This synopsis describes the proposals selected in response to the NASA Research Announcement \textit{CRYOSPHERIC SCIENCE} that is subelement A.14 of NASA ROSES 2015.

NASA’s Cryospheric Sciences Program supports basic research on the Earth’s sea- and land-based ice to understand its connections to the global system. Recent satellite observations show dramatic changes in the Earth’s polar ice sheets, especially in the thickness and extent of Arctic and Antarctic sea ice, and thinning of the outlet glaciers draining the ice sheets covering Greenland and Antarctica. Given the tremendous areas that must be studied to characterize this change, space-based and other remote sensing techniques are required. NASA has extensive datasets available for this work archived at the National Snow and Ice Data Center (NSIDC; \url{http://nsidc.org/data/icebridge/}), including observations from NASA’s IceBridge Mission \url{http://www.nasa.gov/mission_pages/icebridge/index.html}, an airborne remote sensing mission collecting altimetry, radar, gravity and other data in both polar regions and Alaska.

This solicitation called for proposals to understand the mechanisms of change in polar regions and their implications for global climate, sea level, and the polar environment. Selected studies use space-based, aircraft based, and other remote sensing techniques to understand the factors controlling the retreat and growth of the world’s major sea- and land-based ice sheets and their interactions with the ocean, atmosphere, solid Earth, and solar radiation. Specific goals of the program include:

- Determining the mechanisms controlling sea ice cover, including quantification of the connections between sea ice and the ocean and atmosphere;
- Using remote sensing to validate and improve predictive models of changes in sea ice cover, especially on decadal timescales and to elucidate connections to the global system;
- Determining the mechanisms controlling mass balance and dynamics of the ice sheets of Greenland and Antarctica; including studies aimed at improving fundamental understanding of ice flow, ice shelves, grounding lines, bed, melt water formation and role, and connections to the ocean, sea ice cover, and atmosphere; and
- Using remote sensing data to validate and improve predictive models of the contribution of land-based ice to sea level change, especially in the coming century.

Out of 84 submitted proposals, 19 were selected for awards. The total funding for the program is approximately $4 million per year for three years. The Principal Investigator, institution, and investigation title are listed below.

\textbf{Knut Christianson/University of Washington}

\textbf{Assessing the Dynamic Triggers for Thwaites Glacier Variability}

Thwaites Glacier (TG), West Antarctica, is grounded on a relatively deep, wide and complex sill, buttressed by a weak ice shelf. Inland of this sill the bed topography slopes inward to depths greater than two kilometers below sea level, indicating the possibility of significant, rapid ice-stream retreat via the marine ice-sheet instability. However, models that honor current knowledge can simulate either long-term stability or near-future retreat. Sufficiently large retreat is modeled to be irreversible on human economic
timescales, ultimately producing >3 m of global-mean sea-level rise. Paleoclimatic data provide strong but still equivocal evidence of repeated collapse in the geologically recent past. High rates of retreat suggested by some models would make West Antarctica significant or dominant in global sea-level budgets. But, even these scenarios may substantially underestimate the rate of sea-level rise during retreat, because ice-stream flow and iceberg calving tend to be faster for wider and deeper outlets of marine ice sheets, and TG retreat would involve wider and deeper outlets than any now active, potentially introducing additional unanticipated ice-retreat mechanisms. The available models show that improved understanding of dynamic triggers of ice-stream change may significantly reduce uncertainty in our knowledge of the possible timing, amplitude, and character of any future retreat. An integrated remote-sensing, data-analysis, and modeling program is proposed to provide this improved understanding by identifying and assessing possible dynamic triggers of TG retreat.

This project specifically aims to investigate processes that may substantially affect the magnitude and rates of ice retreat and mass loss from TG, or other glaciated basins, but that are not included in current whole-ice-sheet models. Beyond certain thresholds, these dynamic triggers may lead to periods of prolonged ice-stream stability or rapid ice-stream retreat, both crucial to predicting future rates of sea-level rise. Specifically, TG’s reaction to the following five processes will be studied using a suite of specialized data-analysis and modeling approaches: (1) a dynamic ocean where the temperature of water entering the ice-shelf cavity may vary by 1°C or more on annual timescales; (2) spatiotemporal variability of bed rheology (basal flow-law exponent); (3) amplitude variability of bedrock topography in deep basal troughs; (4) tidal forcing; and (5) subglacial outburst floods. Multiple datasets and software toolkits obtained or developed as part of NASA missions will be used to assess the impact of these dynamic processes on ice-sheet dynamics. These data will be supplemented with ground-based GPS, ice-penetrating radar, and active-source seismic data that were collected in a series of past expeditions to TG.

Results and products of this project will provide improved process understanding of TG dynamics, which will contribute to more-accurate projections of sea-level contribution from TG and the WAIS, and thus also future global sea-level rise. Results will be disseminated through publications in scientific journals and presentations at conferences. Data and modeling products of this project will be made publicly accessible through the Antarctic Glaciological Data Center at the National Snow and Ice Data Center.

This project is a collaboration between early- and mid-career researchers and will foster the next generation of scientists through mentoring of undergraduate and graduate students at the University of Washington, the Pennsylvania State University and Temple University. Research results will also be disseminated through coursework and expositions at local museums.

Alex Gardner/Jet Propulsion Laboratory
Contributions of Glaciers to Sea Level Rise Over the Past Half-Century
The largest source of eustatic sea level rise during the past century is mass loss from land ice (ice sheets and glaciers) through meltwater runoff and solid ice discharge to the oceans. Both glacier and ice sheets play an important role in sea level change; Ice sheets contain nearly all of the Earth's land ice (>99% by volume) and will likely dictate changes in sea level rise over the next millennia, while glaciers only contain enough ice to raise global sea levels by 0.4-0.6 m if melted entirely. Even so, glaciers play a major role in present rates of sea level rise and will continue to do so into the next century and beyond. To date, all previous estimates of long-term (30-50 years) glacier mass wastage and all projections into the future have been estimated from and/or calibrated to the existing database of local-scale geodetic and glaciological records of mass change. These records have recently been found to contain a large negative mass budget bias due to non-representative spatial sampling during the period 2003 to 2009 as identified through comparison with elevation changes derived from satellite laser altimetry (ICESat); i.e. the dataset is biased towards observations of glaciers that are thinning more rapidly than the glaciated regions as a whole (Gardner et al., 2013). The identified bias has implications for past estimates of glacier mass change, but at present there is insufficient data to determine if the glaciological records contain a bias prior to 2003. This unknown has major implications for the partitioning of sea level rise over the past half-century and into the future.

