CRYOSPERIC SCIENCE
Abstracts of selected proposals
NNH13ZDA001N-CRYO

This synopsis describes the proposals selected in response to the NASA Research Announcement Cryospheric Science which is subelement A.13 of NASA ROSES 2013.

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; http://nsidc.org/data/icebridge/), including observations from NASA's IceBridge Mission (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.

Out of 32 submitted proposals, 10 were selected for awards. The total funding for the program is approximately $1.5 million per year for three years. The Principal Investigator, institution, and investigation title are listed below.

Alberto Behar/Arizona State University
Towards an Operational System for Estimating Greenland Ice Sheet Thickness Change From Altimetry

NASA and other agencies are invested in obtaining measurements of Greenland Ice Sheet surface elevation with the objective of constraining the ice sheet's contribution to present and future sea level rise. Air and space-based altimetry provides the only direct means for observing changes in ice thickness at high spatial resolution. A major limitation of repeat altimetry measurements, however, is that variations in the density of surface accumulation and the firn layer must be constrained in order to extract ice thickness and mass change. As thinning initiated at the margin of the ice sheet propagates inland this limitation is becoming more problematic for two reasons: first, as thinning propagates and diffuses, the rate of thinning deceases relative to variations in accumulation and

compaction, becoming more difficult to observe. Second, substantial thinning is now occurring in the wet snow and percolation zones of the ice sheet where variations in density are particularly unconstrained and models perform poorly. Additionally, recent warming and historically extreme melt events may be substantially changing the density of the firn, effecting altimeter measurements.

Here we propose to develop and test deploy in situ sensor packages that will aid the deconvolution of surface change observations. Each sensor package will consist of a device for measuring deep-firn compaction, a snow pillow for measuring accumulation mass, and an echo sounder for measuring accumulation thickness. The sensors will broadcast their data daily via iridium uplink and will be designed to withstand at least 2 years of accumulation, depending on location, reducing the revisit time. The sensor data will be used to calibrate meteorological reanalysis model output that will drive a surface accumulation and firn compaction model. For this test phase, we will deploy one sensor above Jakobshavn Isbrae in the west, and another above Helheim Glacier in the southeast; two regions undergoing substantial dynamic changes. The goal of this project will be to provide a foundation for a more extensive operational system in concert with the launch of ICESat-2 planned for 2016.

Cecilia Bitz/University of Washington
Evaluating the Climatology, Physical Processes, Data Errors, and Model Biases in Snow Depths on Arctic Sea Ice in IceBridge and the CESM

Despite its importance for physical, chemical, and biological systems, little is known about current trends in snow depths on sea ice and how snow depths will respond to climate change in the future. The goals of our project therefore are to (i) investigate the physical processes that link sea ice with its snow cover, (ii) understand how these processes respond to greenhouse warming, (iii) assess a valuable new observational dataset and compare it to the Community Earth System Model version 1 (CESM1), and (iv) help improve sea ice and snow physics and projections in the CESM1. The NASA airborne mission Operation IceBridge is now conducting annual surveys in March-April over sea ice since 2009 that provide simultaneous measurements of snow depth, sea ice thickness, and sea ice type. The existing 5 years of IceBridge data, along with the expectation of new measurements during phase 2 of the IceBridge mission, provide a unique opportunity to examine how snow and sea ice occur together in the Arctic today.

We will use IceBridge datasets to evaluate the present-day simulation in CESM1 of the distributions of snow depths across the flight transects and at the local-scale as a function of sea ice type and thickness. After careful evaluation of the CESM1, we will use the model to study feedbacks year-round by diagnosing the seasonal evolution of snowfall and accumulation on sea ice, as well as the consistency of the snow depth to sea ice type, thickness, and concentration relationships in space. CESM1 will also be used to investigate snow depths on sea ice in future climate projections. In light of the comparison with observations, we will work with model developers to make and test improvements to the snow scheme in the developmental version of CESM.

