Studies with ICESat and CryoSat-2
Abstracts of selected proposals
NNH12ZDA001N-ICESAT2

This synopsis describes the proposals selected in response to the NASA Research Announcement *Studies with ICESat and CRYOSat-2* which is subelement A.49 of NASA ROSES 2012.

NASA solicited investigations to derive geophysical information from NASA's Ice, Cloud, and land Elevation Satellite (ICESat) and the European Space Agency's CryoSat-2. These altimetry missions were optimized to characterize changes in the continental ice sheets of Antarctica and Greenland and the sea ice of the Arctic and Southern Oceans. The missions' primary goals are to understand the contributions of polar ice to current and future sea level rise and the coupling of changes in polar sea ice cover to the Earth system. Investigations were solicited that:

- create long term, integrated records of change in the polar ice sheets;
- characterize processes of change in polar ice, especially couplings to climate forcings and insight into physical processes that improves predictive models; and
- any other innovative investigations using ICESat and CryoSat-2 observations for Earth science research.

The NASA Ice, Cloud, and land Elevation Satellite (ICESat) was a space-based lidar launched in January 2003 that ceased operations in 2009. ICESat observations provided critical insight into the thinning of the Arctic sea ice cover, the ice loss from the continental ice sheets of Greenland and Antarctica, and the global distribution of above-ground biomass (details at http://icesat.gsfc.nasa.gov/ and data at http://nsidc.org/data/icesat/). ICESat's planned successor is ICESat-2 (http://icesat.gsfc.nasa.gov/icesat2/), expected to launch in 2016. The gap in observations is bridged by NASA's IceBridge Mission (http://www.nasa.gov/mission_pages/icebridge/index.html; data at http://nsidc.org/data/icebridge/). CryoSat-2 (http://www.esa.int/esaMI/Operations/SEM36Z8L6VE_0.html), launched in April 2010, is a radar altimetry mission of the European Space Agency (ESA) designed primarily to measure sea ice thickness with radar. Its measurements of sea ice freeboard complement those of ICESat, and have been validated with IceBridge observations.

Selected proposals include various studies of land and sea ice in the Arctic, Antarctic and Himalayas using ICESat, IceBridge and CryoSat 2; determination of ocean surface topography using ICESat; and mapping of global forests to understand the earth's carbon budget using ICESat and other land imaging techniques.

Out of 41 submitted proposals, 13 will be recommended for awards. The total funding for the program is approximately $2 million per year for three years. The Principal Investigator, institution, and investigation title are listed below.

Waleed Abdalati/University of Colorado
Assessing Greenland Crevasse Extent and Characteristics Using Historical ICESat and Airborne Laser Altimetry Data: A Baseline for Assessing Changes with ICESat-2

Greenland's ice loss is split between surface mass balance (i.e. melt and runoff) and ice flow (i.e. ice discharge). Predicting the relative contributions of these two terms to future sea level rise is complicated by potential non-linear feedbacks that can be enhanced by and expressed through crevasses, which are ubiquitous features of Greenland's tidewater glaciers. Relative to nearby flat ice areas, heavily crevassed areas (i) enhance surface ablation, (ii) enhance meltwater retention, (iii) enhance deformational velocity and (iv) suppress basal sliding velocity. Crevasses therefore simultaneously influence both the surface mass balance and ice flow components of total ice sheet mass balance. While crevasse extent can directly influence the partition of Greenland ice loss between surface balance and ice flow, Greenland's heavily crevassed areas have been systematically understudied by past glaciological field campaigns due to fundamental safety concerns. Recent research and anecdotal evidence suggests that crevasse extent is increasing at specific study sites. At present, however, no inventory exists of Greenland Ice Sheet crevasse extent or structure. We propose to use Ice Cloud and land Elevation Satellite (ICESat) observations to identify and characterize crevassed areas on the Greenland Ice Sheet, to provide fundamental insights into crevasse extent and characteristics, and provide a baseline assessment of crevasse structure to facilitate ICESat-2 early mission science.

This project will develop novel data products of Greenland Ice Sheet surface roughness/crevasse structure for two discrete years, 2003 and 2009, by assimilating ICESat and ATM/LVIS waveform data. We will forward model the influence of synthetic crevasses on ICESat waveforms. We will then use the insight gained from this forward modeling to develop a statistical model that derives surface roughness/crevasse structure information from observed ICESat waveforms. We will undertake analogous forward modeling and statistical algorithm development for both ATM and LVIS data during both years, as well as along selected repeat flight lines. We will conduct a rigorous validation by comparing our geolocated results to surface roughness/crevasse structure observed in high resolution RISCO imagery. Once validated, our calibrated surface roughness/crevasse structure values within each ICESat footprint will be spatially interpolated across the entire ice sheet using an optimal geo-statistical interpolation schemes (i.e. non-linear interpolation, kriging, etc.). We will then interpret the controls on contemporary crevasse structure and extent in Greenland, as well as a definitively quantify possible ice sheet wide changes in crevasse extent over the study epoch. Our surface roughness/crevasse extent data products will be made available to the research community by NSIDC by the time of project completion.