For this study we propose to provide a more robust estimate of long-term (20-40 yr) glacier mass changes for 6 large glacierized regions that lack published regional-scale geodetic estimates (i.e. not from the interpolation of local scale field observations). These 6 regions comprise 70% of the world's glacier ice by area and, when combined with previously published regional estimates, will provide a nearly complete global (98% coverage) estimate of multi-decadal glacier contribution to sea level rise. We propose to follow a similar methodology to Gardner et al. (2012) who estimated multi-decadal mass changes for southern Canadian Arctic glaciers through the differencing of modern elevations derived from satellite and airborne altimetry and stereoscopic imagery with elevations derived from historic photogrammetric imagery. One major undertaking of this proposal will be the reconstruction of historic glacier topography from declassified Hexagon KH-9 Mapping Camera Sub-system (MCS) imagery that will then be co-registered with, and differenced against, modern elevations derived from satellite laser (ICESat) and radar (SRTM) altimetry and SPOT5 HRS along-track stereo imagery. Because of the scale of our analysis we are proposing to develop a semi-automated workflow that we will share with the research community upon completion of the project. Our analysis will provide a substantially improved estimate of glacier contributions to sea level rise over the past 20-40 years and will lead to an improved understanding of sea level contributory processes and projections of decadal and century scale sea level rise. Reducing the uncertainty in multi-decadal glacier mass changes will also allow us to determine if glacier mass loss has accelerated in recent decades in response to changes in global climatology.

Ute Herzfeld/University of Colorado
Improving the Constraints of Greenland and Antarctic Ice Sheet Mass Change Estimation, Surface Mass Balance and Glacial Accelerations

Improving the Constraints of Greenland and Antarctic Ice Sheet Mass Change Estimation, Surface Mass Balance and Glacial Accelerations
The idea of the proposed project is to constrain uncertainties in the estimation of sea-level rise through mass loss from the Greenland and Antarctic Ice Sheets. There are two main groups of processes that contribute to this mass loss, through melting and through accelerating outlet glaciers. Investigations of mass changes of the Greenland and Antarctic ice sheets, surface mass balance and glacial acceleration are constrained by observations. The proposed research aims at improving the observational constraints through mathematical innovation in the processing of satellite data, especially altimeter and image data, and definition and calculation of parameters that aid in indicating and estimating the mass changes.

The project will contribute to research addressing both main components of mass loss:

Topic 1: Roughness and Melting. Assessment of changes in energy available for surface melting of the Greenland Ice Sheet in the last 20 years (1997-2017), based on Greenland-wide roughness and roughness change maps from ICESat GLAS and Operation IceBridge (OIB) laser altimeter data, using surface roughness field measurements for validation and PARCA micro-meteorological data for climatology.

Topic 2: Glacial Acceleration. Classification of the types of accelerating glaciers, based on altimeter and image data, and understanding of accelerations and elevation changes in outlet glaciers in Greenland, to reduce the uncertainty in assessment of sea-level rise that derives from lack of inclusion of glacial acceleration in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

These ideas will be extended to the Antarctic Ice Sheet, by calculation of roughness maps and classification of acceleration types for critical outlet glaciers and ice streams.

Approach and Methods: Through a new algorithm that will allow height determination from next-generation micro-pulse photon-counting laser altimeter over crevassed ice surfaces and other rough terrain, this work is expected to provide information on the expected spatial detail, accuracy and precision of ICEat-2 ATLAS data (based on observations from airborne predecessor instruments MABEL and SIMPL). Laser altimeter data from ICESat and NASA's Operation IceBridge will be analyzed jointly with imagery, by application of a connectionist-geostatistical approach to automated classification of ice surface types. A small field experiment in the ablation area of Ilulissat Ice Stream, Greenland, will serve to provide validation of roughness parameterizations derived from airborne and satellite altimeter data.

The proposed work is aimed at understanding fundamental processes of change in the cryosphere based on analysis of NASA remote-sensing data and thus is directly relevant to ROSES call A14 on Cryospheric Sciences and to NASA's Earth Science Research Program in general. Project goals are also shared with the IPCC, the World Climate Research Programme, especially Climate and Cryosphere (CliC), and the Research Plan from the Interagency Arctic Policy Committee (IARPC) and are complementary to US CLIVAR in the topic "Understanding the Dynamic Response of Greenland's Marine Terminating Glaciers to Oceanic and Atmospheric Forcing".
Ronald Kwok/Jet Propulsion Laboratory
Thick Arctic Sea Ice: Sources, Sinks, and Fate

If the sea ice cover did not deform, all of the ice in a particular climatic region would approach a uniform thickness of thermodynamic equilibrium. Beyond thermodynamic ice growth, it is ice dynamics that sustain the characteristic tails of the thickness distributions of Arctic sea ice. Deformed ice (rafts and pressure ridges) is formed by the non-uniform ice motion between ice floes and, in particular, convergence at coastal boundaries of the Arctic Basin. And, thick and deformed ice are more likely to survive the summer to form the "perennial" ice cover of the Arctic Ocean and slow the decline of sea ice coverage. Recent observations suggest a significant reduction in the coverage of thick, deformed and old ice in the Arctic. What factors are conducive to the production and survival of deformed ice, and what led to the current coverage of deformed ice? To answer these questions, we propose to examine the sources and sinks of deformed ice of the Arctic Sea ice cover using available data from satellite and airborne observations of sea ice motion, thickness, age, and surface roughness. We are motivated by the unexpected increase in Arctic ice volume at the end of the summer of 2013: the larger tails in the thickness distribution after the summer - unlikely due to growth or melt - points to the extreme convergence of sea ice on the Canadian Arctic Archipelago due to anomalous circulation patterns and the resultant wind-driven ice drift. In the proposed work, we will undertake a retrospective survey of the ice circulation patterns of the Arctic Ocean using the record of satellite ice motion from passive microwave and synthetic aperture radar (SAR) imagery and available thickness data. The focus will be on large-scale convergence at coastal boundaries of the Arctic Basin. We will identify conditions that are favorable to deformed ice production, and examine the impact of the resultant ice cover on summer ice extent. Deformed ice production will be examined with near-simultaneous coverage of satellite ice motion and ice thickness. The results of this investigation will inform our understanding of the impact of deformed ice production on the survival of the ice cover and its importance in predicting summer ice behavior.

Eric Larour/Jet Propulsion Laboratory
A Peek at the Past of the Greenland ice Sheet Using Radar Layers and Modeling.