This project builds on recent work done by the PI and co-PI to assess snow depths and sea ice independently in IceBridge datasets and global climate models. Here we propose to combine our expertise to evaluate observations and model integrations together at a process level to determine what mechanisms control snow-sea ice interactions now and in the future. Our proposed activities include an assessment of the five-plus years of IceBridge data to include yearly means, full-record mean, trend, and variance statistics. Our analysis will include an improved estimate of the snow-depth error. Our proposed project improves understanding of the role of snow on sea ice, which has been overlooked in studies about Arctic sea ice decline and has the potential to improve prediction of sea ice and Arctic climate.

Indrani Das/Lamont Doherty Earth Observatory
Improved Surface Mass Balance Mapping of Antarctica by Quantifying Wind-Blown and Sublimated Snow

This proposal addresses ROSES 2013 NASA Program A.13 Cryospheric Science Subelement 2 and 3 which calls for research to determine the mechanisms controlling mass balance of Antarctic ice sheet and connections to the atmosphere and to validate and improve predictive models of the contribution of land based ice to sea level changes. Each year, tens of gigatons of snow on the Antarctic ice sheet are ablated by persistent near-surface winds interacting with ice sheet surface topography. We have identified persistent wind scoured and glazed areas primarily in East Antarctica with zero to negative surface mass balance (SMB) by developing empirical models that use airborne radar, lidar, regional atmospheric models, and satellite based estimates of surface grain size and radar backscatter. These wind-scoured and glazed areas result in extensive though localized regions (# 200 km2) with reduced surface accumulation. These zones are persistent for tens of thousands of years because they are controlled by steep bedrock topography. The snow eroded from these zones is either redeposited or lost through sublimation. Near the coast, winds often blow significant amounts of surface snow from these zones into the ocean. SMB estimates over Antarctica rely on sparse point measurements or coarse atmospheric models that do not capture these local processes and overestimate the net mass input by more than 40 Gt/yr.

A major goal of this proposal is to improve the net SMB of Antarctica by incorporating the mass lost due to wind-drifted sublimation over the wind-scour zones. In recent studies, the majority of the larger glaciers in East Antarctica have a more positive mass budget estimate compared with satellite estimates. The improved SMB from this work will account for mass loss over the wind-scoured and glazed areas and will improve Antarctic mass budget estimates, particularly of East Antarctica. This proposal aims to expand and refine the initial work the PIs have done on mapping and quantifying wind scour, wind glaze, megadunes, blue ice, and blowing snow using higher resolution input datasets. To do this, we will use a combination of satellite and airborne remote sensing products, and simple models of atmosphere-snow interaction. Another major goal of the proposal is to reconcile the mass-budget estimates over East Antarctica using improved

SMB with gravitational changes determined by GRACE. This proposed work has direct implications to global climate change and to Antarctic ice sheet contributions to sea level rise.

The goals of this research are to:
1) Delineate the regions of zero to negative SMB continent-wide with an improved high resolution wind-scour product. This effort will focus on developing an enhanced algorithm that will reconcile the spatial differences in the wind-scour and the surface glaze mapping. We will also investigate the inter-relation between the wind-scour and wind-glaze product to identify the physical processes controlling spatial differences.
2)Validate the improved wind-scour map using IceBridge radar data and ground based radar data from traverses (e.g., US-International Trans Antarctic Scientific Expedition (ITASE)).
3) Quantify the mass lost through sublimation and ocean deposition as well as the redeposition using IceBridge radar data, CALIPSO and ground traverses. The enhanced quantification of mass loss will be used to improve the local SMB estimates.
4) Estimate continent-wide mass balance rates by using the mass-budget method computed regionally with the improved SMB from Goal 3 and compare with GRACE observations.

