NERC Geophysical Equipment Facility loan 868 Report

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“Calibration and validation of the CryoSat-2 radar altimeter: field studies on the Greenland Ice Sheet”

Abstract

Detailed time series of ice motion data were collected from a transect at a land-terminating margin of the Greenland Ice Sheet between May 2008 and May 2013. The transect consisted of 7 GPS units extending to ~120km inland. The ice-motion data, collected in conjunction with observations of ice-sheet melt and runoff, enabled the coupling between surface melt and ice dynamics to be investigated over a variety of temporal and spatial scales. We observed that the effect of surface meltwater penetration to the ice sheet bed is to perturb the subglacial hydrology at the ice-bed interface causing the ice sheet to flow faster in summer. However, we found that during summers of extreme melt, such as in 2012 (the most extreme melt-summer observed to date on Greenland), the ice sheet at our land-terminating margin flowed more slowly than in the average melt year of 2009, due principally to slower winter flow following faster summer flow. These findings suggest that the annual motion of land-terminating margins of the ice sheet, and thus the projected dynamic contribution of these margins to sea level rise, is insensitive to melt volumes commensurate with temperature projections for 2100. Our data also revealed short-term (<30 day) surface elevation change due to hydraulic jacking of up to 0.5m magnitude. As such, satellite missions should be cautioned against using differencing in ice-sheet elevation between summer melt-seasons in order to avoid erroneous estimates of dh/dt and thus errors in mass change.

Background

The original application specifically targeted using GPS data to help determine the uncertainty of the radar measurements of surface elevation change obtained from the European Space Agency CryoSat-2 radar altimetry mission. The collection of accurate GPS measurements was to i) provide ground-based measurements of actual surface elevation; and ii) assess the contribution of seasonal variations in ice flow to elevation changes. The aim of our work was altered for two reasons. Firstly, the original ESA CryoSat-2 CalVal campaign was not undertaken in 2008 due to delays in the launch of CryoSat-2 (which was finally launched in April 2010). This meant that our 2008 field data collection could not be undertaken in conjunction with the ASIRAS airborne radar altimeter which had been due to over-fly our field site in spring 2008. As such, we modified our data collection procedure and focussed on the section of the original proposal aimed at “logging of seasonal motion … to characterize seasonal variations in ice dynamics that might impact on longitudinal and vertical strain rates and therefore effect elevation change”.

The results from our first 2008 campaign were very successful (eventually published in *Nature Geoscience*; Bartholomew et al, 2010) and this, combined with the award of a subsequent NERC standard grant (NE/F021399/1) in which the loan of four GEF units had been requested resulted in a loan extension request in October 2009. Further successful field campaigns, with published output, revealed the complex links between hydrology and dynamics and made it clear that multiple years (including winter data) were needed to parameterise the forcing between melt and ice-motion required by ice sheet models. This and the fact that a NERC funded PhD student, Andrew Tedstone, investigating “Hydrological controls on diurnal ice flow variability in a Greenland outlet glacier” required GPS data resulted in a further extension request in April 2012. As reported below, this extended time series has resulted in a data-set which has substantially advanced our understanding of hydrology-dynamics coupling across the Greenland Ice Sheet, something that would not have been possible without the extended NERC GEF loan.

Field site and data collection

Data was collected from Leverett Glacier (67º03'N, 50º 07'W), a land-terminating glacier on the western margin of the Greenland ice sheet (Fig. 1) with a potential hydrological catchment of ~1200 km^2 defined by the supraglacial topography. Four on-ice transect sites were installed in May 2008 (Sites 1-4, Fig. 1) and seven sites (Sites 1-7) operated from May 2009 to May–2013. At each site, ice motion, near-surface air temperature and total seasonal melt were recorded, with melt- rates measured at 15 minute intervals at selected sites (1, 3, 5 and 6) using an ultra-sonic depth gauge (Fig. 2). All transect sites were visited by helicopter at the beginning and end of the melt season each year to download data and undertake essential maintenance including redrilling of the support poles (due to exposure by surface melting) and replacing batteries. Sites S1 and S2 were accessible on foot from the field camp near to the ice sheet margin and therefore received maintenance visits more frequently during the melt season. In addition to the on-ice data outlined above, hydrological data (discharge, e.c. and turbidity) was collected from the proglacial runoff draining from the land-terminating margin in order to characterise the subglacial hydrology.