We propose to reconstruct the state of the Greenland Ice Sheet (GIS) during the Holocene epoch, using available observations of both deep and shallow radiostratigraphy from two radar sounders deployed by Operation IceBridge (OIB), together with remote-sensing data including InSAR, surface altimetry (ICESat, LVIS, ATM). Our goal is to invert for key GIS boundary conditions, in particular surface mass balance (SMB), basal friction and any other sensitive state variables during the Holocene period, so that we may quantify exactly how the mass and stress balance of the GIS was impacted by its Holocene evolution.

Our approach relies on the Ice Sheet System Model (ISSM) and its automatic differentiation capabilities to compute the adjoint state of an age model. This age model will be evaluated directly against observed ages from both deep and accumulation radar stratigraphy. A cost function will be computed to assess the differences between modeled and observed age, and gradients of this cost function with respect to model inputs will be simulated. This approach will enable optimized spatiotemporal inversions of the state of the GIS, along with a comprehensive assessment of the sensitivity of our hindcast reconstruction to key model inputs. The impact of firn densification upon the interpretation of shallow radiostratigraphy will also be investigated.
This proposed work represents a breakthrough in terms of assimilation of the numerous radar datasets available to the cryosphere community, which are historically underutilized to constrain models of the past evolution of the GIS. We expect our results/products will quantifiably assess the influence of boundary conditions upon the Holocene evolution of the GIS and further improve the reliability of ISSM projections of the contribution of the GIS to future sea-level rise.

Zheng Liu/University of Washington

The Role of Synoptic Conditions on Cloud and Sea Ice in the Seasonal Ice Zone in the Beaufort and Chukchi Seas

How atmosphere and sea ice interact depends on the prevailing weather. Synoptic activities transport energy and moisture into the Arctic and modify the structure of the atmosphere, clouds, and the energy budget over sea ice. The structure of the atmosphere, e.g. temperature and specific humidity inversions, is critical for the life cycle of Arctic clouds which in turn affect the radiation budget at the surface. Synoptic conditions drive this structure, and determine which processes will govern the interaction between the atmosphere and clouds. For example, warm air advection associated with the passage of a low pressure system will drive sea ice loss though the poleward advection of moisture, resulting in clouds and increases in downwelling longwave radiation, while cold air outbreaks will dynamically drive sea ice through strong low-level winds especially the low-level jets associated with the strong low-level baroclinicity near the ice edge.

The proposed research will advance our knowledge of the interactions among atmosphere, cloud, and sea ice in the seasonal ice zone under different synoptic conditions. The premise of the proposed research is that a better understanding of the "climate" scale sea ice variability can be achieved through a better understanding of interactions between sea ice and atmosphere at the "weather" scale.

Dominant synoptic types over the Beaufort and Chukchi seasonal ice zone (BCSIZ) will be identified from atmospheric reanalysis data sets using a k-mean clustering algorithm. The synoptic classification algorithm categorizes individual weather events in the reanalyses into synoptic types. The typical structure of atmosphere and the transport of heat and moisture will be determined for each type. Cloud conditions and cloud radiative forcings at the surface under different synoptic conditions will be determined using both satellite observations, from MODIS, CloudSat, and Calipso, and modeled clouds in reanalyses.

Using the synoptic classification scheme, the type specific processes that influence sea ice conditions will be investigated. To aid with this analysis, experiments with the Polar Weather Research and Forecast (Polar-WRF) model will be performed. Specifically, processes governing the interaction between atmosphere and sea ice, such as turbulent mixing and cloud microphysical and radiative processes, will be examined. Idealized Polar-WRF experiments will also be performed using lateral boundary forcing derived from the identified dominant synoptic types. These experiments will allow us control specific mechanisms and identify their role in cloud and radiative process. For example, in mixed-phase clouds, the partitioning of water between liquid and ice, cloud lifetime, and the resulting radiative forcing at surface are closely associated with the size distribution of ice particles, which can be investigated through sensitivity tests with key parameters of the ice particle size distribution. Case studies will also be conducted for flights from the Seasonal Ice Zone Reconnaissance Survey (SIZRS) and the Arctic Radiation IceBridge Sea& Ice Experiment (ARISE) aircraft campaigns. Applying modeling and observational analysis to study the interactions between the atmosphere and sea ice in weather situations categorized by synoptic type will reveal processes that would be masked by the analysis of averages over many
different weather situations. The resulting insights will help define pathways for the improvement of numerical models and reanalyses.

To examine how synoptic conditions in the BCSIZ vary in the context of the hemispheric circulation and climate variability, we will examine the patterns driving the frequency of synoptic types and how potential shifts of these circulation patterns affect the interannual variability of sea ice through the thermodynamical, cloud microphysical, and radiative processes. In particular, the role of heat and moisture transport will be investigated.

Brooke Medley/Goddard Space Flight Center
A Novel Approach to Measuring the Meltwater Storage Capacity of the Greenland Ice Sheet Using IceBridge and CryoSat-2 Data

The objective of this proposal is to measure spatiotemporal density variations of the Greenland Ice Sheet’s (GrIS) firn column using both airborne and satellite radar data to measure changes in its meltwater storage capacity. In the ice sheet interior, the presence of a porous firn layer means that surface melt can percolate downwards and remain within the column in either its liquid or frozen state, inhibiting melt from reaching the ocean. Because melt is increasing over most of the GrIS, the ablation and percolation zones are migrating inland, which reduces the size of the accumulation zone and, ultimately, the size of the firm meltwater buffer that acts to delay runoff to the ocean. Thus, our primary research question is: What is the meltwater storage capacity of the Greenland Ice Sheet’s firm column, which acts to intercept meltwater on its route to the ocean?

Understanding the magnitude and evolution of the firm meltwater storage capacity will help constrain measurements of the GrIS contribution to sea-level rise (SLR) now and into the future; however, measuring the capacity at the ice-sheet scale is not easily attained, especially considering the short timescales in play. A recent Nature paper by Harper et al. [2012] highlighted the importance of meltwater storage, through the refreezing of infiltrated meltwater within the firm, in modulating the GrIS contribution to SLR, but the measurements were constrained by the limitations of field work. Therefore, we take a novel approach to measuring the firm meltwater storage capacity over the GrIS using Operation IceBridge and CryoSat-2 data, which has the potential to reveal the size and evolution of this meltwater buffer at unparalleled spatiotemporal coverage and resolution.

Using three IceBridge radars and CryoSat-2 data, we will determine the absorption and scattering properties of the firm column by fitting a physically based model to the radar waveforms. Retrieval of firn density is then achieved through empirical and theoretical relationships between density and the retrieved extinction coefficient. The work proposed will improve upon an existing physical model of the radar return waveform for use over the interior of the ice sheet to:

1. Extract firn extinction coefficients and infer firn density using both IceBridge and CryoSat-2 data in order to determine the Greenland Ice Sheet’s meltwater storage capacity and its evolution between 2009 and 2016/17, and
2. Measure ice sheet surface elevation and its variations between 2011 and 2016/17 using CryoSat-2 data and understand the impact of variable surface penetration on elevation retrieval.

