This synopsis describes the proposals selected in response to the NASA Research Announcement CRYOSPHERIC SCIENCE that is sub-element A.16 of NASA ROSES 2017.

NASA’s Cryospheric Sciences Program supports remote sensing-based research on the Earth’s polar ice sheets, glaciers, and sea ice and their connections to the global Earth system. Increasing ice loss from the glaciers of Antarctica, Greenland, and the Arctic is contributing to sea level rise, and dramatic changes are occurring in sea ice of the Arctic and Southern Oceans. Characterizing these changes and understanding the processes controlling them is required to improve our understanding of the Earth system and forecast continued change and its impacts. The Earth’s polar ice covers continent-sized areas in inaccessible and inhospitable regions making NASA’s satellite and aircraft remote-sensing capabilities critical tools for understanding the changes occurring.

This solicitation supports investigations that use remote sensing to study the land-based ice sheets and sea ice. Supported studies are based on satellite and aircraft remote sensing observations and seek to understand the factors controlling changes in the ice and its interaction with the ocean, atmosphere, solid Earth, and solar radiation.

In addition, the program seeks to continue its longer-term goals to:

- Determine the mechanisms controlling sea-ice cover, such as quantifying the connections between sea ice and the ocean and atmosphere;
- Characterize sea ice properties—such as ice and snow thickness, roughness, melt ponds, and albedo—and physical processes—such as deformation and rifting—such that they can be incorporated into sea ice models;
- Use remote sensing products to validate and improve models of changes in sea-ice cover to elucidate connections to the global system;
- Determine the mechanisms controlling mass balance and dynamics of the Greenland and Antarctic ice sheets, including improving fundamental understanding of the connections to the ocean, sea-ice cover, and atmosphere;
- Characterize land ice properties—such as thickness, surface mass balance, englacial and surface water, layering, bed and grounding line properties, and albedo—and physical processes—such as flow, crevassing, ice shelf behavior, melt water fate, and calving—such that they can be incorporated into models;
- Use remote sensing data to validate and improve models of land-based ice and their contributions to sea-level change; and
- Study the polar and nonpolar mountain glaciers and small ice caps to understand systemic impacts of global change and contributions to sea-level rise.

Out of 67 submitted proposals, 16 were selected for awards. The total funding for the program is approximately $1.5 million per year for three years. The Principal Investigator, institution, project title, and abstract are listed below.
Moulins are vertically oriented shafts that carry surface meltwater to the base of an ice sheet, where it joins the subglacial hydrologic system and modifies ice flow. Thus, constraining the mechanisms controlling moulin formation and longevity are crucial to understanding the future evolution of the Greenland Ice Sheet, where surface melt extent and intensity are projected to increase. However, previous work has focused on identifying moulins in specific regions tractable to manual or semi-automated remote sensing analyses, without exploring the underlying formation mechanisms, limiting the ability to characterize spatiotemporal moulin distribution without the availability of high resolution imagery. To date, global climate models (GCMs) generally port surface melt directly to the ocean, bypassing its transport through moulins to the ice-sheet bed. Because moulins switch water from flowing across the ice-sheet surface to flowing along the ice-sheet bed, their inclusion in the next generation of GCMs is an important research frontier. Within ice-sheets, moulins modulate the location, timing, and volume of surface melt at the bed; these are primary controls on the seasonal evolution of the subglacial hydrologic system. Thus, accurate incorporation of moulins into ice sheet models (ISMs) with subglacial hydrology routines is crucial to capturing observed seasonal variations in the dynamic component of ice-sheet mass balance. Moulins act as filters between the surface meltwater supply and the basal hydrologic system and, as such, must be included in models with these components.

This project will combine process-scale modeling and remote-sensing techniques to develop a stochastic model for the spatial distribution and temporal evolution of moulins in western Greenland. The proposed work will first expand an existing physical model for a water-filled crevasse into a more complete physical model for moulin initiation and evolution across multiple timescales (minutes to decades), including reactivation in subsequent years. Next, an analytic model for the transmittance of basal perturbations to the ice-sheet surface will be coupled to the physical moulin model in an effort to capture the observed cascading nature of many moulin activation events. These models will be informed by and validated with remote-sensing data products, including GIMP, ArcticDEM, Landsat, MODIS, MEaSUREs, and GoLIVE. Finally, the results will be synthesized into a stochastic model that will constrain the spatial density and activation dates of moulins in current and future climates. The stochastic model will be developed for use in ISMs and in GCMs to improve their surface melt – runoff schemes.

The proposed work will contribute (1) a moulin parameterization for ISMs and GCMs for the delivery of surface melt to the bed, and (2) an enhanced understanding of how, where, and when moulins may deliver surface melt to the bed of the Greenland Ice Sheet in future warm climates. The investigation addresses goals of the Arctic Studies component of the solicitation, including determining the connections between glacial dynamics, bed characteristics, and melt water. The project also directly addresses specific longer-term
goals of the NASA Cryosphere program by characterizing land ice properties such as englacial and surface water and physical processes such as melt water fate such that they can be incorporated into models. The product will be developed as a first step toward use in GCMs and ISMs, in collaboration with respective experts from the Global Modeling and Assimilation Office and the Cryospheric Sciences Laboratory at NASA GSFC.

**Ginny Catania/University of Texas, Austin**

**Understanding the Evolving Geometry of Outlet Glaciers in Greenland**

17-CRYO17-0046

Overview: Our over-arching objective is to characterize outlet glacier mass variability in Greenland and to understand the physical controls that limit outlet glacier change.