This proposed research directly addresses A.49 ICESat research priorities by (i) creating a decadal-scale record of Greenland crevasse extent using an innovative processing of existing data, (ii) improving insight on contemporary surface mass balance and ice flow mass loss processes by investigating a previously unconsidered mechanism of mass change, (iii) using satellite altimetry to assess an ice sheet property that is critical to improving models of future sea level rise, and (iv) providing a baseline characterization of Greenland's surface structure that will enable important early mission ICESat-2 science results. This research is relevant to the overall strategic plan of NASA’s Science

Mission Directorate, by addressing the Earth Science question: "What changes are occurring in the mass of the Earth's ice cover?" This question bridges the Science Focus Areas of (i) Climate Variability and Change, and (ii) Water and Energy Cycle.

Falk Amelung/University of Miami
A New Mass Balance Estimation Method from Altimetry and InSAR: Application to the Greenland Ice Sheet and Arctic Ice Caps

One of the greatest challenges associated with climate change is the sea-level rise from the melting of the Greenland ice sheet and the impact of the freshwater influx into the ocean on the climate. We propose a research program integrating space geodesy and Earth system modeling to address these questions. Satellite altimetry and interferometric synthetic aperture radar (InSAR) provide observations of elevation changes of the glacier surface and of the land surface next to the ice sheet. These on-ice and off-ice elevation changes are linked by geodynamic modeling of the Earth's response to changes of the ice load, which lead to local estimates of the ice loss. Climate simulations address the response of the ocean and atmosphere to the estimated freshwater influx into the North Atlantic Ocean by melting of the ice sheet.

Specifically, we will use IceBridge and Cryosat-2 observations for ice elevation change, TerraSAR-X and Radarsat-2 InSAR for ground uplift, elastic surface loading solutions for the geodynamic modeling, and coupled high-resolution ocean-atmosphere-sea-ice eddy-resolving simulations for climate modeling. Our primary focus for geodesy will be on the north and northwest Greenland region where the dry climate favors InSAR observations. Our objectives are to proof the concept of the altimetry-InSAR method and to refine mass balance estimates. The analysis of new observations is complemented by the analysis of archived observations for north and northwest Greenland through 2010.

The advantage of the altimetry-InSAR method is that it does not depend on assumptions on the density of the lost ice volume or on postglacial rebound. The proposed method is potentially more accurate than any other method for ice mass balance estimation. Another advantage is that local and regional variations in ice mass loss can be resolved (e.g. associated with rapid calving of the outlet glaciers and differences between ice caps, respectively)

Intellectual merit and broader impact

New method for ice loss estimation from the combination of altimetry and InSAR.
Improved ice mass loss estimates for northern Greenland.
Proof-of-concept demonstration of the altimetry-InSAR method well ahead of ICESat-2.
First understanding of the climate impact of observation-based melt water influx into the North Atlantic Ocean.
Education of one graduate student.

Alessandro Baccini/Woods Hole Research Center
LiDAR and Optical Data Fusion for Global Carbon Stock Mapping

Robust estimates of the distribution of carbon contained in the aboveground biomass (AGB) of forests are needed for the globe to reduce the uncertainties associated with global carbon budgets and to improve our understanding of how carbon cycle pools and processes vary across space and time. In support of NASA Studies with ICESat and CryoSat-2, and acknowledging the key insights that GLAS LiDAR observations have already provided where the estimation of AGB is concerned, the primary goal of the proposed research is to produce the first globally consistent, wall-to-wall map of AGB at an unprecedented resolution of ~500 m. In doing so, we will demonstrate the great potential of spaceborne LiDAR to fill a critical data gap while solving a scaling challenge that has long plagued large-area mapping studies: how to optimally link sparse field measurements with wall-to-wall satellite imagery to produce consistent and accurate estimates of AGB at the global scale.

