Niels Andela/University of Maryland, College Park

Tropical Savannas in Transition: Tracking Global Savanna-Fire Interactions With ICESat-2

19-ICESAT2-19-0053

Savannas are the largest tropical biome and a critical component of the global carbon cycle, responsible for 30% of net primary productivity and 85% of burned area worldwide. However, fire activity has declined by about 25% across the biome in just the past 20 years. Less frequent fire activity allows woody vegetation to outcompete grasses, increasing carbon storage at the expense of other ecosystem services, including grazing and biodiversity conservation. These competing demands for services from savanna ecosystems have made it difficult to establish policy frameworks for carbon monitoring and ecosystem conservation, similar to REDD+ for tropical forests. New ICESat-2 observations of vegetation structure, combined with long time series of global fire activity, provide a unique opportunity to quantify the response of savannas to changing fire activity, including the ability to characterize pantropical changes in ecosystem structure from woody encroachment and fire suppression.

Here, we propose to use ICESat-2 data to quantify the impacts of changing fire regimes on ecosystem structure across the tropical savanna biome. The proposed effort has four main components. First, we will combine existing field observations and airborne lidar
data to understand the strengths and limitations of ICESat-2 for mapping ecosystem structure across global savannas. Second, we will quantify the distributions of woody cover and vegetation structure using ICESat-2 lidar data across the savanna biome, stratified based on fire history. This analysis will yield observational constraints on the accumulation of woody vegetation across gradients of land use and climate as a function of the time since last fire. Third, we will directly estimate ecosystem changes in burned and unburned savannas based on multiple years of ICESat-2 data (2019 – ). This effort includes an exploration of the potential benefits from repeat track ICESat-2 coverage at low latitudes, an important area for feedback from the science team on future mission operations. Fourth, we will engage with savanna ecologists and ecosystem modelers on the use of ICESat-2 data, bridging the knowledge and data gaps needed to expand the ICESat-2 user community, improve fire emissions estimates, and model changes in savanna structure.

The proposed analysis directly responds to the A.36 solicitation. We will use large volumes of ICESat-2 lidar data to quantify biome-wide ecosystem structure and changes in vegetation structure in response to fire. Savannas provide an ideal use case for ICESat-2 data; not only is the instrument expected to perform well in more open cover types, the savanna biome also covers broad gradients in vegetation structure from open grasslands with sparse shrubs or trees to closed-canopy woodlands and dense gallery forests. The project PI is committed to the objectives of the ICESat-2 science team and to the goal to engage the broader scientific community. Our team has strong connections to global networks of ecosystem modelers, savanna ecologists, and fire scientists who will greatly benefit from new insights from the proposed research and greater understanding of ICESat-2 data. Our team is committed to open science, as demonstrated by the recent development of the Global Fire Atlas, and longstanding efforts to produce, document, and distribute the Global Fire Emissions Database (GFED). To date, savanna ecosystems have been excluded from international climate mitigation and sustainable land management efforts, partially due to the complex tradeoffs between carbon storage and biodiversity conservation. Our proposed research offers an approach to quantify changes in ecosystem structure from human land management and fire based on the extensive sampling from ICESat-2 to support sustainable management of this critical biome.

Kelsey Bisson/Oregon State University
Leveraging ICESat-2 Observations to Characterize Arctic and Global Ocean Phytoplankton
19-ICESAT2-19-0064

Phytoplankton form the base of marine ecosystems and drive CO2 exchange between the atmosphere and the deep sea, where carbon may be sequestered on climatically relevant time scales. The entire phytoplankton stock turns over weekly. Therefore, high resolution observations in space and time are essential to characterize patterns and processes underlying phytoplankton biomass. Over the past few decades, passive remote sensing has transformed our view of ocean biology. However, these methods are biased by clouds and perennial darkness (particularly in high latitude polar regions), whereas active remote
sensing is not. The use of lidar to study phytoplankton has already advanced our view of ecosystem dynamics in the polar regions through the CALIOP instrument on the CALIPSO satellite, but CALIPSO has been in orbit for over 10 years and the efficiency of the CALIOP laser is degrading. Clearly, continued efforts are needed to retrieve biologically-relevant variables from another platform in order to study these sensitive ecosystems in the coming decades. ICESat-2 offers such an opportunity through the ATLAS instrument, with lidar capabilities at 532nm for generating parameters related to phytoplankton activity. The proposed project is highly exploratory and will investigate methods to retrieve relevant biological variables from ICESat-2, including the particulate backscattering coefficient at 532nm that has been shown to covary with phytoplankton carbon. Generated parameters will be used to study phytoplankton in the Arctic especially in areas with sea-ice, as well as on global scales to test and refine vertical structure parameterizations in productivity models. In all cases we will use a worldwide network of autonomous floats equipped with optical sensors to provide oceanographic context to ATLAS-generated profiles.

If successful, the proposed work will 1) demonstrate the utility of ICESat-2 for retrieving ocean ecosystem properties, 2) investigate cryosphere-phytoplankton interactions occurring at the edge of sea ice, and 3) generate high resolution products that characterize marine ecosystem structure and biomass for use in global biogeochemical models.

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**Jordan Borak/University of Maryland, College Park**

**Enhanced Roughness Length Estimates from ICESat-2 Vegetation Products**

**19-ICESAT2-19-0069**

The ICESat-2 mission offers an unprecedented opportunity to capture vertical structure characteristics of earth surface elements from space. Here, we propose to produce an enhanced database of satellite-based vegetation aerodynamic roughness length for momentum by employing ICESat-2 vegetation products (ATL08). Our main objective is to improve roughness length estimates used in land surface and hydrological models by combining these ICESat-2 products with optical remote sensing data from MODIS. The project functions both as a sensitivity analysis, and as a method of uncovering the roughness parameterization that leads to the most accurate modeled fluxes based on reference data. Our products will consist of a) spatially explicit roughness fields over CONUS suitable for data assimilation, for 2002-present at 500-m resolution on an 8-day time step; and b) tables of climatological roughness aimed at improving open-loop land surface simulations. In accordance with Open Science and Open Data principles, we will make available all data and algorithms via NASA's Open Data Portal. This ensures that the research community will have access to the best roughness information available.

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**Sinead Farrell/University of Maryland, College Park**

**Advancing Knowledge of Sea Ice Properties and Processes with ICESat-2**
As the Arctic warms at twice the rate of the global rise in mean temperature, sea ice in the Arctic Ocean is becoming increasingly vulnerable. The satellite record, now spanning 40 years, has revealed that the ice cover is in a state of significant decline. Ice extent is diminishing at a rate of -3 %/decade during the winter, and at -13 %/decade during the summer. While the Arctic comprised ~ 55 % seasonal sea ice in the 1980s, it is now at ~ 77 %, wherein the oldest, thickest ice has been replaced with thinner, seasonal ice, that is more susceptible to summer melt. Models project a continuing decline, with broad-reaching environmental and socioeconomic consequences, ranging from changes in global thermohaline circulation, to impacts on the well-being of indigenous populations, to marine navigation. Our ability to accurately predict the Arctic's future state depends on how well numerical models capture the physical processes and feedbacks that govern sea ice variability on regional, seasonal and inter-annual scales.

With the advent of dedicated polar altimeter missions over the last two decades we have observed a net decline in the volume of the ice cover, but also significant inter-annual variability in sea ice thickness at the regional level. ICESat-2 (I2) continues this time series, and provides near-complete polar coverage. During its first year, I2 has delivered the highest-fidelity measurements of sea ice topography ever obtained from a spaceborne platform, enabling new data discoveries. These include observations of sea ice leads and pressure ridges at high resolution, which are features of dynamic ice divergence and deformation in winter. We have also identified the presence of individual melt ponds on multi-year sea ice, features critical to understanding processes governing sea ice retreat during the summer melt season.