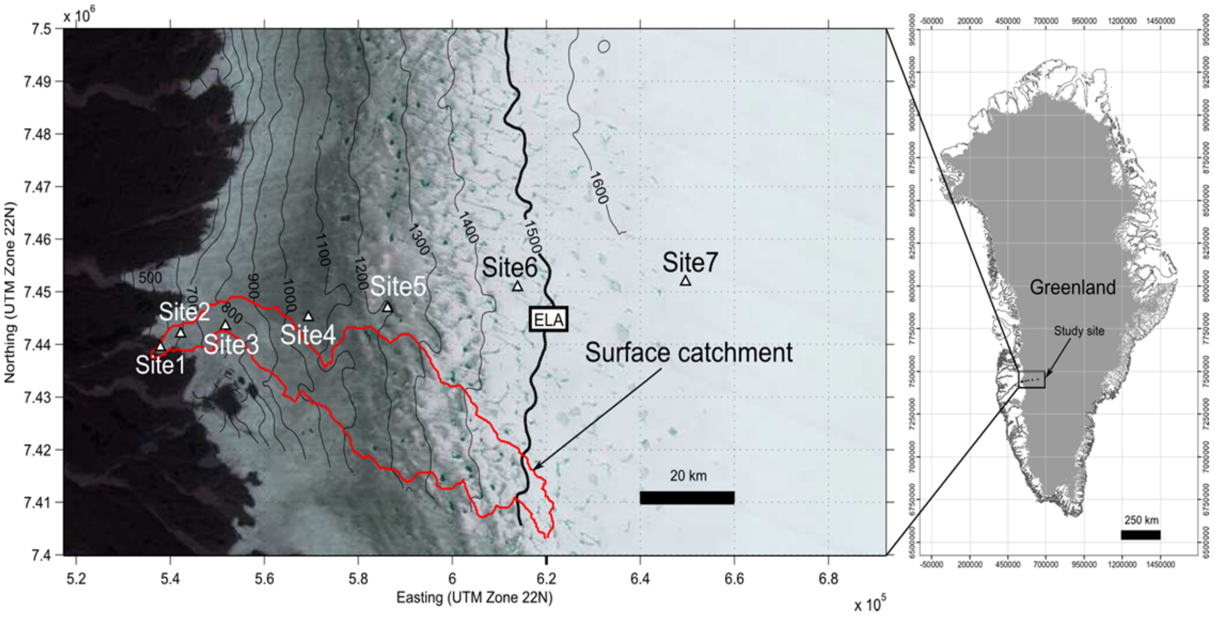

Figure. 1. Location of the study region on the western margin of the GrIS. The GPS sites are located along a transect across an altitudinal range of 450–1700 m.a.s.l. Simultaneous measurements of air temperature and seasonal measurements of ablation were made at each site (Fig. 2). The ELA in this region is at 1500 m. Contours are produced from a digital elevation model derived from InSAR at 100 m intervals.

Survey procedure

At each transect site (Fig. 1) a dual-frequency GNSS receiver, either a Leica System 500 or Leica System 1200, was mounted on a pole drilled and frozen into the ice (Fig. 2), providing measurements of movement independent of ablation. Each receiver was powered by a lead acid or dry cell battery charged by a solar panel mounted on the same pole, with sufficient capacity for observations to be made every 30 seconds throughout the melt season. Power supplies were configured to maximise data acquisition during autumn as the sun's position in the sky progressively lowered. Data acquisition stopped during the dark polar winter as power supplies were depleted, and in most cases did not re-start until the sites were visited prior to the start of the following melt-season. However, it was still possible to calculate net winter ice motion by recording the absolute position of the support pole in spring prior to melt onset.