The proposal team has spent the last decade advancing methods for large-area AGB mapping using strategies that combine field measurements, spaceborne LiDAR, and optical imagery. The proposed research builds directly upon these efforts, specifically leveraging results from a recent peer-reviewed effort to produce the first spatially explicit map of AGB for the pan-tropical belt at a resolution of ~500 m (Baccini et al., 2012). The specific objectives/deliverables are to: (1) Generate a global database of GLAS footprint-level estimates of aboveground biomass. We will develop statistical models linking field-based estimates of AGB with GLAS waveform metrics associated with a subset of co-located GLAS footprints to provide accurate estimates of AGB at the footprint scale for the ca. 2007/08 timeframe. (2) Produce a globally consistent mosaic of MODIS NBAR imagery at a resolution of ~500 m. Leveraging a time-series of MODIS NBAR imagery from the ca. 2007/08 timeframe, we will produce a best-quality, global mosaic of cloud-/snow-free, standardized spectral reflectance data. (3) Generate a global map of aboveground biomass at a resolution of ~500 m. Using the products from Objectives (1) and (2), we will use tree-based regression to model the relationship between GLAS footprint-level estimates of AGB and MODIS spectral reflectance together with ancillary data (e.g., ALOS/PALSAR HH intensity, SRTM elevation, etc.). The resulting model(s) will be used to map AGB wall-to-wall for the globe. (4) Provide uncertainty estimates at the footprint- (GLAS) and pixel-level (MODIS) for the biomass products generated as part of Objectives (1) and (3). We will conduct an error propagation analysis to quantify errors associated with each individual input and step in the modeling process beginning with the field measurements of stem diameter and ending with the global map of AGB. The analysis will provide estimates of uncertainty for each GLAS footprint as well as for each individual pixel in the global map.
The proposed research is highly relevant to the NRA by responding directly to the stated goal of improving our understanding of the Earth system through the provision of information on vegetation structure and estimation of global biomass. Beyond the goals of the NRA, the research is relevant to NASA's Terrestrial Ecology/Carbon Cycle Science programs by improving our understanding of critical components of the global carbon cycle, advancing the integration of multi-sensor approaches to estimating key

carbon cycle variables, and addressing the goal of quantifying biomass in terrestrial ecosystems. The research is also highly relevant to the NASA Carbon Monitoring System initiative, which is focused on quantifying terrestrial vegetation carbon stocks, first for the U.S. and then globally. Finally, our work will contribute to efforts focused on answering key questions relevant to the efficacy of NASA's ICESat-2 mission for ecosystem structure characterization.

Natalia Galin/NOAA
Using CryoSat-2, ICESat and ICEBridge to Constrain the Volume Change of the Antarctic Peninsula and Margins

The objective of this proposal is to constrain past and future volume change estimates over the Antarctic Peninsula and coastal margins using a combination of satellite and airborne altimetry data, coupled with a state of the art ice-sheet model. It is hypothesized that a significant portion of polar ice loss and sea level rise may come from these regions. For example, a recent NASA/ESA collaboration on the "Reconciled Estimate of Ice-sheet Mass Balance" Shepherd et al., [2012] finds that, although the Antarctic Peninsula is only 4% of the Antarctic continent, it contributes 25% of total ice mass loss from regions of negative mass balance.

Better quantifying this loss will help to constrain sea level rise estimates. The Peninsula and other areas of the Antarctic continental margin have however, been poorly sampled by satellite radar altimetry missions prior to CryoSat-2, due to the steep topography in these areas. The proposed work will use CryoSat-2's unique capabilities for radar altimetry over steep topography and will combine these data with data from ICESat and IceBridge to fill in the current omissions in critical areas, improve and validate the accuracy of CryoSat-2/ICESat assessments of these dynamic areas of the Antarctic ice-sheet, and construct a time-series through ICESat (2003-2008), IceBridge (2009-present), and CryoSat-2 (2010-present).

Synthesis of these three datasets will show how to leverage the existing 19 years of radar and 5 years of laser altimetry data to build an integrated record of historical change for the Antarctic Peninsula and margins. Assessment of the performance of satellite altimetry over rough and highly sloping regions of the Antarctic ice-sheet will also furnish insight into how best to exploit ICESat-2 data.

The scientific objectives of our proposal are to:
- develop new methods to estimate the volume change of the Antarctic Peninsula and margins from CryoSat-2 data over the 2010 - 2015 period in the context of improving mass balance estimates of the region, and constraining its contribution to sea level rise,
- connect the CryoSat-2 data set to existing ICESat and IceBridge time-series to better understand how the observations fit into the context of Antarctica's overall secular behavior and evolution,
- characterize how satellite radar altimetry complements and is supported by the existing ICESat and IceBridge datasets and how we can extend our knowledge to ICESat-2 data exploitation,

- utilize our surface elevation estimates in an ice-sheet model (ISSM) to improve our understanding of the physical processes controlling evolution of ice-sheets and increase the confidence of predictions of the Antarctic contribution to sea level rise.

In order to meet these objectives we will develop techniques for the accurate retrieval of ice volume of the Antarctic Peninsula and margins by connecting the ICESat, CryoSat-2, and IceBridge data sets. We will then make the surface elevation data available for modeling studies, which will allow the physical mechanisms of ice volume change and stability to be investigated in an unprecedented manner. Our team is well equipped to achieve the objectives. Members of our team are familiar in detail with processing and usage of all required datasets: CryoSat-2, ICESat, IceBridge data, as well as operation of the ISSM model.

Alex Gardner/Clark University
Multiple Scattering Within Snow, Ice, Firn and Water and Its Impact on Elevation Retrievals from ICESat-2 Data

High accuracy satellite laser altimetry has proven to be an invaluable tool for a diverse range of cryospheric applications. This has motivated the launch of ICESat-2 in 2016 that will continue the legacy of ICESat-1, but it will use a very different altimeter (Abdalati et al., 2010). Not only will ICESat-2 be the first photon counting altimeter in space but it will also operate at a much shorter wavelength (532 nm for ICEsat-2 vs. 1064 for ICESat-1).

