Lars Kaleschke, Caglar Yardim, Alexandra Bringer, Michael Durand, Yuna Duan, Leung Tsang, and Haokui Xu

The ultra-wideband software-defined radiometer (UWBRAD) provides measurements of Earth surface thermal emissions over the frequency range 0.5-2 GHz. UWBRAD has been deployed in airborne measurement campaigns in Greenland (September 2016 and September 2017) as well as in Antarctica (November-December 2018), and a ground-based version of the instrument is currently deployed in the MOSAiC sea ice campaign. Through these experiments, UWBRAD has observed brightness temperatures of ice sheets as well as sea ice, firn aquifers, the ocean surface, and land regions. Because the instrument operates in unprotected portions of the spectrum, RFI detection and mitigation algorithms are included to filter the data in real time. The larger frequency bandwidth of UWBRAD is useful for extending the range of sea ice thicknesses and to improve the determination of ice sheet temperature as a function of depth that can be retrieved with current 1.4 GHz microwave radiometer measurements (as from SMOS or SMAP). The presentation will review the campaign and datasets collected with a particular focus on results from the 2018 Antarctic campaign and the MOSAiC observations. The use of the results to remotely sense sea ice thickness and to retrieve internal ice sheet temperature information will also be reviewed and discussed.

Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat

Michalea D. King, Byrd Polar and Climate Research Center, michaleaking@gmail.com
Ian M. Howat

We apply rigorous methodology to derive a 1985-2018 record of ice discharge for all large (widths > 1 km) outlet glaciers in Greenland, and for the first time combine this length of record with high-resolution observations of glacier front changes over the same time period. We use these contemporaneous data to quantify how the dynamic ice losses from the Greenland Ice Sheet (GrIS) have varied in response to changes at the front on sub-seasonal to multi-decadal timescales. We show that following a period of rapid acceleration from 2001-2005, net ice sheet discharge has remained semi-stable at elevated rates > 50 Gt/yr above the 1985 value. We find that this increase is a direct response to ubiquitous frontal retreat, with glaciers retreating, on average, >3 km since 1985. The sensitivity of ice discharge to retreat is similar for glaciers across various regions of the ice sheet, with discharge increasing an average of 3-4% per every km of retreat. Currently, many large glaciers that contribute a disproportionate volume of ice to net discharge are positioned on retrograde slopes, particularly in the central west and northwest regions, and thus we anticipate continued retreat under current and projected atmospheric and oceanic conditions. Our results suggest that due to the strong relationship between sustained inland retreat and increased discharge, and the potential for further retreat at many large glaciers, net GrIS discharge is unlikely to significantly decrease in the near future and will continue to be an important component of the total GrIS mass budget.

Spatial Representativeness of ICESat-2 Freeboard Products in Canadian Arctic Area

YoungHyun Koo, University of Texas at San Antonio, kooala317@gmail.com
Hongjie Xie

Since a new laser altimeter of ICESat-2 data was released in 2018, the data have been accumulated for a year. With its improved resolution compared to the previous ICESat mission, it is expected to estimate sea ice properties in polar region more accurately. However, one of the biggest limits of ICESat-2 laser altimeter data is that the photon counts data are too spatially sparse to identify sea ice properties over a large area. Therefore, we tried to identify spatial representativeness of freeboard products from ICESat-2 data (ATL10). We selected Canadian Arctic area as the research area and focused on the spatial variation of sea ice freeboard for that area. By using the spatial statistical approach based on spatial variogram, we identified how much area of sea ice freeboard each ATL10 beam profile can represent over the surrounding region.

Furthermore, from these spatial variograms, we estimated surrounding sea ice freeboard from a single beam product. The result was compared with the other beam products, which is available thanks to multiple 6 beam products of ICESat-2.

Deposition of Low Albedo Sediment in Supraglacial Streams Depends on Cyanobacteria

Sasha Leidman, Rutgers University, szl9@scarletmail.rutgers.edu
Asa Rennermalm, Rohi Muthyala, Qizhong Guo, and Irina Overeem

Sediment consolidates in supraglacial stream channels and darken the surface of the Greenland Ice Sheet. Little is known about how sediment in these streams is distributed, what causes them to deposit in certain areas, and the impact of sediment on the albedo of the ice surface. Here we present in-situ field observations of a supraglacial stream in southwest Greenland. Through UAV imagery, we show that sediment is mainly distributed in meander bend floodplains that are wetted during daily high flow. Analysis of the grain size distribution of these sediments shows that sediment has an average D50 of 27 ± 5.7 µm. The grain size distribution is applied to a theoretical framework based on the Shield's criterion to build a relationship between stream slope and minimum water depth for sediment movement. This relationship shows that sediment deposition would not occur in supraglacial streams without the presence of cyanobacteria flocculating grains into millimeter scale granules. These granules were observed in the field and around the world. Additionally, we compare predicted deposition area to GPS'ed bathymetry measurements and classified UAV imagery of sediment cover to show that this Shield's relationship can be reliably applied to a wide range of supraglacial streams on the ice sheet and help infer sediment cover across the Greenland Ice Sheet. Understanding the dynamics of sediment deposition in supraglacial systems is vital for constraining the variability of albedo on the Greenland Ice Sheet and this research will give a process-based framework for how the spatial distribution of stream albedo might change in response to increased melting.