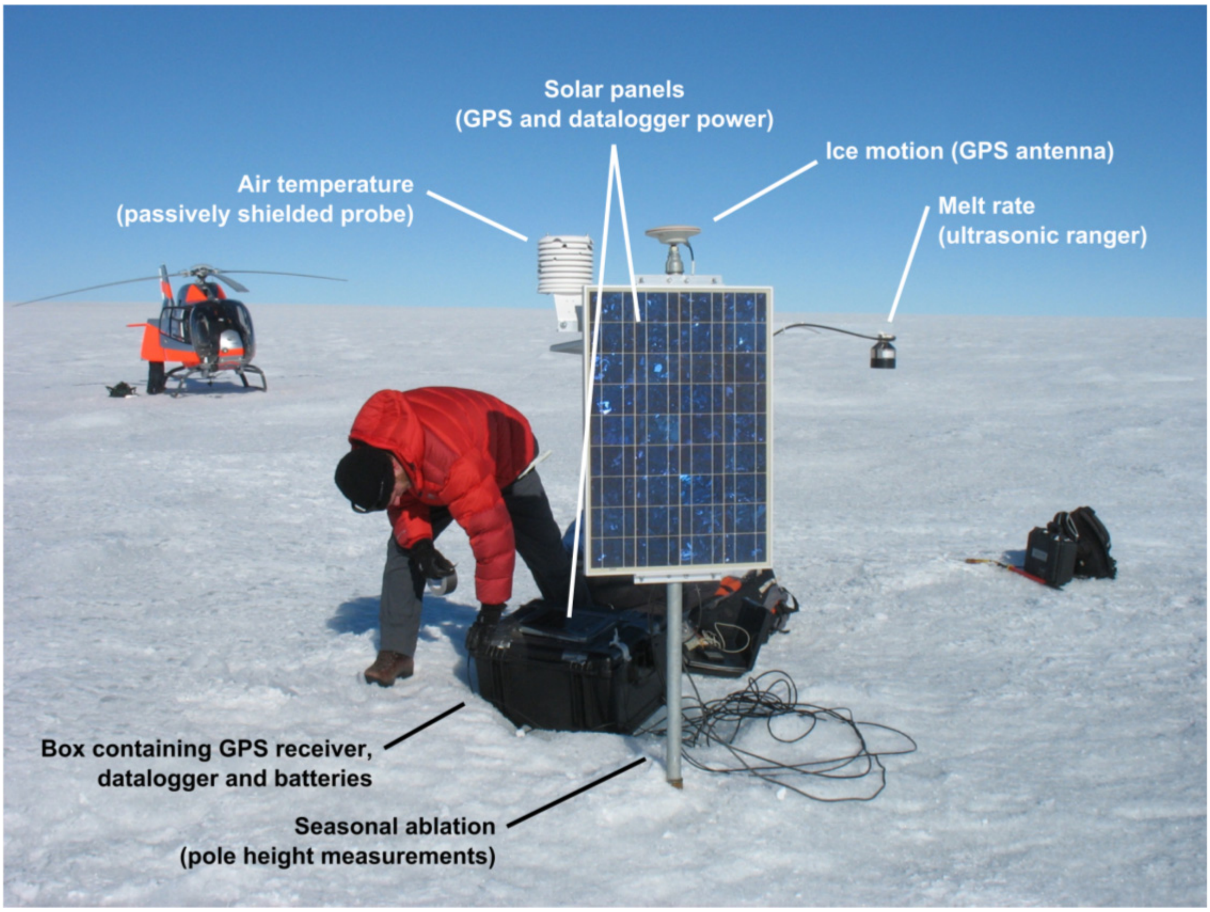

Figure 2. Instrumentation deployed at each transect observation site (site 4 shown here)

Data processing

The data processing methodology outlined below was developed largely through discussion with and support from Professor Matt King (then of Newcastle University). Meetings in Edinburgh with Prof. King, Ian Bartholomew (then a NERC funded PhD student based in Edinburgh), Dr A. Sole (NERC funded PDRA) and P.I. Nienow resulted in a processing protocol that differed from the original plan to use NASA's JPL "autogypsy" facility instead drawing on Professor King's expertise in processing GPS data from his Antarctic research in particular. The benefits gained from this collaboration, notably the generation of high quality position and thus ice-motion data, are reflected in the co-authorship of King on six of the publications resulting from the GEF GPS loan 868 data (see Publications).