We have identified multiple scattering within snow and ice as a potential source of centimeter to decimeter bias in elevations estimated from ICESat-2 and other 532 nm altimetry measurements (e.g. Airborne Topographic Mapper) collected over snow and ice surfaces. If not properly corrected for, multiple scattering can result in spatially and temporally coherent time delays in photon returns that result in a low bias in derived surface elevations. The time delay results from very low absorption and strong forward scattering by ice particles at 532 nm; at this wavelength an incident photon will scatter, on average, 2000 to 8000 times before it is ejected from the snow or ice. For this study we propose to:

1. Characterize the 532 nm photon travel time delay resulting from surface multiple scattering for an extensive range of snow and ice conditions

2. Determine the impact of the multiple scattering delay on proposed elevation retrieval algorithms (e.g. midpoint of fitted Gaussian peak)

3. Develop, if possible, an operational correction for multiple scattering within snow and ice and apply it to existing MABEL data

4. Assess the diurnal, seasonal and interannual variability of the multiple scattering delay associated with changing surface properties of the Greenland Ice Sheet, and subsequent impact on elevations derived from ICESat-2/MABEL data.

To do this we propose to adapt a 3-D Monte Carlo ray-tracing radiative transfer model (MCX) to simulate photon transport within snow, ice, firn and ponded water. MCX is highly computationally efficient and utilizes modern GPU infrastructure. The code is of order 1000 times faster than similar code run on a single CPU, important because we will simulate multiple scattering in complex geometries that are optically semi-infinite. Adapting the model will allow for rapid radiative transfer simulations of photon transport in complex snow, ice, firn and lake geometries with diverse material optical properties. As part of this project we will compute an extensive library of snow, ice and impurity optical properties at 532 nm that we will make publicly available.

We will conduct an exhaustive number of idealized experiments with the modified MCX model to determine expected elevation bias for various snow and ice surfaces. We will use the output from these experiments to develop an operational algorithm to correct for the surface multiple scattering time delay when estimating surface elevations from ICESat-2 photon return data. To assess the impact of multiple scattering delays on ICESat-2 elevation retrievals over the Greenland Ice Sheet we will quantify seasonal and interannual variability in near-surface optical properties through simulations conducted with the Community Land Model, which has a sophisticated snow microphysics package and can be forced with MERRA re-analysis data or other prescribed climate forcing.

Our study will provide a thorough assessment of the multiple scattering time delay for snow and ice surfaces and its impact on elevations derived from ICESat-2/MABEL data. We seek to improve the accuracy of derived surface elevations by developing an operational algorithm that accounts for the time delay due to surface multiple scattering. Developing a detailed understanding of 532 nm photon interactions with the surface will also lead to expanded and novel scientific applications of ICESat-2 data.

Ian Howat/Ohio State University

Cross-Platform Altimetry Validation and Regional Reanalysis Over the Greenland Ice Sheet Margins

The aim of the proposed study is twofold: to constrain uncertainties in surface elevation estimates derived from airborne and satellite-based altimeters over specific regions of the margins of the Greenland Ice Sheet (GIS); and to resolve seasonal and short-term changes in ice volume as well as propagation of thinning towards the GIS interior. For this purpose, we propose three research goals: (1) to quantify differences in altimetry-derived surface elevation estimates between different systems caused by geophysical factors, such as signal penetration depth and slope-induced errors, over areas of the GIS with variable meteorological conditions; (2) to measure short-term changes in ice volume over the same regions in order to both study the propagation of ice thinning towards the ice sheet interior and assess altimetry system response to annual signals (i.e. seasonal thinning and winter accumulation); and (3) reconstruct and link long-term time series from repeated observations made by ICESat, CryoSat-2, and complementary airborne altimetry data acquired over the margins of the GIS. We intent is to compare airborne laser and radar altimetry with altimetry data acquired by ICESat for the period of 2004-

2009, and with data acquired by CryoSat-2 for the period of 2011-2015. Surface-retrieval algorithms will be validated with existing in-situ field measurements from previous and ongoing NASA and ESA campaigns.

Recent advances in altimetry techniques, coupled with growing concern over the potential ice sheet contribution to sea level rise, have motivated both a series of missions and improved altimeters designed specifically to observe the state of the cryosphere (e.g. ICESat GLAS, CReSIS airborne instruments, Operation Icebridge, ESA's ASIRAS, EnviSAT's RA-2, CryoSat-2 SIRAL). NASA's Geoscience Laser Altimeter System (GLAS) onboard ICESat provided with very accurate elevation change estimates by using lidar to track the ice sheet surface; the CryoSat-2 mission, carrying a Ku-Band interferometric radar altimeter, was designed to operate at a 92Â°-inclination orbit to obtain coverage of very high latitude regions with a high density of crossovers. CryoSat-2 Synthetic Aperture Radar interferometric (SARin) mode allows accurate surface tracking and slope determination over regions with high elevation gradients. Each system has its own advantages and limitations, and it is important to assess the influence of these limitations have on estimates of ice mass fluctuations. Therefore, the main goal of the proposed work is to compare elevation estimates from multiple altimetry platforms to quantify biases between systems and to assess the geophysical causes of the observed differences in key areas such as those close to fast flowing glaciers and with observed significant thinning, as well as regions that are subject to seasonal melt and refreezing cycles. This study will also include a few regions with high snow accumulation rates to determine how large variability in accumulation affects signal penetration depth and surface retracking algorithms.

