Basal topography and thinning rates of Petermann Gletscher, northern Greenland, measured by ground-based phase-sensitive radar

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Abstract

Ground based phase sensitive radar measurements of ice thickness and thinning rates were made near the grounding line of the floating tongue of Petermann Gletscher during the 2002 and 2003 northern summers. Preliminary results from this work show that the basal topography of the tongue is complex, with areas of deep flat base interspersed with steep and rough areas possibly caused by basal crevassing or channels. Apparent thinning rates (rate of change of range to closest basal reflector) are highly spatially variable ranging from 0 to >50m/a. While apparent thinning rates have no obvious correlation with distance from the grounding line or ice thickness, they do appear to be related to the basal topography. In areas with a relatively flat base, apparent thinning rates range from 2-7m/a but are generally close to 5m/a. In areas with a steep or rough base, apparent thinning rates are highly variable, ranging from near 0 to > 50m/a but typically from 10-30m/a. In flat-based areas apparent thinning rates can be interpreted as real thinning rates, from which melt rates can be inferred by applying a small correction for vertical strain rate. In areas with a rough or steep base, it is possible that either melt or basal crevasse opening may cause the high apparent thinning rates. If the rapid apparent thinning in rough areas is melt induced, then glacier wide basal melt rates of 20m/a (required for glacier equilibrium (Rignot, 1996)) are feasible but are generated by highly non-uniform, dynamic processes. If the high apparent thinning rates are caused by crevasse propagation, and basal melt rates in these regions are similar to those in flat areas, then this section of the tongue is not loosing mass rapidly enough to maintain its current along-stream profile and therefore must be thickening.

Introduction

Petermann Gletscher, located in north-west Greenland (81N, 60W), is one of the largest and fastest-flowing outlet glaciers in northern Greenland (Higgins 1990). The glacier terminates in a marine floating tongue, approximately 20km wide and 70km long. Based on remotely sensed data, Rignot (1996) has shown that if the tongue is in equilibrium, basal melt rates must average 10m/a over the entire tongue and near the grounding line reach 20m/a. These equilibrium basal melt rates are higher than any of the other northern Greenland outlet glaciers (Rignot 1997) and approximately one order of magnitude greater than typical melt rates on the largest Antarctic ice shelves. Prior to this study no ground-based measurements had been made on Petermann Gletscher.

Methods

Basal melt rates were determined by measuring thinning rates at points on the tongue and subtracting from these the components caused by strain and surface accumulation or ablation. Total thinning rates were measured by repeated radio echo soundings of the ice column while the effects of surface accumulation and compaction were removed by referencing the radar profiles to identifiable internal reflecting horizons below the firn. Vertical strain rates at the sites were either inferred by measuring the horizontal divergence of a surface stake network using differential GPS, or by direct measurement of internal reflector displacement using the radar.

Radio echo sounding

A Vector Network Analyser (VNA) was configured as a step-frequency radar using a pair of identical broadband antenna and a radio frequency amplifier. The system was operated with a centre frequency of 305MHz and a bandwidth of 160MHz. This technique and equipment has previously been used for basal melt rate measurements on Antarctic ice shelves and has been described by Corr et al. (2002). Due to the phase sensitivity of the VNA, small thickness changes can be detected with high precision. For the 305MHz carrier frequency, a phase change of 3° (well within the VNA's precision under normal signal to noise ratios) translates to a 2.3mm thickness change. Even higher levels of resolution (0.75mm) appear to have been achieved through the 450m thick George VI ice shelf in Antarctica (Corr et al. 2002).

Field sites

Field sites were located on the eastern side of the floating tongue from 0-10km downstream from the grounding line. Six sites were visited during both seasons and a number of high-resolution profiles were created during the 2003 season, including nearly 100 melt rates sites. In addition to the static melt-rate measurements a number of kinematic radar profiles were made to investigate spatial variations in ice thickness.

Results

Basal topography

Figure 1 shows an along-flow profile, which reaches from 8 to 11.5 km downstream of the grounding line (downstream to the right). The profile shows areas of flat bed incised by steep grooves that reach over 200m upwards into the ice shelf. The hyperbolic shape of reflections in steep areas is caused by the large beam-width antennas viewing the same point reflector (the high-point of the groove) from a range of positions along the profile. Other profiles sampled also show similar areas of smooth flat base and areas of steep and rough basal topography.