The work will additionally provide insight into the impact of changing absorption/scattering properties of firn on surface elevation retrieval using various retrackers. Such an evaluation is especially important considering recent large melt events (e.g., 2012) have already introduced bias into surface elevation retrievals over Greenland. Also, the proposed work is highly relevant
to two of the Cryospheric Science program's specific goals related to the surface mass balance of and the role of liquid water within the Greenland Ice Sheet.

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**Walter Meier/Goddard Space Flight Center**

**Improved Estimates of the Seasonal and Interannual Evolution of Arctic Sea Ice through Tracking of Sea Ice Parcels**

In this proposal, we will develop and apply a Lagrangian framework to track sea ice parcels and associated parameters to investigate three key questions relating to the Arctic summer melt season:

1) What is the relationship between surface melt, motion, thickness, atmospheric forcing and the evolution of the summer Arctic ice cover and how is the relationship changing over time?

2) How does the initial sea ice thickness, summer melt and atmospheric forcing influence the seasonal evolution of the ice cover and how can a Lagrangian approach be used to improve seasonal sea ice forecasting?

3) How can we increase confidence and spatial-temporal consistency of new remote sensing thickness estimates and better track the seasonal and interannual changes in thickness?

To answer these questions, we propose to enhance a current multisensor sea ice motion product and extend a Lagrangian tracking framework originally developed to track sea ice age. In addition to improved and updated sea ice age estimates, the extended Lagrangian framework will provide a time history of key sea ice melt season parameters for individual sea ice parcels by integrating: (1) remote sensing sea ice thickness estimates from CryoSat-2 and IceBridge instruments, as well as older historical sources; (2) surface melt properties melt onset and freeze-up dates from passive microwave imagery, and melt pond coverage from MODIS imagery; and (3) atmospheric reanalysis fields from the NASA MERRA-2 product. The result will be a 40-year integrated data product that tracks the evolution of sea ice parcels throughout the year, including the summer melt season from 1979 to 2018, providing a time history of age, thickness distribution, melt state, and atmospheric forcing. The data product will be distributed to fellow researchers through the NASA Polar Distributed Active Archive Center at the National Snow and Ice Data Center.

The integrated Lagrangian product suite will be able to better answer the three key questions above by integrating relevant parameters in space and time and track these parameters as they evolve seasonally and through the years. This approach removes uncertainties that occur from using standard Eulerian gridded products for the drifting sea ice. Heretofore, the foundational motion and age fields have been under-utilized. They have been an excellent tool for qualitative assessment of sea ice conditions and estimates of trends and variability in drift and ice age, and they have been used as a proxy for ice thickness and provided a long-term context for the more recent satellite altimetry estimates. The enhancements and extension of the products and the application to the
above research questions will greatly improve the utility of the data products for quantitative analysis of sea ice change. While the focus of this proposed project is to apply the product to the Arctic melt season, the Lagrangian suite of parameters will be created for both the Arctic and Antarctic throughout the year over the entire 35+ year time series. Thus it will be valuable for many other sea ice applications.

This proposal addresses NASA Earth Science goals better by understanding the roles and interactions of the oceans, atmosphere, and ice to improve the ability to predict climate changes. The proposal directly addresses objectives of the NASA Cryospheric Science Program by:

(1) Investigating mechanisms controlling sea ice and its interaction with the atmosphere and ocean,
(2) Using space-based and aircraft based NASA remote sensing platforms and products,
(3) Applying these remote sensing resources to validate and improve predictive models.

Paul Morin/University of Minnesota
PGC: Commercial Imagery Support for the Cryosphere

This project seeks to provide access to sub-meter optical imagery from the National Geospatial-Intelligence Agency's (NGA) Commercial Imagery Program to missions and investigators funded by NASA's Cryospheric Science Program. These data, licensed by NGA under its EnhancedView contract with DigitalGlobe (DG), will complement existing NASA satellite data and improve cryospheric science research. The Polar Geospatial Center (PGC) now holds nearly 600 million km² (1.1 PB or 2.8 million scenes) of sub-meter polar imagery collected since 1999. PGC is also working with NGA and DG to task four high-resolution optical satellites to collect imagery in the right place at the right time to fulfill U.S. government science requirements.

PGC proposes to deliver this collection to NASA Cryospheric Science Program investigators and to integrate their tasking requests into our broader U.S. government commercial imagery tasking plan. To do this we require resources to:

1. integrate NASA tasking requirements into NGA's long-term plan
2. work with principal investigators to answer commercial imagery questions about processing, management, and licensing restrictions
3. develop and maintain PGC's commercial imagery and Digital Elevation Model (DEM) Web ordering and delivery system
4. continue development of PGC Tools, an open source series of tools to manage and process commercial imagery.

Sophie Nowicki/Goddard Space Flight Center
Leading the Next Generation of Ice Sheet Modeling for Sea Level
Satellites have recorded significant changes in the Greenland and Antarctic ice sheet masses. Understanding how ice sheet mass may change in the future has a direct bearing on estimates of regional and global sea level and hence human activities. The proposed study aims to make major quantitative and qualitative improvements in the description and prediction of ice sheet contributions to sea level change by leveraging and enhancing NASA observations, modeling, and data assimilation capabilities. The project also places NASA as a leader and coordinator of results from the international ice sheet modeling community.

Although the Greenland and Antarctic ice sheets have the potential to contribute 7m and 57m to sea level, respectively, projecting sea level and its uncertainty for climate assessments, such as the Intergovernmental Panel on Climate Change (IPCC), is non-trivial. A major impediment is the disconnect between the glaciology and climate communities; future climatic scenarios used by the glaciology community typically lag the Climate Model Intercomparison Project (CMIP) that feed into the IPCC report by one IPCC cycle (on the order of five years). In addition, obtaining forcings from climate models that are suitable for use in ice sheet models is challenging due to the different spatial and temporal scales of the models. Furthermore, the uncertainty in climatic forcing contributes to the uncertainty in the projected ice sheet and related sea level changes. The other major sources of uncertainty are the ice sheet models, and factors such as the choice of ice sheet model initialization method, or poorly known boundary conditions (e.g. basal conditions) that impact ice sheet evolution. Therefore, in order to assess the various sources of uncertainty in sea level, it is essential to use multiple ice sheet models. Furthermore, to eliminate the lag between ice sheet and climate projections, simulations of ice sheet evolution that are in tandem with the scenarios considered by the climate community is crucial. For this reasons, the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) became a targeted activity of the Climate and Cryosphere (CliC) project, and has recently been endorsed by the newly formed CMIP6 effort.