Evaporative moisture sources contributing to summer and winter atmospheric river events over the Greenland Ice Sheet

Kyle Mattingly, Rutgers, the State University of New Jersey, km1348@scarletmail.rutgers.edu
Thomas Mote, and Asa Rennermalm

Episodes of intense water vapor transport within narrow corridors called atmospheric rivers (ARs) have been shown to influence Greenland Ice Sheet (GrIS) melt and surface mass balance through modification of the surface energy balance and precipitation. In this study, the dynamical processes by which ARs link the GrIS, overlying atmosphere, and local and distant oceans and land surfaces are investigated through analyses of the evaporative water vapor source regions for strong ARs impacting Greenland. Conditions preceding ARs are first examined from a Eulerian perspective by comparing large-scale evaporation during the 10 days prior to AR landfall to evaporation during periods of no AR activity. Moisture uptake by air parcels arriving over different areas of the GrIS during is then analyzed from a Lagrangian perspective by tracking humidity changes along modelled parcel trajectories during AR and non-AR time periods. Preliminary results suggest that water vapor reaches Greenland from more distant and equatorward source regions during strong AR events in comparison to non-AR conditions. During non-AR periods, water vapor over the GrIS primarily originates from the seas surrounding Greenland. Water vapor within ARs, in contrast, is sourced from a broad swath of the subpolar and mid-latitude Atlantic Ocean during winter and summer, as well parts of northeastern North America during summer. Although air parcels within ARs gain water vapor from areas of anomalously intense evaporation identified by the Eulerian analysis, moisture uptake also occurs over areas of below-normal evaporation south of Greenland, likely due to convergence within the warm conveyer belts of extratropical cyclones. Thus, ARs affecting Greenland draw moisture from a mixture of distant, lower-latitude sources and more proximate areas of the subpolar North Atlantic Ocean that contribute water vapor as air parcels approach Greenland.

Tracking the evolution of ICESat-2 parcels and related geophysical properties using Lagrangian ice motion

Walt Meier, National Snow and Ice Data Center (NSIDC), walt@nsidc.org
Mark Tschudi, and Scott Stewart

ICESat-2 provides new capabilities for estimating sea ice freeboard and thickness. However, the narrow tracks and relatively sparse coverage limits the ability to investigate specific parcels of ice because they drift and evolve under changing forcing. Here we apply a Lagrangian tracking algorithm to parcels, using buoys and remote sensing imagery to estimate the parcel pathways; the motions are then combined with atmospheric reanalysis fields to provide a fuller picture of how and why the freeboard and thickness change over time. We find that the evolution of parcels depends substantially on their starting location and freeboard height, their drift path, and the meteorological conditions they experience. The approach also yields insights into potential uncertainties due to snow cover and changes in the ice cover, that may suggest paths towards future improvement of thickness estimates. We also note the important correlation scales of freeboard/thickness that need to be considered when advecting ice parcels.

Meltwater Plumes and Iceberg Calving at Helheim Glacier, Visualized in High-Resolution Satellite Imagery

Sierra Melton, Pennsylvania State University, smm1084@psu.edu
Richard Alley, Sridhar Anandakrishnan, Byron Parizek, and Nouf Waleed Alsaad

Ice-cliff failure through calving of large icebergs may cause rapid retreat of outlet glaciers and destabilization of inland ice sheets. An improved understanding of calving mechanisms at ice cliffs is of critical importance to better constrain ice-sheet models and sea-level projections. Helheim Glacier, a tidewater glacier on Greenland's eastern coast, terminates in an ~100m-tall ice cliff with an ice mélange and choked fjord in front. Icebergs calved at Helheim are primarily non-tabular bergs which, if extending the entire terminus thickness, generate globally-detectable glacial earthquakes during calving. Some wider tabular icebergs, which remain floating upright, also calve without producing glacial earthquakes. An additional process occurring at Helheim's calving front involves surface meltwater pooling and the appearance of meltwater-plume-fed polynyas in the mélange. The timing and locations of surfacing meltwater plumes, subglacial drainage, calving behavior, and glacial earthquake occurrence are all associated processes that influence Helheim's grounding state, yet limited observational data focusing on the linkages between these processes exists. Here we utilize high-resolution optical imagery to observe temporal variability in iceberg morphology and meltwater features. Meltwater-filled crevasses often appear in constant positions, suggesting that fjord geometry and glacier topography may control their locations. These crevasses consistently fill with water during the summer. Meltwater plumes also surface in the mélange as polynyas during the summer, but observations of these polynyas are rarer than those of surface meltwater pooling. Polynyas are observed when meltwater is present in crevasses, so these features are likely linked. Furthermore, consistent polynya location in the fjord suggests an established subglacial drainage channel. Most observations suggest that polynyas usually appear a couple of days after a non-tabular calving event and that large iceberg calving is uncommon while a polynya is present. These observations will inform modeling of ice-cliff calving, as Helheim's terminus behavior may serve as an analogue to processes at the future glacial margins of Antarctica after removal of ice shelves by warming ocean waters. Unstable ice cliffs could cause retreat into the deep Antarctic basins containing vast volumes of ice with the potential to contribute several meters to global sea level.