The GPS receivers collected data at 30 second intervals that were processed using a kinematic approach relative to an off-ice base station located at our field base camp at the ice margin apart from in 2008 and 12–29 August 2012 when the Kellyville global GPS network station (located ~25 km west of the ice margin) was used. For post-processing, data from each receiver were first converted to the RINEX format using TEQC (Estey and Meertens, 1999). Position observations from each site were then corrected using TRACK 1.27 (Chen, 1999), which first applies the correction signal from a static reference station and then computes the kinematic trajectory of the corrected data. Processing utilised the Final orbit solutions produced by the International GNSS Service, in which satellite orbits have a stated accuracy of ~2.5 cm. Observations were split into overlapping 28 h windows to negate edge effects when the windows of data were subsequently spliced back together. Each window of data was processed individually using a semi-automated, quality-controlled processing chain developed in collaboration with M. King. A-priori coordinates for each window were taken from the solution for the previous window, or from Precise Point Positioning (PPP) if the window was the first in the time series.

The windowed approach enabled immediate isolation during processing of windows of data in which many ambiguities remained unresolved, as data in the 28-h window would display high scatter. These ambiguities are often due to ionospheric effects which alter the propagation of the L1 and L2 signals, for instance by range errors (varying total electron content changes the effective path length of the signal) or scintillation (small scale irregularities in electron density cause cycle slippage or loss of signal lock) (Klobuchar, 1991). Ambiguous windows of data were therefore reprocessed using modified ionosphere correction parameters, specifically (1) increasing the ion delay period allowed before flagging data biases; (2) reducing the weighting given in the solution to the deviation of the Melbourne-Wubbena wide lane (which gives the difference between the biases in the L1 and L2 signal frequencies) and (3) reducing the weight given to the deviation of the ionospheric delay from zero. Windows of data which remained ambiguous despite re-processing were discarded. Once post-processed, the first and last two hours of each window were discarded and the whole time-series was spliced back together.

Conservative estimates of the uncertainty associated with positioning at each epoch are approximately ±1 cm in the horizontal direction and ±2 cm in the vertical direction. The data were smoothed using a Gaussian low-pass filter to suppress high-frequency noise without distorting the long-term signal. Daily horizontal velocities were calculated by differencing the filtered positions every24 h. Vertical displacements were estimated from the elevation observations by removing the linear trend attributable to down- or up-slope movement, retaining just the signal attributable to dynamic ice motion. Shorter-term variations in ice velocity were derived by differencing positions across a 6 hour sliding window, applied to the whole time series of filtered positions for each site. This window length was chosen in order to highlight short-term variations in the velocity records while retaining a high signal to noise ratio. Estimates of the magnitude of daily cycles in horizontal velocity are therefore minimum estimates.

Uncertainties associated with the filtered positions are <0.5 cm in the horizontal and <1 cm in the vertical direction, corresponding to annual horizontal velocity uncertainties of <3.7 m yr^{-1} and <14.6 m yr^{-1} for the 24 hour and 6 hour velocity measurements respectively. We used the standard deviation of 24 hour and 6 hour sliding window velocities from site 7 (Fig. 1), which has the longest processing baseline and experienced negligible velocity variations, to estimate the noise floor in the GPS velocity records. The standard deviations for 24 hour and 6 hour velocities at site 7 are 5.6 m yr^{-1} and 19.5 m yr^{-1} respectively. These values compare well with the calculated uncertainties and represent conservative error estimates for our dataset.

Results

Processing of the GPS data generated detailed data-sets of ice-position and thus ice motion which were then analysed to determine diurnal, seasonal and annual characteristics in ice motion (Figs. 3 and 4). These data were then interpreted in relation to the hydrological data-sets in order to determine the role of surface meltwater and the evolution of the sub glacial drainage systems in driving ice-motion. The key findings of the research are outlined below.

Our hydrological data revealed a seasonal upglacier expansion and increase in hydraulic efficiency of the subglacial drainage system, across the catchment (>600 km^2) to distances >50 km from the ice-sheet margin. This expansion occurred episodically in response to the drainage of surface meltwaters into a hitherto inefficient subglacial drainage system as new input locations became active progressively further upglacier. The effect of this meltwater penetration to the ice sheet bed was to perturb the subglacial hydrology at the ice-bed interface causing the ice sheet to flow faster in summer. The GPS sensors revealed substantial increases in summer motion, of up to 250%, compared with winter background (Fig. 3). These motion variations displayed an upglacier evolution over the course of the summer, with initial velocity enhancement occurring earliest at sites close to the ice margin. The pattern of ice motion and hydrological characteristics of the proglacial runoff in the land-terminating margin confirms that the seasonal evolution in the subglacial drainage system controls basal sliding through hydraulic-ice dynamic forcing mechanisms comparable to those observed at smaller valley glaciers (Bartholomew at al, 2010 and 2011).