This work directly targets the goals of NASA's Cryospheric Sciences program of i) improve our understanding of the mechanisms controlling mass balance and dynamics of the ice sheets of Greenland, and ii) the use of remote sensing data to develop, validate, and improve predictive models of the contribution of land-based ice to sea level change. We expect to obtain multi-mission altimetry data products for key regions of the ice sheet margins that have been validated with both existing field measurements and cross-platform comparisons. The analysis largely focuses on the margins of the GIS, since the effects of climate change to date have been more significant in these areas. It is expected that this work will reduce current uncertainties in altimetry data products in the study regions, benefiting studies of the state and dynamics of glaciers made within NASA and the wider scientific community.

Nathan Kurtz/Goddard Space Flight Center
ICESat-2 Sea Ice Studies and Algorithm Development: A Proposal for Membership on the Science Definition Team

The recent use of altimetry data sets has enabled the retrieval of an extremely important parameter in sea ice research: sea ice thickness. The ICESat mission has allowed for the accurate, global retrieval of sea ice thickness. Results from the ICESat mission have revealed rapidly declining sea ice thickness and volume in the Arctic, these sea ice losses have influenced the heat budget of the Arctic leading to increased ocean heat transport

into the polar regions. The continuity of the ICESat altimetry data set is critical for determining whether long-term trends and changes are occurring in the sea ice cover and polar climate. In support of this goal, NASA is currently conducting Operation IceBridge, the largest airborne operation ever conducted in the polar regions meant to continue the observations of ICESat over land and sea ice until the launch of ICESat-2. The launch of ICESat-2 will then allow for the continuity of the ICESat and IceBridge record allowing, for the first time, an analysis of the long-term global sea ice thickness record.

In order to advance the use of altimetry data for sea ice studies, the PI seeks membership on the ICESat-2 science definition team (SDT) to guide the direction of the ICESat-2 mission to be successful in the collection of useful scientific data over the cryosphere with an emphasis on sea ice regions. Specifically, work towards the following goals is proposed:

1. Provide expertise on data requirements, and instrument configurations to inform the science team and enable the mission to achieve the science goals.

2. Work towards the development of algorithms for the production of geophysical sea ice data products including surface elevation, sea ice freeboard, and sea ice thickness from MABEL data which can then be applied upon the launch of ICESat-2.

3. Provide expertise and work towards the calibration and validation plans for the mission so that consistency can be maintained between the ICESat, IceBridge, and ICESat-2 missions.

Ronald Kwok/Jet Propulsion Laboratory
Character of the Seasonal Sea Ice Cover of the New Arctic

The recent decline in the extent of Arctic summer sea ice has resulted in a dramatic shift in its composition. With the record minimum in summer ice extent in 2012, seasonal ice now covers more than half of the Arctic Ocean. This rapid shift to a new seasonal ice regime, in less than a decade, is likely to have important implications on the interplay of the thermodynamics and dynamics of the ice cover in its response to external forces at different length and time scales. With the large expanse of thinner and mechanically weaker sea ice, it is anticipated that the dominant processes that govern the coupling between the ocean, atmosphere and sea ice will change as the ice cover becomes more sensitive to processes that were less significant (e.g. ice deformation) in a multiyear ice regime. We propose an integrative analysis of several key variables of the present-day seasonal ice cover with available observations from ICESat, IceBridge, CryoSat-2, field observations, data sets of high-resolution ice drifts from RADARSAT and Envisat, and retrievals of multiyear ice coverage from QuikSCAT and ASCAT. Together, these data sets span more than a decade. The variables include the distributions of thickness and roughness of the ice cover, its drift and deformation, and the thickness of the overlying snow cover. The mean and extremes of the seasonal ice thickness distribution are expressions of growth and deformation (rafting and ridging), and the snow cover is a key

variable in the surface heat budget and the associated melt water plays a key role in ice cover decay during seasonal transitions. We will investigate in detail the trends in deformation and drift speed, and growth rates on the behavior of the ice cover at different time and spatial scales. Our examination will provide insight into the changes in the transition from a multiyear to first-year ice regime and will allow us to address the realism of current numerical models and their parameterizations, and the processes governing the atmosphere-sea ice-ocean system. Further, the results will serve to inform the required space-time sampling and accuracy for the observation of an ice cover that is more responsive to external forcing.