Our primary goal is to investigate changes in the thickness of Arctic sea ice, and improve understanding about the factors driving these changes. Specifically, we address the high-priority goals solicited under the A.36 Studies with ICESat-2 call, i.e. to characterize the “physical processes controlling the growth and retreat of polar ice” and the “dynamic processes controlling ice motion”. We will use I2 sea ice height (ATL07) and freeboard (ATL10) data products to track sea ice evolution during the winter growth season, from the freeze-up period in fall, through to melt-onset in the summer. We will integrate I2 sea ice results with spatially coincident radar altimeter observations from CryoSat-2. These contemporary data sets will be merged with historical results from ICESat (2003-2009) to generate a long-term, multi-sensor record of change in the sea ice thickness distribution, to “offer insight into the drivers of polar change”. We conduct our investigations at two scales: inter-annual change at the pan-Arctic scale; and seasonal variability at the regional scale, and with respect to sea ice type. The results will address the need to “improve Earth system models” by providing novel data that enable evaluation of the predictive capabilities of regional Arctic-system models and global climate models. Detailed, high-resolution I2 sea ice observations will provide novel data products to advance sea ice parameterizations and improve model predictive skill.

The team are committed to the open science goals of the A.36 call to accelerate I2 science and encourage broad community usage. The sea ice products developed under
our proposed research expand the utility of I2 data beyond the existing mission data sets. We have over a decade of experience disseminating data in FAIR archives, and developing novel algorithms, research tools and software. The PI seeks membership of the ICESat-2 science team (I2ST), having served on the Science Definition Team (SDT) since 2012. She will continue to provide expert scientific guidance to NASA related to the sea ice component of the mission.

Temilola Fatoyinbo/Goddard Space Flight Center
Using ICESat 2 Data for Coastal Ecosystem Structure
19-ICESAT2-19-0054

Coastal ecosystems including mangroves, seagrass and corals provide a wide range of essential ecosystem services but are rapidly declining due to a combination of anthropogenic drivers such as sea level rise, warming oceans and changes in land cover. Understanding the spatial patterns of coastal ecosystem structure – both above and below water – are extremely important in valuing their ecosystem services and assessing their current and future vulnerability.

Despite recent advances in global 3D mapping of Blue Carbon habitats, in particular mangroves, there is a lack of sufficient and up to date structural data over these ecosystems. The monitoring of seagrass distribution at a global scale is particularly complex and challenging task as a result of water quality and clarity issues, a wide range of species diversity patterns and increasingly rapidly changing habitats (i.e., mass mortality events). This can be potentially filled by new capabilities of ICESat-2. Here we aim to capture the 3D structure of ecosystems along the coastal margin.

The first release of ICESat-2 data has highlighted the potential of ICESat-2 data to acquire global bathymetric lidar data in shallow (<40m) coastal waters, in addition to vegetation canopy height. This capability is especially timely for coastal ecosystem studies, where the combination of high capacity cloud computing, machine learning, and global repeat optical data availability from Sentinel-2 and Landsat has, for the first time ever, enabled the large-scale mapping of seagrass beds and changes in mangrove, mudflats, saltmarsh, and intertidal zone extent. Shallow coastal bathymetry however, has to this day been a crucial missing dataset that needed not only to improve optical bathymetric and optical depth modeling, but also allow for the differentiation of benthic ecosystem types such as seagrass and coral reefs. We believe that ICESat-2 data can now help fill this gap and we aim to develop and apply novel methods for coastal seascape structure from ICESat-2, and passive optical data

The key points of our methodological approach are as follows:

● Landsat 8 and Sentinel 2 are used to map coastal ecosystems (mangroves, seagrasses and coral) extent. To accurately map underwater habitats, we need to accurately estimate the optical depth and bathymetry. The mapping efforts can be done at
large scales using cloud computing in Google Earth Engine, but global calibration and validation datasets are lacking.

- ICESat 2 bathymetry, if properly characterized by depth, type (clear vs turbid water) may be used to parametrize the Optical Depth retrieval model to obtain more accurate mapped estimates of shallow (0-40m) coastal bathymetry and to better map coastal land and seascape structure and extent.

- 3-D datasets, from Spaceborne InSAR (TanDEM-X) and calibrated to 2 m RMSE, are used to map coastal mangrove canopy height. These datasets will be used to assess ICESat-2 accuracy and potential sensitivity to subcanopy tidal levels.

- ICESat2 data, may also be used as independent training or validation to differentiate between ecosystem types, such as seagrass vs coral or mangroves vs grassy coastal vegetation.

- These measurements of canopy height and coastal bathymetry can provide us with the first continuous training and validation dataset for coastal landscape and seascape characterization.

Our specific objectives are as follows

1. Objective 1 – ICESAT 2 mapping of mangrove canopy height and subcanopy water levels
2. Objective 2- Estimate shallow coastal water bathymetry using ICESat-2 ATL03 and compare that with available acoustic and sounding data as well as depth invariant models derived from Sentinel-2.
3. Objective 3- Calculate benthic rugosity metrics using ICESat-2 ATL03 and use as training and validation for benthic habitat mapping of seagrass and corals.

Helen Amanda Fricker/University of California, San Diego
ICESat-2 Science Team: Studying Three Decades of Mass Balance Processes of Antarctic Ice Shelves with ICESat-2, IceBridge, CryoSat-2 and Earlier Altimetry Missions
19-ICESAT2-19-0089

The Antarctic Ice Sheet is losing mass to the ocean, which is contributing to sea-level rise. Antarctic ice shelves restrain (or “buttress”) the flow of ice from the grounded portion of the Antarctic Ice Sheet. Changes in the extent and thickness of ice shelves alter the amount of buttressing, increasing ice flow across the grounding line and into the ocean, providing a link between the dynamic loss of ice from the ice sheet and sea-level rise. It is, therefore, crucial to understand the processes that control changes in the extent, thickness, and mass of ice shelves. These processes include oceanic and atmospheric controls on mass balance, and glaciological controls on ice flow, fracture, and calving. We will use altimetry data from ICESat-2, in combination with other satellite and airborne altimetry data, to identify the key processes affecting ice shelf stability. We will develop a 30-year record of the spatial variability of surface and basal mass balance terms, and relate these to changes in the atmosphere and ocean. We expect ICESat-2 data to play a key role in this study, by providing precise surface height data for comparison.
with models of firn density as a way of understanding biases in surface height changes from the longer radar altimeter record, for which signal penetration and scattering is poorly understood. We will also take advantage of ICESat-2’s high spatial resolution to study the glaciological processes controlling mass loss by calving, and identify features such as basal channels that are expected to influence the pattern and overall magnitude of basal melting. We will use ice-sheet and ocean models to explore the drivers responsible for the observed changes, as well as the effect of thinning ice shelves on grounded ice.

The proposed work is centred around four goals:

Goal 1: Develop optimal 30-year continuous records of ice-shelf height change and basal melt rates.
Goal 2: Identify primary basal melt modes and climate drivers of ice-shelf change.
Goal 3: Investigate process-scale ice-shelf features and their implications for mass balance.
Goal 4: Quantify large-scale consequences of processes identified in goals 2 and 3.

By addressing mass-loss processes on Antarctica’s floating ice shelves, our proposed work is directly relevant to all four of the program areas that were suggested in the Solicitation for Polar Ice.

