High-Resolution Surface Height and Roughness Derived From ICESat-2 Altimetry With the DDA-ice — New Data Products for Detection of Glacial Changes and Glacier-Related Catastrophes in High-Mountain Asia

Material for summary:

Title of AO: A.33 UNDERSTANDING CHANGES IN HIGH MOUNTAIN ASIA

cover sheet question on high risk/high impact: Risk/Impact Explanation

The proposed work will provide surface heights and surface roughness data at a resolution near that of the ICESat-2 ATLAS sensor (0.7m along-track under clear-sky atmospheric conditions), using a novel algorithm based on the Density-Dimension Algorithm (DDA) family, adapted to the complex topographic relief of the HMA region and its glaciers and periglacial environments. The resultant products of surface height, surface roughness and their changes over time are expected to have a high impact. Because of their expected increase in resolution and accuracy, compared to DEMs derived from satellite image data, the new altimetry products resultant from this project will provide a much-needed data basis to answer a number of open questions of the HMA team, the science community at large and provide monitoring tools to detect glacier-related catastrophes and environmental hazards which often impact society in the HMA region. A large percentage of glaciers in the HMA region are surge glaciers, and surges typically cause disastrous floods and mudflows, especially in a warming climate. The product generation will be carried out on the NASA cloud (ADAPT), using an intelligent auto-adaptive algorithm that keeps up with ICESat-2 data collection, thus creation of a RAPID product may be feasible (data base for disaster response and warning).

In addition, in that the proposed work takes a surface-roughness-centered approach, the proposed analysis of glacier surges is complementary to the existing consensus in the glaciological community that centers on velocity as the primary physical variable. Rapid, often catastrophic acceleration of a glacier during surge to typcially 20-200 times its normal velocity leads to heavy crevassing. Crevassing is captured by the variable "spatial surface roughness", which can be calculated easily from a single observation, whereas velocity determination requires two correlating image or SAR observations (often correlation does not exist for a complex movement such as a surge). The proposed work aims to demonstrate the advantages of using altimetry-derived spatial ice-surface roughness for change detection, disaster warning and monitoring, and for process-based numerical studies of surge evolution in the HMA region.

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Derivation of a high-resolution surface height product at the resolution of the ICESat-2 ATLAS Sensor, utilizing a version of the DDA-ice specifically adapted to the HMA region. The DDA-ice is an algorithm developed for ICESat-2 data analysis, it utilizes novel mathematics, resolves surfaces in complex, rough terrain and of rough, changing ice surfaces, as are typical in HMA. The current ICESat-2 data products do not have this capability. The DDA is an auto-adaptive, fully automated algorithm, it adapts to background, apparent surface reflectance and day-night transitions. The work will leverage big data analysis, cloud computing and parallelization methods to create a product for the entire HMA region.

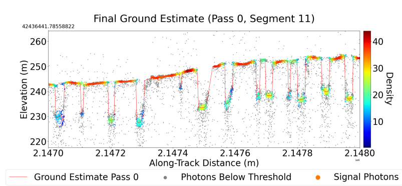
High-Resolution Surface Height and Roughness Derived From ICESat-2 Altimetry With the DDA-ice — New Data Products for Detection of Glacial Changes and Glacier-Related Catastrophes in High-Mountain Asia

Scientific/Technical/Management Section

(1) Science- and applications-driven surface-height and roughness determination and motivation of the approach using the Density-Dimension Algorithm (DDA-ice) – Introduction and Summary of Objectives

High-Mountain Asia (HMA) is the Earth's third-most glaciated region, after Antarctica and Greenland, and provides water resources for more than a billion people. Understanding the response of the Himalayan-Karakoram (HK) rivers to climate change is critical for assessment of the water resources of large river systems including the Indus, Brahmaputra and Ganges, which depend on snow melt and glacial runoff in the HK region [18]. At the same time, the HMA is a topographically complex region and home to many natural catastrophes, which include glacier surges and related flooding and other periglacial events, lake outbursts, rock and ice avalanches, to name a few.

Therefore, assessment of the water resources and planning for food-energy-water nexus security in a highly fragile and densely populated region requires glacio-hydrological and hydrological modeling, which in turn depend on accurate and reliable data sources [17, 18]. To address the challenges associated with changes in the HMA region, NASA launched the High-Mountain Asia Program in 2015 (https://himat.org). Research of the 2015 and 2019 High Mountain Asia Science Teams (HiMATs) led to new understanding of the region and creation of data sets and tools (https://www.himat.org/gmelt/data/). New results concern snowline determination from LandSat and Shuttle Radar Topography Mission (SRTM) imagery, percent snowcover and its changes [29], climatic effects on glacier melt [30], mass balance [31], among others.



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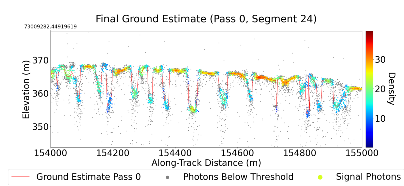

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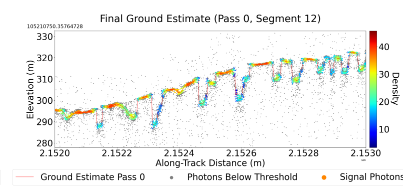

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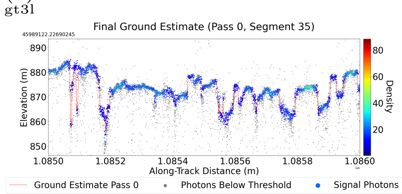

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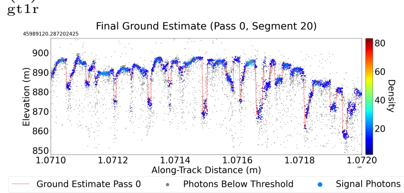

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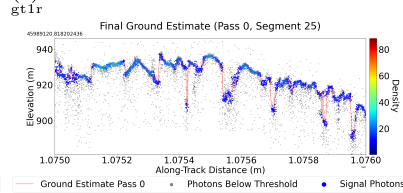

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Figure 1. Examples of surface heights of heavily crevassed glaciers, derived from ICESat-2 ATLAS data using the DDA-ice. Surge crevasses (top), complex crevasses of continuously fast-moving glacier (bottom). a,b,c – Negribreen, Svalbard (prototype of surge crevasses), d,e,f – Ilulissat Ice Stream (Jakobshavn Isbræ), prototype of continuously fast-moving glacier.

In their 2021 science paper, [18] identify major research gaps in the glaciohydrology of the HK, that, if filled, can reduce large uncertainties in glaciohydrological modeling. The first research gap is accurate representation of glacier volumes. Addressing the data analysis and modeling challenges is complicated by the fact that HMA is a topographically complex region and home to many natural catastrophes, which include glacier surges and related flooding and other periglacial events, lake outbursts, rock and ice avalanches, to name a few.

Research completed by the HiMats has provided DEMs from satellite imagery [33, 17], whereas the analysis of ICESat-2 ATLAS data for the HMA region remains an open problem that is specifically called for in [18]. For example, DEMs created from imagery may be incorrect in regions of high topography and result in biased estimation of albedo as needed for modeling of radiation balance [27, 26].

