GNET 2017 Forward:

The future shape of a Greenland GNSS observation network

A whitepaper produced by the participants of the NSF-supported GNET workshop, NASA GSFC, 26-27 January 2017

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Executive Summary

An internationally coordinated research campaign, the *International Polar Year (IPY) 2007-2008*, initiated a coordinated effort to study the polar regions using modern observational techniques, including a major investigation using geodetic and seismic instrumentation. This effort is formally known and funded under the name "POLENET", or the *Polar Earth Observing Network*. In Greenland, the GNET project was developed to establish a network of GPS receivers operating continuously and autonomously on stable bedrock around Greenland. The most prominent institutions involved in supporting this effort have been The Ohio State University, the University of Luxembourg, UNAVCO (Boulder, CO) and the Institut for Rumsforskning og Rumteknologi (DTU Space, Copenhagen). The purpose of the January 26-27, 2017 workshop was to discuss the future of this network from a geodetic perspective. We were especially focused on documenting how GNET data are being used now, to probe how the network could evolve, and to ask what scientific questions motivate its future. GNET data have served a variety of useful scientific purposes, such as providing ground truth for predictive models for post glacial rise/fall of bedrock adjacent to the ice sheet that in turn, play an essential role in correcting satellite gravity and altimetry based estimates of ice mass balance on decadal time scales. A decade of observations now indicate that vertical motions tend to be dominated by the mass unloading caused by secular ice sheet mass loss to the ocean.

In addition to enumerating past successes of GNET, the workshop participants sought to examine the yet unexploited value that the network may provide for achieving new science objectives, such as tropospheric and ionospheric mapping, gaining new insights concerning surface mass balance, ice dynamics and ocean tidal mapping, among others. This workshop report is designed to capture some of these new explorations, but will hardly serve as a comprehensive survey of all of the details or all of the new scientific discovery a new decade of GNET operation could enable, however the network may evolve. There is an emphasis placed upon the components of ice sheet surface mass balance in this report. Surface mass balance is essentially the net input mass component. This is driven primarily by the atmosphere and near-surface ice sheet temperature structure. The emphasis is motivated by three recent science breakthroughs: (i) since about 2006 the negative mass balance of the Greenland ice sheet is dominated by melt processes (and since about 1997 dominated by surface mass balance in general); (ii) recent findings demonstrate that GNET have sensitivities to the loading components of the various elements of the surface mass balance; (iii) the

zenith-delays measured in the carrier phase of the electromagnetic pulses received at the stations are capable of significantly improving hindcast models of precipitation, a fundamental component of the surface mass balance.

The primary recommendations of this report are:

1. Continue to support the continuous and autonomous operation of the current configuration of GNET. The spatial distribution and long time series of observations from the current network has enabled a wealth of scientific discovery, and extending these time series into the future will enable new science.

2. Maximize the utility of the current data by promoting the existing data distribution model, which encourages low-latency access to data. These efforts should be augmented with readily available doi numbers to enable proper data citation.

3. Encouraging new uses of GNET data, such as tropospheric zenith delay analyses to improve atmospheric models in Greenland and use of these data for modeling the ionosphere. This is one example of many of new science that could be supported by the existing data.

4. If possible, densify the current network to better resolve those areas of maximum gradient in GIA, and/or regions of rapid glacier change.

5. Given finite resources, we consider a scoring scheme for evaluating the relative importance of existing stations. Considered are the role of existing stations for fostering an improved understanding of (i) GIA, (ii) surface mass balance minus discharge (*SMB-D*) and (iii) resolving the larger discords (> 4.5 mm/yr) revealed in comparison of GIA models based on relative sea-level data versus those more reliant on GNET uplift rate data. The ultimate decision regarding the relative importance of these competing science objectives should be guided by the acceptance of viable science projects selected by the National Science Foundation.

1 Current state of the network

The Greenland Geodetic Network (GNET; Figure 1) currently consists of 58 geodetic-grade Global Positioning System (GPS) receivers, located on fixed bedrock sites around the coast of Greenland [*Bevis et al., 2012*]. The capability of the extended Global Navigation Satellite System (GNSS) has now surpassed the precise positioning performance of the older GPS due to incorporation of more satellites and advances in on-board technology. The network has the full capability for mm level geodesy. GNET has grown over the years, and is operated in cooperation between several groups. Currently there are 36 stations operated by the Ohio State University (OSU), 1 operated by NASA's Jet Propulsion Lab (JPL), 1 operated by UNAVCO, 15 by Denmark (DTU), and 5 by the University of Luxembourg. It is important to note that though there are a variety of 'owners' of various GNET stations, there is widespread cooperation between the network partners, in terms of sharing of logistics, data management, and collaborating on best practices for station installation. Maintenance is shared and coordinated by OSU, UNAVCO, and DTU.

Each station consists of a geodetic-grade GPS antenna mounted on a permanently-anchored monument on bedrock, a GPS receiver, an extensive power and power-management system (solar panels, wind generators, batteries), and a telecommunications system for telemetering data- this can be wired or wireless, and is frequently provided by the iridium network. These stations have the full capability to monitor very precise crustal movements, as for example, recently described by *Herring et al.* [2016].

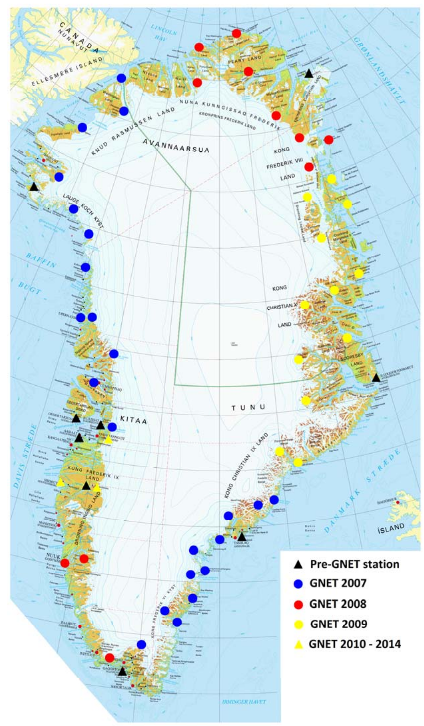


Figure 1. Map of 58 current GNET sites and installation date.

Each station in the network faces its own specific challenges to longevity. Simple wear and tear on equipment can cause failures, but extreme weather conditions at some sites can also pose problems, with high winds, icing and heavy snow loads damaging stations. Satellite communication for data retrieval can fail for multiple reasons. Some stations are visited by wildlife; polar bears are an obvious potential problem (they are naturally curious and very strong), but equally damaging to data return can be the sharp teeth and beaks of Arctic foxes and ravens.

In spite of these potential problems, regular maintenance of the stations has, over the years, produced a 92% rate of data return for the network and gaps in the data streams have steadily reduced over the years. Currently, in any given year, many stations must be visited for routine maintenance, upgrades, and repairs. The cost of these maintenance visits is largely driven by the helicopter time required to access most GNET sites. Continued maintenance, upgrades, and additions to the network will require the investment of resources by national funding agencies. Although expensive, GNET data supports a substantial body of science in Greenland, across many disciplines, as outlined in Section 2.

2 Current and future science using GNET data

2.1 Solid Earth and Isostatic Adjustment

The elevation of Earth's crust is continually changing owing to the continuum mechanical response of the solid Earth to the redistribution of mass on the Earth's surface. One of the primary causes of such changes is the growth and melt of the great ice sheets, such as the Greenland ice sheet. The changes in crustal elevation due to the interrelated changes in grounded ice mass and ocean loading is broadly termed glacial isostatic adjustment (GIA) when these changes have long time scales, generally of order 100-10,000 years. However, very important crustal responses also occur on elastic time scales, essentially the same time scales as seismic wave propagation and a basic observation offered by GNET is that present-day ice mass variability tends to dominate many of the recorded vertical signals [*Bevis et al., 2012*].

Our geophysical and observational understanding of GIA processes were nurtured by study of the emergence of the coastline along the Baltic Sea in Sweden and Finland more than 100 years ago [e.g., *Ekman, 1991*; *Peltier, 1998*]. Land today rises at rates of 2-15 mm/year near the centers of the former great ice sheets of the Late Pleistocene, causing local sea-levels to recede, producing a clear observational record of sea-level drop. This phenomenon was called post-glacial rebound (PGR), yet as it became understood that the process involved the entire spherical earth due to the 125 meters of sea-level load change, and associated geoid changes, the process is now termed glacial isostatic adjustment (GIA). The original design of GNET was primarily focused on the measurement of vertical land motions associated with direct past ice load and viscoelastic responses.

For solid Earth applications, we recommend continued operation of existing GNET sites for as long as possible. This allows us to separate elastic and viscoelastic crust-mantle responses. These lengthened time series will aid in accomplishing this goal, especially as they overlap with altimetry missions (CryoSat-2 and ICESat-2 (launching in 2018)), WorldView imaging satellites, as well as the three Sentinel satellites of ESA's Copernicus program. In addition, the NASA-ISRO joint NISAR mission, launching in 2020 that will enable space-based discharge observations of Greenland's outlet glaciers to better resolve mass balance time series.   This period of temporally coincident observations will greatly improve the elastic correction for solving for GIA. It is important to emphasize that GIA is a time-invariant trend, and moreover, that a GIA correction is used to correct satellite observations that monitor the state of the ice sheet. Great discrepancies remain in our current predictions of viscoelastic GIA [cf., *Lecavalier et al., 2014; Khan et al., 2016*] (see **Error! Reference source not found.**).