The proposed project is a collaboration between PI Fricker (whose research foci are satellite remote sensing and glaciology) and Co-I Padman (oceanography including interactions with sea ice and ice shelves). Fricker would be the ICESat-2 Science Team member, and Padman will attend all ST meetings. We will continue working with the ICESat-2 ST and the Project Science Office on calibration/validation activities and ICESat-2 data evaluation, including refinements to the various corrections applied to ATL03/06 data. We will follow Open Science guidelines and Data Sharing outlined in the Solicitation.

**Alex Gardner/Jet Propulsion Laboratory**

Global Land Ice Contributions to Sea Level: 2003-Present

19-ICESAT2-19-0010

ICESat-2 represents a leap forward in our ability to measure temporal changes in ice surface elevation. Such a capability does not come without its challenges and will require thoughtful and creative solutions to maximize the geophysical information, and thus science insights, to come from the mission’s measurements. Here we focus on overcoming the two major hurdles that remain in deriving global estimates of land ice contributions to sea level from ICESat and ICESat-2 measurements. Specifically, we propose to:

1. Develop methods to determine elevation changes for the substantial area of the globe where ICESat-2 does not produce repeat-track measurements,
2. Develop global observationally constrained surface density using (i) a new firn model forced with 3 models of atmospheric forcing, and (ii) a novel joint inversion of satellite altimetry and time-variable gravimetry to validate modeled firn air content.

We will then derive global land-ice elevation changes from ICESat-2 data, along with data from earlier altimetry missions (ICESat and CryoSat-2). Combining these measurements with new estimates of time-evolving surface density and solid earth response in a formal combination with GRACE and GRACE-FO low-resolution gravity data, we will construct a comprehensive record of land ice contribution to sea level over the past 18 years, at the spatial (5 - 15 km) and temporal (monthly) resolutions needed to isolate underlying drivers of change. The resulting glacier and ice sheet mass change dataset will have broad utility beyond the assessment of sea level contributions; from evaluation of glacier and ice sheet surface mass balance to investigations of ice sheet dynamics, ice-ocean interaction and changes in water resources.

The proposal builds heavily on 5 years of efforts to derive long-term ice-sheet elevation changes from the full suite of satellite altimeters, efforts to develop a state of the art firn model that is coupled to a model of ice flow, and efforts to derive global changes in mass from the joint-inversion of GPS, gravity and altimetry data.

The major goals/deliverables of this work include:
1. Global synthesis of land ice elevation changes (2003 – present)
2. Modeling of firn air content for multiple climate forcings and calibration to observations
3. Geodetic-based estimates of firn air content for continental-scale validation of modeled firn
4. Global downscaled ¼ degree estimates of land ice mass change from satellite altimetry and gravimetry joint inversion (2003 – present)
5. Sum of the above, resulting in revised estimates of global land ice mass change and contributions to sea level (2003 – present)

Niall Hanan/New Mexico State University
Improving Estimates of Vegetation Structure and Biomass in Global Savannas and Drylands with ICESat-2
19-ICESAT2-19-0083

The tropical and temperate drought-seasonal savannas, shrublands and grasslands of the world are under-studied, but critical, biomes found on all continents, except Antarctica. These biomes, collectively referred to in this proposal as "savannas and drylands", are under increasing pressures of land use change for small-grain agriculture driven by population, economic and globalization trends. The drought seasonal savannas and drylands are often overlooked in Earth Observation and remote sensing studies, relative to the taller woodland and forest zones with high carbon-density (but relatively smaller area). However, the savanna-drylands also support large quantities of carbon in above- and below-ground woody biomass and soil organic matter.
This tendency of Earth Observing systems to ignore the savannas and drylands holds true for the Ecosystem Structure and Biomass Estimation research foci of both the ICESat-1 and ICESat-2 missions, where the terrestrial vegetation emphasis has been on taller stature and higher carbon density regions of the World. In particular, the ICESat-2 Land-Vegetation Along-Track Product (ATL08) effectively ignores most of the World's savannas and drylands.

We propose activities that will fill the gaps we perceive in ICESat-2 processing in savannas and drylands and realize opportunities to estimate not only canopy heights but also canopy cover and above ground woody biomass in these regions. Our specific objectives, described in more detail in later sections, include:

Goal 1: Expansion of ICESat-2 along-track processing for global savannas and drylands, most of which are currently omitted from standard ATL08 processing.
Goal 2: Interpolation of ICESat-2 along-track canopy heights using Sentinel-1 and -2 data to create new ~100 m gridded canopy height products for global savanna-dryland systems.
Goal 3: Application of a Google Earth Engine mapping tool (developed with earlier NASA support) to create ~100 m gridded canopy cover products for global savanna-dryland systems.
Goal 4: Collation of existing and new field and virtual field data for improved biomass allometries.
Goal 5: Creation of ~100 m gridded above ground wood biomass estimates for global savannas and drylands using allometric data, canopy height and cover datasets.
Goal 6: Accuracy and uncertainty assessment of gridded products via uncertainty propagation and error analysis using field, virtual field, LTER, NEON and GEDI data.

The products from this research will allow us, and the wider research community, to better quantify and understand the spatial and temporal variability in woody vegetation structure and biomass in global savannas and drylands. The gridded canopy heights, canopy cover and woody biomass products we propose will transform our understanding of global savanna and dryland vegetation structure, opening the door to numerous applications in terrestrial ecology, rangeland science, carbon cycle science and land surface studies.

Ute Herzfeld/University of Colorado, Boulder
DDA-Ice and DDA-Ice-class - A Cyberinfrastructure for ICESat-2 Surface-Height Determination and Classification Driven by Critical Cryospheric Science Questions 19-ICESAT2-19-0077

NASA's ICESat-2, launched Sept 15, 2018, carries a multi-beam photon-counting laser altimeter system, the Advanced Topographic Laser Altimeter System (ATLAS), selected to facilitate measurement of cryospheric heights with a temporal and spatial resolution
that captures previously undocumented signatures of cryospheric change processes, foremost glacial acceleration and melt events in land and sea ice. Glacial acceleration is the largest source of uncertainty in sea-level-rise assessment, according to the latest report of the Intergovernmental Panel on Climate Change. In recent years, wide-spread melt events have affected the Greenland Ice Sheet. An essential characteristic of the new space-borne sensor is the unprecedented along-track spatial resolution of 0.7m. Yet the official ice-surface height product reports surface heights averaged for 40m-along-track segments. A challenge lies in the fact that ATLAS records returns from every photon (at the 532nm wavelength of the sensor) resulting in a photon point cloud whose analysis requires a new mathematical algorithm. The PI has developed a solution to this problem, the density-dimension algorithm for ice surfaces (DDA-ice), which allows to measure surface heights of crevassed glaciers (the signatures of glacial acceleration) and measurement of water depth in melt ponds (the signature of increased melting in a realm of climatic warming), posting heights at or near sensor resolution.

The first objective of the proposed work is to create and provide of a cyberinfrastructure (CI) for ICESat-2 surface-height determination and classification of ice-surface types, building on the DDA-ice, as a shared resource for the cryospheric community and the public. A CI brings together computational algorithms, data analysis, software, hardware, and sharing in the sense of Open Science (OS) and Open Source Software (OSS). This step will include scaling from regional studies to ice-sheet wide data processing and exploration of cloud computing. The DDA-ice bridges between the technological development of the photon-counting sensor and science-driven data analysis. The DDA-ice is an auto-adaptive algorithm that utilizes the radial basis function, a concept from neural networks, for calculation of a density field. Signal photons are identified using a function that automatically adapts to varying noise and background characteristics caused by day-time, apparent surface reflectance, environmental and instrumental sources.