Dimitris Menemenlis/Jet Propulsion Laboratory
Oceanic and Atmospheric Drivers of Recent Arctic and Southern Ocean Sea Ice Changes from a Global, Eddying, Coupled Ocean and Sea Ice Simulation Constrained with ICESat, IceBridge, and CryoSat-2 Data

The proposed work leverages the expanding record of cryosphere measurements, especially satellite and airborne observations of sea ice thickness collected by the United States and European Space Agencies (NASA and ESA), and the modeling and data assimilation infrastructure developed by the Estimating the Circulation and Climate of the Ocean (ECCO) consortium to (i) characterize processes of change in the Arctic and Southern Ocean sea ice by reconstructing the evolution of the global ice thickness distribution, (ii) investigate drivers of coupled cryosphere climate variability by using the sea ice-ocean state estimate to analyze how changes in atmospheric forcing, ocean heat content and circulation, and sea ice dynamics and thermodynamics have contributed to the observed sea ice variability, and (iii) inform improvements in the representation of coupled atmosphere, ocean, and sea ice processes in Earth System Models.

The key technical objective is to create a global, eddying, physically-consistent estimate of the time-evolving coupled ocean and sea ice state for the period 2003 to present, encompassing the complete ICESat data collection period and the 2007 and 2012 sea ice minima. This technical objective is made possible by prior and ongoing work carried out under separate contracts as part of the ECCO consortium. The specific technical contribution of the proposed work will be the addition of ICESat, IceBridge, and CryoSat-2 sea ice thickness data constraints to the ECCO cost function. Although the modeling and estimation infrastructure is already in place, full utilization of ICESat, IceBridge, and CryoSat-2 freeboard retrievals in ECCO requires considerable analysis and experimentation in understanding the strengths and limitations (i.e., the error budgets) of the model and of each data set.

The resulting time-evolving coupled ocean and sea ice solution will be used to investigate drivers of recent observed changes in sea ice thickness and extent, both for the record-breaking September ice extent minima and dramatic loss of thick multi-year ice in the Arctic Ocean as well as for Southern Ocean sea ice patterns of expansion and contraction. The model adjustments and model-data residuals will be analyzed and quantified with the goal of identifying deficiencies in observations of sea ice thickness and in the coupled ocean and sea ice model. In this way, we aim to motivate and inform improved retrieval

algorithms and improved representation of ocean-ice-atmosphere interactions in Earth System Models.

On a longer time horizon, the proposed work will lead to a fuller utilization of NASA and ESA sea ice data products in support of global climate modeling; it will enable rapid utilization of new data from ICESat-2, when they become available, to extend the global sea ice thickness record and to investigate sea ice processes in the climate system.

James Morison/University of Washington
Dynamic Ocean Topography in the Sub-Arctic Seas From ICESat

We propose to derive and interpret dynamic ocean topography (DOT) from ICESat altimetry for the sub-Arctic seas from 2004 to 2009. DOT is the elevation of the sea surface above the geoid. Its horizontal gradients are the driving force of geostrophic upper ocean circulation and the difference between DOT and ocean bottom pressure (OBP) is equivalent to the steric pressure anomaly (StP), which is a measure of average ocean density and freshwater content (FWC). These properties, circulation and freshwater content, are important in the sub-Arctic seas because these regions are the sites of convective vertical heat exchange that is a critical link in the global thermohaline circulation, and because sub-Arctic circulation patterns are critical to exchange with the Arctic Ocean and the ice cover and circulation in the Arctic Ocean.
Sampling DOT in the sub-Arctic has been problematic because of the 62Â°-64Â° N northern latitude limit of the TOPEX/Poseidon/Jason satellite altimeters. Further, although the Gravity and Climate Recovery Experiment (GRACE) samples OBP in the sub-Arctic seas very well, the boundary currents that dominate circulation in the Greenland and Labrador seas are in nearshore regions where GRACE ocean signals are partly masked by gravity signals arising from mass changes on the Greenland ice sheet.

ICESat DOT in the sub-Arctic seas would directly address both these problems. ICESat-derived DOT and upper ocean circulation have been successfully compared to dynamic heights and circulation measured in the Canada Basin by in situ hydrography [Kwok and Morison, 2011]. In combination with GRACE-derived OBP, ICESat-derived DOT has revealed trends in circulation and freshwater pathways over the whole Arctic Ocean from 2004 to 2008 [Morison et al., 2012]. ICESat altimetry has also been compared to TOPEX/Poseidon on a global ocean scale [Urban and Schutz, 2005], but it has not been used for DOT and circulation determination for the open ocean, particularly the sub-Arctic seas. This study will fill the satellite altimetry gap between the mid-latitude oceans and the Arctic Ocean during a period (2004-2008) of profound change in the high latitudes.

Because changes in OBP are the sum of changes in DOT and steric pressure, ICESat DOT combined with in situ hydrographic measurements of StP give an estimate of OBP that is not contaminated by leakage of gravity signals due to changes in the Greenland ice sheet. This ICESat-hydrography-derived OBP will be compared to GRACE OBP to determine the leakage of ice sheet mass signal into the GRACE OBP and vice versa.