(1.2) Summary of Objectives and Expected Results

We propose a three-tiered approach to address these challenges:

(1) The first objective of the proposed work is the derivation of high-resolution surface height and height-change products from ICESat-2 altimeter data, using a novel algorithm based on the Density-Dimension Algorithm (DDA) family [10, 11] adapted to the complex topographic relief of the HMA region and its glaciers and periglacial environments. (2) Second, we will calculate surface roughness and surface roughness change products from the ICESat-2 DDA surface height products. Surface roughness will be applied as an indicator of rapid glacier changes and other surface changes. All products will be derived for the entire HMA region and, additionally, for its glacier regions. (3) A specific focus will be the investigations of surge glaciers in the HMA region, which cause glacial and periglacial natural disasters.

(1.2.1) Surface height, height and volume change

With the Advanced Topographic Laser Altimeter System (ATLAS), ICESat-2 carries the first space-borne multi-beam micro-pulse photon counting lidar altimeter, which registers returns from every photon in the 532nm frequency of the sensor [16]. The fact that the resultant the photon point cloud, reported on the ICESat-2 ATLAS data product ATL03 [24, 23], includes undiscriminated signal and background photons requires development of new algorithms. Especially for high-background situations of day-time data, the separation of signal and background photons is a mathematically ill-posed problem.

The Density-Dimension Algorithm for ice surfaces (DDA-ice) is unique in its capability to derive high-resolution surface topography for crevassed and other morphologically complex ice surfaces [10, 11] (see Fig.1), such as those resulting from surges, mudflows, rock and ice avalanches, as frequently occur in HMA (see, for instance [37]). In contrast, the surface identifier of other ICESat-2 algorithms generally fails over morphologically complex surfaces [11]. The DDA-ice also works for smooth ice surfaces and for land surfaces. An example of the DDA-ice results is given in Figure 1.

The DDA-ice is an auto-adaptive algorithm, designed specifically for surface-height determination from micro-pulse photon-counting lidar altimeter data, such as those collected with the ATLAS (spell out) System of ICESat-2. The DDA utilizes a radial basis function for data aggregation and an auto-adaptive threshold determination. The DDA-ice results in surface heights at the resolution of the ATLAS sensor, which is 0.7 m along-track (under clear-sky atmospheric conditions) [11]. ICESat-2 DDA-ice surface height results are an order of magnitude higher in resolution than satellite-image based DEMs [33], with surface heights and surface roughness validated over a surging glacier in Svalbard [15]. Hence we expect that an ICESat-2 DDA-ice product for the HMA region will be able to solve some of the problems identified as related to the lack of resolution and accuracy of HMA DEMs derived from image data.

The high-resolution product of surface height, derived from ICESat-2, will fill a major research gap that has been identified in [18] and thus help reduce large uncertainties in glacio-hydrological modeling of glaciers in the HMA region. The surface height product will provide a data base, from which glacier volumes can be calculated.

Differencing of along-track surface heights, producing surface-height change products, will facilitate accurate estimates of seasonal and interannual glacier volume changes. ICESat-2 tracks repeat every 91 days. For glacier studies, the DDA-ice data sets will be intersected with glacier outlines from GLIMS and the Randolph Glacier Inventory [28, 2].

The ICESat-2 surface height products will be compared with image-derived DEMs, to provide an assessment of accuracy and a basis for collaborative merging of image and altimetry-based data products within the HiMat-3. All products will be calculated for the entire HMA region. The DDA-ice has been applied to the entire Greenland Ice Sheet, a region of similar size as the HMA region, processing on the NASA cloud (ADAPT). All algorithms that will be applied in the proposed work are fully automated, using state-of-the-art computational mathematics and cloud processing, and computationally efficient, which facilitates application as operational algorithms.

(1.2.2) Spatial Surface Roughness

Spatial (ice) surface roughness (SSR or SISR) is defined by a mathematical concept that captures the morphological complexity and spatial variability of the surface. SSR will be derived from ICESat-2 data processed with the DDA-ice, using geostatistical principles [14]. As a geophysical variable, SISR provides a detection mechanism/ indicator of glacial acceleration and other, especially structurally pervasive, change processes. As will be explained later in the proposal, SSR is easily processed, because roughness is calculated as a forward-operator (i.e. no complicated inversion or modeling or specific analysis is required for change detection using SSR). Outside of glacier areas, changes in surface roughness, beyond a TBD threshold, will provide indicators for other mass transferring catastrophes, such as avalanches and mud slides.

(1.2.3) Surge Glaciers and Glacier Surges in the HMA

Why are surge glaciers important in the HMA?

A glacier surge is a natural catastrophe, during which a glacier accelerates to 10-200 times its normal speed (quiescent speed). A surge manifests itself in heavy crevassing, mass transfer, and is typically accompanied by water outbursts. In the densely populated regions of the HMA, where villages are often in close proximity of a glacier, the natural catastrophe of a glacier surge often leads to a disaster. The surge phenomenon in the HMA region is wide-spread and poorly understood physically, the surge process changes with climatic change. This motivates the third component of our proposed research, the study of surge glaciers in the HMA region and their dependency on climate variables.

While there is a general agreement that surge glaciers are wide-spread in HMA and surges occur frequently, the numbers of surge glaciers reported in various studies diverge widely, ranging from 244-666 [37, 3, 32, 41] The surge glaciers combined are found to occupy a region of over 11% of the total HMA glaciated region [37]. They [37] identified some 2000+ surge-type advances based on a combination of methods, however, they do not identify the surge mechanism.

Surge detection. The proposed surface roughness and roughness change products will provide an automated and objective means for detection of glacier surges, using a simple differencing of surface roughness measures, following methods in [40, 11], and applying roughness thresholds, which will be established for the HMA region using examples of surge glaciers from the HiMat site.

Surge process studies. Surging is the least understood process of the types of glacial acceleration [**?**]. According to [19], there are at least two types of surges, which, by today's knowledge include the type of surges in temperate glaciers (sometimes called Alaska-type surge, e.g. Bering Glacier System [**?**], Variegated Glacier [**?**]) and the type of surges in Arctic, polythermal glaciers (sometimes referred to as Svalbard type [**?**]). The HMA surge types form a separate class (with several subclasses of surge types) and more observational data are needed to investigate the surge mechanisms in the HMA glaciers.

An objective of the proposed work is to provide a high-resolution data basis, which includes several key info data sets that will facilitate glacier surge studies in HMA and carry out some of those for exemplary surge glaciers (e.g. [29, 37]). In addition to the ICESat-2 based data sets, we plan to include data sets on mass balance, climate variables, weather observations and ice-surface velocities from ItsLive [**?** **?**] provided on the HiMat site. As results, we expect (a) an understanding of the physical processes of surge evolution and (b) insights into the changes in surge behavior and frequency with changes in climatic variables. Modeling of surge dynamics may lead beyond the scope of this project, as ice-dynamic modeling requires bed topography and a full-Stokes environment (such as Elmer Ice), see [40, 39] (note that the model by D. Rounce is a mass-balance model, https.....[himatlink]). All scripts and tools for process studies of surge evolution and glacier change in general, tied to the new as well as existing HiMat data sets, will be provided.