Multipass SAR Processing for Radar Depth Sounder Clutter Suppression, Tomographic Processing, and Displacement Measurements

Bailey Miller, Center for Remote Sensing of Ice Sheets (CReSIS), baileyjmiller@ku.edu
John Paden

Multipass and Interferometric Synthetic Aperture Radar (In-SAR) processing techniques allow for the glaciologists to investigate the evolution of ice sheets over time by combining repeated radar measurements over a consistent temporal baseline. These algorithms have primarily been applied to ground based ice-penetrating radar such as the ApRES. However, ground-based platforms have a much smaller coverage area compared to airborne platforms, such as the Multichannel Coherent Radar Depth Sounder (MCoRDS) developed at the University of Kansas (KU) by the Center for the Remote Sensing of Ice Sheets (CReSIS). CReSIS has several datasets that have been repeated almost yearly over the last two decades as part of NASA Operation IceBridge. Calibration flightlines in North-East Greenland between Thule Air Force Base and Camp Century serve as the perfect test set for the InSAR algorithms developed for this work. It is shown that the algorithms developed can compensate for offsets in the flightline trajectory (in elevation and cross-track) and the effects of internal layer slope. Using the developed phase sensitive algorithm, two radar images can be combined across some temporal baseline to measure the vertical velocity field as a function of depth.

Array Manifold Calibration for Multichannel Ice Penetrating SARs

Theresa Moore, John Hopkins University, Applied Physics Laboratory, Theresa.moore@jhuapl.edu
John Paden

Airborne sounders with multiple cross-track sensors may be coherently combined to isolate nadir echoes from co-range lateral surface clutter. The array size, which is limited by the constraints of the platform, determines the degree to which clutter may be suppressed. Array processing techniques offer strategic advantages for mitigating interference in the cross-track dimension but require a well constrained understanding of the array's response to directional sources (referred to as the array manifold). We propose and test an array manifold characterization using a fine resolution digital elevation model of the Arctic and multibeam data collected by a Center for Remote Sensing of Ice Sheets (CReSIS) sensor, the Multichannel Coherent Radar Depth Sounder (MCoRDS), during NASA's Operation IceBridge. The results outline our first efforts to estimate the manifold for improving beamforming and direction of arrival estimation to improve profiling and subsurface imaging performance. We present initial results of a beamformed result that justify the array calibration in processing.

The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6

Sophie Nowicki, NASA Goddard Space Flight Center, sophie.nowicki@nasa.gov
ISMIP6 team

The Greenland ice sheet is one of the largest contributors to global-mean sea-level rise today and is expected to continue to lose mass as the Arctic continues to warm. The two predominant mass loss mechanisms are increased surface meltwater runoff and mass loss associated with the retreat of marine-terminating outlet glaciers. In this paper we use a large ensemble of Greenland ice sheet models forced by output from a representative subset of CMIP5 global climate models to project ice sheet changes and sea-level rise contributions over the 21st century. The simulations are part of the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). We estimate the sea-level contribution together with uncertainties due to future climate forcing, ice sheet model formulations and ocean forcing for the two greenhouse gas concentration scenarios RCP8.5 and RCP2.6. The results indicate that the Greenland ice sheet will continue to lose mass in both scenarios until 2100 with contributions of 89 ± 51 mm and 31 ± 16 mm to sea-level rise for RCP8.5 and RCP2.6, respectively. The largest mass loss is expected from the southwest of Greenland, which is governed by surface mass balance changes, continuing what is already observed today. Because the contributions are calculated against a unforced control experiment, these numbers do not include any committed mass loss, i.e. mass loss that would occur over the coming century if the climate forcing remained constant. Under RCP8.5 forcing, ice sheet model uncertainty explains an ensemble spread of 40 mm, while climate model uncertainty and ocean forcing uncertainty account for a spread of 36 mm and 19 mm, respectively. Apart from those formally derived uncertainty ranges, the largest gaps in our knowledge are the physical understanding and implementation of the calving process, i.e. the interaction of the ice sheet with the ocean, as well as how to best initialize ice sheet models so that they can capture observed contemporary changes.

Metrics for improved reanalyses in polar regions

Chelsea Parker, NASA Goddard Space Flight Center/University of Maryland, chelsea.l.parker@nasa.gov
Richard Cullather, Lauren Andrews, and Amal El Akkraoui

Atmospheric reanalyses are widely used for a variety of scientific endeavors in the Arctic and Antarctic. Reanalyses are used as boundary conditions for a regional and process-based models, for climate model validation, and for diagnostic analysis of physical processes, weather and climatic events. However, reanalyses are typically global and often do not account for specific, regional considerations, such as for polar regions. In this work, we provide a brief evaluation of a prototype for a new GMAO reanalysis, which incorporates higher spatial resolution, an updated approach for data assimilation, and a revised atmospheric model. We identify differences in the representation of the Arctic atmosphere in comparison to recent reanalyses. Furthermore, we provide a forum for Arctic scientists to consider the future improvements for reanalyses, and seek feedback for the following questions: 1) What are important performance factors to consider in evaluating new reanalyses? 2) What physical processes should be incorporated into new reanalyses? 3) What spatio-temporal scales should be considered?

Direct measurements of ice sheet meltwater runoff in Inglefield Land, northwest Greenland

Lincoln Pitcher, Cooperative Institute for Research in Environmental Sciences (CIRES), lincoln.pitcher@colorado.edu
Laurence C. Smith, Adam LeWinter, Brandon T. Overstreet, Kang Yang, Lauren C. Andrews, Asa K. Rennermalm, and David C. Finnegan

Climate model simulations suggest that meltwater runoff is responsible for up to two-thirds of the Greenland Ice Sheet’s modern contribution to global sea level rise. Despite its importance, direct measurements and validation datasets of ice sheet meltwater runoff are rare - particularly outside of southwest Greenland. To that end, we recently established in situ hydro-meteorological instrument installations for the Minturn Elv River in Inglefield Land, northwest Greenland. The installations deploy novel, ruggedized, non-contact water-level sensors that we validate using both traditional pressure-transducer hardware and photogrammetrically derived channel widths. The water-level record is telemetered and transformed into an hourly streamflow data series using in situ hydroacoustic surveys. To our knowledge, this is the northernmost coupled hydrological and meteorological river gauging station in Greenland. It is also uniquely situated in a catchment where all meltwater drains directly off the ice sheet surface with no subglacial routing or delay, thus enabling direct comparison with climatology forced regional climate model runoff simulations. Here, we introduce this new hydro-meteorological station, validate experimental water-level monitoring technologies, present initial results, and discuss forthcoming scientific applications.