The second objective will advance from height measurement to a classification of ice-surface types, driven by urgent science questions such as mapping of melt expansion in the Greenland and Antarctic ice sheets and on the Arctic sea ice, and mapping the distribution of water in crevasses as an indicator of changes in the hydrological system of a surging glacier. A recent example is the surge of a large glacier in Arctic Svalbard (Negribreen), which accelerated by a factor of 200, causing 0.5-1\% of global annual SLR. Melt propagation in the Greenland Ice Sheet will be analyzed using a roughness product from ICESat-2 data and an energy-balance model derived in our group.

The proposal team is in a unique situation to carry out the proposed work, because the PI led a NASA-funded airborne ICESat-2 validation campaign over Negribreen in 2018 and 2019, augmented by a special acquisition of innovative commercial satellite image data. Analysis will be complemented by data from Operation Ice Bridge for other areas. In addition to cryospheric sciences, advances in machine learning, cloud computing and computational methods for modern signal processing are core to the proposed investigation. Generalizations of the DDA-ice are expected to find applications in other science fields including atmospheric sciences (blowing snow and aerosols), bathymetry and ecology. Heights of fractured ice will provide critical data-based information for modeling ice movement and mass loss through calving.
The ice sheets act as a filter for changes in atmospheric and ocean forcing. Their non-linear behavior means some systems respond dramatically to small perturbations, while others appear more resilient to thinning or retreat. Their responses, both short-term and long-term, are mediated by the glacier bed, which acts to restrain ice as it flows to the low-elevation, coastal environments where it ultimately melts. As we work to increase precision in our predictions of future sea-level rise, uncertainty in the physics governing glacier sliding remain one of the greatest sources of uncertainty in total rates of sea-level rise over the next century. This is because the time-scale for unstable ice loss in the marine basins of West Antarctic is highly sensitive to model treatment of the ice-sheet bed.

It is likely that the glacier sliding law depends on the material that makes up the glacier substrate – this means the sliding law would not be uniform within a glacier catchment. One of the grand challenges in modern glaciology is coming up with a method to observationally constrain both the functional form of the glacier sliding law and the parameters that describe the in situ substrate materials. In this proposal, we use cutting edge ice penetrating radar methods together with repeat altimetry from ICESat-2 to test two hypotheses made in the literature within the last year:

1. The bed of Thwaites glacier is characterized by a heterogeneous glacier sliding law, which will control the inland propagation rate for thinning in response to ocean warming (Koellner et al., 2018).

2. The sliding law at Thwaites Glacier is expressed by the morphology of subglacial bedforms, with the stoss side of subglacial features behaving viscously and the lee sides plastically (Muto et al., 2019).

High precision, repeat-track measurements from ICESat-2 allow for local thickness-change measurements over the Thwaites basin, which can be compared with the predicted ice sheet response for different sliding laws to test the first hypothesis. We will combine ICESat derived dh/dt with swath-radar produced maps of Thwaites’ bed topography to evaluate the extent to which fine-scale bed morphology and observed thinning are coupled, thereby testing hypothesis two. Strong correspondence in the thinning-field and morphology of underlying glacial bedforms would substantiate the above hypotheses, and provide a pathway for observation based sliding law prescription in ice-sheet models.

This proposal is designed as a low-cost, highly experimental endeavor. It leverages both the technological advancement in surface height measurement brought by ICESat-2 and
the cutting edge radar signal processing techniques pioneered by Operation Ice Bridge, which have been refined to operate at scale by the PI in recent years. In addition to its scientific priorities, this proposal has a specific focus on ICESat-2 tool development and open science curriculum development for undergraduate Earth Science students.

Christopher Horvat/Brown University
Waves in Sea-Ice: Detection, Attenuation and Floe Size Impacts with ICESat-2
19-ICESAT2-19-0027

The recent precipitous decline in Arctic sea-ice extent, thickness and volume has been dramatic. In September, sea-ice extent has decreased by 40% over 40 years (Stroeve et al., 2007; Fetterer et al., 2017). Over the same period, September sea ice volumes have declined by 70%, and annual-averaged ice thickness has declined by 2 meters (Kwok, 2018). These changes are having profound consequences on the climate, environment, and ecology of the Arctic and further afield, and contributed to increased socio-economic activity in the region and enhanced vulnerability to hazards. In contrast, Antarctic sea ice variability has not exhibited major changes in recent decades (e.g., Maksym (2019)). Coupled climate models have had limited success in predicting the observed trends in sea ice area and volume across regional to hemispherical scales (e.g., Rosenblum and Eisenman (2017)) and there is a significant gap between real-world and potential predictive skill over timescales of weeks to months (e.g., Bushuk et al. (2019)), in part due to limitations in model physics. Ice-wave interactions are a leading candidate for improving model physics.

At synoptic scales, sea ice is a composite granular material composed of many individual pieces, called floes - a flexible interface between ocean and atmosphere. Sea ice is characterized by its ice thickness and floe size distributions (together, the FSTD, Horvat and Tziperman (2015)), which determine its composite rheological and thermodynamic properties. Ocean waves, whether locally-generated or long-period swell waves, have been observed increasingly in the Arctic and are a persistent feature of Antarctic sea ice within hundreds of kilometers of the open ocean. In the presence of ocean surface waves, floes bend, and if the wave field is sufficiently energetic, will break - altering the composite properties of the sea ice cover. Sea ice is a strong attenuator of wave energy as a function of floe size - smaller floes leads to weaker attenuation. When sea ice fractures, it is more mobile and more susceptible to melting - thus a feedback between ocean surface waves and floe melting has been hypothesized by many.

Efforts to understand wave propagation in sea ice are challenged by the limits of observing coupled wave-sea ice evolution. Many observations of waves in ice come using small arrays of a handful of drifting buoys. Such small observational systems may not accurately represent the multi-scale complex interaction of waves and sea ice. We suggest that Ice-Sat 2 offers a solution.
Ocean swell waves have long been studied with the use of radar altimetry using techniques not transferable to ice-covered oceans, with a different surface, less wave energy and smaller surface displacements. The high-resolution Ice-Sat2 laser altimeter, however, can directly sample wavelengths of several meters and up. Armed with new mathematical techniques to understanding sea ice evolution and wave statistics using altimetric data, we believe an the opportunity exists to address: how energetic are waves in ice, how do they alter the shape and structure of the ice pack, and how can their representation be improved in climate models?

Ronald Kwok/Jet Propulsion Laboratory
Snow Depth Over Sea Ice from Differencing ICESat-2 and CryoSat-2 Freeboards
19-ICESAT2-19-0009

Snow is an integral element of Arctic and Antarctic sea ice systems, and one of the geophysical parameters that controls the heat and energy balance between the ice, ocean, and atmosphere. Presently, however, there are no direct measurements of the time-variable snow depth over sea ice at spatial scales needed for understanding seasonal and interannual changes, and for informing improvements in climate projections and regional forecasts. Moreover, accurate calculations of snow loading to estimate ice thickness (from sea ice freeboard retrievals) are critically dependent on measurements of snow depth and density, which to date have been based on climatology or reconstructions from snowfall in reanalysis products. Prior to the launch of ICESat-2 (IS-2), Kwok and Markus [2017] first examined and demonstrated the potential of estimating snow depth by differencing IS-2 and CryoSat-2 (CS-2) freeboards. The combination of IS-2 and CS-2 now in orbit presents a significant opportunity for examining the efficacy of basin-scale snow depth retrievals from these lidar and radar freeboards – the focus of our proposal. Here, we propose to: 1) derive monthly fields of snow depth over Arctic sea ice from the beginning of the IS-2 mission; 2) provide an analysis of the quality of the multi-year dataset, evaluate the impact on ice thickness calculations; and, 3) examine the seasonal and interannual variability within that time frame of this investigation. Our assessment of the snow depth data will include retrievals from Operation IceBridge and other airborne surveys, the field measurements from the MOSAiC drifting observatory, and reconstructions from reanalysis products. The resulting data set will be the first such basin-scale estimates since the Arctic snow depth climatology developed by Warren et al. [1999] two decades ago. As for the Antarctic sea ice, given our less mature understanding of the more complex snow layer, we will address what is achievable in terms of snow depth estimates.