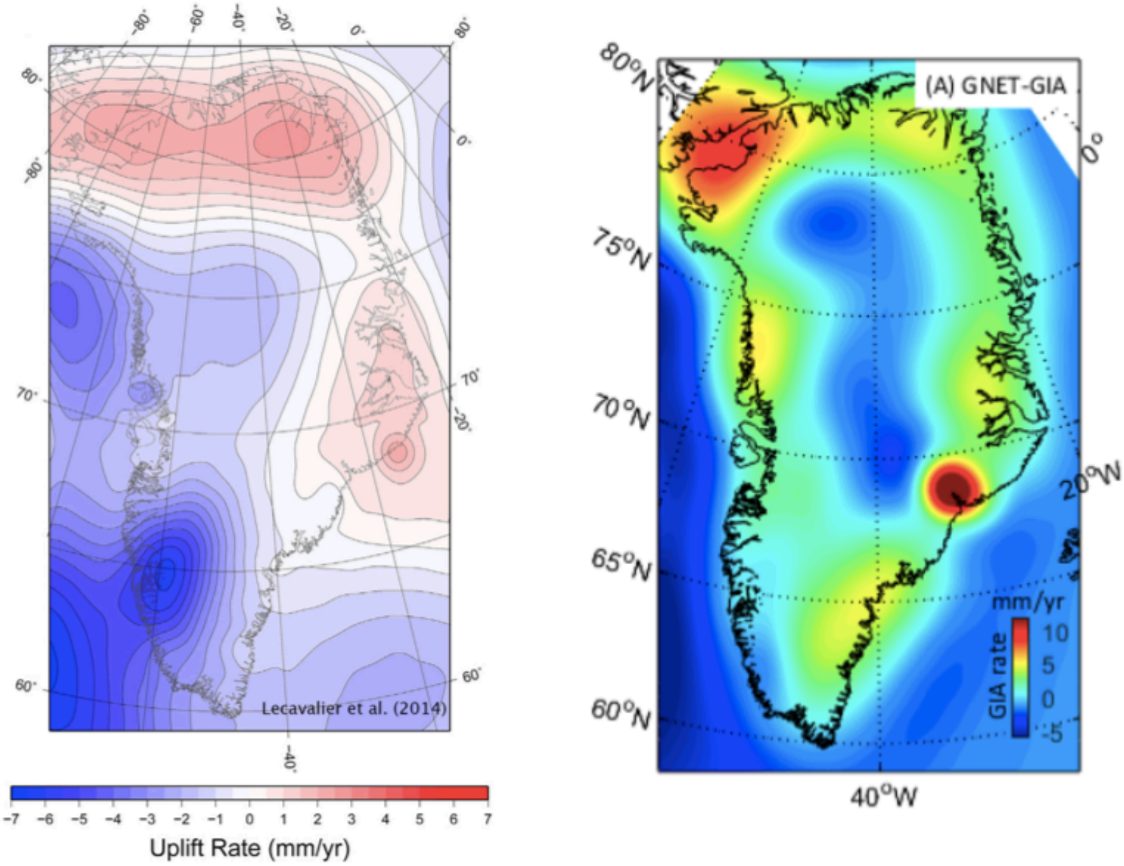
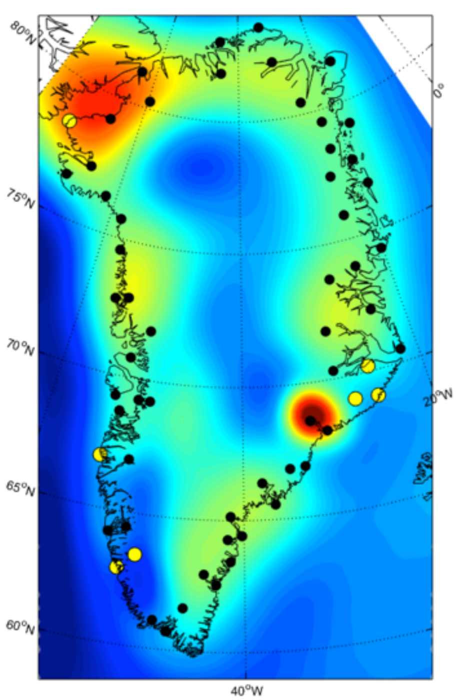


Figure 2. Relative sea-level-based reconstruction (a; *Lecavalier et al., 2014*) and prediction of present-day uplift rate. GIA model with GPS-based uplift data (b*; Khan et al., 2016*) and revised ice history reconstruction. The discrepancy between the two predictions is large enough to be an impediment to properly discriminating between alternative ice history reconstructions. Reconciliation will allow GIA models that properly predict the GPS trends to be used in paleoclimate models.



In addition, the combination of seismic imaging data along with GPS-based crustal uplift data enables improved understanding of Earth structure properties. The NSF-funded GreenLand Ice Sheet monitoring Network (GLISN) project (e.g., *Murray et al., 2015*) will provide improved seismic data. Combining results of GLISN and GNET will help better define basal ice-rock interactions, lithospheric thickness, asthenospheric structure, lateral heterogeneities in the Earth's crust and provide an improved basis for the heat flux boundary condition used in ice sheet models [*Rogozhina et al., 2012*]. Each of these imaging features allows better constraints for forward modeling the GIA response to past loading from ice changes.

Figure 3: Map of current stations with GIA estimates. Current stations (black dots) and suggested new stations (yellow dots) are placed to constrain GIA.

All GNET stations, shown as black points in Figure 3, are currently providing data relevant to constraining GIA. Additional stations, shown as yellow points in Figure 3, are located in places that would enhance our understanding of GIA in areas having notable spatial heterogeneity in solid earth structure.

Seismic constraints from projects like GLISN better constrain the structure of the solid earth parameters used in crustal motion models of both long and short time scales. Combinations of seismic and GPS geodesy can be important for constraining various improvements in Earth structure and constitutive properties [e.g., *Bos et al., 2015*].

2.2 Ice Mass Balance

There are two essential physical components that control annual and inter-annual ice mass balance. These are input, estimated from surface mass balance models, and output, that is generally computed from ice drainage velocity data [*Shepherd et al., 2012*]. One approach to determining the ongoing mass balance of an ice sheet is to independently estimate each of these, i.e., changes in the 1) surface mass balance and 2) the ice discharge. A second approach is to estimate the inter-seasonal height changes over the ice sheet (estimating the volume change) and find an appropriate density scaling to determine mass change. A third approach is to measure the gravity changes from space. This latter approach determines mass changes directly. Each method has advantages and pitfalls. In what follows, we address how GNET has supported the goals of these three methods, but do not discuss the more advanced speculation that GNET might offer a way to advance mass balance on its own [e.g. *Khan et al., 2010; Yang et al., 2013*].

2.2.1 Surface mass balance

2.2.1.1 Background

The surface mass balance (*SMB*) refers to the factors that determine how the atmosphere can deliver rain and snow to replenish the water supply for the GrIS, while other factors are ablation by melting and runoff while also accounting for refreezing. Greenland also has non-ice sheet surfaces which also participate in the mass balance that are measured by both GRACE (directly) and by GPS crustal displacements (indirectly). Figure 4 shows the model representation of *SMB* for Greenland that can be reconstructed from the currently most sophisticated *SMB* model running from 1958-2015 by *van den Broeke et al.* [2016]. Ice mass balance is essentially estimated as *SMB* - *D*, where *D* is the ice discharge due to outlet glaciers exiting to the surrounding ocean. This is also called the input-output method (IOM) [*Shepherd et al., 2012; Hurkmans et al., 2014*]. Technically, this is not the entire mass balance since one other component, grounding line migration (*GLM*) also may come into play [*Rosenau et al., 2013*].

The motivation to study the two components of the *IOM* (*SMB* and *D)* is provided by the important relationship of the ice sheet mass balance to ongoing and future sea-level rise [*Hanna et al., 2013; van den Broeke et al., 2016*]. *SMB* uncertainties are difficult to quantify, but they are often reported at 15-20% *Tedesco et al.* [2017], though locally and temporally they may be much larger [*Schlegel et al., 2016; Alexander et al., 2016*]. Changes in SMB are now accounting for roughly 2/3 of total mass balance [*Enderlin et al., 2014; van den Broeke et al., 2016*], reducing the uncertainties associated with SMB estimates is of considerable practical importance. In this section, we address the various ways in which GNET might help to improve SMB estimates and/or gauge their uncertainty. The sub-components of SMB, and the importance of the subtle physics that control their behavior cannot be underemphasized. For example, it has recently been argued that the negative mass balance of Greenland owes to the energy balance having reached a tipping point, wherein the firn layer began to lose its capability to refreeze near surface meltwater [*Nöel et al., 2017*].

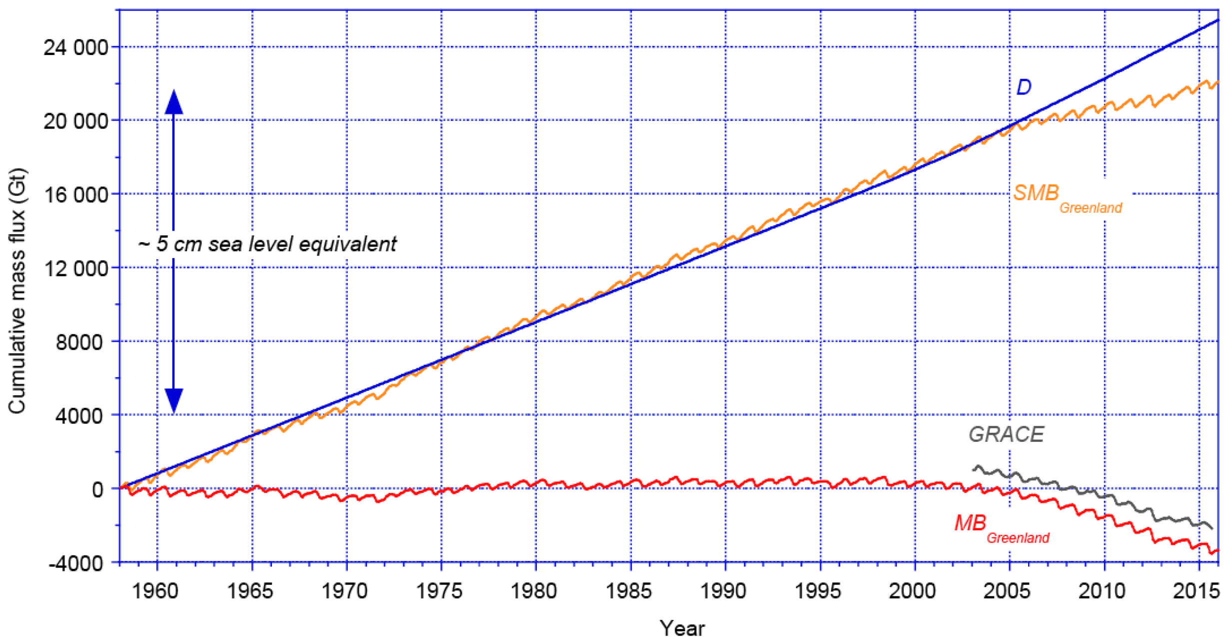


Figure 4. Cumulative surface mass balance (*SMB*) for the full land area of Greenland (orange line), cumulative ice discharge *D* (blue line) and resulting cumulative mass balance *MB*Greenland (red line). GRACE time series included (grey line) has been offset by 1000 Gt for clarity. Note that an increase in slope for *D*(t), and decrease in slope for *SMB* (t) each act to push the mass balance of Greenland into a negative state [*van den Broeke et al., 2016*].

It is worthwhile to disaggregate the constituents of *SMB* and also their spatial and temporal variability. Long-term mass stability of glacier complexes is universally determined by knowing the stability of the annual accumulation and ablation zones.