Interpretation of the ICESat DOT observations will rest on techniques we have used for understanding the circulation and freshwater changes in the Arctic Ocean. Compared to the Arctic Ocean work, we will be aided by absence of the Arctic Ocean requirement of finding open water leads for DOT determination and by the quantity of supporting Argo hydrographic data available for the sub-Arctic seas. We also look forward to being able to compare ICESat results to TOPEX and Jason results in an overlap region extending to at least 60Â°N. As a side benefit, the lessons we learn deriving open ocean DOT from ICESat will inform design of the open ocean processing schemes for ICESat2.

In deriving sub-Arctic DOT from ICESat, we will be aided by our unfunded collaborator Ron Kwok at JPL. Don Chambers and Jenny Bonin of the University of South Florida will advise on GRACE OBP, providing special GRACE products and the GRACE de-aliasing model. Model output we would use to help interpret the DOT and OBP observations will be provided by Jinlun Zhang (PIOMAS) and Ron Kwok (ECCO-2). Kathie Kelly will provide TOPEX altimetry for comparison with ICESat DOT.

Laurence Padman/Earth & Space Research
Multi-Sensor Analyses of Antarctic Ice Shelf Response to Climate Variability

The Antarctic Ice Sheet mass budget is dominated by accumulation through snowfall and dynamic loss to the oceans via the gravitationally forced flow of ice streams and glaciers. Antarctica is currently providing a small contribution (~+0.2 mm/year) to total global sea level rise of ~+3.2 mm/year. However, based on projected climate change, paleo analogs and recent modeling, its contribution may increase dramatically by later in the 21st century.

Most mass loss from the Antarctic Ice Sheet ultimately occurs from the ice shelves, the floating extensions of inland glaciers and ice streams. Ice shelves can act to "buttress" land-ice loss: recent observations show that reductions in extent and/or thickness of an ice shelf can be followed by acceleration and surface drawdown of the adjacent grounded glaciers and ice streams, increasing global sea level. Changing ice shelf extent and thickness impacts coastal Antarctic circulation including fluxes of freshwater and dense shelf water that are subsequently distributed to the broader Southern Ocean and beyond. Ice shelf variability therefore has affects sea-level rise, Southern Hemisphere sea ice, the ocean conveyor belt, the global climate system, and Antarctic ecosystems. Ice shelves are also sensitive indicators of changes in oceanic and atmospheric forcing acting on marine-terminating glacier and ice-stream systems. With these influences in mind, the goals of our proposed studies are as follows:

Primary project goals: Develop a detailed history of Antarctic ice shelf mass and stress changes on seasonal-to-interannual time scales and small spatial scales; improve our understanding of the environmental processes that cause these changes; and assess whether proxies for variability of the ice shelf mass budget can be obtained from coarse-grid global climate models (GCMs).

Our main data sources for this study are: ICESat-1 laser altimeter data (2003-2009); Operation IceBridge (OIB) airborne laser altimeter and radio echo sounding (RES) ice thickness data (2009-present); CryoSat-2 radar altimeter (RA) data (2010-present); and European Space Agency (ESA) RA satellites ERS-1, ERS-2 and Envisat (1992-2012). These will be augmented with Geosat (1985-1989), MODIS visible imagery, SSM/I and AMSR-E sea ice concentrations, atmosphere and ocean reanalysis models, GCMs and, as required, existing in situ data sets such as ice-shelf GPS and ocean hydrography and velocity records.

We propose the following closely inter-related activities.

1) Develop accurate, continuous, and high-resolution (in space x and time t) records of surface elevation h(x,t) for all Antarctic ice shelves from 1992 to near the end of the proposed research in 2016, including seeking methods for heterogeneous multi-satellite altimeter data integration.

2) Investigate whether observations of fine-scale ice shelf topographic features can improve our understanding of changes in specific mass balance terms and stress fields. For this activity, we will focus on two ice shelves representing limits of current ice shelf state; one large and presently stable and one smaller and currently thinning rapidly.

3) Relate observed variability of h(x,t), ice shelf mass balance terms, and fine-scale topography to changes in the ocean and atmosphere resolved by global climate models (GCMs).

We will also support colleagues' analyses of Greenland ice shelves which, although relatively few and small, may play significant roles in the response of the northern Greenland Ice Sheet to ocean change.

The proposed work directly addresses the program goals described in the 2012 NASA ROSES call for A.49 STUDIES WITH ICESAT AND CRYOSAT-2 and NASA's Strategic Goal 2, Objective 2.1.5, to "Improve understanding of the roles of the ocean, atmosphere, land and ice in the climate system and improve predictive capability for its future evolution".