The key objectives of the proposed study are to provide programmatic and scientific leadership of ISMIP6, and in particular to 1) coordinate the ice sheet modeling community in support of ISMIP6, 2) obtain and distribute atmospheric and oceanic forcings for ISMIP6, 3) investigate the dominant sources of uncertainty in projected sea level from ice sheet models, and 4) remove barriers to the use of observational data or intercomparison of ice sheet models.

The proposed research relies on existing modeling capabilities developed at NASA GSFC and JPL, in particular the Ice Sheet System Model (ISSM), which is coupled to the atmosphere of the Goddard Earth Observing System Model, Version 5 (GEOS-5), and the ocean of the Massachusetts Institute of Technology general circulation model (MITgcm), and a range of NASA observations over the ice sheets to assess ice sheet model output and facilitate model intercomparison.
**Summer Rupper/University of Utah**  
*Bayesian Quantification of Antarctic Surface Mass Balance*

Mapping the spatial and temporal variations in surface mass balance (SMB) over the Antarctic ice sheet is essential for understanding ice sheet response to climate forcing, and assessing recent and future impacts of climate change on Antarctic accumulation and net mass balance, and associated sea level rise. Our ability to quantify SMB over space and time is limited by large regions of no data and/or data uncertainty, as well as difficulties in synthesizing these datasets into regional and ice sheet-wide maps of SMB means and trends. In turn, these difficulties hinder our ability to rigorously test the skill of climate models at reproducing the spatial and temporal patterns in SMB. We propose to develop and apply statistical models to (1) integrate all available accumulation data (e.g., ice core, airborne radar, passive microwave) into region-wide maps of accumulation with careful uncertainty analysis, (2) identify regions where additional data are critical to improve Antarctic SMB certainty, and (3) provide a rigorous evaluation of climate model skill at simulating Antarctic SMB.

The proposed research will quantify SMB means and trends across the Antarctic ice sheet, with focus on a rigorous assessment of the uncertainties associated with the SMB estimates. We will accomplish this through state-of-the-art statistical modeling and data compilation. Specifically, we will develop a Bayesian statistical model that allows us to interpolate accumulation values over data poor regions, with the particular benefit of being able to incorporate prior scientific knowledge as well as flexible parameters. The primary advantage is that the model is very flexible and adapts readily to knowledge gained from data. The data used will be a compilation of point-source (e.g., ice cores, snow stakes, snowpits), ground-penetrating radar, and remote sensing (e.g., passive microwave, airborne/satellite radar) data. Each data set will be carefully evaluated for reliability and then weighted based on these reliability criteria. The final SMB maps will be compared to climate model output in order to assess the skill of current regional and global climate models to capture the spatial and temporal patterns in SMB. We then propose locations where knew data would significantly improve the SMB certainties through an iterative selection process which incorporates variability associated with both the model uncertainties and substantial uncertainty and gaps in current data. The statistical model will be designed such that the SMB maps, model-data intercomparisons, and proposed measurement locations will be updated with new data routinely and made publicly available through a web portal.

**Ted Scambos/University of Colorado**  
*Global Land Ice Velocity Extraction From Landsat (GoLIVE): A Robust, Comprehensive, and Near-Real-Time Record of Global Glacier Flow*

Motivation: Comprehensive measurement of change in the amount of land-based ice is required to estimate the cryospheric impact on sea level, and NASA has invested heavily in multiple measurement strategies to achieve this. Maximizing use of the resulting time series requires closing the time-varying ice mass budget underlying each measured geophysical signal. Time-varying discharge of ice is a critical component of that budget. We have built a processing system leveraging the Landsat record, especially the dense space and time sampling of Landsat 8, that is capable of producing a global record of time-varying ice flow. We can now systematically map ice flow across multiple timescales globally, removing time-varying ice flow and its impact on discharge from the list of unknowns that makes closing mass budgets a challenge.
Approach: Landsat 8 acquires by far the most densely time-sampled image archive of land ice at decameter scale yet available. As described below, our team has developed a set of processing chains for these data and earlier Landsat imagery based on image pair correlation. Improvements in computing speed, geolocation, and enhancement of radiometric sensitivity result in significantly improved throughput and highly accurate ice flow maps. We can now extract a detailed, global, near-real-time record of ice flow variation from June 2013 onward, for all significant glaciers and ice sheet outlet areas (wider than 500 m), and at the same time, produce an internally consistent record of past flow changes over the length of the Landsat record (TM, ETM+, and OLI: 1984-present).

Innovation: It was not previously possible to uniformly document ice flow variations on a global scale. The Landsat 8 data stream and our processing system allow us to extract a record of ice flow variation that is complementary to InSAR records, and is more densely time sampled. We will process new images as they are acquired, updating our picture of ice flow variations in near real-time. One-quarter of the requested project support is targeted at building a web-based access system at NSIDC so the ice velocity data can be available to the community in near real time (a five-day delay is envisioned, possibly less). Our work will be the first global documentation of ice flow variability across multiple timescales. We will use this record to: 1) characterize the ice flow pattern and ice flux from the large ice sheets and track areas of change, 2) map the magnitude, spatial extent and timing of seasonal changes in glacier flow, and patterns of velocity change versus time across accelerating outlet systems, and 3) produce an internally-consistent ice flow record across the Landsat missions, to add extensively to the available InSAR ice flow history.

Value to NASA Cryospheric Science: The resulting maps of ice flow change will isolate the impact of flow-related thinning on altimetry and time-varying gravity records, an important step in deconvolving changing flow and surface mass budget signals. Our work will comprehensively leverage the Landsat archive, deliver a systematic view of ice flow variations, and create ice flow variation records from Landsat 8, accessible to the community in near real time, that will capture all future changes in discharge. Such a record is fundamental to understanding the mass budgets of land-based ice that underlie active and proposed measurement campaigns by IceBridge, ICESat-2, Cryosat-2, GRACE, and the GRACE Follow On mission.

Dustin Schroeder/Stanford University
Greenland Basal Water Conditions

Subglacial hydrology exerts primary control on ice flux, the redistribution of melt water, and sediment movement for the Greenland Ice Sheet. Therefore, understanding the base winter state of the hydrologic environment along the bed of Greenland is of critical importance as the base state is key to understanding future changes. Specifically, the base state informs how the subglacial drainage can change and, ultimately, how the Greenland Ice Sheet reorganizes in response to external forcing, including seasonal variations and long-term climate changes. Recent advances in airborne radar sounding technology and analysis approaches coupled with increased survey coverage and density across Greenland provide a unique opportunity for characterizing the basal water system. However, much of the data remains underutilized and can be exploited further to obtain robust estimates of hydrologic conditions.