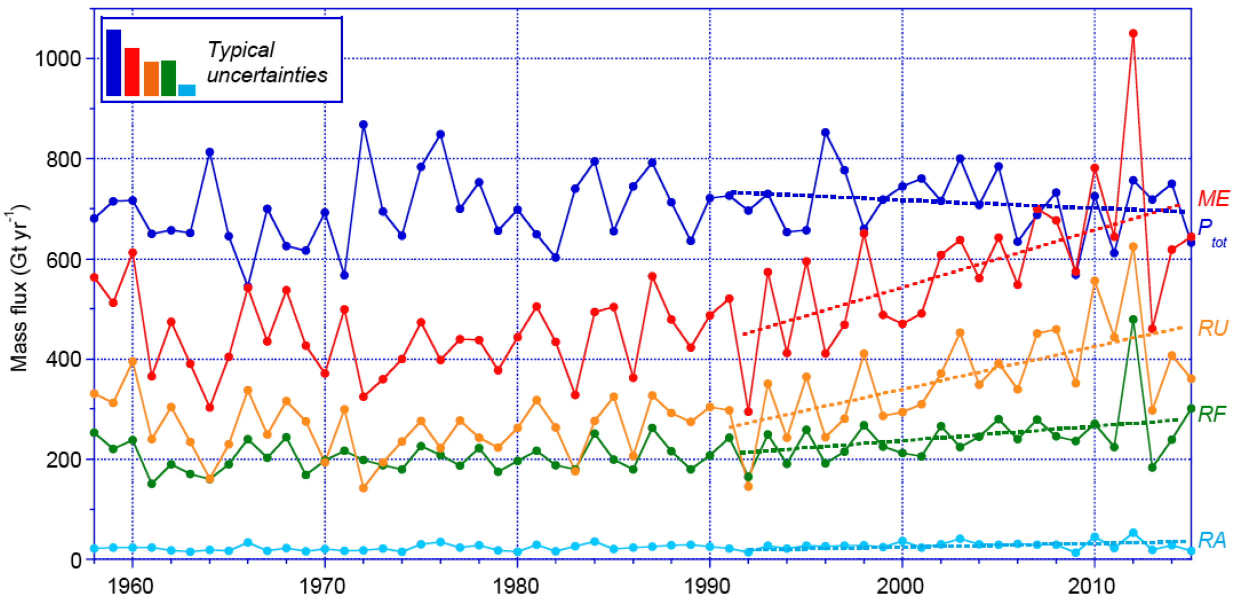


Figure 5. Model based annual values for 1958-2012.25 of *SMB* constituents for GrIS: total precipitation (P_{tot}), melt (*ME*), runoff (*RU*), refreezing (*RF*) and rainfall (*RA*). Dashed lines indicate 1991–2015 trends [*van den Broeke et al., 2016*].

2.2.1.2 The connection of increased melt on discharge

Accumulation and ablation zones of an ice sheet are defined as the areas where the sign of annual *SMB* differ (positive and negative), respectively, with the two zones being separated by the equilibrium line at which *SMB* = 0. In Figure 5 we show the 5 most important constituents as reconstructed in a regional atmospheric climate (RACMO 2.3) *SMB* model from 1958 through winter of 2012 [*van den Broeke et al.,* 2016]. Note that melting (*ME*) has the strongest estimated slope during 1991-2012, and also has the largest excursions from the norm. Melt is also a critical component of changes in discharge, *D*, as water movement to the base of the ice sheet can cause lubrication and glacier speedup [also see Figure 4, and the changes in slope after 2005]. Somewhat paradoxically, over time, extensive meltwater at the base may lead to subsequent decrease in glacier speed [*van de Wal et al., 2008; Sole et al., 2011*]. These processes are not easily modeled *[e.g., Das et al., 2008; Pimentel and Flowers, 2011]* and can see evolutionary complexity that are poorly predicted in models [e.g., *Tedstone et al., 2015*]. Observations of ice-flow enhancement by such lubrication indicates a broad-scale influence as the meltwater spreads over the bed. The pattern of speedup is also quite complex, reflecting the control by bottom topography at sub-km scales, sediment entrainment, subglacial lake filling and flushing, and conduit reorganizations *[e.g., Hewitt and Fowler; 2008; Joughin et al., 2013].* Emphasis should be placed on data sets of high quality and resolution in space and time.

During the past decade, Arctic summers have been trending toward earlier melting onset and extreme maximum heat and duration [*Crawford and Serreze, 2015*]. This fact was evidenced most profoundly on GrIS by the summer 2012 summer melt. An interactive website at the National Snow and Ice Data Center (NSIDC) currently tracks the area extent of melting. Figure 6 shows a summary of the melt extent of 2012 (orange curve) in comparison to the daily median values and their typical deviance from the median. The plot clearly shows summer 2012 to be extraordinary in areal extent. We note that the area is fairly easy to measure from space using emissivity or scatterometry. However, the volume of melt, its subglacial routing and time-scale for flushing from the system is poorly known, at best. Models that derive *IOM,* assume, generally, that water will run through the system instantaneously, since routing models are not developed for operational *SMB* models. This means that while annual errors may stay below 20-25 %, during any given week, or even month, the melt (*ME)*, run-off (*RU)* and re-freeze *(RF)* may be in error by more than 100%. As we seek future sea-level rise estimates, this may become an increasing problem, and there is a desire to get a better control on the space-time evolution of these routing systems.

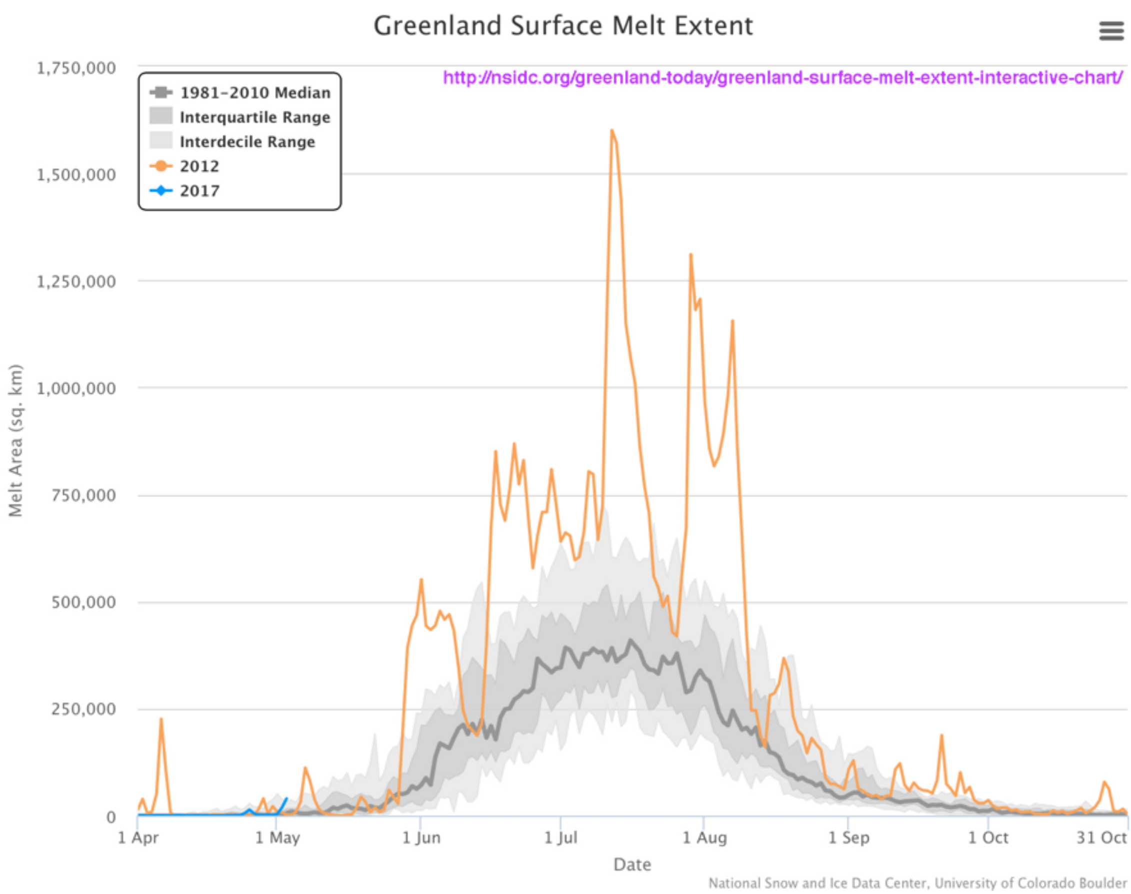


Figure 6. Melt extent measured from space during Spring to Fall months for GrIS (1980-2010) median, with single year 2012 shown in orange and 2017 in blue (from NSDIC interactive web site). Note that in July 2012 the melt extent quadruples over the 30-year median.

Arctic summers have begun earlier, lasted longer and reached more extreme surface temperatures during the past two decades *Crawford and Serreze* [2015]. As a consequence, we are likely to see the role of *ME*, and its feedback on *D,* and the partitioning of *RU* and *RF* come under increased scrutiny for the purposes of making correct model-based projections of future sea-level rise. Typical evaluations of the quality of *ME* in *SMB* models are quantified through inter-comparison of space-based melt-days observed in satellite images to those captured in the reanalysis model. Such inter-comparison is shown in Figure 7. Here we see that melt-days may be discrepant by ± 15 days (these are days in which model and observation on any given pixel disagree). While the models inter-compare in a reasonable way, the uncertainty in routing path, time-lag and ultimate percent of expulsion to the sea is not tested.

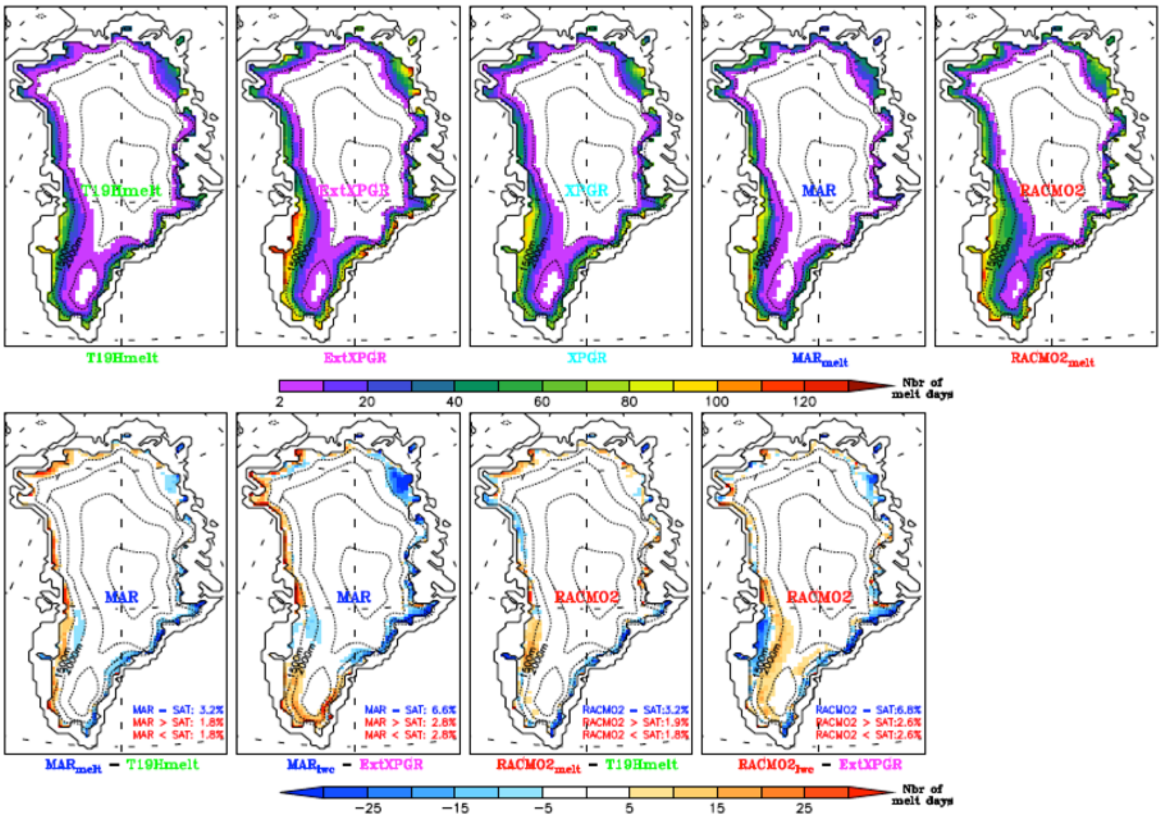


Figure 7. Summary of comparison of two SMB models and satellite-detected annual mean of the total number of melt days (top panel; based on spaceborne passive microwave data). Bottom panel shows the difference between models and the $T19H_{melt}$ and ExtXPGR algorithms used for processing space-based data sets [*Fettweis et al., 2011*]. The mean number of GrIS pixels when RCM and the algorithms detect melt (RCM = SAT), when RCM detects melt but the retrieving algorithms do not (RCM>SAT) and when RCM does not detect melt while the algorithms do, (RCM<SAT) is also listed as a percentage of the number of GrIS pixels°—summer days. [Reproduced from *Fettweis et al., 2011*].