(relate the following to the impact statement – new variable roughness, complementary to velocity)

(2) Expected Results and Relevance of Proposed Work

— integrate the impact statement

The proposed work addresses the first element identified in ROSES A.33 "Understanding Changes in High Mountain Asia", "Earth Science Research", and there specifically the first topic. In that it designs and derives a novel collection of high-resolution surface height and roughness products from ICESat-2 data, the proposed research is a satellite remote sensing study aimed at better characterizing and understanding the processes controlling change of glaciers and related physical variables. The new data products are expected to complement data sets derived by HiMAT-1 and HiMAT-2 in supporting process modeling and model validation and thus leverage work of the previous teams. The data sets will fill a critical gap identified in previous work [17, 18, 27, 26] and as such are expected to provide a basis for collaborative studies within the HiMAT-3, especially subteams working on glacial change and glacial/periglacial catastrophes. The roughness products, which will be continuously updated for each ICESat-2 91-day cycle through the end of the investigation, are expected to yield a data base for detection of sudden glacial acceleration, especially surges, mud-slides and other structurally destructive geophysical processes; and in applications, for disaster warning and response. This addresses the last Earth Science item identified in the solicitation. Thresholded maps of spatial surface roughness may provide a decision support tool for local stakeholders in the future, when updated with 3-day latency ICESat-2 RAPID data products (which are planned to be supported per information from NASA Headquarters, RAPIDs for atmospheric data products already exist). Thresholds would identify critical levels of surface change indicative of a disastrous mass wasting process (such as a surge, avalanche, mudslide, lake outburst).

In the study of the surge phenomenon, the proposed work will find a focus that ties together several of the aspects of HMA research, in the arguably most dramatic/rapid change of a glacier or glacier system. Surge glaciers and active surges are frequent in the HMA region, and the HMA surge type, or types, are characteristically different from surges in temperate glaciers of Alaska and surges in polythermal Arctic glaciers. Because of the sudden onset and rapid acceleration, surges are the epitome of catastrophic change, and often trigger glacial outburst floods, debris flow, and other periglacial changes, affecting ecosystems and infrastructure alike. We will investigate relationships between surge initiation and environmental variables collected and collated under previous HiMat efforts (snow distribution temperature and precipitation fields, glacier change). Expected results include understanding the processes associated with the evolution of HMA surge types and their subtypes, and specifically changes in surge behavior and frequency in a warming climate.

Not only will the surge glacier focus have a high relevance to the changes in the HMA region, surge glacier environments also provide a unique collection of some of the "hardest cases" of satellite data analysis, because of the complexity and occurrence of many different surface characteristics in close proximity. Simply stated, if a satellite data analysis method works for a surge glacier, it likely works everywhere else. The new ICESat-2 DDA-ice products will be shared via NSIDC and tools will be added to the Glacier and Snow Melt Toolbox (GMELT). Advances in Big Data analysis, cloud computing and parallelization that will be developed and applied for this project may be more generally applicable in processing of satellite altimeter data and other remotely sensed data.

In that the proposed work addresses critical climatic science questions, it is directly relevant to the Climate Change Goals of NASA's Earth Observation Mission. The proposed effort shares goals with World Climate Research Programme (WCRP) and especially Climate and Cryosphere (CliC), and the Intergovernmental Panel on Climate Change (IPCC).

(3) Specific Objectives and Approach

(3.1) Specific Objectives

Main proposal objectives will be:

(1) Derivation of a high-resolution surface height product at the resolution of the ICESat-2 ATLAS Sensor, utilizing a version of the DDA-ice specifically adapted to the HMA region.

(2) Derivation of a high-resolution surface roughness product, based on the surface height products in (1).

(3) Application of these products to understand the physical processes during rapid glacial acceleration, especially glacier surges and other natural catastrophes, which have large impacts on human life and infrastructure in HMA. .

(4) Investigation of relationships between increased occurrence of natural catastrophes and climate-related changes.

(5) Derivation of gridded products from (1) and (2).

(6) Elevation-change and roughness-change products; tools / scripts to create change products from any two data sets that we provide. We will provide change maps of: (a) seasonal change maps, (b) annual change maps, (c) change maps for (cycle(n) - cycle(n-1)) for the same product.

(7) Validation/ Comparison of our surface-height products to imagery-derived DEMs created by the Hi-Mats.

(8) Application of our approach to case studies of glacier surges, glacial catastrophes and glacier-related catastrophes.

(9) Contribution of all products to NSIDC and tools to GMELT. Publication and sharing following OS and FAIR principles.

(3.2) Role of Spatial Surface Roughness and its Definition

Understanding the mathematical philosophy of the approach used in the proposed work requires a brief introduction to the concept of surface roughness. The basic notion is that cryospheric change processes manifest themselves in changes in surface morphology, which is a derivative of surface height. ICESat-2 is the first space-borne mission to capture the morphology and not "just" ice-surface height and its changes.

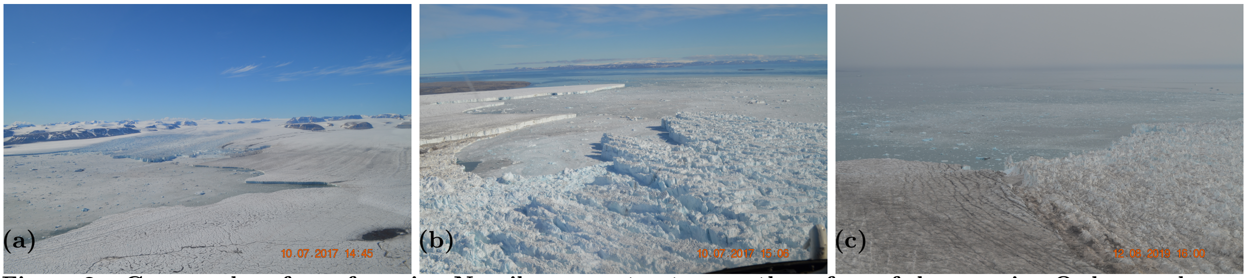

Figure 2. Crevassed surface of surging Negribreen contrasts smooth surface of slow-moving Ordonnansbreen, Svalbard. (a) Negribreen in center, Ordonnansbreen in front and right. 2017. (b) Advancing fractured ice of Negribreen (front), Ordonnansbreen (background). 2017. (c) Boundary between Ordonnansbreen (left) and Negribreen (right) in 2018.

The stark contrast between the fractured and rapidly advancing ice of a surging glacier and the smooth surface of a slow-moving, non-surging glacier (Fig. 2) illustrates that (1) we need to be able to measure heights of crevassed, rough glaciers to estimate their volume and mass changes, and (2) a mathematical representation of a fractured, rough ice surface requires a different approach than the classic calculus of smooth surfaces. Solutions to both problems are components of the proposed work. We will use the mathematical framework for generalized spatial surface roughness, built on vario functions of geostatistics, introduced in [14, 13]. A surface roughness parameter can be employed as the first indicator of crevassed terrain, and thus be used to detect changes in glacial acceleration. An example of using GLAS data for roughness analysis of Jakobshavn Isbræ is given in [6]. With more than 200 times better along-track resolution of ICESat-2 ATLAS data (0.7m) compared to GLAS data (173m), surface roughness can directly be matched to crevassing, as seen in a comparison between Planet SkySat imagery and surface roughness from ICESat-2 DDA-ice processed surface heights (see Figure 3).