Here, we propose to observationally constrain these water systems for three catchments with relatively dense coverage as a part of NASA's Operation Ice Bridge mission: Jakobshavn Isbrae, Petermann Glacier, and the Northeast Greenland Ice Stream (Zachariae/79 North Glaciers). Our
research plan includes (1) characterizing the distribution of subglacial water, including where the bed is frozen and thawed, (2) estimating the roughness and catchment topography at scales relevant to the hydrologic system and (3) using these to understand the spatial variation in processes occurring along the bed, with the goal of understand the directionality of flow and the variation resulting from the difference between the ice and water pressures. Similar studies have proved successful for the Thwaites Glacier catchment in West Antarctica, but the radar systems used to collect data Operation Ice Bridge over Greenland are significantly different and require both the adaptation of techniques and development of new concepts to characterize the Greenland subglacial systems. These new concepts include expanding existing bed characterization techniques to take advantage of cross-track information available in the CReSIS MCoRDS multi-channel radar sounder.

This expansion will provide improved bed roughness and small-scale topography estimates. We will use the statistics of the sampled areas to populate nearby areas between survey lines to provide higher resolution and more geostatistically consistent bed topographies for water routing than other interpolation approaches. We aim to use these in ensemble fashion to quantify the overall structure of the subglacial water system. While commonly used subglacial routing algorithms give a flavor for where water can flow, they are also simplistic because they do not include or predict directionality information. Such information is fundamental to water flow and appears in the hydraulic conductivity. We plan to estimate the directional information of the water pathways from bed roughness, thermal regime, effective pressure and water depth. Therefore, we aim to use the radar jointly with improved models to provide an enhanced the understanding of hydrologic conditions at the bed of the Greenland Ice Sheet.

Together, our objectives will provide the first common template for understanding the hydrology of three different catchments. Work proposed here also includes members of the radar engineering, radioglaciology, and subglacial hydrology communities in order to facilitate a common understanding of radar instrument capabilities and signal information in constraining glaciological observables.

We expect this plan to lead to further developments for understanding subglacial drainage, both from the perspective of optimizing radar data collection and processing as well as understanding the ice flow and discharge along the bed at local and regional scales for the ice sheet.

**Leigh Stearns/University of Kansas**

**Controls on Iceberg Distribution Around Greenland**

Iceberg calving accounts for roughly 50% of the ice mass loss from the Greenland Ice Sheet; however, little is known about how calving varies seasonally and spatially. The size of icebergs that break off glacier termini are dictated by geometry, ice velocity, submarine melt rates, and buoyancy conditions. The freshwater flux derived from icebergs (largely dictated by their size and distribution) impacts fjord circulation and sea ice formation. Understanding the trajectory of mass flux from the ice sheet to the oceans is crucial for the development of fjord circulation models, as well as coupled climate models. We propose creating a comprehensive database of glacier calving and iceberg properties, using freely available satellite imagery and automated image processing software, which will be easily accessible for public use. We will use this data to address calving parameterizations, but the data has wide applicability for physical oceanography, climate models, ecology, sea ice science and polar shipping.
Icebergs provide a direct link between the ice sheets, atmosphere and oceans, however they are poorly quantified in the Arctic. To date, there is neither a consistent representation of calving processes in ice models, nor a satisfactory representation of icebergs in fjord or ocean models. Calving laws are largely based on observational data from a handful of glaciers where comprehensive datasets are available, and as a result, may not be representative of glaciers with more diverse geometries or dynamics. In addition, iceberg size distribution in the Arctic are largely based on ship-board observations and are therefore very site specific and limited.

Our approach to this data gap is to utilize several new, publicly available, datasets and remote sensing imagery to produce a database of glacier calving and iceberg distribution around Greenland. An image classification scheme will enable the automatic detection of boundaries between between glacier ice, sea ice and open water, exporting near-weekly estimates of terminus position and iceberg distribution. This dataset would uniquely link ice-ocean systems by quantifying ice loss at calving margins and how that ice travels through fjords to the open ocean.

The work focuses on the following objectives:
1. Quantify the terminus position of Greenland marine terminating glaciers;
2. Quantify the size and distribution of icebergs in Greenland's coastal waters;
3. Produce an easily accessible database of calving behavior and iceberg distribution; and
4. Test various calving laws using this new dataset, combined with ancillary data.

The aims of the project are closely aligned with the goals of NASA's Science Mission Directorate's Objective 2.2: Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet. By mapping the size and distribution characteristics of icebergs in Greenland's coastal waters, and linking these to the terminus behavior of nearly 200 tidewater glaciers around Greenland, this project also meets several of the specific solicitation requests. In particular, our work will advance observations related to sea ice formation and evaluate mechanisms that control ice sheet mass balance. Finally, the resulting products will be readily available for use by other researchers and the general public, an important component of NASA projects.

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Konrad Steffen/University of Colorado
Surface Climate of the Greenland Ice Sheet and the Assessment of Accumulation Variability and Change - the Greenland Climate Network (GC-Net)

The Arctic climate has experienced some major changes in the past decades. Natural climate variability is organized into spatial patterns of high and low pressure regions, the Arctic Oscillation, and the North Pacific patterns. When either of the patterns is in its positive extreme, the pattern contributes to an overall Arctic warm period. In recent years (2000 to present), the pattern of warm temperature anomalies is circumpolar in distribution and dominates the Polar Regions.

The annual mean air temperature was found to be 4 degrees C warmer along the western slope of the ice sheet as compared to the standard decade 1951-1960. Also, the Greenland cumulative wet snow area increased on average by 40% since 1979 based on passive microwave satellite data. With the increased surface melt, the snow and firm layers increase in density due to the percolation and refreezing of melt water, hence reducing the surface height by near-surface snow densification.
Observations from satellites and aircraft since 1990 show substantial ice loss from Greenland that has doubled in the last decade, both from increased runoff (melt) and from acceleration of glaciers (ice dynamics) draining the ice sheet. Monitoring of these processes are essential to improve our understanding of the ice sheet mass balance, and estimates of the rate and timing of 21st-century and longer-term sea level projections. Therefore, ground-based process studies are required for the interpretation of satellite-derived ice sheet parameters currently used in modelling the response of the Arctic in a warming climate.