2.2.1.3 SMB Analysis with GNET Data

Regardless of the methods of construction, SMB constituents will contribute to any time series representation on mass-bearing grids formed by summing estimates of SMB. Temporal changes to total mass balance are usually dominated by SMB. GNET can be used to test both types (intra-seasonal and secular) of mass change. In some areas, we can actually test SMB estimates by comparing elastic displacement time series computed from the mass grids to the actual displacements measured by GNET as in a recent paper by *Liu et al.* [2017]. For example, a major snowfall event, or rapid sequence of events, should produce a predictable signal in the elastic time series at nearby GPS stations. However, for the length scales known for such events, the signal is likely not detected above the noise level at distant stations. Given two such major snow fall events a month apart in the same area, one can roughly predict the corresponding signals in the de-trended elastic deflections computed from daily or weekly SMB grids to be similarly reflected in the de-trended GPS time series. In theory, any sustained change in SMB should have a corresponding signature recorded in the GNET time series from which a loading mass may be inverted for. In practice, all geophysical sources of loading of the solid Earth must be carefully accounted for, such as the atmosphere, ocean and large scale global hydrology [*van Dam et al., 1997*; *Bevis et al., 2012; Adhikari and Ivins., 2016; Liu et al., 2017*]

2.2.1.4 Use of GNET Data for Fundamental Improvement in SMB Modeling

One obvious way to improve SMB estimates is to increase the prediction skill of hybrid numerical weather and snow models. We note that one of the large uncertainties in Figure 5 is the total precipitation. Coupled weather-snow models are built around high-resolution, regional numerical weather prediction (NWP) models that are embedded within a global model. Typically, this is an ECMWF model, such as its latest global reanalysis, ERA-Interim or ERA-5.

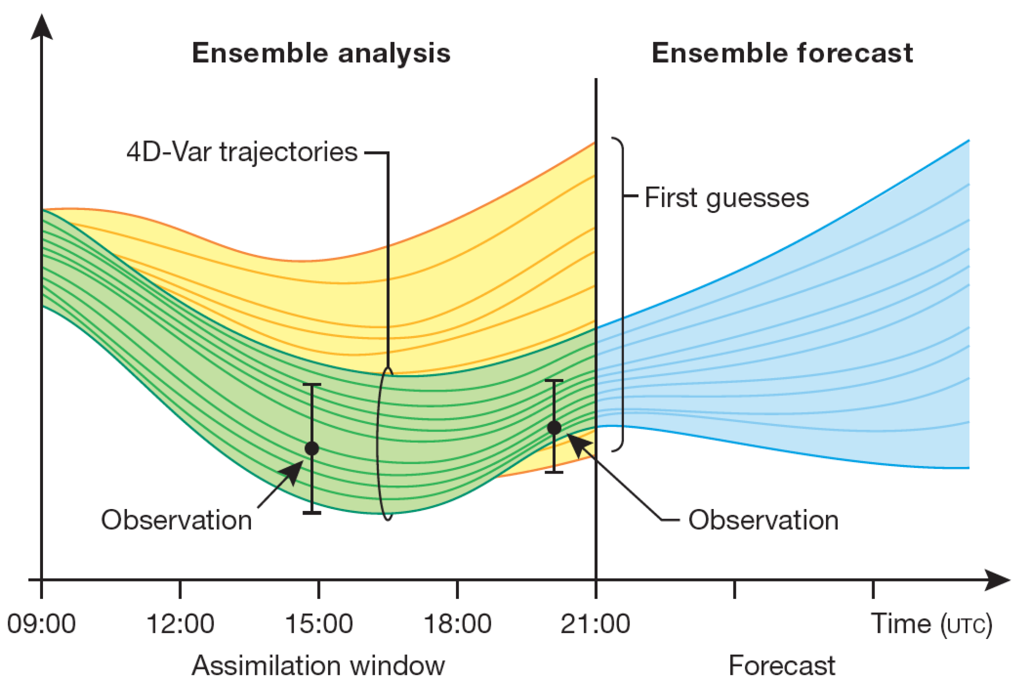


Figure 8. Illustration of an ensemble analysis with (green) and without (yellow) minimization on the statistical range of any individual atmospheric model variable. The example analysis example illustrates the importance for the "forecast cycle". The use of the GNSS phase delay information in the model that is data assimilative ("4D-Var") has the potential to greatly tighten hindcast models that are critical for SMB models like RACMO and MAR. The 50 + GNET station solutions for troposphere parameters can supply data required for variational minimization in four dimensions. It is important to note that relatively greater improvement occurs in model estimates (4DVar trajectories) as the distance to observations is reduced. [*Bauer et al., 2015*].

Coupled weather-snow models like RACMO2 and MAR are quite sophisticated in their capture of the appropriate physics, a weakness is that they lack direct assimilation of the meteorological observations acquired within their model domains. Global models such as those of the ECMWF do assimilate all available meteorological data, including GPS delay data, using variational data assimilation methods known as 4DVar and ensemble 4DVar (En4DVar) *Bauer et al.* [2015]. A general illustration is shown in Figure 8. We advocate that considerable improvement in SMB can be realized by upgrading coupled weather-snow model codes through implementation of 4DVar modules that directly assimilate ground including GPS delay, upper air and satellite observations.

Below we give a synopsis of the gains should be realized using GNET data:

- improved prediction skill in the NWM component
- more reliable boundary conditions for the multi-layered snow model
- improved models of the state of the snow/firn/ice layers beneath the surface.

Toward these goals the following actions are required:

- Routine generation and assimilation of GPS delay parameters from GNET
- Demonstrate the impact of assimilating GPS delay data into high resolution, regional NWMs
- GPS delay parameters should be routinely estimated, in nearly-real-time and used to demonstrate that the delay data improves the water vapor fields and predictions for precipitation
- Address issues that are pertinent to weather-snow assimilation.

As many of these issues may be obscure to those unfamiliar to atmospheric profiling and its consequences for operational models, we offer the following section on the technique.

2.2.1.5 GNET Zenith Total Delay: Use for Regional Atmospheric Models

The goal is to use GNET GPS observations to generate and assimilate zenith total delay (ZTD; *Bennitt and Jupp, 2012*) to greatly improve the prediction of surface mass balance (SMB) over the ice sheet produced by regional atmospheric models, like MAR, RACMO, or WRF that show large differences (Figure 7). ZTD observations implicitly yield the vertically integrated water vapor amount (precipitable water) not the vertical profile of water vapor like radiosondes. However, water vapor is concentrated in the lower part of the atmosphere – moisture content (specific humidity) typically decreases exponentially with height. ZTD is available at ~10 minute intervals if desired in contrast to the twice daily radiosonde ascents, so potentially detailed temporal behavior of moist air intrusions into Greenland can be captured from ZTD usage. ZTD values affected by sensor icing and snow accumulation will have to be screened out by a robust quality control procedure. The accuracy of ZTD values in northern Greenland

during winter may be an issue with annual precipitable water values being 4-5 mm there (*Robasky and Bromwich, 1994*), with much smaller values in winter, comparable to the uncertainty attached to values inferred to ZTD.
Atmospheric motion fields of comparable accuracy to the water vapor information provided by the GPS ZTD will be needed. This is going to be a challenge for Greenland, largely surrounded by data sparse ocean. The dry delay derivable from ZTD corresponds to surface pressure so these observations improve the atmospheric circulation depiction. One approach that will help is to use the GPS observations in conjunction with the automatic weather stations (GC-Net) on the ice sheet. The GNET and GC-Net should be viewed as an integrated network. Additional complementary deployments may be needed. Also, all available non-AWS surface observations will be needed.

ZTD values maybe a significant challenge to assimilate accurately as the sites are located in the complex coastal environment for geodetic applications rather than meteorology where sampling of broad scale conditions is desired. *Mahfouf et al.* [2015] has studied the challenges of ZTD assimilation. These are partly resolution dependent. Model grid spacing of a few km may be required to resolve the necessary terrain details and may not be adequate for all sites. Consequently, a detailed evaluation of the GPS sites is needed to determine those best suited to characterizing atmospheric behavior.

The *Mahfouf et al.* [2015] study of Europe is for a case wherein summer thunderstorms show that GPS ZTD assimilation improves prediction of large precipitation events – more than 0.5 cm (water equivalent) per day. Greenland is a very different environment. The events of concern for Greenland are synoptic scale cyclones, fronts and hurricane remnants that result in large moisture flows into the island. The greatest impact seems likely to be from sites on the west, south and east coasts of Greenland probably in the warmer part of the year. Multi-layered airflows associated with moisture intrusions as a result of low-level terrain blocking will complicate effective use of ZTD values.

The question of an assimilation approach used to incorporate ZTD observations into regional atmospheric models is being debated, the much more complex 4DVAR versus simpler approaches like 3DVAR and/or ensemble approaches. Perhaps the most compelling argument for 4DVAR comes from *Mahfouf et al.* [2015] where 4DVAR, like that used by the global ARPEGE model with a 6-hour assimilation window, would include 10 times more ZTD observations (or equivalent) than their 3DVAR approach. However, there are other strategies for simpler data assimilation approaches to incorporate more ZTD observations. Of equal, or greater, importance is the care with which ZTD values need to be treated to achieve accurate assimilation.

Our recommendation is that data for ZTD (and GC-Net values) from Greenland be assimilated from 2007 onward into the Arctic System Reanalysis version 3 (ASRv3) for 1979-2020 at 15 km with 71 vertical levels. It has a pan-Arctic domain and extends from ~45°N to the North Pole. The primary focus is to examine extreme weather and climate conditions in the Pan Arctic. A secondary goal is to achieve better surface mass balance estimates for the Greenland ice sheet for the last 14 of the 42 years to be covered by ASRv3.

Prospects for using the HIRLAM regional model *(Christensen et al., 2007)* and its 4DVAR assimilation capability to perform a very high resolution (grid spacing of a few km) of Greenland from 2000 onward is quite promising. All data within the domain will be assimilated including GNET ZTD also with the goal of better surface mass balance estimates for the ice sheet. To summarize we emphasize two key recommendations in this white paper:

1. ZTD observations from the comprehensive GNET array around Greenland show great promise for improving surface mass balance (and firn density) estimates from regional atmospheric models. These data have hardly been examined by the atmospheric science community and their spatial and temporal behavior are not well characterized; and this knowledge is needed to make effective use of these observations via data assimilation into atmospheric models. Two or more graduate students should be supported to evaluate GNET ZTD data, their assimilation into regional atmospheric models, and comparisons with simulations produced with MAR and RACMO2 and reanalysis results produced by ASR version 2.
2. Support the use of GNET ZTD in regional reanalyses encompassing Greenland, ASRv3 and the HIRLAM-based effort.