This proposal uses nine NASA airborne and satellite datasets. We will use IceBridge shallow ice and deep ice radar and ATM datasets, MODIS visible and grain size imagery,MISR surface roughness, QuickScat wind products, RADARSAT backscatter, CALIPSO wind-blown snow data,GRACE mass balance, RACMO2 derived SMB and wind speed, the anticipated CRYOSAT DEM and ICESat profiles.

Ellyn Enderlin/University Of Maine, Orono
Intra-Annual Force Balance Analysis of Tidewater Glaciers

The primary process responsible for uncertainty in sea level rise (SLR) projections is the dynamic acceleration and thinning of tidewater glaciers (TWG). TWG acceleration is likely triggered by external perturbations supplied by the atmosphere and/or ocean, but internal controls, like differences in outlet glacier geometry and ice rheology, likely influence the sensitivity of TWGs to such perturbations. Consequently, understanding the relative roles of internal and external controls in modulating the TWG force balance is a key step towards modeling the long-term evolution of glacier behavior and associated sea level change.

Our primary objective is to advance understanding of internal and external controls on TWG dynamics. We will achieve this goal by synthesizing a near-daily, high resolution, 2-D force balance time series for two glaciers that have rapidly retreated through basal depressions: Helheim Glacier, Greenland and Columbia Glacier, Alaska. These glaciers share several key characteristics (e.g., width, speed, large and time-invariant accumulation zones) that are similar enough to facilitate comparison, but have other

characteristics (e.g., ice temperature, pinning points, total area) that can be used to elucidate the mechanics of unsteady dynamics that characterize calving glaciers.

Not only do the two glaciers provide recent behavior ideal for analysis, these two glaciers have robust existing data sets assembled for an examination of TWG dynamics with unprecedented detail. Our group will construct force balance time series, extending from 2010-2015 from near-continuous 11-day TSX pairs, satellite-derived digital elevation models and IceBridge altimetry data. Sub-daily time-lapse records will be leveraged to significantly increase the temporal resolution of the remote sensing series. Data exist to characterize and constrain environmental processes including tides, hydrography, meteorology and mass balance to assess how external perturbations modify the balance of forces. The observational resources available for this project represent the most comprehensive existing dataset for any TWG. Our team has rich experience working on TWG in Greenland and Alaska, and focused attention to these data will enable new understanding of force balance evolution, unsteady TWG dynamics, and in turn, improved SLR projections.

Our goals include 1) resolving how the near-terminus, full-width (i.e., glacier-wide) force balance responds to discrete and short-term perturbations; 2) assessing internal sensitivity of TWG to external perturbations; and 3) determining the critical temporal/spatial scales of observation and dynamic response. These goals align directly with the primary goals of the NASA Research Announcement and the A.13 Cryosphere Program by, "determin[ing] the mechanisms controlling mass balance and dynamics of the ice sheets…including studies aimed at improving fundamental understanding of ice flow…and connections to the ocean…and atmosphere." • This project also "use[s] 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." •

Deliverables from the project will include: 1) detailed high temporal-resolution velocity, thickness change, terminus position and melange condition datasets, 2) sub-monthly strain rate and force balance fields, and 3) compiled meteorological and oceanographic data. Each product will be compiled for Columbia and Helheim glaciers for the 2010-2015 period. These gridded products will be submitted in a format suitable for additional observational and numerical modeling studies to the National Snow and Ice Data Center (NSIDC). We will also provide practical spatial and temporal sampling requirements useful for future NASA mission planning.