Bradley Lipovsky/Harvard University
An Antarctic Rift Catalog from ICESat-2 Observations
Ice shelves promote the stability of marine ice sheets and therefore reduce the ice sheet contribution to sea level rise. Rifts are through-cutting fractures in ice shelves that serve as the eventual boundary for tabular icebergs. Because rifts limit the extent of ice shelves in this way, it is important to have mechanical theory that describes their behavior. Despite previous work on this topic, there currently does not exist a theory for the propagation, deformation, and eventual iceberg calving from ice shelf rifts. We propose to address the need for such a theory through a combination of observation and modelling.

We propose to harness the revolutionary observational ability of ICESat-2 to construct an Antarctic Rift Catalog (ARC). The ARC itself will consist of observations of rift evolution through time. We will then use patterns in the catalog to test fracture mechanical theories of rift propagation. This work will result in a better understanding the stability of ice shelves with respect to rifting.

The proposed work will consist of several related objectives. Objective 1 is to carry out a validation of our ICESat-2 rift measurements. This work will leverage an ongoing collaboration with scientists conducting field-based GPS measurements of rift deformation. (Note, however, that we do not request funding for fieldwork.) This measurement validation will give us an understanding of the uncertainties in our rift measurements. Objective 2 is the development an automated method for measuring ice shelf rifts called the Rift Feature Detection (RFD) algorithm. Objective 3 is to carry out modelling of rifts as constrained by the ARC observations. Objective 3 will examine both the rheology and fracture properties of rifts. The rheological work will place new constraints on the appropriate rheology for ice shelves damaged by rifts. The fracture work will test several hypotheses, including 1) Ice is elastic during individual bursts of rift propagation (i.e., as opposed to being viscoelastic, having transient creep, or having steady, “Glen”-creep), and 2) Rift propagation occurs upon at a critical rift width, analogous to the crack tip opening displacement (CTOD) condition used in classical engineering fracture mechanics. Objective 4 is to describe long term trends as documented in the ARC. This final objective will relate rifting to the broader climatic conditions and the stability of marine ice sheets.

The proposed work will contribute to NASA’s 2018 Strategic Objective 1.1, “Safeguarding and Improving Life on Earth,” by addressing a significant source of uncertainty in future sea level rise. The Intergovernmental Panel on Climate Change has determined that significant economic, social, and environmental cost is associated with uncertainty in future sea level rise estimates. The proposed work will improve forecasts of future ice sheet change by creating an improved, physics-based and observationally-grounded description of ice shelf rifting and calving.

The proposed work will radically embrace Open Science principles. We envision an ARC that is available in near-real time in the same way that earthquake catalogs are published. The ARC itself will adhere to a strict paradigm of reproducibility where every
data point in the ARC will be able to generate a script/notebook to reproduce itself from the underlying ICESat-2 data product. We will regularly push code updates to public GitHub repositories during code development. At the time of publication these repositories will be pushed to a FAIR-compliant repository such as Zenodo. All codes will be made available under a suitable open source license. We will avoid the use of closed-source software in our modeling. Our workflows will follow best practices in the use of notebooks to disseminate and explain our workflow.

Lori Magruder/University of Texas, Austin
ICESat-2 Bathymetric Studies, Product Development and Data Validation
19-ICESAT2-19-0043

Currently there is a lack of nearshore bathymetry around the world (IHO, 2018; NRC, 2004). The global lack of nearshore bathymetry hinders monitoring of coral reefs and other fragile marine ecosystems. The data void also limits the ability to accurately model inundation, due to hurricanes, nor’easters, and tsunamis. Space-based bathymetry is particularly important in these regions with limited or no valid measurements and can hold the key to research on addressing critical coastal science and management needs, such as benthic habitat mapping, and storm surge modeling. ICESat-2 affords a powerful new capability to address this information gap in nearshore regions with global coverage, a water-penetrating laser and high-resolution measurements. This proposed project will standardize and automate ICESat-2 bathymetry retrievals with a focus on producing an accurate product, at the global level, for exploring characteristics of the coastal benthic environment. Specific tasks required to accomplish the overarching goals of ICESat-2 global bathymetry extraction, validation and dissemination are summarized into the following proposed research studies:

1) Development of an along-track bathymetric research product.
2) Qualitative and quantitative bathymetry data analysis for accuracy and uncertainty prediction.
3) Investigate continuity with the bathymetry product (land/water interface) as well as the connection to other relevant geophysical Level 3a along-track products.
4) Explore benthic habitat analysis to support coastal science and management.
5) Provide open-source computational analysis tools for community bathymetry research and in support of broader scientific collaborations.

These focus areas will enhance current knowledge and provide innovation and discovery with Earth observing laser altimetry based on previous work by the proposing team to provide the initial assessment of ICESat-2 bathymetric performance (Parrish et al., 2019). The results of the evaluation indicate that ICESat-2 is well suited to provide accurate underwater topography mapping with vertical accuracy of better than a meter and depth penetrations of up to 40 m in some locations. Additionally, a global bathymetry product from ICESat-2 combined with data from other sensor phenomenologies will enhance our current knowledge of coastal dynamics and nearshore mapping with active and passive
data fusion. Ultimately, the planned outcome of this proposed work is not only the production of a bathymetry product poised for science discovery but also a comprehensive understanding of the true capabilities of ICESat-2 for bathymetric applications based on understanding the quality of the data, the expectation of the instrument performance in specific environments and feasible data fusion with other coastal resources.

Ted Maksym/Woods Hole Oceanographic Institution
Snow Depth and Antarctic Sea Ice Thickness Evolution from ICESat-2
19-ICESAT2-19-0067

In contrast to the Arctic, where strong reductions in sea ice thickness are readily observable due to the concomitant declines of sea ice extent and multiyear ice, we do not know if there are any trends in sea ice thickness and volume in the Antarctic. This hampers our ability to evaluate the role of climate variability on the Antarctic sea ice–ocean system. Moreover, because the ice is relatively thin over much of the Antarctic, and its snow cover relatively thick, we cannot reliably determine regional and seasonal variability in Antarctic sea ice thickness (or its snow cover) with much confidence. Further, techniques used to independently estimate snow depth on sea ice in the Arctic are ineffective in the Antarctic due to a combination of high ice divergence, conversion of snow to snow ice, and wind-blown redistribution of snow. This uncertainty currently limits our ability to use ICESat-2 to understand sea ice variability and its causes in the Antarctic.