2.2.1.6 Changes in GrIS driven by both glacier discharge and SMB

In practice, crustal motions respond to the full set of load changes that inevitably involve both ice discharge and SMB. While the SMB changes have greater amplitudes and clear coherence and fidelity in their seasonality, changes in *D* occur simultaneously, although these changes tend to be of lower frequency in their temporal domains. Observations of ice discharge variations are governed by changes in glacier speed and geometry [*Ahlstrøm et al., 2013; Moon et al. 2014; Joughin et al., 2013*]. However, it is an inescapable fact that the SMB *ME* and *D* constituents are intimately coupled [e.g., *Palmer et al., 2011; Pimentel and Flowers, 2011; Schlegel et al., 2013*]. There are relatively new and promising directions that GNET might contribute to disentangling the interrelationships of coupled ice discharge systems. If the GNET time series can be appropriately filtered, they should contain sequential load signal responses that are driven by the coupling of *ME* and *D*.

Approximately 60% of the GPS receivers in GNET are capable of making contributions to our understanding of the discharge of GrIS glaciers and ice streams. *Khan et al*. [2010] and *Liu et al*. [2017] recently discussed cases in which GPS data have been used to place constraints on glacier dynamics. Additional research has investigated glacier flow by using GPS trackers on moving glacier ice. Here data from GNET stations play a critical role as reference base stations *Andersen et al.* [2010]. The best bedrock GNET receivers for this observation are either very close to the glacier terminus being studied, or exist as pairs of receivers, wherein one is close to the terminus of the glacier, and one is at a distance far enough away to be unaffected by glacier changes. A similar geodetic strategy was used by *Dietrich et al. [2007]* for Jakobshavn Isbræ.

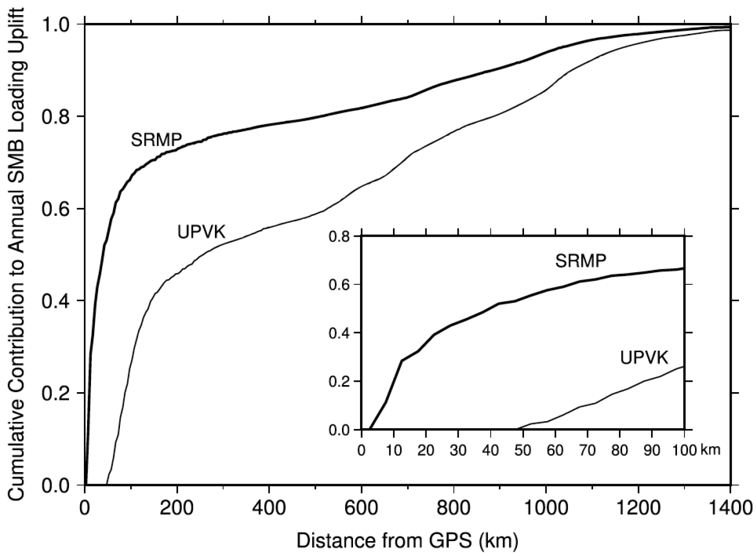


Figure 9. Analysis of a normalized SMB contribution to vertical crustal displacement for SRMP (thick line) and UPVK (thin line) stations. The inset shows a zoom-in distance range of 0–100 km. This study concluded that modeled SMB loading based on RACMO2.3 actually increased the annual variance of the GPS residuals, which made it difficult to estimate contributions from the annual variability of glacial dynamics to the total ice mass balance. The study reveals the potential use of GNET on evaluation of SMB models. (From *Liu et al., 2017*).

In Figure 9, station SRMP has a very tight radius of sensitivity with respect to 4 adjacent outlet glaciers, while UPVK, having a coastal bedrock location, is more sensitive to broad-scale SMB features such as P_{tot} (see Figure 5). A new treatment of GNET data sensitivity by *Adhikari et al.* [2017] employed the 3-D crustal motions to study coupled SMB-*D* on seasonal time scales for each GNET station. One example for the Rink Glacier in west central Greenland used the GPS-determined 3-D bedrock motion to unambiguously isolate mass transport in a solitary wave that occurs only during the intense melt seasons of 2010 and 2012 (see Figures 5 and 6). Some of the basic concepts of employing 3-D motions are described by *Wahr et al.* [2013]. In the latter paper two features were highlighted: horizontal motions drop off more quickly than do vertical motions as one moves away from the water-ice load center. Additionally, horizontal motion data contain different diagnostic information about the location of the load source (see Figure 9). For studying glacier-specific SMB-*D* coupling the latter feature is critical. A subtle feature to be extracted from the *Wahr et al.* [2013] example (Figure 9) is the fact that there is an inherent directional anisotropy to the horizontal displacements, and these can be used to locate, under certain conditions, the physical location and size of the changing water load. This is not a new discovery, as *Sauber et al.* [2000] has pointed this out in regards to changes in glacier mass in Alaska, and *Heki et al.* [2004] has used the dense network in Japan to measure mountain snow load changes, with the advantage of the later study being both the existence of dense GPS network and knowledge of the approximate location and timing of the load.

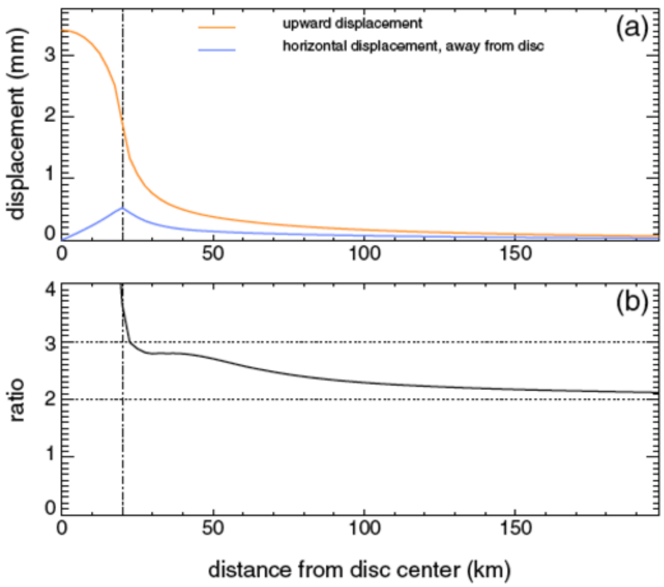


Figure 10. A prediction of 3-D crustal motions from a simple single disk water load removal. (a) shows the vertical (positive upward) and horizontal (positive away from the disc center). Crustal displacements are caused by removing a uniform disc load of radius 20km having a 1-m water thickness. Predictions are given as a function of the distance to the center of the disc. The vertical dot-dashed line marks the edge of the disc. Results are computed using seismologically realistic Earth model. (b) The ratio of the vertical to horizontal displacements shown in (a). Note the different position in frame (a) of the peak values with respect to 0. [*Wahr et al., 2013*].

GNET stations, being originally placed to measure GIA, are not necessarily close to the rapidly changing outlet glaciers. For the purposes of using 3-D crustal motions, the stations closest to outlet glaciers are the most promising for providing new constraints. *Adhikari et al.* [2017] used all the stations that had processed 3-D time-series available and derived a sensitivity gradient map (see Figure 10) for these stations. The main principle follows from that used in geophysical model data assimilation for adjoint systems [e.g., *Tromp et al., 2005; Larour et al., 2016*]. Each station may be influenced by on-land mass changes in its immediate local area, including atmospheric loading and loading from ice-snow-water mass systems. The latter changes, when they are large in amplitude, dominantly occur within the outlet glacier systems, yet the full *SMB* loading, including that occurring on bedrock must be also computed. It is possible that stations may have all three of their crustal displacements sensitive to mass changes associated with *ME-D* coupled events, or to local *RU* or *PE* induced-changes.

Figure 10 shows 33 stations with mapped sensitivity to mass loading in the vicinity of each of the GNET station receivers that have 3-component displacement data available. Here a three-color wheel is used. Cool to hot colors represent progressively higher sensitivity zones for the stations, such that at least 1% of maximum displacement induced by a unit load applied over a unit area in these zones would be recorded in one (blue), two (green) and three (red) components of the displacement vector, respectively. These are referred to as zones of influence (ZOI) by *Adhikari et al.* [2017], and it is important to understand that these fully account for load variations occurring at a 2-km scale, so these can show where a potentially *ME* lubricated ice stream might quickly loose or gain mass. For the marine terminating Rink Glacier, the 3-D motions capture a large wave transiting down-glacier during summer-to-winter months during the intense melt year of 2012 (see Figures 5, 6). Figure 11 shows the trajectory of the horizontal displacement vector of the RINK station during the down-glacier transit of the *ME-D* mass ejection during summer to winter of 2010 and 2012. Note that there is no evidence of the wave during years of nominal *ME.*