Results show that the relationship between melt and ice motion varies both at-a-site and between sites during the melt season. We found a strong positive correlation between rates of annual ablation and changes in summer ice motion, with sites nearest the ice sheet margin experiencing greater summer acceleration in ice motion (15–18%) than those above 1000 m elevation (3–8%) (Bartholomew et al, 2011).

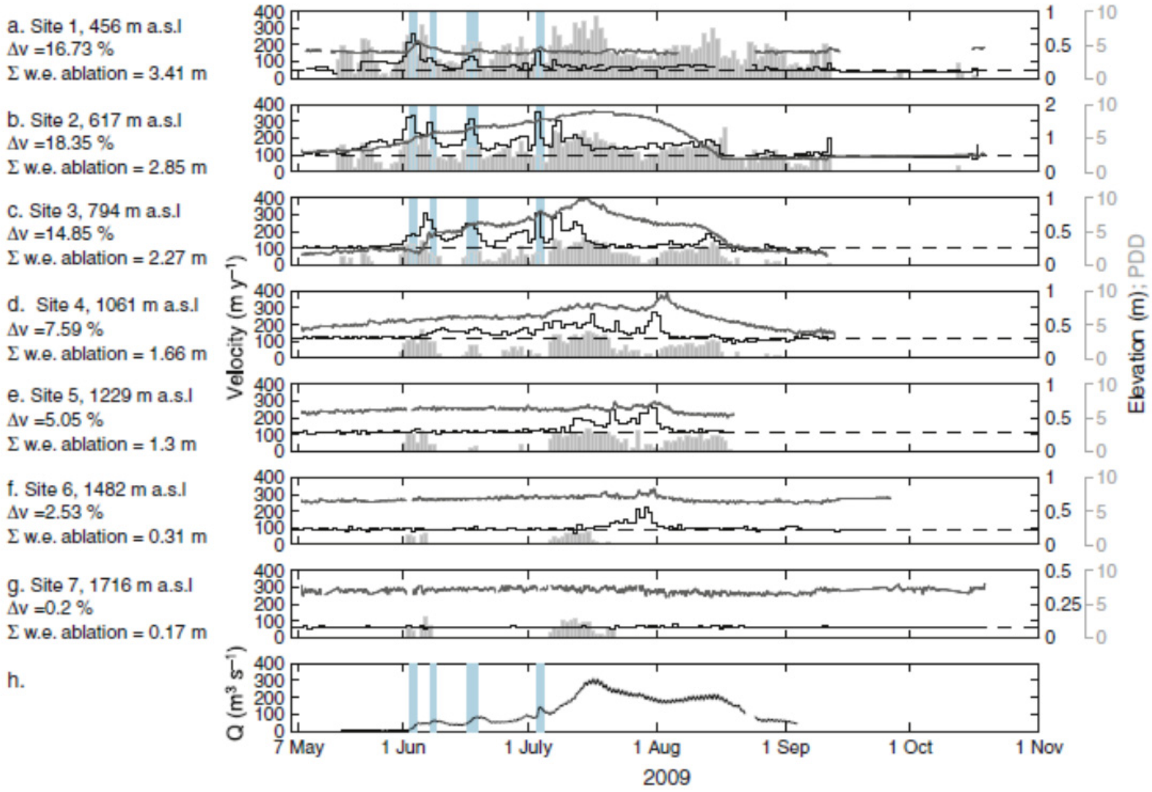

Fig. 3. a–g. 24-h horizontal velocity (black stairs), surface height (grey line) and positive-degree days (grey bars) at sites 1–7 during 2009. The surface height is shown relative to an arbitrary datum, with a linear, surface-parallel slope removed. Winter background velocity (black dashes) is determined by bulk movement of each GPS site over the subsequent winter. Text to the left of each panel shows the elevation, percentage velocity change due to summer velocity variations compared with values if the ice moved at winter rates all year and the total surface ablation in water equivalence at each site for the whole survey period. h. Discharge hydrograph (black; m^3s^{-1}) from Leverett Glacier. The blue shaded sections identify pulses of meltwater which are associated with dramatic reorganisation and expansion of the subglacial drainage system within the catchment. (from Bartholomew et al, 2011, Fig. 2).