C. K. Shum/Ohio State University
Improved Quantification of Global Mountain Glacier Mass Balance Estimates

PROBLEM TO BE SOLVED AND OBJECTIVES. Shrinking mountain glaciers and ice caps, and their seasonally delayed melt water feeding the world's major rivers can significantly affect the stability of freshwater availability especially under anthropogenic climate change. The Asian High Mountain (AHM) glaciated system borders eight countries and its glaciers and snow covers are sources of 19 of the world's major rivers, bringing water resource to 3 billion people, or 43% of the world's population, in the region. It is important to understand the current state of these other glaciers and ice caps

in the world. The current knowledge of the contributions of mountain glaciers and ice caps to global sea-level rise has a wide range: from 0.55 to 1.4 mm yr-1 equivalent sea-level rise, and the discrepancy represents a significant amount of freshwater wastage of 304 gton yr-1. We propose to provide an improved quantification of the world's mountain glacier mass balance estimate using ICESat laser and CryoSat-2 radar interferometric (SARIn) altimetry, to narrow the uncertainty of mountain glacier's contribution to global sea-level rise, and to generate long term, validated and integrated records of ICESat and CryoSat-2 elevation change and mass balance for the world's mountain glacier systems and ice caps.

APPROACH AND ANTICIPATED RESULTS. Our approaches include: (1) the use of SAR (TerraSAR-X, SRTM-X, ASTER/SRTM-C, ALOS) and CryoSat-2 SARIn radar waveform, along with the new Randolph Glacier Inventory (V2.0) for classifying especially rock glaciers in the AHM glacier regions, to improve the estimates the total glaciated areas needed for computing mass balance, (2) development of SARIn/SAR/LRM CryoSat-2 land waveform retracking techniques to improve elevation retrieval, and use historic radar altimeter profiles (TOPEX, Envisat, Jason-2, AltiKa) and other DEMs to provide improved gradient corrections to generate ICESat and CryoSat-2 elevation time series, (3) the use of SMB, temperature, and if applicable GRACE to estimate firn cmpaction/ice column density corrections, and to mitigate radar penetration errors, (4) to validate resulting mass balance time series using in situ data, other altimeter data and GRACE and to obtain uncertainty estimates, and (5) to conduct glacial dynamic modeling with a focus in the Himalayan glacier system to understand the dynamic process and to conduct projection of glacier mass balance to future sea-level rise.coarse resolution (~200 km) GRACE data to estimate composite mass changes in the region.

RELEVANCE TO NASA AND THE ICESAT/CRYOSAT-2 NRA. Our anticipated results include improved quantification of mountain glaciers' and ice caps' contribution to sea-level rise, and to study their coupling to the Earth System. This proposal directly addresses NASA's NRA: Studies With ICESat and CryoSat-2: "Changes in the major glacial systems of North & South America, and Asia.., and their significance to sea-level rise and Earth System". The proposal directly addresses NASA Science Questions within NASA's Strategic Plan Sub-goal 3A, "study planet Earth from space to advance scientific understanding and meet societal needs".

Benjamin Smith/University of Washington
Ice-Sheet Dynamic Change from Decade-Spanning High-Resolution Altimetry Records

The two great ice sheets have undergone large changes over the past decade, increasing their contribution to global ocean levels by as much as three fold. In this project we investigate two important ice-sheet sectors that have made large contributions to sea-level rise: the Bellingshausen coast of Antarctica, and the Northwest coast of Greenland. Data continue to become available that tell us about the changes happening in these regions, but detailed analysis is needed, first, to extract information about elevation change and

velocity change, and, second, to infer the glaciological processes that have led to these changes. Towards these goals we propose two glaciological tasks, and two that will make important cryosphere data available and useful to this project and to other researchers. Our glaciological tasks are:
(1) We will develop elevation-change records for our survey areas, using a data from a combination of sources to extract changes at scales relevant to changes in glacier dynamics. These records will span the ICESat-1, IceBridge, and Cryosat-2 periods, ending just before the launch of ICESat-2. They will resolve changes in outlet glaciers, and give accurate estimates of regional mass-balance rates.

(2) We will analyze these elevation-change records together with ice velocity data to infer the dynamic processes leading to surface-elevation changes and to infer the sensitivity of the ice sheet to ongoing changes in atmosphere and ocean temperatures. For this goal we will develop basal-shear-stress models and ice-dynamic models that can be perturbed using different scenarios of future sea level, grounding-line retreats, and elevation changes. This part of the project will help with predictions of global sea-level contributions from our field areas, and with general understanding of the processes at work in glacier-discharge and melt variations.

Our data-improvement tasks are:
(3) We will develop techniques to allow the correction of Cryosat-2 radar altimetry data for biases caused by subsurface scattering within the ice sheet. These corrections will be developed using comparisons between Cryosat-2 data and laser-altimetry data, and using comparisons between aircraft laser-altimetry and Ku-band radar altimetry data collected simultaneously by NASA's Operation IceBridge.

(4) We will develop baseline photogrammetric DEMs for the field areas that will be made available for comparison against ICESat-1 and ICESat-2 altimetry data, allowing mapping of decadal-scale elevation-change trends at high spatial resolution.

Data processed in (3) and (4) will be used in accomplishing (1) and (2), but will also be shared with the broader community to help with other groups' analysis of ice-sheet change.