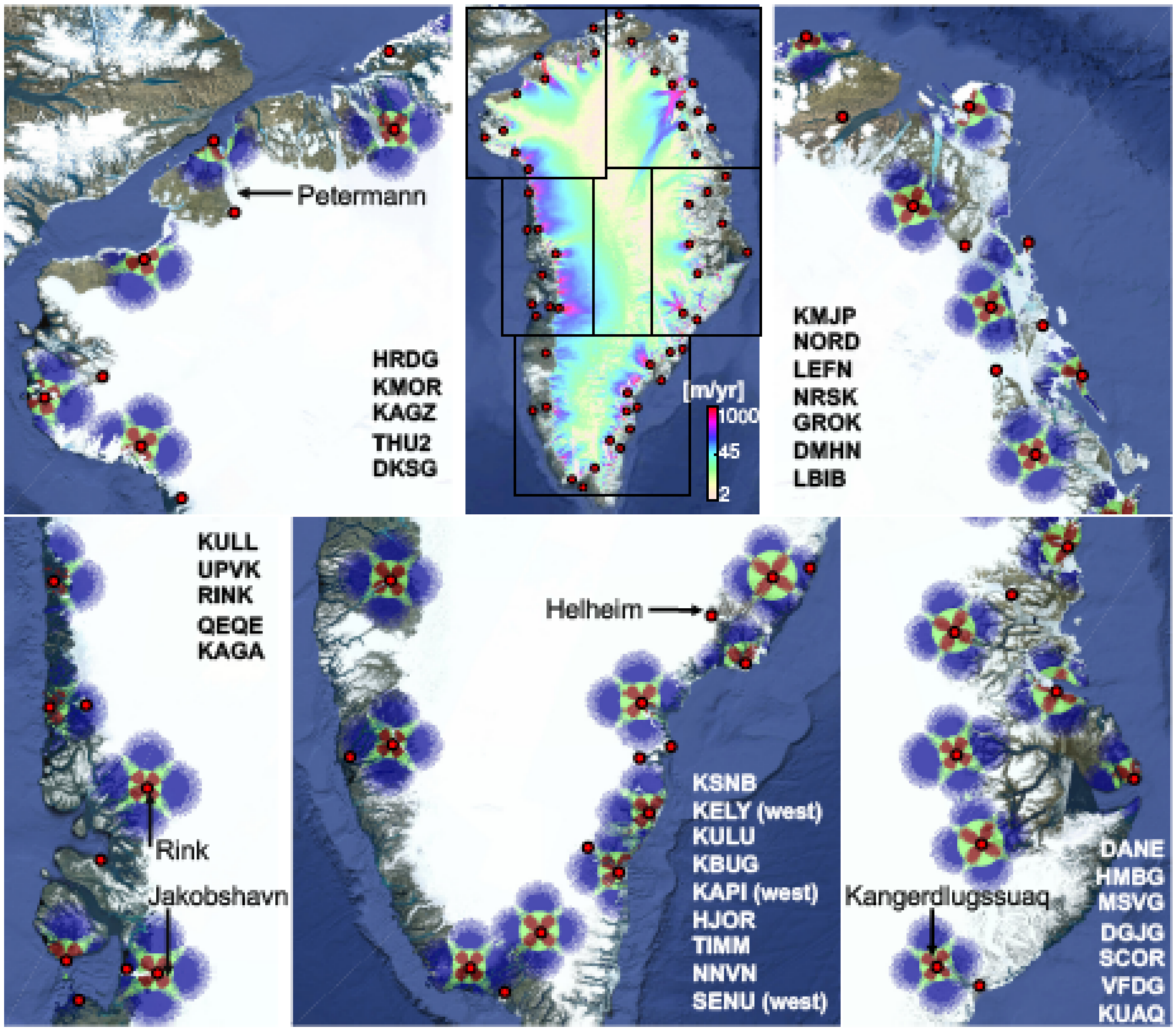


Figure 11. ZOIs for 33 GNET stations. The center map in the top panel shows measured ice surface velocities, locations of all 54 GNET stations (red circles), and 5 regions of Greenland (black boxes displaying ZOIs. The ZOIs are computed using high-resolution (~2 km, see *Adhikari et al., 2016*) gradient maps. Blue, green, and red signify the progressively high sensitivity zones for the corresponding GPS stations, such that at least 1% of maximum displacement induced by a unit load applied over a unit area in these zones would be recorded in one, two and three components of the displacement vector, respectively. For each region, station IDs are listed (from North to South) only for those stations that have ZOIs. Major outlet glaciers are also shown [*Adhikari et al., 2017*].

Vertical motions tend to reflect mass gains and losses over larger regions, while horizontal over smaller ones. This is reflected at the Rink Glacier by the excellent comparison of 3°GRACE-mascon based loading, *Schlegel et al*. [2016] (red line in Fig. 12a) and the 90-day mean of the vertical GPS time-series. Horizontal motions show no clear correlation (lower two frames in Figure 12a), being more sensitive to the 10-50 km scale loading events and more rapid shifts in loading structure than 3 months. The 2-D plot of horizontal position is shown in Figure 12b, for all years of RINK data, with amplitude standout at the 0.5 – 1.0 cm level during the intense melt years. During the two years of intense melt the trajectory is northing and easting from about June to October, and then reversing in late Fall to early Spring of the following year. The spatial distribution of the MAR SMB loading is shown by the background colors of the frames (c) and (d) of Figure 12.

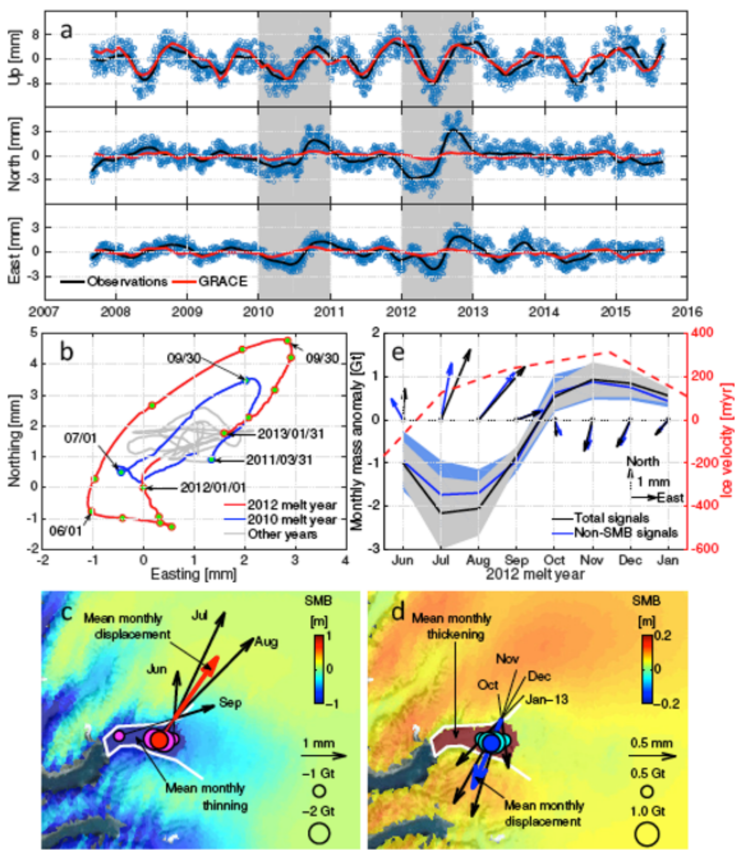


Figure 12. Mass transport waves detected in horizontal displacements at RINK. (a) Components of detrended daily crustal displacement (circles) measured at RINK station, with 90-day running means (black lines). Models (red lines) derived from GRACE-based surface loading reconcile the observations of vertical displacement, notable deviations occur during intense melt years (gray shadows) for the horizontal components. (b) Map-view trajectories of horizontals. (Large only in 2010 and 2012.) Circles show monthly station positions. (c) Pattern of mass deficit transiting the Rink Glacier during 2012 summer. About -7.1 m of monthly thinning over the optimal domain (blue fill within the glacier trunk outlined by white line) is required to explain the mean monthly displacement (red arrow). Also plotted are the magnitudes and fulcrum positions of monthly mass anomalies (circles) that satisfy the monthly displacement data (arrows). A down-glacier propagation of (negative) mass anomaly represents the negative phase of the mass transport wave. Mean monthly SMB loads are shown in the background. (d) Same as (c), but for the fall/mid-winter season that follows. It requires +2.8 m monthly thickening over the optimal domain (red fill within the glacier trunk) to explain the mean monthly displacement (blue arrow). (e) Summary of (c) and (d), revealing the solitary seasonal wave of ice mass transport.

2.2.1.7 Other possible surface mass balance studies benefiting from GNET

In addition to the familiar use of GNET stations as GPS reference points for on-ice studies and the motion of the GNET stations to infer ice discharge and changes in ice loading of the crust, there are a number of as-yet unexploited topics that could benefit from GNET GPS data.

1. To use the time series of horizontal GPS station positions to determine mass loss over an unknown area that would affect a GPS station at a certain distance from the locus of mass loss.

2. To use multipath reflections of GPS/GNSS signals to obtain surface parameters (snow depth, ocean tides). *Larson et al*. [2009] provides a proof-of-concept and Siegfried et al. [submitted] present a real-world application in Antarctica of this methodology. The GNET archive provides a means to do this on a large scale.
3. To use GPS seismology to provide information about calving mechanics resolved at high (~1 Hz) frequencies [e.g., *Holland et al., 2016*]
4. To use GPS on the surface of marine terminating glaciers to observe grounding/hinge line flexure. Such studies would benefit from fixed reference GPS stations such as GNET.
5. To use buried GPS antenna to obtain snow water equivalent above the antenna employing the wave propagation principles in snow-ice, as for example outlined by *Nievinski and Larson (2014)*.
6. To further couple GPS observations with remote sensing to understand the near surface rheology of the crust around Greenland. [e.g., *Kuchar and Milne, 2015*]
7. Examine the influence of tides (from GPS-IR) on ice loads and GPS response (e.g., *De Jaun et al., 2010*).

The above list of new projects would, in several cases, require targeted densification of the GNET network. Such additions to GNET would necessarily be the result of proposal-driven science investments from NSF, NASA or other funding agency, and are therefore not a primary recommendation of this report.

2.2.2 Support for Interpretation of Altimetry

GNET can also help to calibrate or correct the altimetry used to form SMB estimates. Although not yet exploited, some ICESat tracks have very close approaches to GNET stations. Crustal uplift measured at these GNET sites could be used to correct the uplift of the snow surface measured by ICESat, allowing an assessment of the change of the thickness of the ice sheet. A similar study could be done with ICESat-2, following its 2018 launch. In addition, the ground track pattern of ICESat-2 is expected to be much denser than that of ICESat, expanding the number of GNET stations that could be used in altimetry validation.

Stations in the GNET network are on exposed bedrock near the ice sheet periphery, and record changes in the rock surface height to a few millimeters per year. ICESat-2 tracks in some cases will naturally pass within a few tens of meters of a specific station, and in other cases, ICESat-2 can be pointed to within a few tens of meters of a given GNET station (the pointing control of ICESat-2 being ~40m). The rough terrain and steep slopes near many of the GNET stations will broaden the laser pulse return of ICESat-2 compared to the return over a flat surface, and should yield elevation precision to within a few tens of centimeters. Given the locally rough terrain, an intermediate height product would be needed in order to compare the sub-centimeter precision from GNET to the nearby ICESat-2 measurements. In order to bridge this scale gap, GNET stations could be surveyed using LIDAR, stereo photography, and/or a total station survey. With these data, it will be possible to determine location of the

GPS monument, the GPS antenna (and its phase center) relative to the rock surface in which the antenna was installed. These local area, geodetic grade DEMs, with apertures of hundreds of meters or even a kilometer, would enable the generation of epoch-specific DEMs using WorldView satellite imagery adjusted to the local antenna and rock surface DEM. The WorldView DEM could have an aperture of 10 km, for example, and allow the GNET station's footprint to be extended onto the ice sheet, characterizing the height of the surface crossed by ICESat-2's track within a day or so of the ICESat-2 measurement.

2.2.3 Support for GRACE and the Total Mass Balance Time Series

The other way in which GNET can improve our estimates of MB is to supplement the mass change estimates inferred from GRACE and GRACE-Follow On. Improvements are two-fold: GRACE has very low resolution (250 km x 250 km at the very best) and cannot deal with complicated coastlines, snow covered areas and small glaciers vs. ice sheet, etc. Secondly, GRACE mass change determination is heavily reliant on an accurate "GIA correction" that can only be provided by a combined modeling and GPS-determined vertical motion retrieved from the secular component of the time series. GRACE measures both ice and rock mass changes associated with GIA. The vertical rock mass flux is estimated using a GIA model, and this is removed from the total mass change sensed by GRACE to isolate the ice mass change. The problems with this GIA correction are that (1) it can be larger than the resulting estimate of ice mass change in some regions, and (2) the potpourri of current models predict different rates of GIA. The only way out of this problem is to improve the observational constraints on GIA, so that the GIA models are better constrained by a wider range of observations. This was one of the original goals of GNET, and the recent work by *Khan et al.* [2016] has demonstrated that errors in the GIA correction traditionally used by the GRACE analysis groups have led to major errors in mass change estimates for specific drainage basins.