The new snow surface model MAR-L shows the firn evolution response to changing atmospheric conditions over Greenland

David Porter, Lamont-Doherty Earth Observatory, Columbia University, dporter@ldeo.columbia.edu
Patrick Alexander, Xavier Fettweis, and Marco Tedesco

Surface mass balance (SMB) models over Greenland are used to correct altimetry data for height changes due to temporal variations in the near-surface density, but also for estimating the contribution of SMB anomalies to the observed height changes. We have developed an uncoupled, offline version of the MAR surface model (MAR-L) for rapid development and prototyping, paving the way for structured improvements in the firn densification schemes in fully-coupled MAR. Fast model integration times allow for comprehensive model parameter and boundary forcing sensitivity experiments, while also aid in bounding projections of Greenland runoff responses to changes in radiative and turbulent fluxes. To improve the MAR densification scheme we evaluate the bias in firn evolution in this newly developed offline surface model. Comparisons of with coupled model results show that at low accumulation sites (e.g. Summit Station) offline biases are small and mostly driven by differences in turbulent heat flux calculation. In the ablation zone, the uncoupled surface model shows less skill at reproducing the original MAR output. The offline surface model was then run with different atmospheric forcings to evaluate the impact of the uncertainties in boundary conditions on the error between modeled snow density profiles and in situ measurements from NASA SUMup program. First, we assimilate in situ surface meteorological, such as radiative fluxes, surface air temperature, and wind speed observations, from nearby stations (e.g. GC-Net), and find a significant improvement in modeled melt, refreezing, and densification of the uppermost 15 m. Secondly, we construct multiple ensembles of the uncoupled, offline model forced with a variety combinations of artificially perturbed atmospheric forcing and model parameters. For changes in winds, the input time series of wind speeds are increased by 50% whenever winds are above the 6 m/s threshold. This arbitrary value is chosen to cause MAR-L to ‘feel’ gustier conditions (something that most coarse weather models underestimate). The result of these increased winds at Swiss Camp are a noticeable impact on the evolution of snowpack densities, with the development and burying of a weak, low-density layer to about 1 m. The second ensemble of sensitivity runs included the scaling of cloud cover by a factor varying from 0 to 2x, in increments of 0.2x, to understand how clouds affect the radiative fluxes at the surface, an important component of the surface mass balance of Greenland. We parse out changes in daytime and nighttime clouds (as determined by shortwave flux less than 10 W m-2). We find that an increase in daytime cloud fraction cools the surface significantly more than the opposing warming effect of nighttime clouds.

Influence of Melange on Tidewater Glacier Calving Activity

Ziad Rashed, Georgia Institute of Technology, zrashed@gatech.edu
Alexander Robel

Calving is critical to glacier mass balance and ice-ocean interactions. Due to its dependence on the detailed glacier stress and fracture state near the terminus, calving is difficult to understand and predict without high-resolution information about the glacier and other critical ice front and ocean processes. One of these processes is the two-way interaction between calving and iceberg mélange, the aggregation of sea-ice and icebergs sometimes found concentrated within fjords occupied by tidewater glaciers. At some of the fastest flowing tidewater glaciers, mélange has been shown to buttress glacial termini and suppress calving events. However, the influence of mélange on the frequency of calving events, and the corresponding influence of calving events on mélange state is not well understood. Using the Helsinki Discrete Element Model (HiDEM), we simulate an undercut calving glacier and vary the degree of applied buttressing stress. Through explicit fracture simulation, we assess the mélange's ability to prevent fracture initiation and iceberg detachment. We then discuss the implications for determining the importance of mélange from calving event catalogues, and the future incorporation of mélange parameterizations into ice sheet models.

Spatio-temporal changes in freshwater budget in Sermilik fjord from high resolution imagery

Soroush Rezvanbehbahani, University of Kansas/Center for Remote Sensing of Ice Sheets (CReSIS), soroushr@ku.edu
Leigh Stearns, Siddharth Shankar, and Cornelis van der Veen

Icebergs constitute nearly half the ice loss from the Greenland Ice Sheet. Identifying icebergs in Greenland fjords as a source of freshwater has implications for fjord circulation as well as for constraining models of calving and fracture mechanics. We use high spatio-temporal satellite imagery (Planet data, ~3 m resolution) and use deep convolutional networks that enable identification of small icebergs. Our analysis spans the summer months of 2018 and 2019 for Sermilik fjord in east Greenland, allowing us to evaluate the temporal changes in freshwater budget. Comparing a similar analysis with Landsat imagery (at ~15 m

resolution) highlights the significance of using high resolution images for accurate assessment of freshwater budget in Greenland fjords.

How much snow falls in the ablation zone of the Greenland Ice Sheet?