We propose to develop ‘optimal’ estimates of snow depth on sea ice thickness in the Antarctic using two complementary techniques. First, a deep learning convolutional neural network technique that has been developed to derive Antarctic sea ice thickness from high-resolution sea ice surface morphology data will be adapted to ICESat-2 sea ice freeboard data. Comparison with Operation Ice Bridge data will be facilitated through the construction of simulated ICESat-2 freeboard data from the higher-resolution Operation Ice Bridge data, so that the predictive capability of the neural network can be evaluated. Second, we will develop a novel method of examining the statistical evolution of patches of sea ice as they evolve through the winter with a Lagrangian ice tracking system. By classifying and tracking a large number of ice patches as they drift under subsequent ICESat-2 overpasses, we will examine the statistical evolution of the sea ice freeboard to untangle the role of key sea ice processes in the development of the sea ice freeboard, and hence snow and ice thickness evolution. This analysis will address the following key questions:
1. Can snow depth on Antarctic sea ice be estimated with sufficient accuracy to detect regional and interannual variability in ice thickness distribution?
2. How much snow accumulates on sea ice, and how much is redistributed by the wind to leads or converted to snow ice.
3. What role does ice deformation play regionally in the mass balance of Antarctic sea ice?
Through this effort we will develop (1) an independent means of estimating snow depth on Antarctic sea ice from ICSat-2 data, (2) provide a best estimate of snow and ice thickness, with regional and seasonal error estimates, (3) evaluate reanalysis precipitation products over Antarctic sea ice for the first time, and (4) determine the relative roles of key processes, including snow ice formation, snow redistribution, and deformation in different regions and seasons, in controlling Antarctic snow and sea ice mass balance.

This work is anticipated to produce a circumpolar estimate of both snow and ice thickness over the three year period of the project, with regional and seasonal error estimates suitable for evaluating models and climate impacts on sea ice volume, and a Lagrangian snow and ice thickness dataset for sea ice process studies.

James Morison/University of Washington, Seattle
ICESat-2 Sea Ice and Open Ocean Altimetry to Characterize Changing Arctic and Sub-Arctic Ocean Circulation
19-ICESAT2-19-0004

In order to understand the modes of circulation of sea ice and upper ocean water in the Arctic Ocean and Sub-Arctic Seas, we propose to analyze sea surface height (SSH) data from ICESat-2 (2018 onward), CryoSat-2 (2011- onward), and ICESat (2003-2009) along with dynamic heights of the sea surface (1950-1989) estimated from the US-Russian Atlas of the Arctic Ocean Oceanographic Conditions. There is currently debate over whether Arctic Ocean circulation is tending to be more anticyclonic (clockwise) or cyclonic (counterclockwise). This is important to the fate of the sea ice cover because anticyclonic circulation tends to trap ice so that it can grow thicker before being exported to the North Atlantic. Cyclonic circulation tends to release ice. In fact, in the early 1990s, after preconditioning by rising air temperatures, the global atmospheric index Arctic Oscillation hit a maximum and triggered strong cyclonic circulation in the Arctic Ocean. This flushed much of the thick old multiyear ice out of the basin and allowed more radiative melting of ocean and ice that has essentially kept the Arctic Ocean in a seasonal ice regime ever since.

Because most oceanographic measurements are made in the anticyclonic Beaufort Gyre, and this has intensified, some feel the Arctic Ocean has been in an anticyclonic mode. However, recognizing that the AO forcing has remained relatively high, we would argue that the ocean circulation has tended to remain cyclonic and continued to flush sea ice out of the basin relatively soon after it is formed. The obstacle to settling this question is that the heart of the cyclonic circulation is on the remote Russian side of the Arctic Ocean and gets very few of the traditional kinds of measurements. Evidence of the cyclonic circulation changes has come from short snippets of remotely sensed SSH. Evidence we do have of the cyclonic circulation changes has come from short snippets of remotely sensed SSH. With ICESat-2 combined with other past satellite measurements of
SSH, we can settle the debate and unequivocally find out if the circulation has remained cyclonic because a) the gradients in SSH are what drive average circulation and b) ICESat-2 and the other altimeters measure SSH over the whole Arctic Ocean, including that part most prone to cyclonic circulation.

Consequently, we will assemble a 70-year record of SSH patterns from satellites and historical ocean data and use an analysis scheme that identifies the most important spatial patterns of variability to characterize the circulation. We will then look at how the key patterns vary in strength through time. These histories will tell us if circulation is still cyclonic and will be compared to the AO and other global indices of atmospheric circulation to tell us how global climate affects the Arctic Ocean circulation and sea ice.

As side benefits of this research, and in keeping with membership in the ICESat-2 Science Team, we will contribute to development of the NASA ICESat-2 project ATL19 data product by merging ATL12 ocean data and ATL10 sea ice data to yield gridded ocean sea surface heights plus a sea ice concentration parameter for the open ocean and ice-covered seas. We will also be contributing hydrographic data and in one case GPS SSH data from a new buoy to aid in the calibration and validation of ICESat-2 SSH measurements.

Amy Neuenschwander/University of Texas, Austin
Estimating Boreal-Wide Forest Biomass Density With ICESat-2
19-ICESAT2-19-0044

The overarching research goal of this proposed work is to develop biomass estimation methodologies for boreal forest using ICESat-2 data and to produce a boreal-wide biomass product. The research proposed here expands upon a recently funded proposal under the NASA Terrestrial Ecology ABoVE program titled “Mapping boreal forest biomass density for the ABoVE domain circa 2020 with ICESat-2” led by Dr. Duncanson (PI) and Dr. Neuenschwander (Co-I). Under this proposal, we will apply the same methodology developed for the ABoVE project to the Eurasian boreal zone and create an ICESat-2 biomass product (research product) that will be available for download through the National Snow and Ice Data Center (NSIDC). In order to achieve this goal, several research steps are required to enable the production of a biomass product. First, we will quantify the accuracy of ICESat-2 derived canopy height (and canopy height metrics) in boreal forest compared against high point density airborne lidar data. We will assess what surface characteristics (e.g. surface slope, canopy cover, forest type, etc.) affect the canopy height error and how those errors propagate to biomass estimation. We will also compare ICESat-2 heights to GEDI heights in the northern 2 degrees of GEDI data coverage to assess the transferability of GEDI’s globally predictive biomass algorithms to ICESat-2 data. Through this process, we will assess whether GEDI’s field and airborne lidar database, and associated biomass algorithms, are transferable to ICESat-2, or whether ICESat-2 specific algorithms are required. We will explore both parametric and machine learning algorithms in this analysis. This work will use field and airborne lidar
data both from existing datasets in North America, but importantly new datasets collected for this project from Nordic country partners for training European boreal models. Since much of the ICESat-2 data collected over the boreal zone will be snow covered, it is also imperative that we have an understanding on the role of snow on the terrain height (and subsequent canopy height and biomass retrievals). The biomass algorithms and maps generated by this research will fill a final data gap in planned global biomass products for 2020, complementing GEDI’s tropical and temperate biomass maps, and extending the North American boreal map for a complete global forest structure product leveraging NASA lidar data.