2.3 Ionosphere, Troposphere

The ionosphere and troposphere affect GNSS signals traveling from satellites to receivers. The ionosphere extends from about 50-1000 km above the Earth's surface and acts as a dispersive medium for GNSS signals. Thus, the phase delay of a radio signal in the ionosphere is frequency-dependent and determined by the number of free electrons in the ionosphere. Dual-frequency GNSS observations can be used to estimate ionospheric delay and also determine the total electron content (TEC) along the signal path [*Misra and Enge, 2011; Komjathy et al., 2016*]. Processes affecting the ionosphere include space weather effects due to solar and geomagnetic activity, lower atmospheric coupling (such as stratospheric warming, tidal signatures), and natural and man-made hazards (tsunamis, earthquakes, rocket launches). Hence, the monitoring of TEC has uses ranging from space weather monitoring [*Basu et al., 2001; Coster et al., 2003; Coster and Komjathy, 2008*], large and small-scale weather monitoring such as studies of global stratospheric warming signatures *Goncharenko et al.* [2010] to tsunami tracking *Komjathy et al.* [2016], and thunderstorms *Lay et al.* [*2013*], and evaluation of co-seismic [*Calais and Minister, 1998*] or co-eruptive energy release [*Heki, 2006*].

Spanning 60-85° north latitude, GNET presents a unique opportunity to observe the high-latitude ionosphere with pierce points ranging from about 55-90° north latitude. Ground-based GNSS measurements can provide a complete latitudinal profile of the Arctic ionosphere. Geomagnetic processes are commonly observed with magnetic stations that are co-located with GNSS stations in some places, and benefit from sharing resources between the two station types.

For several years, GNET has been used for ionospheric studies with a focus on studies of the polar cap and auroral oval processes via TEC and scintillation observations [*Durgonics et al., 2017*]. Routine processing generates hourly to sub-hourly TEC maps over Greenland for near-real time application. However, insufficient data access to most GNET stations limits this to only 10-15 stations, which impacts the spatial resolution of the results. While real-time streaming capabilities should be the long-term target for all sites, data access on a sub-hourly basis would be extremely beneficial. An increase in resolution can be achieved by addition of inland stations in regions that move less than a few mm per day (this stability requirement can be relaxed for stations that only observe the ionosphere) and upgrading from GPS-only to multi-GNSS constellation observations that include all available satellite constellations. Sampling rates of 1 Hz for TEC and 50-60 Hz for scintillation studies are ideal for such studies. To minimize the bandwidth requirement for scintillation applications, scintillation indices can be calculated locally and then transmitted, instated of the raw GNSS observations. To fully enable science during strong scintillation conditions, the raw data should be stored locally in a ring-buffer such that on-demand download is possible. This would not only benefit navigation or potentially power grid protection, but enable streamlining of the science such that routine anomaly detection, cataloging and analysis is possible; ultimately expanding ionosphere studies from event-based to a continuum.

The troposphere, ranging up to about 9 km high at the poles, is a non-dispersive medium and as such its impact on a radio signal is frequency independent (*Misra and Enge, 2011*). The effect of the troposphere on GNSS signal propagation can be separated into dry and wet phase delays. The former is caused by dry gases such as N_2 and O_2, and the latter is due to water vapor. In standard GPS positioning processing, these delays are corrected with models and obliquity mapping functions. However making use of observations from the global network of GNSS receivers and local measurements of pressure and temperature, the dry and wet terms of delay can be derived, and from them, parameters such as the zenith precipitable water content can be estimated [*Bevis et al., 1992*].

Water vapor estimation should be a standard product for GNET and would benefit satellite mission validation and calibration (e.g., improvements to the tropospheric models used for ICESat-2 range delay correction). The current low temporal, but high spatial resolution MODIS water vapor estimates can be merged with GNSS products to improve temporal resolution. While GNET's spatial layout makes it difficult to fully capture the heterogeneity of the troposphere, moving to full constellation GNSS tracking at high data rates will increase the number of troposphere piercing points. The network should be densified along the coast as most of the water vapor is expected there. However, interior Greenland stations will allow tracking of water vapor in the interior. Recent melting events that affected the ice sheet interior can be expected to increase the water vapor concentration in the atmosphere. For example, thin, low level liquid clouds were recently shown to occur over Greenland frequently and enhanced the 2012 melting event [*Bennartz et al., 2013*]. The additional interior GNSS stations proposed for ionosphere studies could also benefit climate research for tracking the atmospheric water content and, using GNSS-reflectometry *Larson et al. [2009],* record snow height / snow water content. Meteorology instrumentation should be included at all stations as these observations at high temporal resolution can be used in validation efforts of numerical weather models. All of these applications would be a completely new use of GNET data.

2.4 Large scale geodesy

GNET GPS stations play an important role in realization of accurate and stable global international references that can be used for observing changes in the geosphere such as changes in the ice sheets, sea level, the Earth's tectosphere and strain field across the North America plate. As discussed above, GNET also serves as a consistent reference for individual surveys and campaigns thereby linking such data together.

The importance of an accurate reliable international reference frame (such as the International Terrestrial Reference Frame; ITRF) for supporting a sustainable development of international society and international collaboration have been acknowledged by the United Nations (Resolution 69/266), and all nations benefit from well-coordinated reference frame determination.

2.4.1 GNSS coordinate time series and reference frames.

The computation of coordinate time series is a fundamental and non-trivial task that is crucial for obtaining the best results for subsequent time series analysis. In the computation of coordinate time series for the GNET stations there are issues related to handling of GPS clock and orbit errors, ionospheric delays, and related topics. Furthermore, such computations are dependent on the stability of the reference frame. Changes in computation strategies and reference frame instabilities and uncertainties affect the resulting coordinates substantially. Often the reference frame needs to be redefined when coordinate time series for GNET stations are computed.

Such studies have become more powerful as the GNSS satellite network has expanded (GPS, GLONASS, and/or GALILEO) and the corresponding processing strategies have matured. These developments are ongoing among many research groups around the world. In addition, as the number and location of reference stations globally has evolved, the selection of stations used in securing a stable realization of the reference frame has also evolved.

To satisfy the stringent requirements for reference frame determination, potential reference stations require continuous data series from geodetic GNSS receivers equipped with choke ring antennas mounted on stable monuments. By design, GNET stations have that quality. The observables from all GNET stations are converted to the standard RINEX data format. The GNET raw data has been archived as two sets of data: UNAVCO and Luxemburg data. These are online through the UNAVCO web site, and the DTU Space GPS data, which are stored at DTU Space and only available on request. The data portals may be used for post-processing and estimation of coordinate time series, or used as reference stations for temporary GPS station installations for a wide range of applications described above.

In order to maximize the benefit of the GNET network for coordinate system studies or reference frame determination, stations should log GALILEO and GLONASS signals as well as GPS. Furthermore, GNET stations may need to be augmented by reference clocks, met sensors, and other geophysical equipment such magnetometers, radiation sensors etc.

2.4.2 Making ITRF available to the users.

To support research and development projects it is essential that the reference frame is realized locally and made accessible to end-users. Today, the reference frames are realized using permanently operating GNSS reference stations for which the reference coordinates and GNSS data are applied for accurate and consistent positioning of vehicles/platforms/payloads mapping the quantity of interest (e.g. ice sheet/glacier geometry, velocities, etc.). Currently, the SDFE and DTU are operating GNSS stations in Greenland to fulfill this task as the national authority to realize new ITRFs locally and define transformations to the official national frame.

The main challenges to making ITRFs available to users are that the few on-line reference stations do not provide sufficient coverage to define and maintain a sufficiently detailed reference frame in all parts of Greenland to support research and development projects and authority tasks, and that data from all existing reference stations has not yet been made available to the users in the required rate and format. This task requires reference coordinates supplemented by higher rate GNSS data from the GNSS stations. Currently, the SDFE and DTU are supporting this task as the national authority. Reference coordinates are available for all GNET stations. Only a minor subset of the stations, however, can provide higher rate data.

GNET stations could potentially, under an upgrade, provide the reference coordinates and higher rate GNSS data needed to support ground and airborne operations in research and development projects over the entire island. By upgrading GNET stations with higher rate receivers and communication links the gaps can be filled. Furthermore, stations may need to be upgraded with multi GNSS (as opposed to GPS-only) receivers. Optimally, near-real-time data may be needed.

2.4.3 GNSS reflectometry.

Analyses of the reflected GNSS signals show new interesting applications of GNET data for studying changes in sea level and snow accumulation. Both applications may provide valuable supplements to the existing observation networks, especially in Greenland where deployment of such instrumentation is challenging.

One challenge in implementing GNSS reflectometry for sea level work, is that only a few stations are located near the oceans capable of obtaining sea level information. For snow accumulation work, most stations are located on bedrock on the periphery of the island, and as such are outside of Greenland's accumulation area. However, valuable estimates of snow height and mass of precipitation (snow/firn densification) is important to assess in the ablation zone, thus adding to our knowledge of SMB processes. Additionally, these applications require reflections at very low angle that are normally eliminated from the data stream by an elevation mask.

This is a new application of GNSS recently presented at conferences, but at present only a few GNET stations can be used. However, application to GNET data may be developed using existing data acquired by the network under certain conditions.

For best results, stations located close to the ocean may be used for monitoring sea level and support tidal studies and studies of sea level rise. Stations located close to, or actually on, the ice sheet may be used for monitoring changes in the ice sheets and support studies of ice sheet mass balance and of snow/firn properties. To support this work, more stations in close vicinity to the ocean and to the ice sheet are needed.

3 Data Management

3.1 General Background

For broader use of GNET raw data, it is recommended that all data be made available online, with a minimal delay, as far as feasible (a few stations like Station NORD are not routinely downloaded for high-rate data). With just two agencies involved, it is probably easiest to maintain the separate UNAVCO and DTU sites, as long as data formats, RINEX versions and site maintenance logs are similar and well documented. It is recommended that both of the data centers provide doi numbers for their respective raw data, for proper citation. Having clear formats and simple access to all data would benefit numerous other applications for non-expert GPS users, e.g. in the meteorology domain, and also make sure that the GNET data is used much more widely for local Greenland surveying, both for society use and mining/resource development (this is essentially not happening today, mainly because of lack training for local non-expert users).

3.2 Ancillary Data

Absolute repeated gravity data, observed irregularly both by ULux and DTU Space, should similarly be assigned doi's, and also be posted within a short interval of the observations (ideally <1 year) on DTU Space and ULux web site, respectively. The urgency for this kind of data is lower, and only science oriented. The final processed gravity values should be provided along with estimated standard errors, tidal corrections, operator issues, hardware type, and vertical gravity gradient used (if any). It is likely not relevant to include individual drop data and similar, but improved access to data would stimulate more scientific investigations of GNET and gravity changes, and thus better GIA understanding.

3.3 Generation of Time Series

A central GNET web page should provide the necessary data links to all data, both raw and processed GPS data, as well as gravity. It could also link to other 3rd party relevant web sites, such as the national Greenland monitoring site www.promice.dk and other Greenland data portals. It would also be relevant to include some resource material for local non-expert users.

In addition to the raw data access described above, processed GPS data in the form of time series of standardized latitude, longitude and heights at e.g. 30 sec resolution are recommended for provision by one or more "official" data processing centers. It has been a major limiting factor for the widespread use of GNET data that only the "raw" GPS data are available. Processing such data are beyond the capability of many users, e.g. for glaciologists and other geoscientists primarily interested in using GNET for direct Greenland mass balance estimation. A "level 2" GNET product should be routinely provided by one or more data centers (e.g. OSU, U Nevada, UNAVCO and/or DTU Space), using a well-described and documented methodology. Only by providing the "Level-2" coordinate product will a broader user community really be able to utilize GNET (and ANET) data for innovative science. The availability of L2-data would nourish new scientific advances, possibly lending greater strength for annual mass balance, especially when interwoven with other satellite data. With the high temporal resolution of GNET, it would then also be possible to turn this upside down, and improve satellite monitoring of ice sheet changes by GRACE, altimetry and ice flow velocity mapping.