Jonathan C. Ryan, Brown University, jonathan_ryan@brown.edu
Laurence C. Smith

Snowfall in the ablation zone of the Greenland Ice Sheet has a disproportionate impact on surface mass balance because it not only replenishes mass but also inhibits melt by covering dark bare ice and reducing the amount of absorbed shortwave radiation. However, the amount and spatial variability of snowfall in the ablation zone is not well constrained due to a sparsity of in situ observations and poor performance of regional climate models (RCMs) over steep, mountainous terrain. Here we present a new, independent estimate of snowfall in the ablation zone by assimilating remote sensing observations from MODIS satellite imagery with outputs from the MAR3.9 RCM. Our method, inspired by mountain snow literature, first identifies the earliest date of seasonal bare ice exposure. We then integrate modeled snow melt backward in time during the melt-season using energy flux outputs from MAR3.9 to derive the amount of snow that accumulated before the melt season began (i.e. from ~Oct to ~Jun). Our product provides a spatially continuous estimate of snowfall across large parts of the ablation zone at an interannual timescale. We validate our product using snow radar data from NASA's Operation IceBridge surveys and in situ field observations where available. We use our product to evaluate spatial patterns of modeled snowfall from the latest generation of RCMs from 2001 to 2017. We also use it to investigate the extent to which interannual snowfall variability controls the timing of bare ice exposure and associated elevation of Greenland's snowline. Our results demonstrate that assimilating observations from MODIS with RCM outputs could significantly reduce uncertainty in winter/spring snowfall in the Greenland Ice Sheet ablation zone.

Landsat Shows Decades of Change in East Greenland

Christopher A. Shuman, University of Maryland, Baltimore County, cshuman@umbc.edu

A branching network of glaciers that empty into Greenland's Sermilik Fjord appeared brownish grey in a true-color Landsat 8 satellite image from Aug. 12, 2019. The color indicates that the snow at the surface has melted, a process that concentrates dust and rock particles and leads to a darker recrystallized ice sheet surface. That intense melt in 2019 extended much higher onto the ice sheet than it did in 1972, when the first Landsat satellite gathered data on the area, a few months after the first in this series of imaging sensors was launched. Comparing image composites between Landsat 1 and Landsat 8 provides a record of almost five decades of change to this region of southeast Greenland. Helheim Glacier, one of the largest in Greenland and the one of the fastest flowing large outlets from the interior of the ice sheet, has retreated about 7.5 kilometers up a wide fjord, leaving a jumble of sea ice where its calving front used to be. To the east, Midgard Glacier has retreated approximately 16 kilometers, splitting into two branches farther up the fjord. Area increases of the rocky outcrops of the mountains between the glaciers are also visible by comparing the series of Landsat images. The images also reveal that there's a lot more bare rock visible now, which used to be covered with ice. Besides Helheim and Midgard, many nearby glaciers in the area are retreating, thinning, and darkening. There are scores of examples of ice mass change just in this one area of East Greenland.

What lies beneath: subsurface Atlantic Water variability near Helheim Glacier from a new sea surface temperature-derived proxy

Tasha Snow, Cooperative institute for Research in Environmental Sciences (CIRES), tasha.snow@colorado.edu
Fiamma Straneo, James Holte, Shane Grigsby, Waleed Abdalati, Ted Scambos, Carolyn Roberts, and Michalea King

The Greenland ice sheet is now the leading contributor to global sea level rise each year and over one-third of its mass loss occurs at outlet glaciers. Melting at the ice-ocean boundary through interactions with relatively warm ocean water is one mechanism for this loss, however, it is unclear how large of a role this mechanism has played in past glacier retreat events. Satellite-derived sea surface temperatures (SST) may hold clues to changes in ocean heat content and mechanisms for transporting that water to the glacier face, especially where no in situ observations exist, but to date they have been rarely used. Here, we build a novel proxy for subsurface water temperatures on the continental shelf near Helheim Glacier using MODIS Level 3 gridded SSTs and identify a wind mechanism for rapidly transporting ocean heat from offshore onto the shelf. Our work reconstructs subsurface water temperatures from the proxy as well as variability in the intrusion of Atlantic Water onto the continental shelf from 2000 to 2018. We show that while trends in the proxy sometimes parallel changes in the temperature of the source Atlantic Water offshore, they also frequently diverge. Variability in the extent of the intrusion of Atlantic Water onto the shelf is often a better indicator of inner-shelf subsurface water temperatures, which we show is closely linked to changes in alongshore winds. While our results are specific to southeastern Greenland and the utility of SSTs specific to the oceanography of a study location, our work illustrates that SSTs have the potential to broadly provide new insight into ocean variability around Greenland and Antarctica that can better inform our understanding of the drivers of glacier change.

New Capabilities and Opportunities with the Airborne Topographic Mapper (ATM): Building on 26 years of Polar Ice Mapping

Michael Studinger, NASA Goddard Space Flight Center, michael.studinger@nasa.gov
Serdar Manizade, Matt Linkswiler, and the ATM Team