Kenneth Jezek/Ohio State University
Radiometric Approach for Estimating Relative Changes in Intra-Glacier Average Temperature

We propose to investigate the degree to which ultra high frequency (UHF) radio emission can be used to investigate subsurface physical temperature in the polar ice sheets. We propose to combine electromagnetic-emission forward-models with models of depth-dependent physical temperature in the ice sheet. Emission models will include layering

and boundary conditions at the ice sheet surface and base. Temperature models will be parameterized with variables including accumulation rate, geothermal heat flux, surface temperature, and flow speed. Electromagnetic absorption will be modeled using dispersion processes together with impurities, and also with existing direct measurements of loss through polar ice. Using our models and available satellite data, we will address four research goals: (i) investigate the depth to which physical temperature in the ice sheet influences brightness temperature at the surface, (ii) investigate the physical origin of Tb anomalies observed in Antarctica by ESA's 1.4 GHz Soil Moisture and Ocean Salinity (SMOS) satellite, (iii) extend our analysis to include the Greenland Ice Sheet, and (iv) investigate approaches for utilizing NASA's Soil Moisture Active Passive Satellite (SMAP) brightness temperature and radar data in studies of intra-glacier temperatures.

Eric Larour/Jet Propulsion Laboratory

Modeling the Dynamic Evolution of the Greenland Ice Sheet Under Different Scenarios of Atmospheric Forcings, Using ISSM

During July of 2012, the percentage of the Greenland surface exposed to melt was the largest in recorded history. And, even though evidence of increased melt rates had been captured by remote sensing observations throughout the last decade, this particular event took the community by surprise. How Greenland ice flow will respond to such an event or to increased frequencies of extreme melt events in the future is unclear, as it requires detailed comprehension of Greenland surface climate, basal hydrology, and ice-ocean interaction, as well as the ice sheet's sensitivity to the uncertainties associated with each of these processes. In the proposed study, we will use the Ice Sheet System Model (ISSM) and remote sensing observations to focus specifically on determining the Greenland ice flow sensitivity to surface climate. We will do so asking the question: how do the errors in surface forcing translate to uncertainties in outlet glacier mass flux, and therefore contributions to sea level? To answer this question, we propose to use uncertainty quantification (UQ) tools to determine the dynamic response of Greenland outlet glaciers to changes in surface mass balance (SMB). Parameter-space studies will be performed to compare different SMB forcing products, including output from two high-resolution mesoscale climate models, high-resolution SMB reconstruction, observationally-derived analyses, and remote-sensing data (including Operation Ice Bridge datasets of surface height changes, spanning 1993-present). Forward simulations will be forced at varying temporal resolutions ranging from sub-monthly to decadal, and assessed for their impact on dynamic change of ice flow in different key outlet glaciers. Sensitivity analyses will be performed to determine how perturbations in each component of SMB affect model output and then used to investigate the locations where variations most significantly affect the ice sheet, and on what timescales. We will also apply sampling analyses, using estimates of error in SMB components to quantify uncertainty in model diagnostics during short-term transient ice flow simulations. These results will allow us to investigate the discrepancies between models and observations and determine the processes that should be improved in numerical modeling. We propose to (1) identify which SMB components most significantly affect Greenland ice flux, and on what

timescales; (2) understand the uncertainties in modeled sea level projections associated with errors in SMB and its associated components; (3) determine the regional resolution requirements for simulations of the Greenland ice flow; (4) investigate the likelihood and extent of shifts in the ice sheet dynamic flow due to trends in SMB; and (5) compare results with remote sensing observations to evaluate the model and ultimately determine what key processes may be missing or mis-represented. Remote sensing observations including that of ice sheet and bedrock topography, ice flow, and surface mass balance are necessary for all aspects of this work, and will be used extensively in model initialization and parameterization, as well as data assimilation, and estimates of SMB error margins and model validation.

Overall, the proposed work will contribute to a better understanding of how surface climate drives changes in ice dynamics and will assess the likelihood that atmospheric changes can be responsible for large shifts in ice sheet flow dynamics.