Figure 6 from SRS paper. reference [11] in the caption.

(3.3) Levels of the Proposed ICESat-2 DDA-ice HMA Products

The core of the project is structured according to levels 1-4 of increasing complexity with (A) goal, (B) algorithm, (C) resultant products and (D) applications for each level (see, Figure 4).

(3.3.1) Level 1: Surface-height Determination in Crevassed (and Smooth) Terrain

(1A) The goal of the first level is simply the identification of signal photons in the received point cloud and calculation of surface height for crevassed and otherwise morphologically complex ice surfaces.

(1B) Algorithm: The Density-Dimension Algorithm for Ice Surfaces (DDA-ice)

The density-dimension algorithms are a suite of algorithms specifically developed for the analysis of ICESat-2 ATLAS data and more generally, micro-pulse photon-counting lidar altimeter data. The radial basis function is the basic mathematical concept used in the data aggregation for calculation of density. The data aggregation by density calculation forms the basis for all other steps of the DDA [10, 11], which include threshold separation of signal and noise photons and application-specific ground followers. The DDA-ice for ATLAS data utilizes the geolocated photon cloud as reported in the ATLAS product ATL03 (but not the photon classification given in ATL03). Data postings after analysis have the same spatial resolution as the original data.

A *radial basis function (rbf)* is a real-valued function whose value depends on distance from a *center* $c \epsilon \mathcal{D}$ for all x in a definition area $\mathcal{D}$

$$\Phi(x, c) = \Phi(\|x - c\|) \tag{1}$$

with respect to any norm $\|\cdot\|$. In the algorithm, we utilize a Gaussian radial basis function (letting $r = x - c$

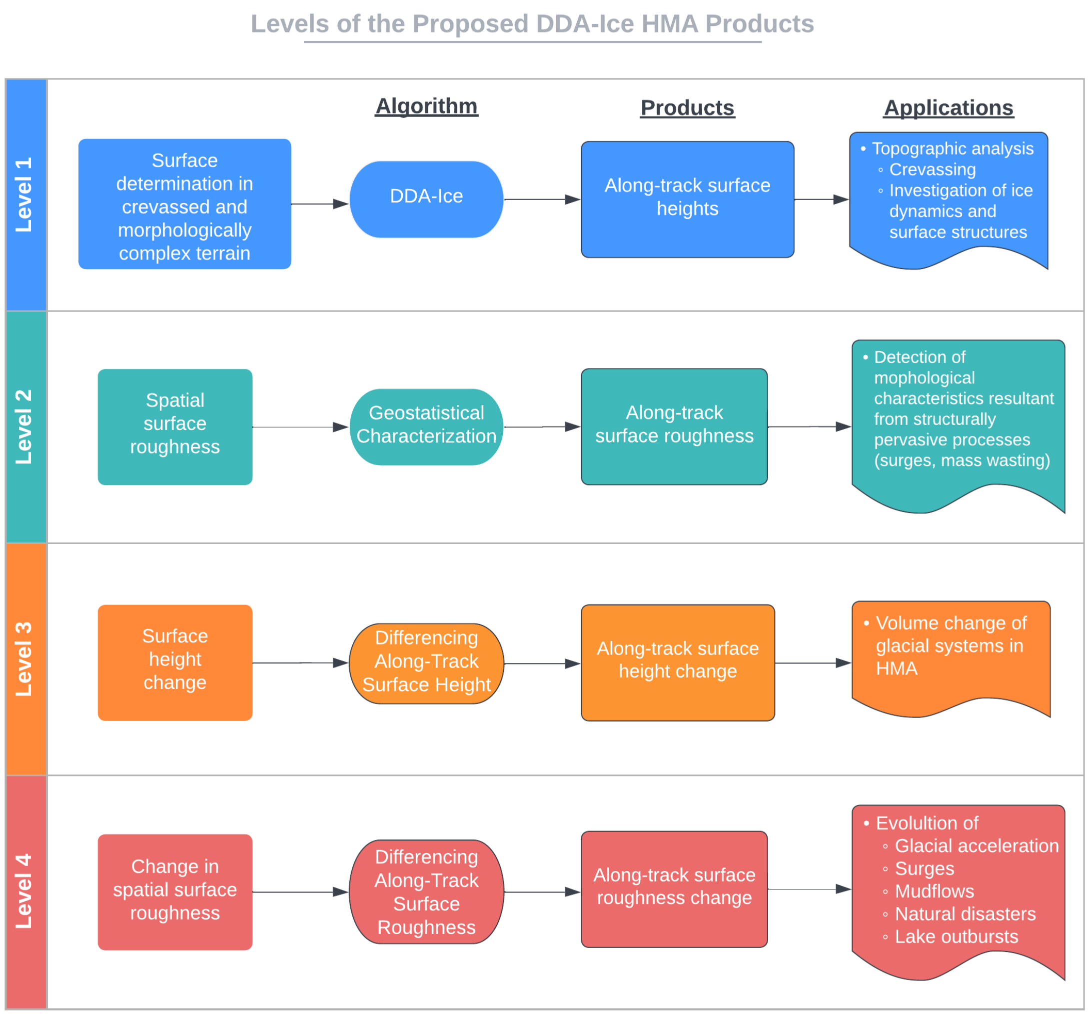

Figure 4. Flow Diagram of ICESat-2 DDA-ice HMA product development and applications.

and $s \epsilon \mathcal{R}$)

$$\Phi(r) = e^{-(\frac{r}{\sqrt{2}s})^2} \tag{2}$$

Visualized as a surface in $\mathcal{R}^3$, this rbf has the shape of (half) a Gaussian bell curve rotated around the location of a center $c \epsilon \mathcal{R}^2$. In the photon-data analysis, we have $c \epsilon \mathcal{R}^3$ and the surface is in $\mathcal{R}^4$. More formally, the Gaussian probability density function is

$$f_{normpdf} = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(\frac{x-\mu}{\sqrt{2}\sigma})^2} \tag{3}$$

with standard deviation σ and mean μ of the population; replacing $\sigma = s$ and $\mu = 0$ yields eqn. (4):

$$\Phi(r) = \sigma\sqrt{2\pi} f_{normpdf} \tag{4}$$

An early version of the density algorithm is described in [7] for vegetation data (ground and canopy). The DDA is used as the official algorithm for ICESat-2 atmospheric products (cloud layer, aerosol and blowing snow detection) and described in the Algorithm Theoretical Base Document [8]. The DDA-ice is applied to ice surface height determination during a surge in [11]. The DDA-ice utilizes a ground-following algorithm that adapts to the roughness of the surface or the crevasse morphology.