Approach: This objective will be accomplished through construction of a remote sensing dataset that will in and nearly double the temporal record of outlet glacier elevations in select regions (extending to 75 years) and increase the spatial resolution significantly. These observations will then be used to examine the nature and evolution of glacier dynamic change through empirical, theoretical, and numerical techniques. First, we will use kinematic wave theory to determine the limits to upstream elevation change following grounding line perturbations, allowing us to identify glaciers that are most susceptible to far-reaching inland thinning. Second, we will test kinematic wave theory by applying known changes at glacier termini to model the temporal evolution of thinning using the Ice Sheet System Model (ISSM). Lastly, we will use ISSM to test various calving laws to reproduce the observed retreat rates, allowing us to better understand the calving mechanism and to identify the mass losses possible from the most susceptible glaciers identified in the kinematic wave analysis.

Uniqueness: Greenland’s mass balance is partially modulated by the changing dynamics of marine-terminating outlet glaciers. Our project aims to take advantage of a rich, historical database of imagery for coastal Greenland going back to the 1940s. By doing so, our project will result in the most complete, long-term record of glacier elevation change for Greenland. Using this data set, we will determine the limits to sea-level rise contribution from some of the most rapidly changing locations around the Greenland Ice Sheet, as well as those that have the potential to change rapidly in the future. This will be done by querying our observational data set to understand the degree to which regional versus local controls mitigate glacier dynamic change. We will improve understanding of glacier response to terminus perturbations and calving processes, which is presently a major gap in our understanding of ice sheet change. Our remote sensing efforts will produce valuable, widely-disseminated data products including: 1) improved measurements of ice surface topographic evolution; 2) improved tracking of glacier terminus positions through time and; 3) estimates of glacier susceptibility to terminus perturbations.

Value to NASA: A major objective of ice sheet and climate research is to understand the response of the ice sheets to climate change driven by present-day and future increases in greenhouse gases. Of particular importance is reducing uncertainty in the amount of
expected future sea-level rise. Understanding the spatial and temporal controls on Greenland glacier response to climate change is thus of immediate importance. Our proposal responds to the NASA-Cryosphere solicitation to use remote sensing data to validate and improve models of land-based ice and their contributions to sea-level change. Further, identifying the glaciers that might pose the largest risk to sea-level rise is critical in order to focus limited scientific resources where they are most needed. Our work will enable more focused efforts to understand satellite-altimetry-derived estimates of elevation change in those areas deemed to be more susceptible to future changes.

Ellyn Enderlin/University of Maine, Orono
Quantification and Analysis of Greenland Glacier and Ice Cap Discharge using Automated Landsat Terminus Change Time Series and NASA Data Products 17-CRYO17-0056

Overview: The overall objectives of the proposed project are to 1) develop and validate an automated terminus tracking algorithm for Landsat optical imagery and 2) quantify ice discharge from Greenland’s peripheral glaciers and ice caps (GICs) using the generated terminus change time series, high-resolution digital elevation models, and NASA datasets. The development of an automated terminus tracking algorithm will enable the efficient construction of terminus change time series for marine-terminating glaciers worldwide, without the need for time-consuming and subjective manual terminus tracing. The terminus change time series will be combined with ice flux estimates to generate ice discharge time series for Greenland’s GICs. The discharge time series will be paired with surface mass runoff estimates to construct the first partitioned mass loss time series for Greenland’s GICs. Analysis of dynamic change patterns for Greenland’s GICs with respect to atmospheric and oceanic conditions, as well as ice sheet outlet glacier discharge, will yield insights on variations in dynamic mass loss from marine-terminating glaciers.

Approach: An automated algorithm that exploits image intensity gradients to automatically segment images, called the 2D Wavelet-Transform Modulus Maxima approach, will be used to delineate glacier terminus positions in cloud-free optical Landsat images. The algorithm will be used to construct sub-annual terminus position time series for >600 peripheral marine-terminating glaciers spanning the Greenland periphery. The results of the automated approach will be validated using manually-traced terminus maps. The terminus change time series will be paired with NASA GoLIVE and MEaSUREs surface speed time series and ice thickness estimates to construct time series of ice discharge from Greenland’s GICs. NASA IceBridge radar observations will be used to directly estimate ice thickness when and where they are available as well as to develop thickness-scaling parameterizations in regions where no thickness estimates exist. Spatial patterns and temporal trends in Greenland GIC ice discharge will be compared to variations in Greenland ice sheet discharge, RACMO surface meltwater runoff estimates, NASA Oceans Melting Greenland datasets, and NOAA sea ice concentration datasets.
Value to NASA: Terminus change time series are often used as a metric to infer changes in glacier dynamics from readily available observational data and as a means to validate the performance of numerical ice flow models. Manual terminus change tracking is a tedious process that is often repeated by multiple investigators at different institutions. The terminus tracking algorithm developed for this project will represent a step advance in our ability to efficiently measure changes in glacier length using optical satellite images, which is valuable for the observational analysis of modern changes in glacier dynamics for Greenland’s GICs here and for future analyses of marine-terminating glaciers across the globe. The ice discharge and RACMO runoff time series will be used to construct a nearly two decade-long record of mass loss from Greenland GICs, directly addressing the NASA Cryospheric Science program objective to study polar and nonpolar mountain glaciers and small ice caps to understand systematic impacts of global change and contributions to sea level rise. If we treat Greenland GICs as analogs for the ice sheet’s marine-terminating glaciers as they recede from their deep marine troughs in the coming decades, then the response of Greenland GICs to atmospheric and oceanic change revealed by this study will also yield valuable insights into changes in dynamic mass loss from the Greenland ice sheet in the coming decades. Thus, this project also contributes to the NASA Cryospheric Science program objective to improve our understanding of the mechanisms controlling the mass balance and dynamics of the Greenland ice sheet.