We propose to maintain a climate network of 16 automatic stations on the Greenland ice sheet to extend the climate record which started in 1995. The continuation of this climate record is crucial for understanding the decadal climate variability and to capture the recent Arctic warm phase. Further, the climate parameters are widely used for process studies by the polar research community, and for model validations and verification. The GC-Net data are the only climatological measurements covering all major climatic zones of the ice sheet for a duration of 20 years.

We propose to install multi-frequency radars at two locations on the ice sheet to monitor the accumulation and melt at the resolution of individual snow layers (storm event) in the firm. The upward-looking radar systems is capable of monitoring depths of melt percolation and can quantify the amount of liquid water remaining in the snowpack which is essential for the interpretation of satellite data such as altimeter, passive microwave, or radar.

We propose to collect a comprehensive dataset consisting of high-resolution snow profiles at each GC-Net location on the ice sheet. This study will link snow physics with snow cover modeling through the measurements of high-resolution snow microstructure parameters. The snowpack and its mechanical and structural properties are important to improve firn densification and mass-balance models as well as larger scale climatological models (e.g. RACMO, MAR).

These objectives are consistent with the research priorities of the NASA Science Plan 2014 (Earth Science) to improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land and ice in the climate system, and NASA's Strategic Goal 2.1 to advance Earth system science to meet the challenges of climate and environmental change. Further, it meets NASA's strategic objective to explore the interaction among the atmosphere, oceans, ice sheets, land surface interior, and life itself, and to inform decision makers about possible impacts.

Julienne Stroeve/University of Colorado, Boulder
Bridging the Snow Sea Ice Gap: A Snow on Sea Ice Assimilation System for the Arctic

Sea ice has been visibly changing in recent decades; most notably the annual minimum extent, which has shown a distinct downward, and recently accelerating, trend. Should this loss continue, there will be wide-ranging impacts on marine ecosystems, coastal communities, prospects for shipping and resource extraction, and weather conditions within and possibly beyond the Arctic. Key to understanding the long-term evolution of the sea ice cover and improving seasonal predictions of ice condition is knowledge of ice thickness. A fundamental impediment to obtaining thickness from satellite missions (e.g. NASA ICESat/2 or ESA CryoSat-2) is the lack of knowledge of snow depth atop the sea ice and snow density. We propose to meet this need through development of the Snow
on Sea ice Assimilation System (SNoSAS). SNoSAS will develop daily and monthly snow depth and density products, initially focusing on the ICESat and CryoSat-2 time-periods. Snowfall on sea ice will be determined using an improved Lagrangian sea ice tracking approach in conjunction with snowfall data from a suite of atmospheric reanalyses, observations of solid precipitation from Arctic coastal stations and drifting stations, snow depth from IceBridge and data from field campaigns (e.g. CryoVEx). Snowmelt will be determined from an energy budget approach, making use of surface fluxes from satellite data and reanalyses. A Lagrangian-modified Optimal Interpolation data assimilation scheme will be used to combine available snow observations and the modeling system. While SNoSAS has the primary aim of enabling improved sea ice thickness retrievals from satellite sensors, it will also be used for process studies of seasonal and interannual variability of snow depth. Estimates of ice thickness across the Arctic Ocean have become available over the past 20 years based on data from ERS-1/2, Envisat, ICESat, CryoSat-2 and Operation IceBridge. While there is potential to combine data sources into consistent time-series, the variety of measurement approaches, sensor technologies and spatial coverage (among other factors) present formidable challenges. By providing daily and monthly snow depths and densities, with error estimates, we can better understand the observed changes in sea ice both from existing data streams and upcoming missions such as ICESat-2.

Julienne Stroeve/University of Colorado, Boulder
Near-Real-Time Science Analysis of Arctic and Antarctic Sea Ice and Greenland Melt

We propose to continue and greatly enhance the National Snow and Ice Data Center (NSIDC) Arctic Sea Ice News and Analysis (ASINA) and Greenland Today (GT) websites. Since 2008, ASINA has provided near real time monitoring of Arctic sea ice conditions as well as regular (monthly to weekly, depending on the season and conditions) discussion of evolving conditions, comparisons with previous years, trends, and highlights of recent research. ASINA has subsequently expanded to include periodic discussion of Antarctic sea ice conditions. GT, a companion to ASINA, focuses on near-real-time monitoring, analysis and discussion of surface melt over the Greenland ice sheet. It was developed in response to growing interest in the evolution of the ice sheet and its contribution to sea level rise. Since its inception, ASINA has been NSIDC's most visited site, averaging over 150,000 visits per month. Visits to GT are growing quickly. ASINA and GT serve as resources to the broad science community and the general public, and bring high visibility to NASA's earth science enterprise. Community feedback on ASINA and GT has been overwhelmingly positive and the NASA Polar DAAC User Advisory Group has strongly urged continuation of the projects. Beneficiaries of ASINA and GT include:

1. **The Scientific Community:** We offer immediate and concise assessments of observed sea ice conditions and Greenland surface melt that allow scientists to plan and focus areas of research. We also provide a location for scientists to share recent research and we vigorously recruit contributions from NASA-funded researchers and other scientists. The postings routinely highlight the most relevant published research. The project also supports an NSIDC contribution to the Sea Ice Prediction Network (SIPN) Sea Ice Outlook (SIO), which brings together sea ice experts from around the world to provide seasonal forecasts of Arctic sea ice conditions.

2. **NASA's Earth Science Enterprise:** ASINA and GT utilize NASA-developed data sets archived at NSIDC, including SMMR, SSM/I, SSMIS, AMSR-E, MODIS, and ICESat GLAS, as
well as research-level products developed by NASA-funded grants (e.g. IceBridge), resulting in increased visibility and user requests of these products. NSIDC’s participation in the SIPN brings NASA data products into the SIO reports.

3. Journalists, educators, and the general public: ASINA and GT provide a platform for promoting widespread understanding of emerging environmental changes in the Arctic and Antarctic. NSIDC scientists regularly answer questions from the media, public and policymakers regarding our reports, their implications, and the NASA data that we use.

Plans for 2016-2018: As outlined in the body of this proposal, renewal of funding will enable ASINA and GT to evolve and meet changing user needs through combining different data sets in near real time, including new data from NASA-funded projects (i.e. ice age, ice thickness, higher resolution sea ice concentration, MERRA atmospheric reanalysis, ice sheet albedo products, and snow/firm model results) and improving the web site with enhanced climatology compilations, display and analysis features. The main deliverables include the enhanced ASINA and GT web sites (http://nsidc.org/arcticseaicenews/, http://nsidc.org/greenland-today/). We will continue to collaborate with NASA on press releases, press telecons, and other avenues to convey sea ice information to the science community and the general public.