Stephen Palm/Science Systems and Applications, Inc.
Improving Ice Sheet Mass Balance Estimates With High-Resolution ICESat-2 Measurements of Blowing Snow and Diamond Dust
19-ICESAT2-19-0056

This proposal seeks to study the properties of blowing snow and clear-air precipitation (diamond dust) over the Antarctic Ice Sheet using data from the ICESat-2 atmospheric channel and the photon cloud. These observations will be used to evaluate and improve blowing snow transport and sublimation in a high-resolution (100 m) distributed snow model. In particular, we will combine our observations and model to study the impact of strong blowing snow events on atmospheric and surface properties (derived from ATL06), as well as ice sheet surface mass balance. The analysis of ICESat-2 data will also enable us to extend the existing climatology of blowing snow over Antarctica (based on CALIPSO), and to better assess inter-annual and seasonal variability as well as long-term trends in blowing snow. In addition, we will study the spatial and temporal distribution of clear-sky precipitation over the ice sheets, and use these observations to evaluate interior ice sheet precipitation in atmospheric re-analyses, including NASA’s MERRA-2, and in fully-coupled climate models. These work elements have relevance to the solicitation which calls for “gaining insight into ice surface mass balance, especially to improve representations of polar precipitation”. Also, the extension of the blowing snow climatology is also relevant to the solicitation’s call for “integrating ICESat-2 with other satellite observations to create multi-decadal records that offer insight into the drivers of polar change”. The solicitation also encourages the use of ICESat-2 observations to improve Earth System models for precipitation and sublimation, which is a major focus of this proposal. Our primary research areas include:

1) Application and improvement of an algorithm to detect clear-air precipitation over Antarctica and estimation of precipitation amount and compare with model estimates.
2) Utilization of ICESat-2 blowing snow retrievals to extend the CALIPSO-based, Antarctic blowing snow climatology (2006 – present) through 2022.
3) Perform case studies of blowing snow events to evaluate and improve blowing snow transport and sublimation in a high-resolution (100 m) distributed snow model and impact on surface properties.
NASA’S ICESat-2 (Ice, Cloud, and land Elevation Satellite-2) photon lidar satellite mission provides unprecedented high-resolution measurements of the current state of vegetation canopy heights, in addition to measurements of ice sheets, sea ice, inland water and cloud characteristics. This proposal is submitted as a successor to an existing NASA award for ICESat-2 Science Team (Grant # NNX15AD02G). The overall goal of this proposed study is to increase our understanding of the canopy products from ICESat-2 and facilitate their synergistic integration with field inventory data and satellite imagery to derive area-wide estimates of canopy structure, height and biomass at various scales. More specific objectives include to: 1) validate the Land Water Vegetation Elevation product (ATL08) against reference datasets of airborne lidar and photogrammetric products and understand sources of uncertainty in photon classification and canopy metrics; 2) scale up from along-track to area wide canopy products using machine learning methods with a synergistic integration of ICESat-2 data, field inventory, and optical and radar satellite data; 3) investigate new products and the photon lidar capabilities for characterizing changes in the three-dimensional structure brought about by forest fires and for mapping forest burn severity; and 4) create a suite of software tools in the public domain to facilitate ICESat-2 photon classification, processing and visualization for increased adoption and science use of data.

Our preliminary investigations with on-orbit ICESat-2 data and pre-launch simulated data show that the photon lidar system on ICESat-2 has the ability to retrieve information on both canopy and terrain heights using both strong and weak beams. Archiving transformational vegetation science discoveries enabled by ICESat-2 and synergistic NASA missions, such as GEDI and NISAR, will require continued validation of relevant data products. Our proposed data validation is a key step in determining the usefulness of the data but also enables sound interpretation of and informs limitations of scientific results. We propose to integrate our deep learning methods previously developed with simulated ICESat-2 data with real, on-orbit data, and scale up from along-track to area wide estimates of vegetation biophysical parameters. We propose methods to use the three-dimensional information of photon lidar profiles to quantify the severity of wildfires and provide useful information to help managers make informed decisions. The proposed open source software tools have been demanded by the user community and include at least four packages for classifying canopy photons, visualizing photon data, and processing ICESat-2 data with deep learning tools.

The proposed work is significant to NASA’s strategic objective of safeguarding and improving life on Earth. Understanding canopy structure, biomass, and carbon is relevant for managing natural resources and informing decision makers of environmental policies. Moreover, the investigations of canopy structure affected by burn severity is relevant for improving national capabilities for responding to natural disasters such as fires and their
environmental effects. With the international collaborators for this study, the proposal addresses NASA’s goals of implementing effective partnerships with international programs to leverage NASA resources and expand scientific reach. This proposal also fosters an understanding of NASA data products that are brought directly into the classroom and expands NASA’s education and outreach functions that aim to inspire and engage the public and educate undergraduate and graduate students.

Jonathan Ryan/Brown University
Towards Global Characterization of Inland Water Reservoir Use from Space
19-ICESAT2-19-0038

Motivation: Accurate, globally available information on reservoir storage is a prerequisite for managing transnational water resources and their impacts on downstream populations and ecosystems. However, no complete global database exists because reservoir water level data are not commonly distributed and the current generation of satellite radar altimeters resolve only the world’s largest reservoirs. The amount of water stored and primary function of thousands of reservoirs around the world therefore remains unknown.

Approach: We propose to combine validated ICESat-2 water surface elevation retrievals with ancillary surface water masks, and artificial intelligence methods to characterize the seasonal behavior, climatic sensitivity, and societal function of reservoirs globally. Once completed, we will use these data to train supervised machine learning algorithms to search for managed water resources around the world and determine their seasonal management strategy and sensitivity to local hydro-climatic net water balance, as determined from P-E (precipitation minus evaporation) in MERRA-2 and ERA-Interim climate reanalysis data.

Outcomes: The proposed research will (1) produce a “first-of-its-kind” baseline dataset that characterizes the current state of managed global water resources over the 2019-2022 study period, (2) lay the foundations for long-term investigation of global reservoir response to climate change and human demand. (3) Foster collaboration with the upcoming Surface Water and Ocean Topography (SWOT) mission.

Relevance to NASA: The proposed research is relevant to the NASA A.36 “Studies with ICESat-2” solicitation NNH19ZDA001N-ICESAT2 under section 4.2 “Research Foci Outside of Polar Ice (A.36-5)”. The proposed research is also directly responsive to stated priorities of the solicitation, including: “Low-cost, highly experimental proposals are especially encouraged. (A.36-1)” and “NASA recognizes that ICESat-2’s global, high-resolution data stream presents an exciting opportunity to utilize emerging methods in data analytics, including but not limited to artificial intelligence, machine learning… (A.36-3)”. The proposed research is keenly relevant to the NASA Surface Water and Ocean Topography (SWOT) mission, which would be communicated directly to that scientific community by the research team. More generally, the proposed research is
This project will use measurements from ICESat-2 and other platforms (1) to improve models of critical glacier flow processes that are not yet completely understood and (2) to reconstruct glacier flow of the recent past. The theoretical advances from this work will help glaciologists predict future ice flow and estimate the sea-level rise contribution from Greenland and Antarctica. In addition, the project will contribute to the development of the open source ice sheet model icepack and data sets that will be made freely available to glaciological community. The unifying theme behind our approach is the application of time-dependent data assimilation algorithms for integrating models, in our case the diagnostic and prognostic model physics of glacier flow, with observations. Time-dependent algorithms represent an advancement over commonly used snapshot data assimilation approaches in glaciology and are uniquely equipped to harness the high-resolution data stream from ICESat-2.

Using a common data assimilation core, we will apply the algorithms in three cases studies representing three different environments. For each of our target sites, we will combine contemporary observations from ICESat-2 and other platforms with the existing 25-year observational record. The higher spatial resolution of ICESat-2 data can be used to refine the pattern of elevation change from past altimetry measurements. We will use this improved data for three case studies:

1) We will estimate the time-varying basal friction under Jakobshavn Isbrae, West Greenland. These results will help determine which sliding law best reproduces observations. Additionally, the degree to which the basal shear stress exhibits secular and seasonal variation has implications for the effects of hydrology.

2) We will estimate the time-varying rheology of Larsen C Ice Shelf in the Antarctic Peninsula and isolate the component of the fluidity due to damage. We will then fit these estimates to the Albrecht/Levermann model of damage propagation, a physical process that is not yet completely understood, to estimate the rate constants and threshold stresses in this model. If this model can reproduce the inferred time-varying damage, then it would confirm that the model is effective for modeling coupled ice-sheet/ice-shelf evolution.