Laurie Geller/National Academy of Sciences
Polar Research in Support of NASA’s Missions 2017-2020
17-CRYO17-0001

The National Academies of Sciences, Engineering, and Medicine are private, nonprofit institutions that provide expert advice on some of the most pressing challenges facing the nation and the world. Our work helps shape sound policies, inform public opinion, and advance the pursuit of science, engineering, and medicine. The Polar Research Board (PRB or Board) is the focal point for providing advice on issues related to the Arctic, Antarctic, and cold regions in general. The PRB serves the Nation at the international level as the U.S. National Committee to two international nongovernmental polar science organizations, the Scientific Committee on Antarctic Research (SCAR) and the International Arctic Science Committee (IASC).

The activities overseen by the Board will help advance NASA’s strategic goals overall and in particular Objective 2.2: Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet. Our Board has traditionally been most directly engaged with NASA’s Cryospheric Sciences Program, but our efforts also relate to NASA’s Earth Sciences program more generally. We serve NASA by organizing discussion forums on topics it suggests, examining issues relevant to its mission and goals, and standing ready to conduct specific, ad hoc activities to meet requests including community consensus building, examination of new research frontiers, program reviews and evaluation of relevant technologies, assistance in setting
priorities and identifying research opportunities, and analyses of controversial and nationally important topics.

In the coming years, the PRB expects to serve the Nation by addressing priority issues either requested by agencies or identified by the Board’s members, and by continuing to facilitate U.S. participation in IASC and SCAR, and seeking ways to make these organizations valuable to U.S. interests. Through all of these means, the PRB will help NASA to effectively leverage and increase the impacts of its investments in polar science.

This proposal requests a total of $750,000 over a period of five years from the National Aeronautics and Space Administration (NASA) to partially cover the expenses associated with the activities and operations of the PRB from June 1, 2017 to May 31, 2022.

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**Ian Howat/Ohio State University**

**Daily to Decadal Variability in Discharge from Greenland Outlet Glaciers**

**17-CRYO17-0035**

We propose to extend and substantially improve the comprehensive record of thickness, velocity, and ice discharge for Greenland’s marine-terminating outlet glaciers in order to constrain ice sheet and ocean models and better understand changes in ice dynamics, freshwater flux, mass balance and contribution to sea level rise. Predictions of the future behavior of Greenland’s fast-flowing outlet glaciers remain highly uncertain due to their complex and variable dynamics. Existing ice-sheet wide records of glacier velocity, discharge and freshwater flux cover too short a period and are too coarse in temporal resolution to provide adequate constraints for numerical ice sheet models and efforts to quantify freshwater forcing on ocean circulation. Recent expansions in observational capacity from air and space, new data access, improved data processing methods and enhanced surface mass balance modeling now enable backward expansion of these records to mid 1980’s, with seasonal to daily temporal resolution. We will merge observations from a wide range of Earth observing sensors, utilizing NASA products from the MEaSUREs Greenland Ice Mapping Project and Operation IceBridge, as well as sub-meter resolution imagery from DigitalGlobe. The latter offers the transformative potential to bridge the measurement gap between ground observations and remote sensing by enabling ~daily resolution ice velocity observations over large areas. We will also utilize high resolution reanalysis model estimates of surface mass balance and melt runoff to determine glacier/fjord scale freshwater fluxes. We will use our improved record to assess variability in ice dynamics, discharge and freshwater flux at a range of timescales, from short-term changes due to iceberg calving and sea ice conditions to multi-decadal shifts due to long-term climate and ocean trends. Our project includes collaborators who will use these observations to constrain numerical ice sheet models and quantify freshwater forcing on ocean circulation, offering immediate and wide-ranging science return.
Our proposal responds to several of the objectives of the NRA, including to determine the mechanisms controlling mass balance and dynamics of the Greenland, advance understanding of land-ice processes, especially connections among the warming ocean and increases in glacial flow rates, characterize land ice properties... and physical processes such that they can be incorporated into models and use remote sensing data to validate and improve models of land-based ice and their contributions to sea-level change. Our observations will cross-validate and improve measurements obtained from the NASA GRACE and upcoming ICESat-2 missions.

Jennifer Hutchings/Oregon State University
Observational Study to Constrain Rheological Models for Sea Ice
17-CRYO17-0022

Leads, that occur in repeating patterns, and the formation of coastal shear zones control the winter and spring sea-ice drift, opening and ridging. Climate models do not accurately simulate these processes, and have large variability in simulating sea-ice change, drift and lead opening. We aim to improve the rheological component of sea-ice models. This rheology controls the relationship between wind and current forcing on the ice pack and its deformation, which controls the ice motion. We have identified along-shore boundary conditions needed for accurate simulation of ice drift. In light of our recent advances in our understanding of the mechanical control of ice motion in the Beaufort Gyre, we anticipate model improvements will allow constraint of future climate projections of Arctic sea ice.

We propose to use satellite and airborne imagery of the Arctic ice pack to identify the modes of failure that result in leads and ridges forming. Our previous work has identified lead pattern geometry aligns with Mohr-Coulomb theory (a rheological model). We will catalog 38 years of clear sky satellite sea-ice imagery by fracture pattern, and use ice drift and deformation products to further classify by mode of failure (e.g. failure in tension, shear or compression). We will extend previous work by using available ice tracking products, in particular the RADARSat Geophysical Processing System (RGPS) ice deformation products, to identify compressive modes of failure, and to extend beyond the clear sky database. A subset of high-resolution airborne imagery from Operation Ice Bridge (OIB) will be used to verify if particular failure modes are fully resolved in lower-resolution satellite imagery.

The catalog of classified failure patterns will be searched for case studies captured close to the time of failure. We will perform stress analysis on these case studies, initially assuming a Mohr-Coulomb rheology. Identifying if there are consistent parameters in the rheological model across the case studies, or if these parameters vary seasonally, by ice type, or confinement (applied stress) on the ice pack. This information will be used to identify appropriate rheological models for pack ice. Which will be tested in a stand-alone sea-ice model. Our previous work has identified the importance of the landfast ice edge in the location of large scale lead patterns. We will test such boundary conditions in
the model, along with exploring how the ice state responds to modifications to rheological models our observational study finds necessary.