Mike Willis/Cornell University

Mid-20th Century Ice Heights From Archived Antarctic Aerial Photography

Understanding how the Antarctic ice sheet operates is vital, changes there affect global sea level, thermohaline circulation, and climate and weather patterns. Numerical models with realistic physics make it possible to decipher the processes and phenomena that control the behavior of the ice sheet. Advancements in both ice sheet and Glacial Isostatic Adjustment (GIA) modeling have been hampered by a lack of data with which to constrain and validate the models. Antarctica is under-sampled and the addition of even a few data points can radically re-shape our view of the ice sheet as a whole. Confidence in predictions on how the configuration of the Antarctic Ice Sheet is likely to evolve in the near future under various warming scenarios will improve with new data assimilation and validation sources that we will provide. Understanding the Antarctic is critical to understanding the Earth system, a core mission of NASA.

Our work will produce a novel Antarctic ice-height data source derived from archived aerial photography collected between 1946 and the late 1990s. These elevation data will be used to ascertain how parts of the Antarctic Ice Sheet have changed over the last 15 to 70 years. The elevation data will be assimilated into coupled atmospheric/ice-sheet models and can also be used by input to ice-history/Earth rheology GIA models. Our data will allow the ice sheet modeling community to improve model skill and reduce the uncertainties on the prognostic model output. Improved models will help predict the future behavior of Antarctica, allowing assessment of how close components of the Antarctic system are to glaciological "tipping" points and provide more precise examination of the threat of accelerated sea level rise in the near term.

The mid 20th century elevation data set will allow close inspection of regional ice mass changes and ice front instability along the coast of West Antarctica, the Transantarctic Mountains and around bedrock outcrops everywhere else in Antarctica where there is sufficient and useable archived aerial photography. This examination will let us test our main question: Are recent Antarctic ice mass loss rates, especially in the Amundsen Sea Embayment, exceptional compared to average mass loss rates over the last 50-70 years? The project relies on the melding of new technology and old data and is leveraged by the wholesale scanning of analogue photographs from expeditions that occurred between the mid-1940s through the early 1990s; the availability of
sub-meter resolution satellite imagery; along-track stereo satellite derived meter-scale topography; advances in computer vision and structure from motion algorithms; and remotely sensed ground control data available from the NASA ICESat and IceBridge Missions, supplemented with ESA Cryosat-2 data where necessary.

The project will:

1) Create a database of time-tagged ice and bedrock high-resolution Digital Elevation Models (DEMs)
2) Co-register the derived DEMs to existing sources of ground control, such as ICESat, Airborne Topographic Mapper (ATM) and Land, Vegetation and Ice Sensor (LVIS) laser altimetry using tie points over prominent bedrock feature.
3) Orthorectify the sub-meter satellite imagery to the high-resolution DEMs.
4) Use Affine Scale Invariant Feature Tracking (ASIFT) algorithms to co-register aerial photography to orthorectified sub-meter satellite imagery. This will provide ground control for the aerial photography.
5) Use a two pronged approach using Structure from Motion algorithms and stereo-photogrammetry, assisted with the ground control, to produce DEMs from mid-century aerial photography.
6) Produce ice height change time-series at many hundreds of locations around Antarctica. Examine these for patterns that are indicate common forcing factors.
7) Assimilate mid-century ice geometry into coupled atmospheric/ice-sheet models.
8) Make elevations data set publically available to a broad community.

Jinlun Zhang/University of Washington
Prediction of Sea Ice Thickness and Floe Size Distributions in the Marginal Ice Zone of the Arctic Ocean: Modeling and Remote Sensing

Accelerated decline of Arctic sea ice has increased the area of open water and the marginal ice zone (MIZ) - the transition region from open water to pack ice. This allows greater access to the Arctic region than ever before, which presents challenges and opportunities for activities such as fisheries, transportation, and resource exploration. To assist in the management of increasing economic and transportation activities, it is important to enhance our ability to predict sea ice for various Arctic regions, particularly the MIZ. Because the MIZ consists of floes of varying thicknesses and sizes, the state of sea ice in the MIZ is best described by an ice thickness distribution (ITD) and a floe size distribution (FSD).

We propose to develop a new ensemble forecast system based on the Pan-arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) that is capable of predicting both ITD and FSD in the MIZ (including ice edge locations) on daily to seasonal time scales. A critically important component of the forecast system is its initialization using all available and relevant satellite and airborne observations, including sea ice concentration, thickness, and floe size, and sea surface temperature. The proposed study will enhance our understanding of variability and predictability of MIZ processes and will develop and strengthen our ability to make reliable forecasts as well as effective representations of the forecast uncertainties through improved model physics and use of satellite data for model initialization. Particular attention will be placed on assimilating IceBridge and CryoSat-2 ice thickness observations to improve the representation of initial conditions and predictions. Assimilating these observations may guide utilization of ice thickness data from the anticipated ICESat-2 to be launched in 2016.
The research has six primary objectives: (1) Calibrate and validate PIOMAS and improve model physics based on FSD; conduct hindcasts that assimilate satellite (and airborne) ice concentration and thickness and SST over 1979-present. (2) Develop an ensemble forecast system to predict both ITD and FSD in the MIZ and ice edge locations with lead times from days to three seasons. (3) Quantify the historical and contemporary evolution of ITD and FSD in the MIZ and ice pack interior; identify key linkages and interactions among the atmosphere, sea ice, and ocean to understand mechanisms affecting the variability and predictability of ITD and FSD. (4) Maintain and expand the Unified Sea Ice Thickness Climate Data Record to ease assimilation of satellite and IceBridge ice thickness data to improve PIOMAS initial conditions and forecast accuracy. (5) Assess the system's predictability through careful forecast skill evaluation and uncertainty analysis and identify areas for further improvement. (6) Participate in the Year of Polar Prediction (YOPP) and maximize the exposure and utility of the forecasts.

As we conduct hindcasts and forecasts of sea ice in the MIZ using the forecast system, we will strive to address the following science questions: (a) What are the variability and trends of ITD and FSD in the MIZ in both the Pacific and Atlantic sectors of the Arctic Ocean over the period 1979-present? (b) How do Arctic cyclones affect the variability and predictability of MIZ ITD and FSD and ice edge locations on daily to seasonal time scales? (c) What is the relative importance of preconditioning versus atmospheric forcing in the variability and predictability of the MIZ? (d) What are the effects of initialization using satellite and airborne ice thickness data in the forecasts of MIZ ice conditions and ice edge locations? (e) What is the impact of summertime heat storage in the upper ocean on the variability and predictability of ITD and FSD in the MIZ as well as in the interior of the ice pack?