The DDA-ice is an auto-adaptive algorithm, which uses the mathematical concept of an artificial neural network (NN) (the *rbf*) in an entirely new way, but it is not a NN. Herein lies the reason that, while conceptually advanced, the DDA is computationally inexpensive, a property which makes it feasible to process surface heights for the entire Greenland ice sheet. The auto-adaptive capability means that the algorithm adapts automatically to changes in background in the photon point cloud, and it can correct for some undesired instrument effects. For example, the afterpulse cannot be mistaken as a signal because of its characteristic lower density. The algorithm is driven by a set of algorithm-specific parameters. The parameters can be set to adjust to changes in instrument characteristics, but also to highlight certain morphological characteristics or to adapt to predominantly high topographic relief, as is typical in HMA. An uncertainty measure will be implemented using a 10% bracket for the threshold quantile $q \pm 10\%$. Before running the actual DDA-ice, a cloud-ground separation algorithm is applied to ascertain that returns from clouds are not mistaken for ground returns. This is necessary because the micro-pulse signal is easily attenuated in clouds and the simple cloud flag in ATL04/ATL09 does not always work properly.

Comparison of DDA-ice results to standard ICESat-2 ATLAS surface height products. For the HMA region, surface height information from ICESat-2 is provided in the ICESat-2 ATLAS data products ATL08 (Land and Vegetation Height) [22, 21, 20] and, where glaciers exist, also in ATL06 (land ice height) [34, 35]. The DDA-ice is a data aggregation method that calculates a density field, using each single recorded photon as the center point. The signal-noise separation is carried out in a space that includes the density field as an added dimension. Herein lies the reason that the DDA-ice is a powerful method that can resolve morphological characteristics of crevassed glacier and other complex surface types, under easy and difficult signal-to-noise (background) situations (the latter include all day-time data because of the high background during day-time) [11]. All other data analysis methods utilized for creation of ICESat-2 ATLAS products utilize reduction of information (as typical for statistics) early in the algorithm, thereby losing the high-resolution spatial variability information. This is illustrated in Fig xx for ATL06 (the land-ice surface height product). The DDA-ice has the following advantages: (1) It produces signal (versus background) classification at the resolution of the senso (0.7m along-track), (2) surface heights in an interpolated ground follower at 2.5m for rough surfaces (5m for smooth surfaces), ATL08 has 20m postings (and 100m interpolated ground heights) [21], ATL06 has 40m segments w 20m postings [35], (3) the ATL06 algorithm fails over crevassed and other complex surfaces (i.e. no surface height is returned) [11], (4) ATL08 only provides heights for strong beams, ATL06 provides heights for weak and strong beam but fairs poorly for strong beam records over complex surfaces, the DDA-ice resolves surface topography for strong and weak beams in easy and difficult signal-to-noise situations [11].

[FIG] Use herzfeld_ssr, fig 10i,j (night-time data, simple crevassing) and fig 11 (day-time data and complex crevassing, Jak) to illustrate the differences.

[FIG] Use figures from Adam/Rachel for DDA-ice of the HMA region.

(1C) Products. At this point, the surface height products can be derived: (1C.1) Surface height for the entire HMA region, and (1C.2) Surface roughness intersected with glacier outlines from GLIMS and the Randolph Glacier Inventory (RGI) [**?**].

(1D) Applications

(1D.1) Evolution of the surface signature of surges in HMA glaciers and other mass-wasting processes. The most obvious manifestation of a surge is crevassing, with different crevasse types characteristic of the propagation of the surge through the glacier system. Crevassing serves as a useful geophysical

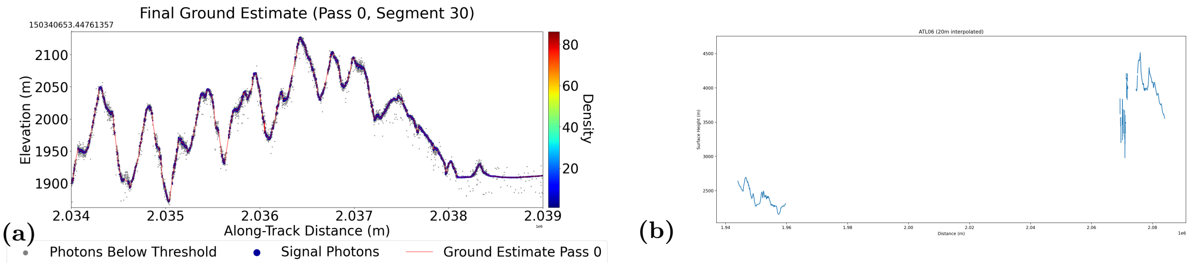

Figure 5. Example of surface heights from ICESat-2 DDA-ice for a crevassed glacier surface in the HMA region (a). (b) Example of ATL06 data. The segment in (a) falls into the stretch where no surface height is reported in ATL06.

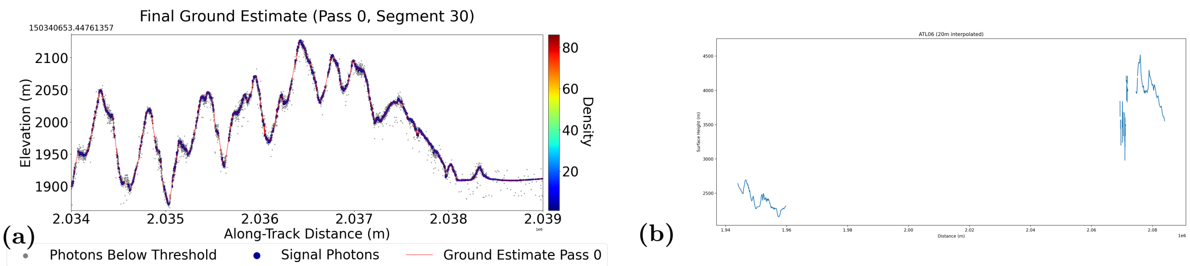

Figure 6. Comparison of surface height determination for crevassed areas in Negribreen, Svalbard and Jakobshavn Isbræ, Greenland, in DDA-ice analysis and ATL06. (a) Simple crevassing and night-time data (low background level). (b) Complex crevassing and day-time data (high background level).

variable because it has sufficient spatial resolution and locally specific characteristics that can be derived from both observational data analysis and numerical modeling [40]. Here, we will utilize high-resolution topography as the primary means for identifying and analyzing surface signatures of surges (crevassing) and of other mass-wasting processes (avalanches, mud slides, lake outbursts).

(1D.2) Evaluation of surface heights of satellite-image-based DEMS. Because height measurement is a direct result of satellite altimetry, the ICESat-2 based along-track surface height products can be employed for evaluation of DEMs derived from satellite imagery using photogrammetry, for which surface height is a derived value (see also [36]).

The goal of the EarthDEM project (https://www.pgc.umn.edu/data/earthdem/) is to create a DEM with 2-m grid-size from SmallSat satellite image data (mostly MAXAR WorldView-1/2/3 data and some GeoEye Data) using stereo-photogrammetric techniques based on [25]. WorldView image data have sub-meter pixel sizes. For the HMA region, so far this has been completed for the area of Nepal (pers. comm. Polar Geospatial Center.) The DEM has not yet been evaluated for accuracy of height determination. It is generally well-known that complex topographic relief and surface roughness are factors that present challenges for surface-height determination from imagery.

We will obtain both strip-DEMs and mosaic DEMs for quantitative comparison of ICESat-2 DDA-ice surface heights, for several small and large regions of different surface and roughness characteristics. Results will provide quantification of uncertainty for elevation and volume-change detection from imagery. Furthermore, results of the comparison may be expected to provide a path forward for improving accuracy of image-derived DEMs, such as EarthDEM, by merging with the ICESat-2 DDA-ice surface heights and roughness information (which could be addressed in a future proposal).