We address the NASA Cryosphere Program long-term goals of using remote sensing products to validate and improve models of changes in sea-ice cover. We will identify physical properties, in particular material properties, of pack ice and incorporate these into sea-ice models. This work is needed to determine the mechanisms controlling recent observed reductions in sea ice thickness in the Arctic. We utilize NASA remote sensed and OIB data to improve models of sea-ice motion, opening and ridging. This will better constrain sea-ice drift and deformation, and associated feedbacks, in climate projections.

Project outcomes will include model improvements to be shared with the sea-ice community through publications and conference presentation. By constraining the mechanical response of sea ice in climate models, modelers will be able to improve the dynamic component of sea ice models. Interacting with the CESM Polar Working Group, the International Ice Chart Working Group, and the Sea ice Prediction Network (groups Hutchings participates in), findings will be shared directly with those providing climate projections and short range to seasonal forecasts. It is anticipated this will result in improvements (i) to ice drift fields in climate models, (ii) in our ability to forecast the locations of leads and pressured ice, and (iii) in representing recent and projected sea-ice change.

Lora Koenig/University of Colorado, Boulder
Constraining Aquifer Formation and Expansion in Greenland Using Enhanced Resolution Brightness Temperatures
17-CRYO17-0052

Earth’s sea level is predominantly determined by the amount of ice contained in the Greenland and Antarctic ice sheets. Recently accelerating ice mass loss from the Greenland ice sheet, is a major contribution to sea level rise with changes in surface mass balance, particularly surface melting, driving the increase. Despite the global significance of surface melt and subsequent runoff from Greenland, the complex processes of melt water production, transport, storage, and evacuation from the Greenland Ice Sheet are not well quantified. This deficiency in knowledge of the hydrologic system is exemplified by the fact that until 2011 it was unknown that aquifers, currently storing an estimated 0.4 mm of sea level equivalent, were hidden below the surface of the Greenland ice sheet. The storage of large amounts of water raises two important questions for assessing future sea level rise contributions from the Greenland Ice Sheet, What is the spatial and temporal variability of the stored water in the Greenland ice sheet? and How much water is being retained and/or stored in the Greenland ice sheet over the winter today and in the past?

This proposal will improve our understanding of aquifers by investigating the time evolution of water storage in the Greenland ice sheet by utilizing the earliest datasets available capable of detecting water. We will use the NASA MEaSUREs Calibrated
Enhance-Resolution Passive Microwave brightness temperatures, Nimbus-5 brightness temperatures and backscatter measurements from a variety of missions, like Seasat-A, to investigate the spatial onset of water storage in aquifer regions. Additionally, we will improve surface melt mapping resolution and investigate the relationship between aquifer expansion and surface melt extent, melt duration, and estimated melt volume.

This proposal directly addresses the Cryospheric Sciences call to use remote sensing methods and a MEaSUREs dataset to study land ice on the Greenland ice sheet for improving estimates of sea level change and validating models. The improved resolution surface melt maps produced from this proposed work will support the Greenland Today Blog post hosted by the National Snow and Ice Data Center that receives over 250,000 hits per year.

Kristin Laidre/University of Washington, Seattle
Variability of Glaciers and Fjord Ice in Southeast Greenland With Application to Resident Polar Bears
17-CRYO17-0007

Southeast Greenland, between approximately 60-68oN, contains 69 major tidewater glaciers that generally discharge into long, deep fjords covered by sea ice from fall to spring. These systems are undergoing rapid changes with a broad degree of spatial and temporal variability that is not well documented. Little is known about the intra-annual variability in Southeast Greenland glacier terminus position, calving patterns, and the interaction between the glacier, glacial malange and fjord sea ice. Addressing this gap in our knowledge is important from a glaciological perspective, and because the area is a specialized productive ecosystem. In particular, Southeast Greenland is host to a subpopulation of polar bears that is resident at glacier fronts year-round, hunting for seals on the floating ice malange and traveling inland on the glaciers themselves to reach adjoining fjords. Our project will answer key questions about Southeast Greenland glaciers, glacier-derived ice, and fjord sea ice. We will then use this information to link these physical characteristics of the environment to the behavioral patterns of the regional polar bear subpopulation. We will provide the first detailed characterization of Southeast Greenland glaciers at a roughly weekly resolution, including glacier advance and retreat time series, ice discharge, ice malange concentration and extent, and metrics of sea ice break-up, extent, and freeze-up. We will make use of multiple data sources including the NASA MEaSUREs Program (Making Earth System Data Records for Use in Research Environments), Landsat 8 optical imagery, sea-ice concentration from satellite passive microwave data, bathymetry from NASA’s Oceans Melting Greenland Program, data from NASA’s Operation IceBridge acquired over the glaciers of Southeast Greenland, and surface air temperature from coastal weather stations and from NASA’s MERRA-2 reanalysis product. Finally, we will use movement data acquired by satellite telemetry of more than 100 polar bears collared in Southeast Greenland from 2015 to 2017 to establish spatial habitat models for bears at glacier fronts and to quantify which features of glaciers are important to maintaining the subpopulation. The interdisciplinary nature of this science team enables the cross linkages between glaciology, sea ice, and ecology. This
work develops important cryospheric time series that will allow for an improved understanding of glacier/fjord interactions in a less-studied region of Greenland and at the same time elucidates the relationship between the physical environment and the resident polar bear subpopulation.