The ATM name is known for its 26 years of polar ice LiDAR mapping, all available from NSIDC. Less well known are numerous recent innovations that extend the science that can be done with it. The ATM instrument suite (https://atm.wff.nasa.gov/) is a versatile package of airborne science instruments that can be tailored to many different science applications and platform configurations. ATM has collected high-precision topographic and ancillary data from a wide variety of platforms and altitudes on over 750 polar missions. The main component of the instrument suite are two conically-scanning laser altimeters that have mapped geomorphology, coastlines, ice sheets, sea ice, lake bathymetry and ocean waves. The dual-color (532 & 1064 nm), high-rate (10 kHz), narrow pulse (1.3 ns), small footprint (~1 m) LiDARs allow dense surface coverage with different customizable scan widths. High-bandwidth detectors and multi-trigger waveform recording for precision elevations and detection of multiple surfaces enable extraction of custom geophysical parameters for bathymetry, measurements of laser scattering within snow and ice surfaces and a variety of other applications such as surface characterizations. The two LiDAR instruments are complemented by a thermal imaging camera, a hyperspectral imager (400 - 2500 nm), and high-resolution (10 cm), visible-color imagery for self-contained mission support. Several smaller auxiliary instruments are available and can be added based on customer needs. ATM LiDAR data are a valuable tool for ICESat-2 calibration and validation as well as synergistic science analysis. The high density of 200 - 270 ATM laser shots within an ICESat-2 footprint allows the synthesis of near exact ICESat-2 footprints for comparison and scientific analysis. The high-fidelity, dual-color ATM waveform products enable classification of surface characteristics, information on subsurface scattering, as well as estimates of snow-grain size for ICESat-2 elevation bias studies. Co-located dual-color ATM waveform data can support estimates of spatial and temporal variability in subsurface penetration in ICESat-2 data products. The narrow ATM laser pulse combined with a suite of ancillary instruments enables the study of shallow melt ponds over sea ice as well as supra-glacial lakes and streams on the Greenland Ice Sheet in conjunction with ICESat-2 data. The ATM

team can provide guidance in the use of the various ATM data products including the experimental hyperspectral imager data and suggestions for custom reprocessing of the ATM waveform data products for particular applications.

The exceptional 2019 melting season over the Greenland ice sheet: drivers and implications

Marco Tedesco, Lamont-Doherty Earth Observatory, Columbia University, mtedesco@ldeo.columbia.edu
Xavier Fettweis

The Greenland ice sheet is the sole largest contributor to sea level rise (SLR), making it imperative monitoring surface melting, its drivers and implications. As we are submitting this abstract, the summer of 2019 has been exceptional in terms of surface melting, according to passive microwave spaceborne observations. Similarly to 2012, atmospheric forcing in 2019 has been promoting early melt onset (also close to the one established in 2012 and several of the melt pulses that occurred in June and July (when melting reached up to about 50 % of the surface of the ice sheet) were directly linked to the persistency of high-pressure systems over the ice sheet, associated with the disruption of the jet stream. As of the end of July (when we are writing this abstract), surface melting ranked second within the 40 years of passive microwave data collection (1979 – 2019) and could potentially break the record set in 2012. Concurrently, air temperature at East Grip (2700 m a.s.l.) reached values in June 2019 close to the melting point while albedo along the western margin of the ice sheet was extremely low because of the exposure of bare associated to the early melting and potentially because of the evolution of biological processes. Despite it is not possible at this stage to anticipate weather the 2019 summer season will be breaking the 2012 record (as we have to wait for August to be over), the exceptional nature of this past summer in terms of surface melting indicates the tremendous impact that the combination of atmospheric circulation and surface processes can have on promoting and enhancing melting during a period when (starting a few years ago) the atmosphere is supposed to be slowing down melting (through cyclonic conditions masking the incoming solar radiation) rather than promoting it. Despite implications for sea level rise, the early and enhanced melting can catalyze meltwater production hence affecting both the englacial and subglacial hydrological systems and impact, among other things, compaction processes that needs to be accounted fro when estimating mass changes from elevation changes, such as those obtained from the recently launched ICESAT-2 mission.

Bathymetry of Northeast Greenland from aerogravity

Kirsty Tinto, Lamont-Doherty Earth Observatory, Columbia University, tinto@ldeo.columbia.edu
Caitlin Locke, and Dave Porter

NASA’s Operation IceBridge (OIB) and Oceans Melting Greenland (OMG) projects combine aerogravity surveys with radar and acoustic soundings of the adjacent grounded ice and open sea to provide high quality, well constrained bathymetry inversions. Where geological variations influence the observed gravity, additional constraints are required to distinguish the geological and bathymetric components of the gravity signal. In Northeast Greenland, OIB and OMG surveys combine gravity and magnetic data with sparse bathymetric constraints to provide a model of the geology and bathymetry across the grounding line and offshore from 79N and Zachariae Isstrøm. The resulting bathymetry model presents a shallower basin in the Southwest area of the surveyed region in front of the Zachariae Isstrøm grounding line than previous models, in addition to numerous interconnected seawater cavities. The geological interpretation reveals a change from hard, gneissic rock to low-density sediment along a single offshore ridge structure, indicating the influence of basement geology in steering sedimentary deposits during past glacial cycles.
In 2019 Operation IceBridge demonstrated the successful deployment of the lightweight, small-footprint LDEO gravity system on the NASA GV in Antarctica. This versatile system has the capability to extend the coverage of aerogravity for both bathymetry modelling and investigations of the geological controls on ice flow in Greenland.