The same process will be applied for evaluation of the 8m-resolution DEM linked on the GMELT site [33].

In addition to EarthDEM, we will use DEMs of glaciated regions, shared through GMELT, for test cases of our algorithms and products. We will create combined maps from those images, their DEMs and the ICESat-2 DDA height and roughness products for assessment and demonstration.

(3.3.2) Level 2: Spatial Surface Roughness

(2A) Goal. The goal is the detection of morphological characteristics resultant from sturcturally pervasive processes.

(2B) Algorithm: Geostatistical characterization. To calculate SSR, we will use a method introduced in [**?**], based on characteristic parameters derived from vario fucntions. Vario functions are inspired by geostatistical functions, but defined in a discrete mathematics framework, as

$$v_1(h) = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2 \tag{5}$$

for pairs of points $(x_i, z(x_i)), (x_i + h, z(x_i + h)) \epsilon \mathcal{D}$, where $\mathcal{D}$ is a region in $\mathcal{R}^2$ (for satellite tracks). Using

$$m(h) = \frac{1}{n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)], \tag{6}$$

the residual vario function is defined as:

$$res_1(h) = v_1(h) - \frac{1}{2} m(h)^2. \tag{7}$$

The (*pond_res*) parameter, defined as the largest value in an along-track calculated residual vario function, will be used for the calculation of SSR.

(2C) Product: Along-track surface roughness

(2D) Application: Signatures of Change Processes. The salient concept is that change processes that affect the morphology of a surface leave surface signatures. For example, the sudden glacial acceleration during a surge results in crevasse fields. These can be detected in a single data set (see, Fig. 8b). In contrast, calculation of velocity requires two correlated image or SAR data sets. Needing only one data set greatly increases the number of observations from which quantitative results can be derived, which is important especially for image or lidar data which are affected by (most) clouds. Other examples of structurally pervasive changes that affect surface roughness are land slides, mud flows and lake outbursts (surface is rougher after the flood).

(3.3.3) Level 3: Surface Height Change

(3A) Goal. Monitoring of changes in surface height and volume.

(3B) Algorithm: Differencing along-track surface height. The algorithm is obvious.

(3C) Product: Along-track surface height change

(3D) Applications: Volume change in glaciers and peri-glacial areas. Mass transfer resultant from surges and avalanches. See sections (3.4) and (3.5).

(3.3.4) Level 4: Change in Spatial Surface Roughness

(4A) Goal. Capturing the Evolution of all the change processes that can lead to natural disasters in the HMA region.

(4B) Algorithm: Differencing along-track surface roughness. The algorithm is obvious.

(4C) Product: Along-track surface roughness change

(4D) Application: Detection of glacial acceleration, surges, mudflows, natural disasters, lake outbursts. See sections (3.4) and (3.5).

(3.3.5) Level 5: Gridded Products

Gridded products will be derived using a geostatistical estimation method summarized as Advanced Kriging, a form of universal Kriging with specific parameters and algorithm components adapted to the situation of geophysical track-line data such as altimeter data [12, 38, 4, 5].

On the uses and limitations of gridded products. ICESat-2 has the advantage of collecting data with coverage of the entire Earth, except for two small pole holes. The sensor is operate continuously, with exact track repeats every 91 days (called cycles; currently we are cycle 18 since start of the science data acquisition in 2018). The DDA-ice always produces a surface height, as long as the surface is captured. Thus there is a data base for production of gridded elevation, for the entire region or study areas, which is most meaningful where no other surface heights exist. Calculation is computationally feasible and uncertainty in the height product will be derived as standard deviation of the kriging height; this value depends on track spacing. The geometry of the ICESat-2 ground track patterns results from the beam geometry of the observatory [11]. ICESat-2 has three pairs of beams, a strong beam and a weak beam each, where the strong beam has 4 times the energy of the weak beam. The ground tracks of the three strong beams are spaced 3.3km apart, with the weak beam spaced 90 m from the strong beam for each pair. However, beams from adjacent ground tracks overlap on a glacier (on any surface). A 500-m grid can be derived. The grid is expected to be valuable for large-scale studies, whereas for small-scale studies the along-track data sets and their time-differences will be more useful. To create assessments of volume changes, gridded maps calculated from differenced along-track height will be suitable.

At the time of this writing, DEMs from image data are being developed at 2m resolution as part of the Earth-DEM project. So far, this only covers essentially Nepal (pers. comm. from the Polar geospatial center, see also https://www.pgc.umn.edu/data/earthdem/). The HiMAT site (https://www.himat.org/gmelt/data/) has image-based DEMs for a number of glacier basins, but not for the entire HMA region. High Mountain Asia 8-meter DEMs derived for the glaciated regions from along-track optical imagery are available at NSIDC (https://nsidc.org/data/HMA_DEM8m_AT/versions/1) [33], these are based on MAXAR data (largely Quickbird2, WorldView1/2/3 and some Geoeye data), integrating data from 2002-2016.

We will employ the proposed ICESat-2 DDA-ice surface height products for comparison and assessment of height accuracies of these image-derived DEMs. The expected results of these comparisons will reduce uncertainties in any analyses and modeling efforts that utilize these DEMs. However, none of these products allows change detection.

To meet the change-detection goals of the A.33 "Understanding Changes in HMA", a time series of consistently derived DEMs for the entire HMA region is expected to be valuable, even if rendered at 500m resolution. Such a time series can be derived from ICESat-2 surface height products, as described above, for every 91-day cycle of ICESat-2 observations. The Big Data analysis methods summarized in section (3.6) will ascertain operability of our approach.

(3.4) Glacier Analysis

The steps summarized in the flow diagram (Fig. 4) will provide along-track height and roughness products for the entire HMA region, facilitating observations and analysis of any mass transfer (including rock falls, mud slides, lake outbursts, Earthquakes). For analysis of glacier regions, these data sets will be intersected with glacier outlines of the Randolph Glacier Inventory (RGI) and GLIMS, resulting in a glacier height and roughness data set. This will facilitate a bulk analysis of glacial volume change in the HMA or any subregion. Scripts will be provided for other users to perform a study of a single glacier or glacial region. As part of this project, we will carry out investigations of select surge glaciers that have been surging during the ICESat-2 observation time frame, which started in 2018.