Mathieu Morlighem/University of California, Irvine
Greenland Bed Mapping Using Mass Conservation, IceBridge and InSAR Data

Detailed maps of bed elevation and ice thickness are essential to many glaciological applications, including ice sheet numerical modeling and ice sheet mass balance assessment. In the last few years, NASA's Operation IceBridge has provided a quantum leap in the density of radar-derived ice thickness measurements of ice sheets, especially in Greenland. In order to be usable by ice sheet models, these along-track measurements are interpolated onto regular grids, typically using Kriging (Bamber et al. 2001, Bamber et al. 2013). While this approach provides continuous maps of bed elevation, it generates artifacts (bulls eye, string-of-beads) and errors away from radar tracks that make these products impractical for high-resolution ice flow modeling of fast flow regions. To overcome this issue, we have devised a method based on mass conservation that optimally derives bed elevation at high resolution using the radar-sounding profiler data in combination with independently gridded high-resolution ice velocity data. Mass conservation preserves features and delineations, and reveals a bed structure, carved by the waxing and vaning that plays a fundamental role in the control of ice flow channels. In particular, the results highlight the presence of ice-covered fjords, with valleys, ridges, bumps and hollows that reproduce with fidelity and high resolution what the three-dimensional bed topography looks like. In an ongoing project, we mapped a large fraction of the periphery of the Greenland ice sheet.

Here, we propose to extend this effort by mapping the entire periphery of Greenland (excluding ice shelves), extend the algorithm inland to the limit of what is possible to achieve with the existing data, and construct a new bed topography and ice thickness of Greenland. This dataset will provide a continuous and seamless digital product at ~400 m resolution that will be posted at the National Snow and Ice Data Center, Boulder, CO. As part of this study, we will also employ the Ice Sheet System Model (ISSM) to evaluate the impact of this new dataset on decadal to century time scale projections of glacier evolution compared to simulations using prior maps. This exercise will help quantify the

impact of the new bed topography on glacier and ice sheet evolution from models, and demonstrate the practical use of the data from improving models.

Laurence Padman/Earth And Space Research
High-Frequency Variability of Arctic Sea Ice

Arctic sea-ice concentration, extent, mean thickness and age have rapidly declined over recent decades. Observations and models suggest that the Arctic may be transitioning from a primarily multi-year, perennial ice pack to a seasonal thin-ice cover reminiscent of Antarctic seas. However, we still don't sufficiently understand the processes and complex feedbacks relating Arctic sea ice characteristics to forcing from either the atmosphere or the ocean. As a result, we do not yet have confidence in projections of sea-ice behavior over the decade-to-century time scales of most relevance to assessing the cost-effectiveness of various mitigation and adaptation responses.

This proposal focuses on high-frequency ("HF"; periods of hours to days) variability of the Arctic sea-ice cover, as (a) a net contributor to climate-relevant ocean/atmosphere heat and freshwater fluxes, and (b) a method for diagnosing sea-ice/ocean coupling. These processes generally depend on bathymetric and other variability (e.g., ocean fronts and eddies) at small spatial scales (10's of km) that are not resolved in modern coupled climate models. We know that sea ice responds to HF ocean processes including tidal currents and near-inertial oscillations excited by wind forcing. Models suggest that interactions between HF ocean processes and sea ice can have a large impact on time-averaged sea-ice production, extent and thickness, and surface mixed layer development. Advection by low-frequency flows can lead to these effects on ice being broadly distributed well beyond the region of large HF ocean variability. I hypothesize that HF ocean processes will become more important to climate as the Arctic sea ice thins and becomes more seasonal.

The project's Primary Goals are: (1) Use single-swath AMSR-E passive microwave estimates of ice concentration for 2002-2011 to document interannual variability of the HF signal in Arctic sea ice concentration; (2) Quantify the net impact of HF ocean variability on broader-scale sea-ice variability as a mechanism for altering Arctic ocean-atmosphere heat and freshwater exchanges, and sea-ice growth and decay; and (3) Develop new ocean barotropic tide models to satisfy modern accuracy and spatial resolution requirements of Arctic and Greenland research communities.