Derrick Lampkin/University of Maryland, College Park
Evaluating Recent Changes in the Percolation Zone of the Greenland Ice Sheet using Airborne Radar and Satellite-Based Estimates of Melt Magnitude
17-CRYO17-0045

The percolation zone of the Greenland Ice Sheet (GrIS) is characterized by heterogeneous snow and firn structure mitigated by short duration melt events in which meltwater percolates through the snowpack and mostly refreezes. The GrIS has experienced significant and wide spread warming over the last couple decades resulting in increasing occurrence and intensity of surface melting over the percolation zone even though this facies has remained spatially stable below 2000 m during the 20th century. Melt enhancements within this facies could facilitate near subsurface conditions suitable for the encroachment of more developed supraglacial hydrologic systems (i.e. lakes, streams). Given this, we seek to leverage NASA Operational IceBridge radar to update the spatial extent of the percolation zone from 2009 to present. Over this period we will evaluate spatial variability in conditions in the transitional zone between the ablation and percolation facies which includes examination of ice sheet-wide changes in the occurrence and distribution of supraglacial lakes and streams. We will also employ a novel satellite-based retrieval model based on a data fusion of passive microwave and coupled optical/thermal measurements to assess the spatio-temporal variability in melt magnitude or surface liquid water fraction. Lastly, we seek to assess how changes in the percolation facies correlate with previously detected firn aquifers and diagnose how contemporary seasonal variability in surface mass balance conditions allow for the development and proliferation of aquifer systems.

Ignatius Rigor/University of Washington, Seattle
Coordination and Data Management of the International Arctic Buoy Program (IABP), and Reinvigorating the International Program for Antarctic Buoys (IPAB)
17-CRYO17-0009

Our ability to predict weather and sea ice conditions requires in situ observations of surface meteorology and sea ice motion (SIM). These observations are assimilated into Numerical Weather Prediction (NWP) models that are used to forecast weather on synoptic time scales, and into the many long-term atmospheric reanalyses such as NASA’s Modern-Era Retrospective Analysis for Research and Applications (MERRA, Koster et al., 2016) and the NCEP/NCAR Reanalysis (Kalnay et al., 1996) that are used for innumerable climate studies. The impact of these in situ observations can be seen in Fig. 1 where Inoue et al. (2009) shows that the standard deviation in gridded sea level pressure (SLP) reanalyses fields over the Arctic Ocean was over 2.6 hPa in areas where there were no buoy observations to constrain the reanalyses, and this uncertainty in the
SLP fields spreads to cover the entire Arctic when the observations from buoys are removed from the reanalyses. The buoy observations also help constrain of estimates of wind and heat. In situ observations of sea ice motion are also important for estimating the drift of various areas and types of sea ice, and for understanding the dynamics of ridging and rafting of this ice, which changes the age and thickness distribution of sea ice. For example, the analyzed fields of sea ice motion (SIM) that Kwok and Cunningham (2016), Kwok (2015), and Tschudi et al. (2016) produce are based on retrievals of ice motion from sequential satellite images and buoy drift. Over the Arctic Ocean, this fundamental observing network is maintained by the IABP, and is a critical component of the Arctic Observing Network (AON), Polar Prediction Program, Year of Polar Prediction [in 2018 2019], Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC, in 2019).

The United States contribution to the IABP is coordinated through the United States Intergency Arctic Buoy Program (USIABP), which is managed by the National Ice Center (NIC) and the PSC/APL/UW. The USIABP is a collaborative program that draws operating funds and services from a number of U.S. government organizations and research programs, which include the DOE, NASA, NOAA, NSF, ONR, and the U.S. Coast Guard. From these contributions, the USIABP acquires and deploys buoys on the Arctic Ocean, and supports the Coordination, Data Management and Enhancement for the IABP by the PSC/APL/UW.

The observations from the IABP have been essential for: 1.) Monitoring Arctic and global climate change (many of the changes in Arctic climate were first observed or explained using data from the IABP); 2.) Forecasting weather and sea ice conditions; 3.) Forcing, assimilation and validation of global weather and climate models; 4.) Validation of satellite derived estimates of SIM, surface temperature, sea ice thickness, etc.

This proposal is for the renewal of NASA funding of the IABP through the USIABP, and ancillary funding for the US Interagency Program for Antarctic Buoys. Through this proposal we plan to: 1) maintain the fundamental IABP/USIABP AON; 2) continue our assessments of thermistors and other sensors used by the IABP; and 3) produce more accurate gridded fields of surface meteorology (primarily surface temperature) that the community uses for research.

In 2016, over 30 papers were writing using data provided by the USIABP/IABP. During the past 3 years, over 58 papers have been written, which acknowledge funding from NASA, and since 1979 over 800 papers have been written using the observations and data sets produced by PSC/APL for the IABP (see references for selected publications, and http://iabp.apl.washington.edu/publications.html). These observations provide the longest continuing record for the Arctic, and have been one of the cornerstones for environmental forecasting and studies of climate and climate change.

Helene Seroussi/Jet Propulsion Laboratory
Exploring the Dynamic Response of West Antarctica to Ocean Variability
17-CRYO17-0025
Observations of glaciers in the Amundsen and Bellingshausen Sea sectors over the past three decades have revealed rapid and sustained changes, and highlighted the potential instability of these areas over the coming century. Enhanced melting at the ice-ocean interface has been identified as a main factor in the instability of the West Antarctic ice shelves and the consequent increase in the discharge of their tributary glaciers into the ocean. Much remains to be explored in how the thickness and flow changes of outlet glaciers and ice shelves are affected by the temporal and spatial variations of melting at the ice-ocean interface, ocean circulation patterns, sub-ice-shelf geometry and tributary glacier bed topography.