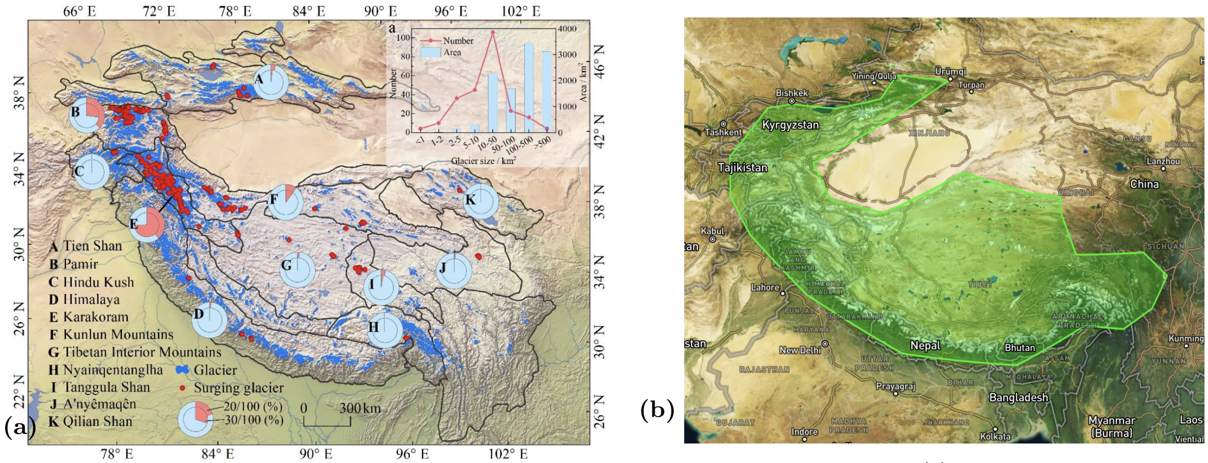

Figure 5. Maps of surge glaciers and processing polygon for the HMA region. (a) Distribution of surge glaciers, from [37]. (b) Polygon of ROI for processing ICESat-2 data with the DDA-ice, used for calculation of computational feasibility.

(3.5) Surge Processes

The surge phenomenon and its relevance for the HMA region has already been discussed in the introduction. Here, we give examples of the data products and their application to studying the surge process. The examples stem from Negribreen, Svalbard. Surge glaciers in the region that may be suitable study objects include the Hispar Glacier, Pakistan the Musta Glacier, the Oshanina Glacier and the Engilchek glacier, Kyrgystan [29, 37]. Using SSR and SSR change, glaciers will be identified that surged since the launch of ICESat-2 (2018). The distribution of surge glaciers is indicated in the map in Fig. 5a.

The Negribreen Glacier System (NGS) in Arctic Svalbard has been surging since 2017 and thus provides a good example to demonstrate the concepts of surface height, height changes, spatial surface roughness and roughness changes and the relevance for investigations of the surge process. Height and height change records reveal times and locations of opening of new crevasse fields, which document the advance of the kinematic front of the surge through the glacier system, both upglacier and downglacier. Surface lowering can be calculated across crevassed and uncrevassed ice surfaces and combinations that include crevassed and uncrevassed ice. The map of surface height rate of change illustrates the mass transfer during a surge (Figure 8c). A surface roughness map shows that roughness values from ICESat-2 DDA-ice heights line up with crevasse fields seen in Landsat imagery (Figure 8b). The maps of roughness rate of change (Fig. 8d) then documents the expansion of the surge over time.

(3.6) Big Data Analysis Using Cloud Computing and Parallelization

To demonstrate the computational feasibility of the proposed Big Data analysis task of running the DDA-ice over the HMA region, we use the following considerations.

To adapt to a new data analysis task, the DDA-ice performs best after optimization of a set algorithm-specific parameters. This will be carried out for test data sets of different spatial characteristics on local machines in the lab of the PI. ICESat-2 ATL03 data will be downloaded from the Earthdata site.

Computational Environment: NASA Explore/ADAPT Science Cloud. We plan to carry out large-

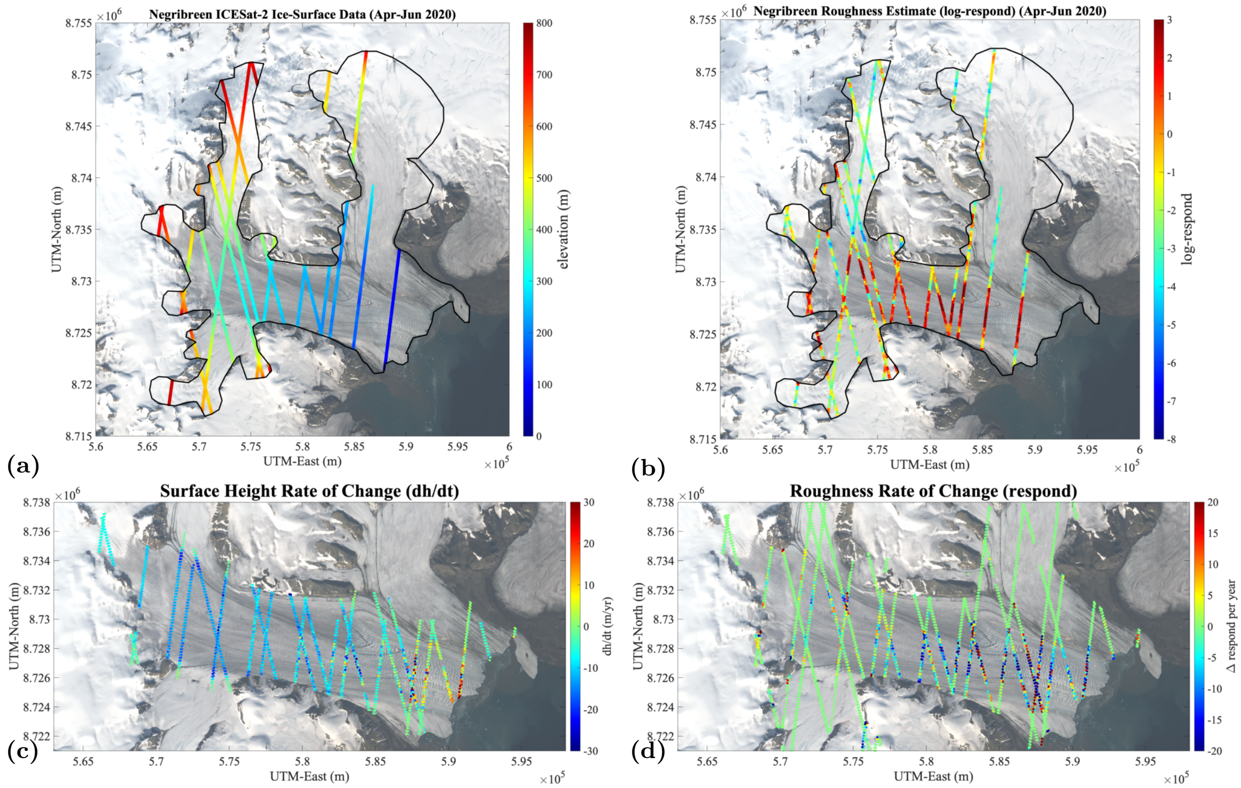

Figure 8. Surface height, roughness and rates of change of surface height and roughness during the 2019-2020 phase of the Negribreen surge. Calculated from ICESat-2 ATLAS data using the DDA-ice. (a) Surface height. (b) Ice surface roughness. (c) Surface height change rate in meters per year. (b) Roughness (log of respond) change rate in Δpond per year. Change rates have been adjusted for the time interval between ICESat-2 passes. Background: Landsat image from the same time.

scale data analysis for the entire HMA region on the Explore Platform as a Service (PaaS), also known as the Advanced Data Analytics Platform (ADAPT), operated by the NASA Center for Climate Simulations (NCCS) at Goddard Space Flight Center (https://www.nccs.nasa.gov/systems/ADAPT). ADAPT is a private, NASA-supported cloud computing environment built with managed Linux virtual machines (VMs) specifically designed for large-scale data analysis. The platform incorporates storage, compute, container, and cloud computing capabilities. The architecture consists of over 300 physical hypervisors that host one or more VMs each. A unique advantage of this environment is that every VM has access to the same centralized data repositories which include dynamic collections of some of the most commonly used NASA-supported datasets such as ICESat-2, Landsat, MODIS and MERRA/MERRA-2, where newly acquired data is continuously added. ICESat-2 ATL03 data, as needed as input for the proposed HMA project, is added for every new ICESat-2 release. It is more efficient to bring the code to the data than vice versa. ADAPT has a designated ICESat-2 compute cluster for processing of ICESat-2 data. A request for High-End Computing (HEC) has been submitted in anticipation of the proposed work on ADAPT and is included with the proposal documents.