I address Goals (1) and (2) through methods developed by Mack, Padman and Klinck [2013: GRL] for analyzing tidal impacts on Antarctic sea ice, augmented by analyses of output from an NSF-funded, coupled 3-D ocean and sea-ice model of the eastern Arctic Ocean. I address Goal (3) through now-standard procedures for inverse modeling of barotropic tides. Our present best pan-Arctic tide model, AOTIM5, is aging and no longer satisfies the community's accuracy requirements for either elevation or current predictions. We will also develop a high-resolution circum-Greenland tide model (dx=1

km), motivated by recent requests from researchers interested in land-ice/ocean interactions at the marine margins of the Greenland Ice Sheet.

Our primary data sources are single-swath passive microwave estimates of ice concentration from AMSR E, ICESat (2003-2009) estimates of averaged sea ice thickness, and laser altimeter measurements of instantaneous sea-surface elevation for open water within the ice pack. We will also test the use of the lower spatial resolution SSMR and SSM/I products for detecting HF variability of ice concentration over the full satellite record (~33 years).

Relevance: The proposed work directly addresses the specific program goals described in the 2013 NASA ROSES call for A.13 Cryospheric Science, "Quantification of the mechanisms of sea ice loss from remote sensing; especially the roles of surface melting and export" and, secondarily, "Integration of bed mapping and bathymetric data to support ice sheet models".

Mark Simons/California Institute of Technology
Subglacial Mechanics Using Repeat-Pass InSAR Measurements and Numerical Models of Temperate Ice Caps in Iceland

Understanding the role of subglacial hydrology and basal mechanics in controlling the flow of glaciers is a fundamental challenge in glaciology. Estimates of eustatic sea level rise and predictions of the future state of the cryosphere, from continental ice sheets to small mountain glaciers, hinge on our knowledge of the mechanics of glacier beds and the influence of surface meltwater flux on glacier flow. We propose to collect the observations necessary to produce time-series of high-resolution, low-noise interferometric synthetic aperture radar (In- SAR) data from multiple vantage points, high-rate GPS time series, and estimates of surface meltwater flux. We will use these observations to constrain numerical ice flow models addressing subglacial mechanics and hydrology of relatively small, land-terminating ice caps. To this end, we propose to collect airborne repeat-pass InSAR data using NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), as well as supporting field observations, for two temperate ice caps in central Iceland. These data will complement similar data collected with UAVSAR over the same ice caps in June 2012. Our plan calls for UAVSAR to collect data for six days in February 2014, the coldest time of year in Iceland, and six days in May 2014, the beginning of the melt season. We can broadly classify our overarching goals in terms of remote sensing and glaciological objectives.

We have three primary remote sensing goals. First, we will investigate the influence of surface moisture content on InSAR measurements of temperate ice. Our preliminary results suggest that differential surface moisture content causes phase shifts that bias InSAR measurements of surface ice velocity. Second, we intend to compare glacial velocities inferred from L-band UAVSAR data with earlier C-band ERS data and X-band COSMO-SkyMed data (via an existing collaboration with ASI/Matera). These comparisons will include velocity field estimates from both InSAR and pixel-tracking

techniques. Finally, we will characterize the behavior of L-band InSAR imaging for temperate ice in order to help plan for a future US InSAR mission (e.g., estimates of maximum and optimal repeat-pass times, characterization of temporal and seasonal behavior of InSAR correlation, and reliability of 1D and 2D model-constrained estimates of ice flow).

We define four glaciological goals. First, we will estimate wintertime velocity fields of Hofsjokull and Langjokull ice caps in central Iceland to (1) constrain fully 3D finite element models designed to estimate the bulk rheology of the ice and (2) to compare with older ERS observations to constrain decadal-scale changes in winter velocities. Second, we will collect a time series of InSAR data at the beginning of the melt season to infer the temporally varying velocity fields at a time when we expect the subglacial hydrological system to begin to evolve from an inefficient system in which surface meltwater flux can reduce basal stress, thereby increasing the surface velocity, to a more efficient system in which the influence of surface melt on the basal stress diminishes with time. These velocity fields will constrain ice flow models designed to characterize the evolution of basal stress. Third, by comparing InSAR-derived velocity fields collected May 2014 to similar velocity fields inferred from UAVSAR data collected in June 2012, we intend to constrain characteristics of seasonal acceleration across entire ice caps. Finally, using comprehensive observations of ice caps whose outlet glaciers have unique characteristics, we will investigate potential dependencies of seasonal velocity variations on factors including bdrock topography, hydraulic gradient, and catchment area.