Analysis of GPS data at sub –diurnal resolution (Fig. 4) revealed short-term velocity variations (<1 day), which are forced by rapid variations in meltwater input to the subglacial drainage system from the ice sheet surface (driven either by diurnal melt variability or supraglacial lake-drainage). The seasonal changes in ice velocity at low elevations (<1000 m) are dominated by events lasting from 1 day to 1 week, although daily cycles are largely absent at higher elevations, reflecting different patterns of meltwater input (Bartholomew et al, 2012). We find that the seasonal record of ice velocity can be understood in terms of a time-varying water input to a channelized subglacial drainage system.

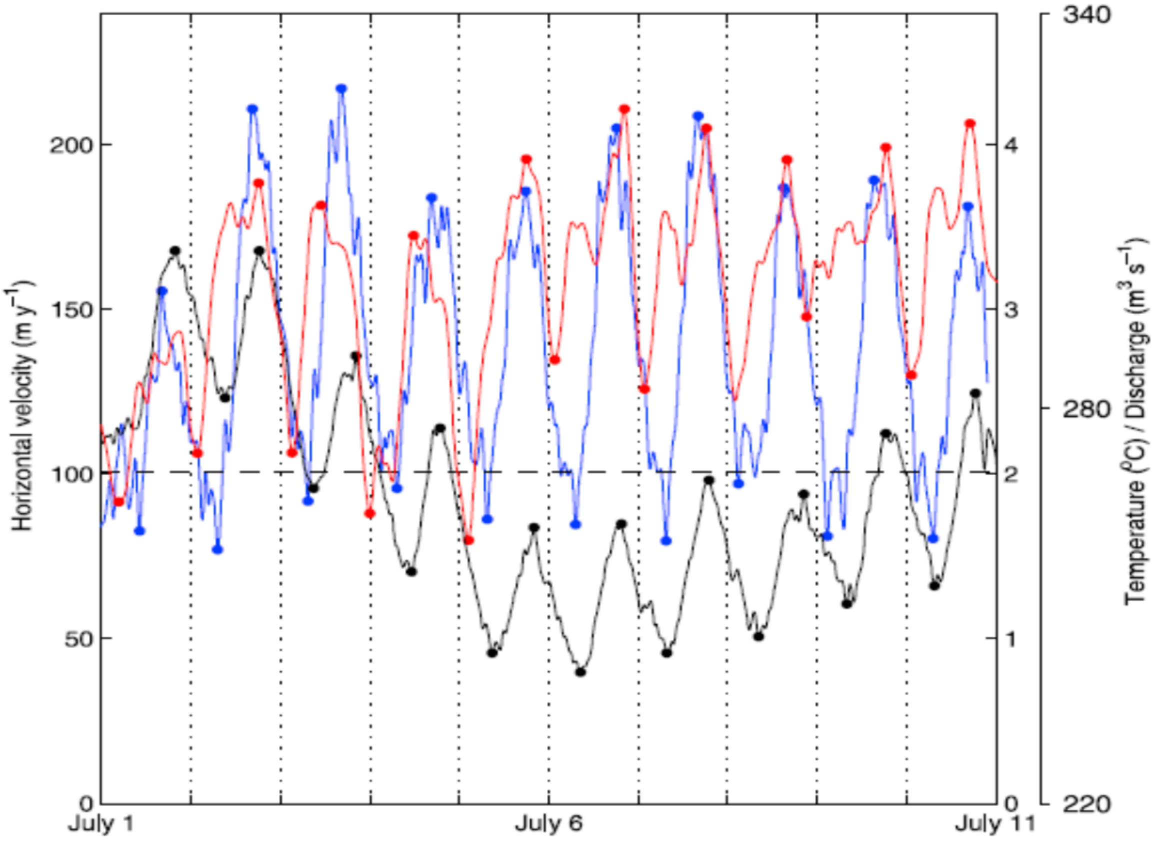

Figure 4. Data showing the temporal relationship between diurnal cycles in ice velocity (blue), air temperature (red) and proglacial discharge (black) at site 2 between July 1 and July 10, 2010. Daily peaks and troughs are marked by colored dots. Winter background ice velocity is indicated by a black dashed line (from Bartholomew et al, 2012, Fig. 7).