A combined active and passive method for the remote sensing of ice sheet temperature profiles

Leung Tsang, University of Michigan, Ann Arbor, leutsang@umich.edu
Haokui Xu, Joel.T.Johnson, Kenneth.C.Jezek, Stephen J.Yan and Prasad Gogineni

The temperature within an ice sheet plays an important role in ice sheet dynamics and ice stiffness. The Ultra-Wideband Software defined microwave radiometer (UWBRAD) was developed to retrieve internal ice sheet temperatures using 0.5-2GHz microwave radiometry. The airborne brightness temperature measurements of UWBRAD in 2017 and 2018 over Greenland however show a significant influence of firn reflections created by near surface density fluctuations. These near surface density fluctuations introduce undesirable uncertainties in the temperature profile retrieval if they are not compensated. In this paper, we develop a coherent reflectivity model for both ice sheet thermal emission and backscattering. The impact on brightness temperatures of near-surface density fluctuations is shown to be describable as a reflectivity function of frequency that is measurable by a radar system operating in the same frequency range. Results are then shown to demonstrate the use of radar measurements to compensate reflection effects on brightness temperatures, so that the corrected brightness temperature is directly related to the physical temperature profile of the ice sheet. We also investigated the use of satellite radar data at L and C band to infer the near surface density fluctuations.

Ice velocity changes of Greenland's marine-terminating glaciers

Saurabh Vijay, Byrd Polar and Climate Research Center, Ohio State University, vijay.20@osu.edu
Winnie Chu, Michalea King, Bidhyanada Yadav, Ian Howat, S. Abbas Khan, and Anne Solgaard

Greenland's marine-terminating glaciers' flow vary on different time scales. In this study we observe dense and year-round ice velocities of 221 Greenland glaciers using Sentinel-1 radar mission. We find strong signals that indicate potential links between changes in ice velocities and subglacial hydrology, inferred from the surface melting conditions, for nearly half of the study glaciers. These glaciers show two distinct velocity patterns and they appear to respond differently to the onset of melt season. A section of these glaciers speedup with the onset of surface melt and take nearly half of more of the melt season to achieve annual maximum velocity followed by slowdown dropping to similar speeds as of pre-melt season's. Other set of glaciers show high winter-time velocities, which speedup or remain comparable with the onset of melt and quickly attain annual maximum velocity followed by consistent slowdown during most of the melt season falling back to the speeds lower than pre-melt season's. These set of glaciers, in most cases, speedup again during the autumn-winter period. Apart from these seasonal fluctuations, we find dramatic velocity fluctuations (e.g. Zachariae Iss. northeast Greenland) linked to supraglacial lake drainage (SGL) events. For this we combined Landsat-8 OLI, Sentinel-1 radar backscatter and ICESat-2 elevation changes together with 6-day Sentinel-1 based ice velocities to investigate SGL drainage related ice velocity changes.

Automatic detection of ice surface depression features using ICESat-2 altimetry measurements

Shujie Wang, Lamont-Doherty Earth Observatory, Columbia University, swang@ldeo.columbia.edu
Marco Tedesco, Qiusheng Wu, Song Shu, and Patrick Alexander

Surface depression features over ice sheets and ice shelves, such as ice crevasses, rifts, and lake basins are important morphological features that impact surface hydrology and ice calving processes in Greenland and Antarctica. The Ice, Cloud, and Land Elevation Satellite - 2 (ICESat-2) is equipped with the Advanced Topographic Laser Altimeter System (ATLAS), employing photon-counting lidar techniques and providing six-beam surface measurements with a ground footprint of ~17 meters and an along-track offset of 0.7 meters. The high-resolution and spatially dense measurements collected by ICESat-2 offer an excellent opportunity to consistently monitor the three-dimensional changes of those structures. Here we develop an algorithm based on a multilevel hydrological filling approach to automatically extract the surface depression structures from the repeating ICESat-2 profiles. Based on the extracted morphological information, our method can differentiate different depression features. We tested the algorithm over the Greenland Ice

Sheet to extract supraglacial lake basins and over the Amery Ice Shelf in Antarctica to extract ice rift features. The results indicate that our automatic method can well delineate the boundaries of ice rifts and lake basins, showing a great potential of applying the proposed method to ICESat-2 measurements to study the temporal changes of the surface depressions over ice sheets.

Greenland GNSS Network (GNET)

Malte Nordmann Winther, The Danish Agency for Data Supply and Efficiency, mawin@adfe.dk
Kelly Brunt, Robert Hawley, Finn Bo Madsen, and Søren F. Christensen

The continuous existence of GNET has been secured, due to a successful transfer of GNET to the Danish Government and inclusion of GNET in the Danish Finance Act. Further, US research interests are secured by support from and collaboration with the National Science Foundation. With addition of a working professional governance structure, a continuously updated website, and international stake-holders from many interdisciplinary fields, the future of GNET as a continuously updated geodetic infrastructure is bright. The presentation will include a status of the network, as well as short and long-term plans and perspectives.

Dynamic elevation change on Greenland glaciers 2016-2019 revealed by NASA's GLISTIN-A radar interferometer

Michael Wood, California Institute of Technology/NASA Jet Propulsion Laboratory (JPL), mike.wood@jpl.nasa.gov
Ian Fenty, Ala Khazendar, Jeremie Mouginot, Eric Rignot, Helene Seroussi, and Joshua Willis