We propose here to investigate the evolution of marine terminating glaciers in the Amundsen and Bellingshausen seas by combining remote sensing observations with coupled ice-ocean models. We therefore intend to use depth-sounding radar, laser and radar altimetry as well as gravimeter measurements to find the rates of ice thickness and basal melting changes, ice-ocean interface morphology, bed topography beneath grounded ice and sub-ice-shelf bathymetry. These data will be complemented with InSAR-derived measurements of ice flow velocity and grounding line locations, and other measurements of thickness and surface elevations to extend the time series. Concurrently, we will investigate the dynamics and evolution of outlet glaciers over the last 30 years and the next 100 years in response to varying ocean conditions using a coupled ice-ocean model. We will employ the finite element Ice Sheet System Model (ISSM) asynchronously coupled to the Massachusetts Institute of Technology general circulation model (MITgcm) to perform simulations with varying atmospheric forcing and oceanic boundary conditions in order to represent their interannual variability. We will compare model results with remote sensing observations to validate the models and determine if key processes are missing or mis-represented in the model. We will finally assess the possible evolution of these glaciers over the coming century.

The main anticipated outcomes are a better identification of factors that have most effect in modifying ice-shelf and tributary glacier flow and configuration, enhanced understanding of the combination of factors that can result in ice flow instability, and improved scenarios of glaciers evolution in the Amundsen and Bellingshausen Sea Sectors over the coming century.

Laurence Smith/Brown University
Representing Surface Meltwater Runoff in Greenland Ice Sheet Models
17-CRYO17-0038

The production and transport of meltwater (runoff) is an important hydrological process operating on parts of the Greenland Ice Sheet surface today and is projected to become more prevalent in the future. Runoff generated on the ice sheet surface typically passes through moulins to the bed thus influencing basal conditions, and/or emanates from the ice edge to the ocean thus contributing to global sea level rise. The physical process of surface water runoff on ice sheets therefore warrants study, both for basic scientific
understanding and to enable better representation and parameterization of ice sheet surface runoff in ice-dynamics and surface mass balance (SMB) models.

The proposed research would use remote sensing, in situ measurements, established hydrological theory, and models to address three current knowledge gaps about GrIS surface runoff. The principal scientific goals are to learn what areas of the Greenland ice sheet receive inputs of surface runoff to the bed; to improve representation of surface runoff in ice sheet models; and to assess whether supraglacial drainage patterns that form on the ice sheet surface influence ice dynamics. We propose to achieve these goals through testing of three scientific hypotheses and a four-part work plan. In brief, the work plan would:

1) Use 2016 Sentinel-2 visible/NIR satellite imagery to create a first pan-Greenland map of surface runoff drainage pattern;
2) Obtain in situ measurements of proglacial river discharge at sites optimal for validation of climate/SMB runoff models, including a new hydro-meteorological gauging station in Inglefield Land, a uniquely advantaged, little-studied area of NW Greenland;
3) Assess and refine climate/SMB model runoff products and calibrate a classic surface water routing parameterization for use with ice sheet models; and
4) Conduct sensitivity tests to determine the influence of routing supraglacial runoff to mapped moulins in the simulations of subglacial and ice flow models.

By the conclusion of the project, we anticipate delivering i) a first pan-Greenland map of supraglacial drainage pattern, surface catchments, and terminal moulins, revealing where and how much observable surface runoff penetrates the ice sheet; ii) validation of climate/SMB model runoff products using in situ proglacial discharge records; iii) improved representation of GrIS surface runoff in the MERRA-2 and ISSM models; iv) a sensitivity study of the influence (or lack thereof) of surface fluvial drainage patterns on ice dynamics.

The proposal is responsive to this NASA Cryospheric Science solicitation’s call for synergy among observations, modeling and field campaigns, and to three (of seven) of the solicitation’s stated long term goals, namely:

Determine the mechanisms controlling mass balance and dynamics of the Greenland and Antarctic ice sheets including studies aimed at improving fundamental understanding of the connections to the ocean, sea-ice cover and atmosphere characterize land ice properties such as thickness, surface mass balance, englacial and surface water, layering, bed and grounding line properties, and albedo and physical processes such as flow, crevassing, ice shelf behavior, melt water fate, and calving such that they can be incorporated into models Use remote sensing data to validate and improve models of land-based ice and their contributions to sea-level change

The investigative team consists of university academics and civil servants with previous experience in Greenland remote sensing, field work, and/or modeling. Four summer field assistantships would introduce graduate students to Greenland. New collaborations would be established with the Geological Survey of Denmark (GEUS) and the Greenland
water survey (Asiaq), including supplying automated weather station data to the Danish Programme for Monitoring of the Greenland Ice Sheet (PROMICE) to fill a gap in NW Greenland AWS coverage.

Courtenay Strong/University of Utah, Salt Lake City
Impacts of Cloud-Lead Coupling on the Surface Energy Budget of the Arctic Sea Ice-Atmosphere System
17-CRYO17-0039

The ocean and atmosphere exert stresses on sea ice that create elongated cracks or openings (leads) where the ocean is exposed directly to the atmosphere. Leads cover a small fraction of the surface but dominate the vertical exchange of energy, particularly in winter when turbulent heat fluxes over leads can be orders of magnitude larger than over thick ice. The width of leads and their orientation relative to atmospheric flow markedly influence associated vertical fluxes relevant to cloud formation with recent studies suggesting that these fluxes can influence the atmospheric properties tens to hundreds of kilometers downstream.

Arctic sea ice is changing rapidly, and observational and modeling results suggest an increasing influence of lead-induced feedbacks on the climate system. For instance, positive feedbacks can result if leads act to increase cloud cover which then warms the surface, leading to more or persistent open water.

If convective plumes cause entrainment of drier free tropospheric air that decreases cloud cover, surface cooling and a negative feedback would result. Because leads are a crucially important driver of the Arctic surface energy budget, their increasing prominence makes the need for quantifying and understanding their impact on the Arctic climate system especially pressing at this time.

The proposed project targets the NASA Cryospheric Science Program’s focus on understanding sea ice processes and observed changes to the Arctic surface energy budget including sea ice-atmosphere feedbacks. Our overarching objective is to understand through joint observational and modeling activities, the relationships between lead area fractions and cloud properties and the Arctic surface energy budget. This objective entails the following specific activities:

Use remote sensing data including sea ice lead properties we derive from AMSR-E, AMSR2, SAR (ERS, ENVISat, RADARSAT), optical (AVHRR and MODIS), IceBridge DMS, areal photos, and submarine data to quantify the statistical properties of sea ice leads on multiple time and space scales.