The collection of a long time-series of GPS velocity data between 2009-2013 enabled investigation of the extent to which summer melt enhances ice-motion and thus the extent to which the ice sheet might respond in a warming climate. Our data demonstrates a positive correlation between melt and summer ice displacement, but a negative correlation with winter displacement. This response is consistent with hydro-dynamic coupling; enhanced summer ice flow results from longer periods of increasing surface melting (e.g. summer 2010 and 2012) and greater duration ice surface to bed connections, while reduced winter motion is explicable by drainage of high basal water pressure regions by larger more extensive subglacial channels. Increased summer melting thereby preconditions the ice-bed interface for reduced winter motion resulting in limited dynamic sensitivity to interannual variations in surface melting. As a result, despite mean interannual surface melt variability between 2009-12 of up to 70%, mean annual ice velocities changed by <7.5% with no significant correlation between surface melt and annual ice ice flow. In 2012, extreme summer ice sheet runoff ~3.9σ above the 1958–2011 mean resulted in enhanced summer ice motion relative to the average melt year of 2009. However, despite record summer melting, subsequent reduced winter ice motion resulted in 6% less net annual ice motion in 2012 than in 2009. These findings suggest that surface melt –induced acceleration of land-terminating regions of the ice sheet will remain insignificant even under extreme melting scenarios.

Results directly relevant to the CryoSat-2 and other altimetry missions

The data collected during the loan period generated data of considerable relevance to all types of satellite altimetry mission. Our results reveal substantial diurnal, seasonal and intra-seasonal variations in both vertical and horizontal rates of ice-motion (with associated impacts on longitudinal strain rates). For example, GPS emplaced 20 (site 3) and 30 km (site 4) from the ice sheet margin (Fig. 1) reveal vertical uplift of up to 0.50 m over a 25 day period with subsequent lowering of the ice sheet surface of a similar magnitude over the subsequent 40 days (Fig. 3). This vertical motion is driven primarily by hydraulic jacking at the glacier bed due to high subglacial water pressures resulting from inputs to the bed of large volumes of surface meltwater. These substantial short-term variations in ice sheet surface elevation over the course of a melt-season are considerably larger than the net changes in annual ice sheet elevation due to fluctuations in mass balance. They therefore have the potential to introduce substantial errors to estimates of ice sheet mass balance if they are not taken into account by altimetry missions such as CryoSat-2. This is especially important near ice sheet margins where hydraulic jacking is most likely to cause significant uplift and subsequent surface lowering during the course of the melt-season and yet the pattern and magnitude of uplift/lowering will vary both spatially and inter-annually. As such, satellite missions should be cautioned against using change in ice-sheet elevation between summer melt-seasons in order to avoid erroneous estimates of dh/dt and thus errors in mass change.

Conclusions and recommendations

The provision of GPS units through NERC loan 868 enabled the collection of a detailed time series of ice-motion observations. These records in conjunction with observations of ice-sheet melt and runoff are significant because they provide a conceptual framework to understand the impact of hydrologically-forced velocity variations on the future mass balance of the Greenland Ice Sheet. In particular, the data generated which characterises the relationship between the volume of meltwater input at the glacier surface and the magnitude of the dynamic response has now been used by the ice sheet modelling community, through the EU funded Ice2Sea consortium, to improve parameterisations of a sliding law incorporated into a suite of models to estimate the contribution from Greenland to sea level rise in a warming world (Shannon et al, 2013).

Crucial to all of the findings generated from GEF loan 868 data was the longevity of the time-series of ice-motion data. If data collection had ceased at the end of summer 2010, the interpretation of our results would have been completely wrong; we would have believed that the motion of our land-terminating sector of the ice sheet scaled positively with melt leading to a positive runaway feedback effect. We presented results to this effect at the December 2010 AGU meeting in a talk entitled “Acceleration of a land-terminating margin of the Greenland Ice Sheet in contrasting melt-seasons” in which the key conclusions were i) clear evidence that the land terminating ice sheet goes faster in warmer years; and ii) with clear implications for the dynamic response of the ice sheet in a warming world. Only as a result of the longer time-series, which enabled us to collect multiple winter data-sets, have we been able to show that increased summer melting preconditions the ice-bed interface for reduced winter motion resulting in limited dynamic sensitivity to inter-annual variations in surface melting (Sole et al, 2013; Tedstone et al, 2013). The extensions provided to the original loan request have therefore been invaluable and we recommend that this potential provision be continued.