Laurence Smith/University of California, Los Angeles
Drainage Efficiency of the Greenland Supraglacial River Network

The production, transport, and export of meltwater from the surface of the Greenland Ice Sheet (GrIS) is critically important to our understanding of global sea level rise, yet remains one of the least-studied hydrologic systems on Earth. To date, efforts to measure GrIS contributions to global sea level rise have prioritized solid/dynamical ice losses, gravity anomalies from GRACE, and calculations of surface mass balance from automated weather stations and/or climate modeling. None of these explicitly considers the fast transport of meltwater through supraglacial river networks, despite their ubiquity across much of the ablation zone and being a primary mechanism by which surface meltwater is routed to the englacial and proglacial parts of the ice sheet.

This currently poor state of knowledge about supraglacial rivers impairs understanding of GrIS contributions to global sea level rise for at least four reasons. First, there is a recognized positive feedback between the penetration of surface meltwater to the bed and ice sliding velocity, thus impacting ice dynamics. Second, there is a growing appreciation in the Greenland science community that meltwater runoff contributes as much if not more mass loss to the global ocean than does solid/dynamical ice loss. Third, the intensity and areal extent of meltwater production on the GrIS surface are projected to increase. Fourth, virtually nothing is known about the hydraulics of GrIS supraglacial rivers, so numerical modeling of meltwater fluxes flowing over and into the ice sheet

cannot be done with confidence. To address this knowledge gap, the proposed research seeks to answer five science questions: 1) To what extent does ice surface topography dominate the movement of water across the ice sheet? 2) Are fluxes of supraglacial meltwater into the GrIS subsurface uniformly distributed or do some parts of the ice sheet receive greater concentrations of meltwater than others? 3) Do supraglacial river flows attain supercritical velocities? 4) Was a 100% efficient surface water drainage pattern observed following the extreme July 2012 melt event unusual or typical for the ice sheet? 5) How efficiently is GrIS surface meltwater transported off the ice sheet surface and out to the global ocean? To answer these questions, the project would build upon new remote sensing capabilities developed in previous NASA Cryospheric Sciences grant NNX11AQ38G (ending 8/18/2014). It would use archived and scheduled high-resolution visible/NIR imagery and stereo digital elevation models from WorldView-1/2, QuickBird, and Geoeye-1 satellites, and cold-season IceBridge Digital Mapping System (DMS) camera imagery, to study supraglacial river drainage pattern and flow efficiency for a ~15,000 km2 area of the ablation zone in western Greenland. Remotely sensed estimates of river flow direction, velocity and flux (discharge) would be calibrated/validated using a dataset of in situ hydraulic measurements from two field campaigns in the ablation zone. The operation and maintenance of four previously established terrestrial river gaging sites near Kangerlussuaq would be continued. Finally, all of these remotely sensed and field datasets would be incorporated into a GIS-based hydrologic modeling framework to enable a first "snow-to-sea" simulation of GrIS meltwater runoff that explicitly includes principles of open-channel flow through supraglacial river drainage networks.

This proposal is directly responsive to three general and specific goals of this research announcement concerning ice sheet mass balance, meltwater formation and connections to the ocean; predictive models of the contribution of land-based ice to sea level change; and synthesis of information on the Greenland Ice Sheet; and a specific request for utilization of IceBridge airborne datasets. It is also responsive to two broader NASA Research Objectives from the Science Plan for NASA's Science Mission Directorate 2007-2016.