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Seasonal dynamic thinning at Helheim Glacier

Suzanne L. Bevan [a,*], Adrian Luckman [a], Shfaqat A. Khan [b], Tavi Murray [a]

[a] Geography Department, College of Science, Swansea University, SA2 8PP, United Kingdom
[b] DTU Space, National Space Institute, Technical University of Denmark, Department of Geodesy, Kgs. Lyngby, Denmark

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ABSTRACT

We investigate three annual mass-balance cycles on Helheim Glacier in south-east Greenland using TanDEM-X interferometric digital elevation models (DEMs), bedrock GPS measurements, and ice velocity from feature-tracking. The DEMs exhibit seasonal surface elevation cycles at elevations up to 800 m.a.s.l. with amplitudes of up to 19 m, from a maximum in July to a minimum in October or November, concentrated on the fast-flowing areas of the glacier indicating that the elevation changes have a mostly dynamic origin. By modelling the detrended bedrock loading/unloading signal we estimate a mean density for the loss of 671 ± 70 kg m^{-3} and calculate that total water equivalent volume loss from the active part of the glacier (surface flow speeds >1 m day^{-1}) ranges from 0.5 km^3 in 2011 to 1.6 km^3 in 2013. A rough ice-flux divergence analysis shows that at lower elevations (<200 m) mass loss by dynamic thinning fully explains seasonal elevation changes. In addition, surface elevations decrease by a greater amount than field observations of surface ablation or surface-energy-balance modelling predict, emphasising the dynamic nature of the mass loss. We conclude, on the basis of ice-front position observations through the time series, that melt-induced acceleration is most likely the main driver of the seasonal dynamic thinning, as opposed to changes triggered by retreat.

1. Introduction

The Greenland Ice Sheet (GrIS) has been losing mass since the early 1990s; observational evidence is based on airborne (Krabill et al., 1999, 2000; Thomas et al., 2006) and satellite altimetry (Johannessen et al., 2005; Pritchard et al., 2009; Zwally et al., 2011a), satellite gravity anomaly experiments (Velicogna and Wahr, 2005; Chen et al., 2006; Velicogna, 2009) and flux-balance calculations (Rignot and Kanagaratnam, 2006; Rignot et al., 2008). An attempt to reconcile these methods arrived at a 1992–2011 mass loss rate of 142 ± 49 Gt a^{-1} (Shepherd et al., 2012). Loss rates have been increasing, and recently CryoSat-2 altimeter observations showed that over the 3 yr up to January 2014 volume loss rates were 2.5 times greater than between 2003 and 2009 (Helm et al., 2014). On an ice-sheet wide basis the ice-dynamical and surface mass balance (SMB) contributions to the change are roughly equal (van den Broeke et al., 2009; Khan et al., 2014).

Mass balance at the marine-terminating outlet glaciers of the GrIS, however, can be dominated at times by losses resulting from glacier acceleration (Howat et al., 2011). For example, between 2002 and 2005 peak speeds on Helheim Glacier, a large marine-terminating outlet glacier in south-east Greenland and the focus of this study, increased by almost 30% and the front retreated by 7.5 km (Howat et al., 2005; Luckman et al., 2006). Helheim has since slowed and readvanced (Howat et al., 2007; Murray et al., 2010) but is yet to recover its pre-retreat state (Bevan et al., 2012). Peak rates of thinning of 60 ± 13 m a^{-1} occurred between 2004 and 2005 on the lower part of the glacier (Stearns and Hamilton, 2007), with dynamic thinning evident between 2003 and 2007 on fast-flow (>100 m a^{-1}) regions penetrating 95 km up-glacier (Pritchard et al., 2009).

Ongoing mass loss from the GrIS is superimposed on a seasonal cycle in ice-sheet mass balance which is dominated by the SMB processes of winter accumulation and summer ablation (van den Broeke et al., 2009; Bamber et al., 2012). This cycle is also detected in time series of gravity anomalies from the GRACE system (Velicogna, 2009; Ewert et al., 2012; Wahr et al., 2013), and in the vertical displacement solutions to bedrock-located continuous Global Positioning System (GPS) receivers (Bevis et al., 2012). Seasonal loading/unloading of ice causes the Earth to respond elastically (Farrell, 1972), resulting in vertical elastic surface displacement of the crust (Wahr et al., 2013). The magnitude of the displacement is proportional to the mass of the load and inversely

* Corresponding author.
E-mail address: s.l.bevan@swansea.ac.uk (S.L. Bevan).

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proportional to the distance between the load and the observing point (Nielsen et al., 2013).

The processes that concentrate long-term dynamic mass loss on the outlet glaciers also influence the seasonal mass-balance cycle, as meltwater and runoff can affect flow velocities (Andersen et al., 2010; Sole et al., 2011; Joughin et al., 2008), submarine melt (Motyka et al., 2003; Jenkins, 2011), and iceberg calving (O'Leary and Christoffersen, 2013). Supraglacial melt is able to rapidly reach the bed at elevations below 1000 m via the development of moulins and crevasses (Clason et al., 2014; Bartholomew et al., 2010, 2011), and once it enters the subglacial hydrologic system it can reduce the effective pressure at the ice-bed interface to promote faster sliding. For example, the onset of melt has been observed to cause early season flow acceleration on many glaciers in western Greenland (Sole et al., 2011; Ahlstrøm et al., 2013). Evidence of melt-enhanced flow for glaciers in the southeast is weaker, but small variations in daily summer surface velocity on Helheim Glacier in 2007 and 2008 were found to be strongly correlated with daily melt (Andersen et al., 2010). At marine-terminating outlet glaciers meltwater and runoff will eventually reach the fjord.