Quantify how leads modulate the surface energy budget of the Arctic system through forced changes to the extensive cloud systems that overlie the sea ice using data from CloudSat, CALIPSO and the A-Train supplemented by data collected at the Atmospheric Radiation Measurement (ARM) sites in the Arctic.
Extend our prior modeling research using a three-dimensional, nonhydrostatic, cloud-resolving (large-eddy simulation) model to understand how plumes and clouds respond to surface lead orientation and size distributions under a range of synoptic atmospheric regimes, and quantify the associated impacts on the Arctic surface energy budget.

These activities will be strongly coupled by using advanced statistical methods to relate the lead width and orientation distributions to the cloud properties controlling for confounding factors and then using the observed relationships to inform the modeling work. Observed lead statistics and a range of atmospheric regimes will be used as boundary conditions, to simulate the response pattern and associations identified via remote sensing. This quantitative knowledge is essential for evaluating and refining formulations proposed for parameterizing fluxes over subgrid-scale leads in climate models, thus supporting the overall NASA Cryospheric Sciences Program goal of using remote sensing products to validate and improve models of changes in sea ice cover to elucidate connections to the global system.

Luke Trusel/Rowan University
A Coupled Antarctic Cryosphere System: Linking Ice Sheet Surface Mass Balance Processes and Ocean Surface Variability Across Coastal Antarctica
17-CRYO17-0037

The Antarctic ice sheet (AIS) is an integral component of the Earth system at risk of undergoing rapid change. Societally-relevant estimates of future sea level rise mandate understanding how the AIS responds to natural and anthropogenic forcing, particularly across Antarctica’s climate-sensitive ice shelves. To date, research investigating changes to ice shelves has largely focused on the role of the ocean in driving submarine ice shelf melting. Relatively little attention has been directed towards understanding the impact of ocean surface variability on the surface mass balance (SMB) of the AIS and ice shelves. This lack of research is despite the central role SMB plays in total AIS mass balance, and emerging (but still poorly constrained) lines of evidence pointing to the potential importance of the ocean surface in impacting ice sheet SMB. Given growing concern over the future of the AIS centering on the buttressing role of ice shelves, a better understanding of the current state of ice shelf/sheet SMB, as well as the mechanisms in the ice-ocean-atmosphere system impacting ice shelf/sheet SMB are paramount.

Motivated by these knowledge gaps that introduce uncertainty in estimates of 21st century sea level rise, we propose a 3-year research project that will combine state-of-the-art measurements derived from Earth-observing satellites with new, high-resolution regional climate model experiments to: (1) constrain AIS SMB processes, including the most detailed observations of Antarctic surface melting to date; (2) quantify the importance of Antarctic sea ice and ocean surface variability on AIS SMB; and (3) develop and improve simulations of the coupled Antarctic ice-ocean-atmosphere system.
Specifically, we will develop a new multi-decadal (1978–present), near-daily, high spatial resolution (3.125–6.25 km), surface melt dataset derived using a novel albedo-incorporating melt detection scheme. This approach will be applied to a newly-released MEaSUREs enhanced-resolution passive microwave satellite dataset. We will also focus on understanding how variability in the ocean surface surrounding Antarctica (namely sea ice and sea surface temperature) impacts the availability of heat, energy, and moisture, and in turn, how this impacts the SMB of coastal ice shelves. To accomplish this task, we will utilize a suite of complementary atmospheric remote sensing products, augmented by a dynamic downscaling of NASA’s MERRA-2 reanalysis and key in situ validation sites. To more fully quantify the physical mechanisms underlying covariability in the sea ice-ocean-ice sheet system, we propose a suite of new, high-resolution regional climate model experiments, which will be performed at no computational cost to this project. Our first experiment is forced by the MERRA-2 reanalysis and will provide important context for our satellite observations. Next, three, thirty-year simulations where only sea ice is altered (in low, near-observed, and high sea ice states) will isolate the SMB response to ocean surface variability. This synthesis of state-of-the-art observations and regional climate modeling will identify critical Antarctic ice-ocean-atmosphere connections and constrain projections of future Antarctic change.

This proposal supports three early career scientists, a research associate, two PhD students who will play central roles in ice sheet remote sensing and climate modeling, and undergraduate students who will gain hands-on experience analyzing polar climate data. The proposed project directly aligns with many of the goals of NASA’s Earth Science Division and Cryospheric Science program by developing a better understanding of AIS mass balance, ice-ocean-atmosphere interactions, and facilitating more informed projections of future AIS change.

Leung Tsang/University Of Michigan, Ann Arbor
Improved Estimates of Cryospheric Subsurface Properties Using New Combinations of Radiometer and Radar Data
17-CRYO17-0008

Today, the spaceborne L band radiometers SMOS and SMAP provide partial ice sheet internal temperature information through their single frequency measurements. Under the recent NASA Instrument Incubator Program (2014-2017), the Ultra-Wideband Software-Defined Microwave Radiometer (UWBRAD) has been developed to allow ice sheet internal temperatures measurements at depths of hundreds of meters or more. In contrast to SMOS and SMAP, UWBRAD is a wideband radiometer operating from 0.5 to 2GHz using 12 frequency channels. The use of multiple frequencies in UWBRAD is intended to resolve ambiguities in temperature retrievals associated with single frequency measurements. The wideband data will enhance the research community’s ability to determine the ease at which ice deforms internally, the rate at which an ice sheet flows across its base, the monitoring of aquifers, to compile mean annual temperatures and to monitor climate change. The UWBRAD instrument was installed on a tower at Dome C Antarctica in 2015, and was deployed during a 2016 airborne campaign over Greenland, with a second flight planned in 2017. The results from the 2016 flight reveal strong
spatial and spectral variations that correlate with the subsurface physical properties of the Greenland ice sheet. Based on these findings, this proposal will advance current understanding of wideband measurements by (i) investigating novel combinations of UWBRAD data with complementary active and passive data for developing a subsurface temperature product of ice sheets, and (ii) studying the use of UWBRAD data with other active and passive data for the determination of sea ice thickness.