There is a parallel to satellite missions here: imagine that the GRACE team only provided Level-1 data (satellite range and range-rate data); this would have severely limited use of GRACE data to a handful of users. For GRACE the "competition" in providing the better Level-2 data by improved methodology has indeed helped to generate better Level-2 products, for the benefits of all users.

To be able to benefit from the satellite/phone line data communication to most GNET stations, the Level-2 processing should ideally be set up in a near real-time fashion, with a latency of few days, to match the present 6-day near-real time processing of Sentinel-1 ice outlet glacier velocity data, already running routinely around the entire Greenland ice sheet (e.g.,http://cryoportal.enveo.at/). Also, the reference system and tidal/atmospheric corrections applied should be agreed upon between all processing centers, to the degree possible.

The Level-2 GNET data providers should be provided secure long-term funding for running the routine processing service, just like University of Texas, JPL, and GFZ (Germany) does for GRACE. Giving the 10-year experience in analysing GNET data by key PI's, this should not require large resources (compared e.g. to the GNET maintenance costs), as standard processing tools such as GIPSY, GAMIT and Bernese are available and applications for network analysis proven.

The Level-2 processing could also be augmented with other parameters, such as ionosphere and atmospheric related processing, but this might be a bigger challenge (and potentially fewer users) than the "clean" L2 coordinate products. Derived higher-level products, such as improved GIA models, would still be "pure" science and kept out of the L2-service, although links and recommendations should be provided on the GNET data portal / web site.

3.4 Data Stream and Archiving Funded by NSF

Data from the National Science Foundation (NSF)-funded GNET network is downloaded either through TeleGreenland ADSL modems (3 sites) or through Iridium satellite modems (38 sites). GNET makes use of two different types of Iridium modems to connect to the remote GPS receivers. One type involves dialing 29 remote sites from an Iridium download hub based in Boulder, Colorado. This download hub consists of one base modem for approximately every 6 remote sites. The second involves using Iridium Router-Based Unrestricted Digital Internetworking Connectivity Solutions (RUDICS) modem, which uses multi-protocol Mobile Originated (MO) and Mobile Terminated (MT) circuit switched data connectivity. In the case of RUDICS modem, data are routed through an ethernet tunnel maintained at UNAVCO. The RUDICS modem provides a higher bandwidth connection, and thus can pass through higher GPS data rates. The main trade off is the two-fold increase in cost for the RUDICS modem.

The dial-up and RUDICS Iridium modems require a server and automated scripts to access the GPS data and receiver state of health information. Once connected, a script looks for the last successfully archived file, and proceeds to retrieve all remaining whole data files. If the connection is interrupted, the download script will reattempt the retrieval on the next connection, which often occurs multiple times per day. Enough bandwidth overhead is maintained to catch up on data that might have been missed or delayed due to technical issues with the site, regardless of the duration of the communications outage.

Raw data in receiver-specific, binary compressed format files downloaded from the GPS receivers through the Iridium network or ADSL modems are promptly archived at UNAVCO. Additionally, the raw data are converted to RINEX 2.11 and posted as daily files on the UNAVCO public ftp server, which is accessible via anonymous ftp. Data quality checks are performed with TEQC *[Estey and Meertens, 1999]*, and resulting summary files are archived along with the observation and navigation files. Ongoing data processing is performed by the PI team at Ohio State University, which yields position estimates and other ancillary information. Unlike the Geodesy Advancing Geosciences and EarthScope (GAGE) Facility processing system, which produces daily GNSS solutions for >1700 continuous stations including the NSF-funded Plate Boundary Observatory, TLALOCNet (Mexico), and COCONet (pan Caribbean), neither daily position estimates and their associated uncertainties nor velocity estimates and their uncertainties are provided by OSU to UNAVCO for publication on its website.

Iridium service is provided at subsidized Department of Defense rates to the NSF. Iridium costs are approximately $285/month per device. This cost is not currently based on data usage, but instead is a set cost to NSF that is divided equally among users. The DOD rates are currently under review and we anticipate changes it the rate structure in the coming months.

4 Best configuration moving forward

4.1 Evaluation of GNET stations

A necessary detail of this report is to establish the relative merits of the GNET stations as they have recorded scientific data since 2007. Given that the original scientific goal of GNET was to retrieve the GIA signal and improve models, this must be one of the main criteria we use toward a quantitative evaluation of performance. Additionally, as the data clearly have shown, a present-day mass balance component is present in the time series of crustal motions recorded at each of the stations that is useful for making connections to *SMB* and *D*, or in-other-words, the ongoing mass balance of coastal Greenland [*Jiang et al., 2010; Bevis et al., 2012*]. In order to make this comparison in a both straightforward and intelligible way, we rely heavily on three recent analyses of GIA and *SMB-D* responses. A powerful source of constraint on GIA models comes from relative sea-level (RSL) data sets, as these sample the crustal and sea-level responses at different times during the GIA process. A recent model of this type is the model by *Lecavalier et al. [2014]* (see Figure 2a). An alternative model for comparison is one that has been heavily influences by the GPS data from GNET by *Khan et al. [2016]* (Figure 2b). We also rely on the ZOI analysis of *Adhikari et al. [2017]* (Figure 11).

We adopt the following scoring technique for 40 of the GNET stations and present these results on Table 1. GIA is evaluated in two ways. First, the station has an intrinsic relative value in isolating the viscoelastic signal by its proximity to crust that is both free from present-day ice sheet changes and near places where the past ice sheet advances over land. We term this latter category “GIA-merit”. For evaluation of a stations value in measuring *SMB-D*, we use two criteria: the location of the mapped ZOI

(Figure 11) and the location of the station with respect to annual averages of outlet glacier velocity (see Figure 11, inset). Thirdly, a station may also be shown to be of value in helping to sort out differences in RSL vs. GNET-weighted GIA model solutions (Figures 2 and 3). The later evaluation category we term "GIA-discrepancy", and the scoring system is slightly different than that for GIA-merit or *SMB-D*. For the former, scores are either 0 or 2, for each station, while the latter two can score 0, 1 and 3. A score of 3 in the latter cases means that the station lacks ambiguity in its sensitivity, and therefore, merit in evaluating the signatures related to either GIA or to *SMB-D.*

Table 1. Scores for 40 of the existing GNET stations. A '*' indicates that additional information may be found in *Bevis et al. [2012]* or *Adhikari et al. [2017].*

Northwest	GIA-merit	*SMB-D*	GIA-discrepancy
HRGD	1	3	0
KMOR	3	0	2
KAGZ	3	0	2
SCBY	3	3	2
THU2	3	0	2
DSKG	3	3	0
Northeast			
KMPJ	3	0	0
NORD	3	1	0
NRSK	3	0	0
JBLG*	3	0	0
LBIB	1	3	0
DMHN	3	0	0
GROK	1	3	0
LEFN	1	3	0
East Central			
DANE	3	0	0
HMBG	1	3	0
MSVG	3	1	0
DGJG	1	3	0
SCOR	3	0	0
VFDG	1	3	0
KUAQ	3	3	2
MIK2	3	0	2
South Greenland			
KSNB	3	1	0
KELY	3	0	0
KULU	3	1	0
KBUG	3	1	2
KAPI	3	0	2
HJOR	3	0	2
TIMM	3	0	2
NNVN	3	1	0
SENU	3	1	0
NUUK*	3	0	2
West Central Greenland			
KULL	3	0	2
UPVK	1	3	2

RINK	1	3	0
QEQE	3	0	0
AASI*	3	0	0
ILUL*	3	1	0
SRMP*	1	3	2
KAGA	1	3	0

For interpreting the scores shown in Table 1, it is advised that a total added score is inappropriate to employ for evaluation. For example, *Adhikari et al. [2017]* showed the merits of the sensitivity of the RINK station to *SMB-D* with very high fidelity during extreme melt years, whereas, station HMBG would have identical total score, even though no demonstration of horizontal crustal motion sensitivity has yet been fully carried out. Also, it might be tempting to add the two GIA related scores, but some differences could be due to lateral heterogeneity in mantle viscosity, or some other part of the ice history, that is currently under development [*Glenn Milne, personal communication, July 2017*]. Obviously, this table is most helpful once decisions are made as to the preferred approach to the future of GNET: to isolate SMB-D on one hand, or GIA on the other. The ultimate decision regarding the relative weighting of the scores in Table 1 should be guided by the acceptance of viable science projects selected by the National Science Foundation.

4.2 Adding stations to the existing network

Many disciplines would benefit from the addition of stations to the network, but the addition would be targeted. The Glacial Isostatic Adjustment community has pointed out a handful of key locations where the addition of only a few new stations would help constrain GIA estimates. The Dynamic Mass Balance (ice flow) community would also suggest targeted densification of the network, but driven by specific science goals and likely targeting specific key outlet glaciers. The tropospheric and ionospheric communities would also benefit from a denser network along the coast. To benefit reflectometry studies of sea level, new stations would need to be closer to the ocean than existing stations, allowing multipath reflections from the ocean surface.

Another desire expressed by multiple groups was to have stations added on the inland ice. Both the reflectometry community (for studies of accumulation and firn densification) and the tropospheric/ionospheric community expressed this desire. Such stations would pose unique challenges, depending on where they were placed on the ice surface. In particular, stability would be a significant problem. In the ablation zone, ice would melt out from underneath anchors and monuments, increasing the challenge- this has been handled with varying degrees of success by shorter-term campaign groups, but maintaining a long-term station under such conditions would be difficult. In the accumulation zone the problem is simpler, but no less a problem to be solved- in particular the antenna would need to be raised periodically to keep ahead of the accumulating snow, and on all parts of the ice sheet, the ice is flowing, resulting in significant changes in the position of a station over the course of even one year. These challenges are significant but are not impossible to overcome.

4.3 Detailed site characterization of existing sites, additional measurements

Several groups expressed a desire for a more detailed site characterization of existing (and future) GNET sites. The site characterizations ranged from detailed topographical surveying via terrestrial lidar or structure-from-motion photography, to additional atmospheric and geophysical measurements. Gravity measurements exist at some sites, but expanded measurements at other GNET sites is desirable. Finally, a greater understanding of the meteorological conditions at the sites was desired. This could take the form of anything from a full-scale weather station (unlikely) to a micro-meteorological station, some of which can plug directly into the GPS logger power and data streams.

4.4 Expanded sky coverage and data access for existing sites

There are several improvements that can be made to the network without the need for additional stations or measurements at existing stations, but which will add value to the data for multiple users. Many of the groups expressed that limiting the data collection to the GPS constellation was a problem, and wanted GLONASS and GALLILEO coverage as well, making the network truly GNSS and not only GPS. Many applications including space weather, geodesy, and others need access to data in near-real-time for it to be useful, so rapid access to data is essential. In addition to fast access to the data, many applications would benefit from higher-rate data than what is currently available through GNET. Finally, traditional GPS usage requires that the signal path between satellite and ground station be a single straight line, and any interference with this is a problem. For this reason, it is common to limit data collection to only satellites that are above a certain angle in the sky, reducing the risk of multipath reflections. For users who utilize the multipath reflections for added-value data products, however, these low-angle measurements are essential. Thus, removing the masking for low-angle data is desirable.

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