In recent decades, the Greenland Ice Sheet has been losing mass at an accelerating rate, primarily controlled by increased discharge from marine-terminating outlet glaciers. However, in the past several years, many glaciers have exhibited slower change and surface mass balance has constituted a larger proportion of mass loss from the ice sheet. Here, we investigate elevation changes on the periphery of the ice sheet at marine-terminating glacier margins using digital elevation models from the Glacier and Land Ice Surface Topography INterferometer (GLISTIN-A) collected between 2016 and 2019 during NASA's EVS-2 mission ``Oceans Melting Greenland''. We find an average thinning rate of 3.2 m/yr (1.8 m/yr) for 155 (210) marine-terminating glaciers measured in the period 2016-2019 (2017-2019). Yet, there are clear regional differences: the largest and most ubiquitous thinning rates are observed in the southeast (6.1 m/yr) and central east (3.2 m/yr) while glaciers along the west coast showed a mixed signal of thickening and thinning. By comparing reconstructions of surface mass balance with the observed trends, we find that southeast and central east glaciers thinned primarily as a result of ice dynamics (76% and 74% respectively). Ice dynamics in the northwest, central west and southwest also explain the thickening of glaciers there, which counterbalanced some of their elevation losses due to SMB. The spatial pattern of dynamic elevation change is consistent with the proximity of glaciers to deep, warm Atlantic water and regional trends in ocean temperature, and inconsistent with both regional patterns in ice sheet runoff and the presence of rigid wintertime ice mélange. We conclude that the recent pattern of dynamic glacier changes around Greenland is likely driven by ocean melt, highlighting ocean variability as a key modulator of mass loss from the ice sheet

---

A Quasi 4-Year Oscillation in Arctic Spring-Summer TOA Radiation

Dong L. Wu, NASA Goddard Space Flight Center, dong.l.wu@nasa.gov

Arctic radiation budget is a key variable that drives recent rapid change in the cryosphere. The 19-yr Clouds and the Earth’s Radiant Energy System (CERES) and Multiangle Imaging SprectroRadiometer (MISR) data are analyzed to study interannual variabilities of the top-of-atmosphere (TOA) radiation in the Northern Hemisphere (NH). The TOA fluxes at 60°N-85°N during the spring-summer appear to have a robust oscillation with period of ~4 years. The fluctuations of the net TOA flux over the Arctic are dominated by the shortwave (SW) flux in May-August. The MISR TOA albedo measurements reveal a consistent oscillation pattern with the CERES SW flux, confirming the albedo-driven interannual variation in the spring-summer SW flux. The quasi 4-year oscillation is also seen in MERRA2 reanalysis TOA SW flux data, which appears to have intensified since 2009. An empirical orthogonal function (EOF) analysis reveals two centers of action over the summer Arctic: Beaufort Sea and Queen Elizabeth Islands (BS-QEI) and the Barents-Kara Sea (BKS). These regions are subjected to strong interannual variability in spring snow cover and summer sea ice extent, which are likely the main sources of the 4-year Arctic spring-summer TOA flux fluctuations. The excessive and deficient Arctic TOA energy fluctuations at the quasi 4-year period have profound impacts on climate at mid-to-high latitudes.

A combined active and passive method for the remote sensing of ice sheet temperature profiles

Haokui Xu, University of Michigan, xuhaoku@umich.edu
Leung Tsang, Joel.T.Johnson, Kenneth.C.Jezek, Stephen J.Yan, and Prasad Gogineni

The temperature within an ice sheet plays an important role in ice sheet dynamics and ice stiffness. The Ultra-Wideband Software defined microwave radiometer (UWBRAD) was developed to retrieve internal ice sheet temperatures using 0.5-2GHz microwave radiometry. The airborne brightness temperature measurements of UWBRAD in 2017 and 2018 over Greenland however show a significant influence of firn reflections created by near surface density fluctuations. These near surface density fluctuations introduce undesirable uncertainties in the temperature profile retrieval if they are not compensated. In this paper, we develop a coherent reflectivity model for both ice sheet thermal emission and backscattering. The impact on brightness temperatures of near-surface density fluctuations is shown to be describable as a reflectivity function of frequency that is measurable by a radar system operating in the same frequency range. Results are then shown to demonstrate the use of radar measurements to compensate reflection effects on brightness temperatures, so that the corrected brightness temperature is directly related to the physical temperature profile of the ice sheet. We also investigated the use of satellite radar data at L and C band to infer the near surface density fluctuations.

An open-source Python toolbox for the analysis of ICESat-2 data: Case studies from Alaska, Greenland, and Antarctica

Bidhyananda Yadav, The Ohio State University, Byrd Polar and Climate Research Center,
Yadav.111@osu.edu
Saurabh Vijay, and Ian Howat

The Advanced Topographic Laser Altimeter System (ATLAS) of ICESat-2 mission allows the determination of geo-located individual photons within a dense point cloud that can help resolve many of the cryospheric and land surface processes. The mission has a global acquisition strategy and provides high-quality elevation products like ATL06 and ATL08. We develop an open-source toolbox, which consists of a sequence of Jupyter notebooks to search, download, subset, visualize and analyze ICESat-2 ATL06 and ATL08 elevation products. Our workflow makes use of Python libraries such as Numpy, Scipy, Pandas, h5py, Shapely, and Geopandas for general computation and geospatial processing, and Matplotlib, hvPlot, and Geoviews for data visualization. In this presentation, we share the potential of ICESat-2 ATL06 and ATL08 products across various study sites in Antarctica, Alaska, and Greenland. For instance, we compare Arctic and Antarctic DEMs with near-time ICESat-2 elevations for vertical adjustments of the former DEMs. This is quite important in the areas where no stable surface (e.g. nunataks) is present on the DEMs. In another case study, we observe time-series ICESat-2 elevations over the supraglacial lakes of Zachariae Iss., northeast Greenland that are known to drain seasonally and influence ice flow. Our primary results suggest that these lakes have 9-12 ICESat-2 observations per year, and if combined with Arctic DEM time-series can potentially highlight the drainage events. Our overall goal is to share our best practices to allow for easier adoption of our workflow by a wider scientific community and scale the capabilities of ICESat-2 products for various applications.