The proposed project team has previously performed physical modelling studies of UWBRAD measurements. These studies have shown significant influence from density fluctuations near the surface of the ice sheet on ice sheet emission, as well as the influence of ice-lens structures in the upper firn on the measured brightness spectrum. Based on these developments and findings, we propose to: 1. Develop physical models of layering and volume scattering for combined active and passive microwave observations of the Greenland ice sheets from 0.5 GHz to C band. The active data include PALSAR, Sentinel, and archived Aquarius. We will also use available airborne radar data from Operation IceBridge (collected by the University of Kansas) which operates over a frequency range similar to UWBRAD. The passive data include UWBRAD, SMOS, SMAP, and archived Aquarius. 2. Develop the physical models to incorporate surface and internal interface roughness effects. 3. Apply the models developed to analyze UWBRAD airborne data collected over Greenland as well as spaceborne active and passive observations of the Greenland ice sheet. 4. Apply the models developed to analyze UWBRAD and DOMEX tower-based brightness temperatures at Dome C Antarctica as well as spaceborne active and passive observations of Antarctica. 5. Apply the developed models to the retrieval of subsurface properties including ice sheet temperatures, and perform science analyses to explore the significance of the resulting temperature information. 6. Apply the developed models to the prediction of active and passive multi-frequency signatures of sea ice, and investigate the retrieval of sea ice thickness information.

Achieving these science goals will improve our ability to retrieve useful geophysical information about polar ice sheets from present SMOS and SMAP brightness temperatures, the existing and forthcoming UWBRAD brightness spectrum measurements, and from active radar signatures. It will further exploit the wide band radiometry of UWBRAD and other active and passive sensor measurements to retrieve sea ice thickness. It will enhance the technology readiness of wideband passive measurements for spaceborne missions. It will further promote understanding and characterization of the effects of global climate change through the science products produced.

Isabella Velicogna/University of California, Irvine
Evaluation of Ice Sheet Surface Mass Balance Models in the Ablation Zone Using ICESat, Operation IceBridge and Other Data
17-CRYO17-0063

At present, the Greenland Ice Sheet is undergoing rapid changes, losing mass to the ocean at an increasing rate. Various techniques have been used to document these changes, including radar/laser altimetry, time-variable gravity, and mass budget combining ice
discharge with surface mass balance (SMB) reconstructions from regional atmospheric climate models (RCM).

This proposal addresses the largest remaining uncertainty in ice sheet mass balance which is the runoff production from surface melt. While snowfall accumulation from RCM and MERRA2/GEOS-5 Global Climate Model (GCM) has been evaluated in detail from a network of automated weather stations (AWS), snow pit and ice core data, runoff is known with a default uncertainty of 20% due to a lack of in-situ data for evaluation. As runoff will remain a dominant component of the mass loss for decades to centuries to come, it is imperative to better quantify its uncertainty and document the RCM/GCM ability to model it.

We will quantify the uncertainty in runoff by comparing the RCM/GCM SMB output products with time series of laser altimeter data from NASA Pre-Operation IceBridge (OIB) Airborne Topographic Mapper (ATM) for 1993-2009, ICESat-1 for 2003-2009, OIB/ATM and Laser Vegetation and Ice Sensor (LVIS) for 2010-2019, and ICESat-2 after 2018. We will construct time series of changes in surface elevation across Greenland’s ablation zone mostly the bare ice zone but also extending into the slush zone - and convert them into mass changes. We will compare the altimetry-derived mass changes with the mass loss from RCM/GCM to evaluate how well runoff and trends in runoff are captured over the years. Using altimetry data along identical tracks collected in early spring and late summer from 2015 to 2017, we will quantify the precision of summer runoff at the seasonal level. The analysis will be conducted in regions of low ice dynamics (<30m/yr) and small changes in speed. Corrections for ice dynamics will be implemented using time series of ice velocity measurements from MEaSUREs and other projects. We will flag out areas where altimetry cannot provide estimates of the precision of SMB models. We will include uncertainties in the density conversion of elevation to mass above the bare ice zone (density 0.9) into the slush zone when perennial snow participates in the production of melt water using information from RCMs.

To conduct this analysis, we will employ a novel method that merges results from all available altimeter missions in space and time since there is no merged ATM, LVIS and ICESat-1 products. By constructing a merged product, we will vastly improve the capability of altimeter data to evaluate SMB models in the ablation zone. We will place error bounds on runoff and temporal trend in runoff. In collaboration with RCM/GCM developers, we will evaluate newer versions of the models, with improved physics (e.g. improved description of albedo and turbulent heat fluxes, meltwater retention processes, etc.), to quantify their improvement in modeling runoff in Greenland. Our results will provide a framework and data structure for using altimetry to evaluate climate models in a systematic fashion, for years to come and going back two decades.

The results will document uncertainties in runoff and SMB, identify how the errors vary in space and time across different snow/ice regimes in Greenland. This will in turn improve the reliability of climate models at projecting future changes in ice melt, which is a dominant component of the mass loss from Greenland for decades to centuries to come.
This research will support the science goals of NASA ICESat-1/2 and OIB missions to observe the evolution of the Greenland ice sheet mass balance and understand the physical processes controlling it. The project will directly serve NASA overarching goal in Earth Science to study the evolution of ice sheets and their contribution to sea level.