Location of the archived data

The GPS positional data has been archived at the BAS Polar Data Centre as follows:

https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/00841

References used (that are not published as a result of loan 868)

Chen, G., 1999. GPS kinematic poisitioning for the airborne laser altimetry at Long Valley, California., (PhD thesis), Massachusetts Institute of Technology.

Estey, L. H. and C. M. Meertens, 1999. TEQC: The Multi-Purpose Toolkit for GPS/GLONASS Data, GPS Solutions, 3, 42–49.

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PUBLICATIONS RESULTING DIRECTLY FROM LOAN 868 (WITH WEB OF SCIENCE CITATIONS)

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M. and Sole, A. 2010. Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. *Nature Geoscience.* **3**, 408-411, doi: 10.1038/NGEO863. 129 citations.

Bartholomew, I., Nienow, P**.**, Sole, A., Mair, D., Cowton,T., King, M. and Palmer, S. 2011. Seasonal variations in Greenland Ice Sheet motion: inland extent and behaviour at higher elevations. *Earth and Planetary Science Letters.* **307**, 271-278, doi:10.1016/j.epsl.2011.04.014. 44 citations.

Bartholomew, I., Nienow, P., Sole, A., Mair, D., Cowton,T. and King, M. 2012. Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater inputs: implications for the relationship between subglacial drainage system behavior and ice velocity. *J. Geophys. Res*., **117**, doi:10.1029/2011JF002220. 35 citations.

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Shannon, S., Payne, A., Bartholomew, I., van den Broeke, M., Edwards, T., Fettweis, X., Gagliardini, O., Gillet-Chaulet, F., Goelzerg, H., Hoffman, M., Huybrechts, P., Mair, D., Nienow, P., Perego, M., Price, S., Smeets, P., Sole, A., van de Wal, R. and Zwinger, T. 2013. Enhanced basal lubrication and the contribution of the Greenland ice sheet to future sea-level rise, *Proceedings of the National Academy of Sciences*, doi/10.1073/pnas.1212647110. 22 citations.

Sole, A., Mair, D., Nienow, P., Bartholomew, I., Cowton,T., King, M., Burke, M. and Joughin, I. 2011. Seasonal speed-up of a Greenland marine-terminating outlet glacier forced by surface melt-induced changes in subglacial hydrology. *Journal of Geophysical Research*. **116**, F03014, doi:10.1029/2010JF001948. 33 citations.

Sole, A., Nienow, P., Bartholomew, I., Mair, D., Cowton,T., Tedstone, A. and King, M. 2013. Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers, *Geophysical Research Letters*, **40**, doi:10.1002/grl.50764. 21 citations.

Tedstone, A., Nienow, P**.**, Sole, A., Mair, D., Cowton,T., Bartholomew, I. and King, M. 2013. Greenland ice sheet motion insensitive to exceptional melt water forcing. *Proceedings of the National Academy of Sciences,* doi/10.1073/pnas.1315843110. 14 citations.

Tedstone, A., Nienow, P., Gourmelen, N. and Sole, A. 2014. Greenland ice sheet annual motion insensitive to spatial variations in subglacial hydraulic structure, *Geophysical Research Letters*, **41**, doi:10.1002/2014GL062386. 1 citation.

PhD theses published at the University of Edinburgh that utilised Loan 868 GPS data

Dr Ian Bartholomew, 2007-2011 (NERC quota award): "Investigating the subglacial hydrology and ice dynamics *of a* Greenland outlet glacier"

Dr Tom Cowton, 2009-2013 (University Scholarship): "Investigating the hydrology of a Greenland outlet glacier"

Dr Andrew Tedstone, 2011-2015 (NERC quota award): "Hydrological controls on diurnal ice flow variability in a Greenland outlet glacier"

Appendix 1 – Location of GPS deployments in Greenland during loan 868

See Figure 1 for a map showing the GPS sites

site	lat dd	lon dd	elevation
Lev1	67.06940169	-50.13070662	445.44
Lev2	67.09262000	-50.03462000	601.07
Lev3	67.10414350	-49.81476781	788.51
Lev4	67.11504380	-49.40900344	1051.15
Lev5	67.12607527	-49.01827330	1213.84
Lev6	67.15336110	-48.37715363	1473.10
Lev7	67.16266243	-47.55346856	1712.73