3) We will create a reanalysis product of Pine Island and Thwaites Glaciers in West Antarctica for the past 20 years. This reanalysis will be updated as more observations come in from ICESat-2 and other future remote-sensing platforms such as NISAR. This reanalysis product will both be useful for other process studies and for estimating uncertainty in predictions of future glacier flow.

The glacier flow model icepack that we use for this project is free and open-source software. All new modeling code will be included in the icepack source repository and all
experimental setups will be publicly available under the same license on the icepack website. One of the main goals of icepack is to lower the barrier to entry for early-career researchers to using numerical models. We routinely hold training and education events on how to use icepack in order to expand the community of users. The model-data fusion approach that we apply here is generalizable to other glaciers and problems. While we focus on a few target sites that are likely to yield the most insight into physical processes, this same experimental setup can also be used for studying ice sheets at continental scale.

Benjamin Smith/University of Washington, Seattle
Extending ICESat-2 Data Products to Achieve Multi-Decadal High-Precision Records of Ice-Sheet Mass Change
19-ICESAT2-19-0002

Altimetry over ice is one of the critical tools for monitoring both the net contribution of the ice sheets to sea level, and the smaller-scale dynamics that drive these changes. Tools for elevation-change calculations developed within the project, and the use of ICESat-2 data as a reference for previous altimetry measurements offer a way to create long-term elevation-difference time series that should show both mass and dynamic changes from the start of ICESat to the present. In addition, feasible improvements to ICESat-2 processing algorithms under clouds and over coarse-grained surfaces should allow better data coverage and smaller biases in ICESat-2 time series. We propose to generate a set of enhanced along-track elevation change (ATL11) and gridded elevation-change (ATL15) products that are extended to decadal time spans, and include corrections for forward and subsurface scattering that are not currently envisaged in the standard altimetry products. We will use these products as part of a study of ice-sheet mass balance for Greenland, Antarctica, and the ice caps surrounding Greenland that combines temporally extensive altimetry records with GRACE/GRACE-FO gravimetry to evaluate net ice-sheet contributions to the ocean during the full GRACE-ICESat-ICESat-2 period. Expected results of our products will be a set of enhanced ATL11 and ATL15 products, and a set of mass-balance records for Greenland and surrounding ice caps, and for Antarctica. We expect these results to be distributed as a mix of independent products (through NSIDC), publications, and, potentially, as enhancements to the standard ATL06, 11, and 15 data products.

Julienne Stroeve/University of Colorado, Boulder
Sunlight Under Sea Ice: A Multisensor and Modeling Synthesis for Ecosystems in a Changing Arctic
19-ICESAT2-19-0088

Arctic sea ice is changing, melting earlier and forming later; it is now a region dominated by thinner, more dynamic first-year ice. The shift from thick multiyear to thinner first-
year ice has consequences for the transfer of light to the upper Arctic Ocean. Changes in the light field under the ice is one of the main drivers that will likely affect large-scale ecosystem and biogeochemical functioning of the Arctic marine environment. In addition to ecosystem concerns, solar heat transmitted through the ice cover increases upper ocean heat content, impacting bottom and lateral ice melt. Our understanding of the amount of light reaching the water column beneath the ice has been largely derived from a multiyear ice setting, rather than the first-year-ice dominated Arctic of recent years. As a result, our current state of knowledge of these processes and the validity of many of the parameterizations presently embedded in climate models becomes questionable. For example, recent studies revealed that the transition from multiyear to first-year summer ice cover corresponds to an increase of 200% in light transmittance into the upper ocean. With this information in mind, our primary research objective is to understand and quantify how the changing snow and ice regime in the Arctic will influence the 'light climate' under the ice cover, and importantly, how these changes will influence the timing and duration of primary production and ocean solar heating. We will achieve this by combining current NASA satellite and atmospheric reanalysis products, together with in situ data on the distribution of light under sea ice as a function of snow and ice thickness, melt ponds, and season, in order to upscale observed light regimes below the ice to the pan-Arctic scale. In particular, the ATLAS multi-beam photon-counting instrument on ICESat-2, with its small footprint, has the ability to provide ice freeboard during summer, and resolve small-scale features such as ridges and melt ponds.

Light is a critical ingredient that controls solar heating of the Upper Ocean and primary production under sea ice. If we are to understand and predict ecosystem function in the 'new Arctic', we must understand and correctly parameterize the light climate under today’s first-year ice environment. To do this correctly requires a holistic approach that seamlessly brings optics, snow, sea ice, and ocean physics, together with satellite remote sensing and cutting-edge modelling. Our program will bring a step change in understanding of climate-induced changes that will occur to the functioning of Arctic ecosystems. We will utilize the optical and remote sensing expertise of the Co-PIs to improve the parameterizations of light transmission processes and develop new satellite data products to predict the effects of changing snow-ice-ocean constituents on the under-ice light climate. Given the broad impacts of Arctic change, enhanced knowledge of the Arctic under-ice light environment has a high socio-economic impact.

Rachel Tilling/University of Maryland, College Park
Advancing Understanding Sea Ice Topography Across Scales and Seasons
19-ICESAT2-19-0065

Satellite observations of Arctic sea ice began in the late 1970s. Passive microwave measurements now provide a four-decade record documenting the rapid decline in Arctic sea ice extent. Since the early 2000s, satellite altimeters (laser and radar) have collected data that can be used to estimate Arctic sea ice thickness. In addition to sea ice extent and thickness, detailed and consistent observations of small-scale sea ice topography (such as floe length, surface roughness, and melt pond cover) are needed to understand changes in
the sea ice cover, and implications for our global climate. Providing Arctic-wide observations of these features, which can vary significantly along an individual sea ice floe, still remains a major challenge.

Continuous advancements in satellite technology are improving the resolution of sea ice altimetry from space. In September 2018, NASA’s ICESat-2 (IS2) laser altimeter was launched. IS2 provides observations of the Arctic sea ice cover up to 88°N, with an unprecedented resolution ranging between 30 m and 75 m. Since October 2010, the European Space Agency (ESA) CryoSat-2 (CS2) radar altimeter has surveyed the Arctic Ocean with the same orbital coverage as IS2. The synthetic aperture radar (SAR) altimeter on-board CS2 has a footprint along the flight direction of ~300 m, which is an order of magnitude improvement compared with conventional radar altimeters. A new data processing technique for SAR altimeters known as fully-focused SAR (FF-SAR) processing further improves the along-track resolution of CS2, down to just a few tens of meters. To date, the FF-SAR capabilities of CS2 have not been applied across the whole Arctic sea ice pack.

In this project we will use high-resolution IS2 and the novel FF-SAR CS2 observations to survey the Arctic sea ice cover in unparalleled detail. This will allow us to close the critical gap in sea ice topography observations by generating a new suite sea ice product suite that comprises floe length distribution, surface roughness distribution, and melt pond fraction.

The inability of previous satellite altimeters to resolve small-scale topography features also limits the accuracy of their sea ice thickness estimates. Therefore, we will use our high-resolution topography data to enhance our understanding of how laser and radar satellites sample small-scale sea ice features, and use this knowledge to improve Arctic sea ice thickness estimates. These observations will be available year-round due to the inclusion of melt ponds in our topography products. Following evaluation with independent airborne datasets and high-resolution satellite imagery, we will reconcile our sea ice topography and thickness estimates from IS2 and FF-SAR CS2. The CS2 data will enable a decade-long time series since 2010.

The data we generate in this project will be the highest resolution, decade-long, all-season observations of Arctic sea ice topography and thickness to date.