Once discharged to the fjord the melt-season runoff can amplify submarine melting by forming bouyant plumes (Jenkins, 2011). These plumes drive an estuarine circulation within the fjords which, combined with the shelf-forced intermediary circulation, have a strong impact on the stratification of water within the fjord (Sutherland et al., 2014). Frontal ablation and the nature of waters present within the fjord therefore both depend significantly on meltwater discharge (Sciascia et al., 2013).

The importance of submarine melt lies not only in the first-order process of frontal mass loss via melt but also on the potential impact on calving. Modelling has shown that submarine melt could lead to undercutting of an ice front and hence increase the rate of calving (O'Leary and Christoffersen, 2013), though a more recent study has shown that this might not be the case in a time-evolving stress field (Cook et al., 2014). Seasonal melt water may also directly affect calving rates via crevasse hydrofracture processes. Where a crevasse-depth calving criterion is used to model calving rates, rates have been shown to be highly sensitive to water depth within the crevasses (Cook et al., 2012). Both submarine melting and increased calving can lead to terminus retreat and a subsequent reduction in resistive stresses at the terminus. This force imbalance may result in faster ice-flow and glacier thinning which rapidly propagates upstream (Howat et al., 2005).

Thus meltwater reaching the bed and progressing to the fjord may cause an increase in ice flow through two mechanisms — reduced basal friction and reduced terminal backstress, both of which will lead to dynamic thinning of a glacier during the melt season. Backstresses at the terminus may also vary seasonally owing to the formation and clearance of an ice mélange within the fjord (Howat et al., 2010; Amundson et al., 2010). In this study we investigate these processes by employing an unprecedented series of interferometric digital elevation models (DEMs) from June 2011 to May 2014. Using these data we map the timing and distribution of seasonal ice loss over Helheim Glacier below 800 m a.m.s.l. (above mean sea level) through three annual cycles. We calculate volume change using the DEM time series and associate this with mass loss by considering GPS measurements of relative vertical bedrock displacements from 2011 to 2014 at a permanent site located a few hundred meters from the Helheim Glacier (Fig. 1). Feature tracking of ice-flow is used to consider the relative contributions of SMB and dynamic effects to the annual mass-balance cycle, and the importance of ice-front processes versus meltwater penetration in driving dynamic processes.

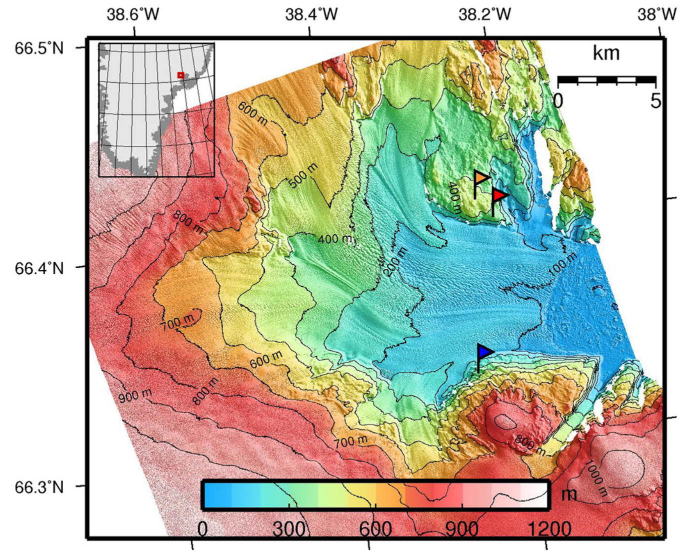

Fig. 1. Shaded digital elevation model for 02/07/2013. The orange flag marks the location and height for the ground control point (468.6 m), the blue flag the validation height point (347.1 m). The red flag marks the location of the GPS bedrock measurements. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Methodology and data

2.1. Surface elevation

Synthetic Aperture Radar (SAR) data from the TanDEM-X satellite system were used to generate a series of DEMs of the lower portion of the Helheim Glacier catchment. The TanDEM-X mission is a public/private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH to generate a highly accurate consistent global DEM (Krieger et al., 2013). We use GAMMA Remote Sensing software to generate interferometric DEMs using the bistatic stripmap mode Co-registered Single look Slant range Complex products (CoSSCs). These experimental data are available over Helheim Glacier from June 2011 to May 2014 and have a spatial resolution of approximately 2 m which we multilook by a factor of 4. We rely solely on the provided orbital vector data to geolocate the images and to calculate the phase scaling. The DEMs are tied in the vertical dimension using a ground control point from the Danish Geodata Agency (http://gst.dk/emner/landkort-topografi/groenland/ground-control-greenland/, July 2014). The control point is at an elevation of 468.55 m above mean sea level in the GR96 datum system with a second point (347.10 m) used as a validation point (Fig. 1). All elevations quoted in this work will be in the GR96 datum system. The main error sources in generating interferometric DEMs from TanDEM-X data include errors in orbit or baseline information, unwrapping, and geolocation and orthorectification; only DEMs with less than a 2.5 m error relative to the validation point are included in this analysis. Estimates of orbit accuracies (Krieger et al., 2013) suggest that we cannot expect relative elevation accuracies better than 2 m.

Volume changes are calculated by differencing DEMs, only including ice-covered areas down to the most retreated frontal position. Area-mean surface elevation changes are calculated by dividing volume changes by the relevant area.

2.2. Surface velocity

We used TanDEM-X and earlier TerraSAR-X image pairs to measure surface velocities based on feature tracking (Strozzi et al.,