Computational feasibility. It has been demonstrated [9, 1] that large-scale analysis of ICESat-2 ATL03 data can be carried out on ADAPT using a form of the DDA. The study in [9] utilizes the DDA-bifurcate-seaice to automatically detect melt ponds on sea ice for the Multi-year Arctic sea-ice region (MYASIR) [figure]. The DDA-bifurcate-seaice is a 2-level algorithm, whereas in the proposed project, we will only need to use a 1-level algorithm, requiring significantly less computational effort.

The HMA region is approximated by a region of interest (ROI) outlined by a polygon in Figure 5b. The area of the ROI is 2.7 million km^2, thus similar in size to Greenland (2.6 million km^2). The DDA-ice can be run for the entire Greenland area on ADAPT.

Parallelization. In order to perform efficient Big Data analysis for the HMA region, we propose to leverage the parallel nature of the ICESat-2 compute cluster on ADAPT, which consists of 10 virtual hosts with 10 compute cores each (total of 100 CPUs). We plan to develop two levels of parallelization (1) modularized, internal parallelization in the density computation of the DDA-ice and (2) execution-level parallelization for allocating the work over separate hosts. The first type of parallelization is part of the algorithm development for this project, while the second type will utilize the Slurm workload manager provided on ADAPT to distribute the work of executing the DDA-ice over multiple compute nodes within the ICESat-2 cluster.

(4) Integration of the proposed surface height and surface roughness products into GMELT.

(4.1) Sharing/ Publication of the Data products via NSIDC

The NSIDC has been identified as the DAAC that will handle and share the results from the A.33 HMA projects.

All resultant products will be documented and shared via NSIDC. For details, we refer to the DMP.

(4.2) Contributions to GMELT

The data products will be integrated into GMELT via links to the NSIDC HMA data product repository.

[details form Amanda Leon email in my notes.]

- documentation of the data sets

- publication describing the data sets at large

- publication describing the surge case studies (along with exemplary scripts for creation of maps from a number of sources.)

[note - in the surge section, that here we'll utilize all tools and data sets available, including GMELT data sets [may better describe which ones], velocity fields, image data, what not. we could use ItsLive or Sentinel data.

- scripts and tools, jupyter notebooks, docus.

- it is required to submit the algorithm and code.

(4.3) Additional Open Science and Open Source Software Approaches

- all of 4.1 and 4.2

- refer to TOPS and other items with links in the AO.

well all the above. Offer online tutorials (in year 2?) for folks interested in using our product.

- copy stuff from the ST2019 proposal.

(5) Time line/ Schedule of milestones

Year 1. (1) Selection of a year of ICESat-2 data: 2021, 4 cycles, 4 season, to establish HMA-specific work-flow and algorithm-specific parameters. (2) Polygon of HMA region; pull ICESat-2 granules; (3) Processing of ICESat-2 granules for select Reference Ground Tracks (RGTs); (4) Sensitivity studies for optimization of algorithm-specific parameters; (5) Selection of a stamp collection of regions with different surface characteristics, surface types (glacial, periglacial, lake surfaces, several roughness types); utilizing info from the HMA data base to identify the stamps (prototype regions); (5b) Identify surge glaciers with active surges after start of the ICESat-2 science observations (October 2018); (6) Set up intersection of RGI outlines with ICESat-2 RGTs; [note so far, on local computers] (7) Transfer and run it all on ADAPT; create an HMA height data set, an HMA glacier height data set, an HMA surface roughness data set and an HMA ice surface roughness data set; (8) Q/R: evaluate products under various assessment criteria; (9) Surge studies; (10) Collaborate within the team on the glacier change problem; (11) Publication and presentation of results; (12) Document everything and share according to OS and FAIR principles; provide data sets to NSIDC and tools to GMELT.

Year 2. (1) Big Data analysis: run more ICESat-2 cycles; (2) Seasonal comparison - change detection component; (3) Interannual comparison - change detection component; (4) Comparison to satellite-image-based DEM heights from (a) EarthDEM, (b) select glaciers from GMELT repository, (c) 8m DEM product from GMELT; (5) Surge glacier studies, integrating ICESat-2 DDA-ice products and several other data types from GMELT; derive process understanding of surge evolution. (6) Investigate the hypothesis that spatial surface roughness serves as an indicator and detector of rapid change; develop several thresholds of roughness values, for different categories of change processes; use any information on GMELT site or satellite imagery (LandSat, WorldView) to validate the occurrence of a change process; (7) Surge glaciers studies: use ancillary data to investigate out potential surge initiators (rain? warming event?) and surge causes, other than bed topography (likely not available); (8) Collaborate within the team on the glacier change problem; (9) As time permits, add more cycles to the processing line; (10) Collaborate within the team on the glacier change problem; (11) Publication and presentation of results; (12) Document everything and share according to OS and FAIR principles; provide data sets to NSIDC and tools to GMELT.

Expertise and Resources Not Anonymized - I better supplement the time schedule by addressing it in the non-redacted experience and facilities docu as well.

such as: The PI and her group are in a unique position to perform the proposed work and, especially, to complete it in two years. (1) because we already have the computational infrastructure developed on ADAPT (paralellization of the DDA-ice). (2) extensive experience wiht image data, including WorldView and other SmallSat data. (3) exhaustive experience working with ICESat-2 data. (4) previous work on surge glaciers, linking observations (satellite data analysis) and numerical modeling.

In the non-redacted item: make a section “Open Source DDA results” and state: we are currently in the process of releasing the ICESat-2 melt-pond results from the DDA-bif-seaice to NSIDC. The Sea=ice melt-pond study provides an example of Big Data analysis, detection of many small-scale features for a large-scale region. as such, it is exemplary for the type of computational capabilities that will be derived under the proposed project, using an algorithm from the same DDA family. We hope that the sea-ice melt-pond product will be available online by the time this proposal reaches review stage.

The DDA-bif-seaice will be implemented as part of the operational algorithm for ICESat-2 processing, in collaboration of the PI and the I2 Project and the SIPS (spell out).

DDA-surface height and roughness products are at a stage of validation and actually, running products on ADAPT, for several I2 cycles. We have started the process of sharing the data via NSIDC here for this series of research products as well.

Data Management Plan

- an extra item.

- use the email. from Amanda Leon

- use the language linked to in the proposal call for DMP rules.

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