Thinning rates

Thickness change between years was measured at six sites by timing the 'first bed reflection' while short-term thinning rates within seasons were calculated by measuring the carrier frequency phase change at the first bed return. These rates of range change are hereafter called 'apparent thinning rates' as several processes other than true ice shelf thinning by melt or divergence may affect the observations (see below). Short-term apparent thinning rates during the second season were estimated by linear least squares analysis of a series of thickness measurements made over a two-week period. In general this series included up to five soundings per site, however at several sites much higher resolution time series were recorded. Figure 2 shows a series of measurements made over 36 hours at site 8E. (Site 8E is located at the 0m x position on the profile in Figure 1). The time series shows an apparent thinning rate of 33.2 +/- 0.8 m/a. This compares with an apparent thinning of ~53m over 345 days between the 2002 and 2003 seasons at the same site.

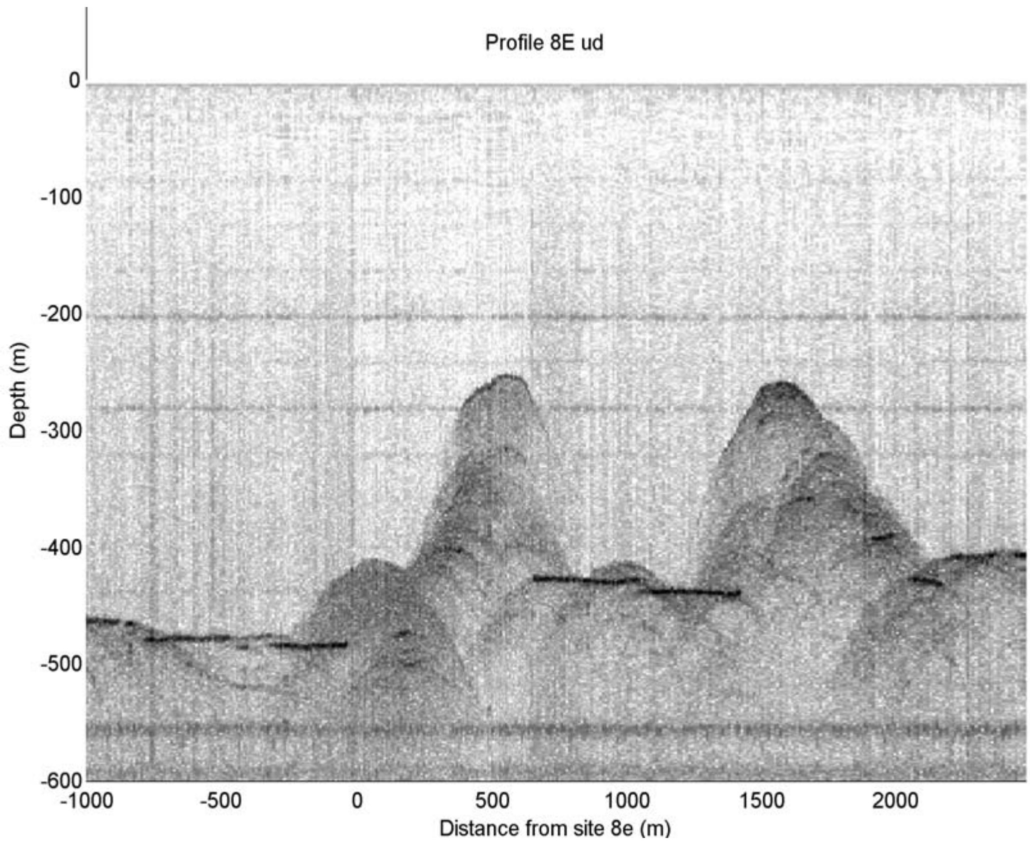

Figure 1. Radar profile 8E (downstream to the right). Shading represents reflection strength with darker shades indicating stronger reflectors (corrected for range squared geometric spreading). Depth is plotted relative to the glacier surface (positive upwards). Regular horizontal bandings (particularly at -200 and -280m depth) are system artefacts. The hyperbolic shape of many of the reflection patterns indicates point reflectors on a rough basal surface.

Discussion

Apparent thinning rates were highly spatially variable between sites, ranging from thickening of several m/a (due to strain compression) to thinning of over 50m/a. No obvious correlation of apparent thinning rate to depth or distance from the grounding line is clear, however rates do appear to fall into two categories according to basal topography. In areas with steep or rough basal topography apparent thinning rates are highly variable and often over 20m/a. In areas of smooth flat bed, apparent thinning rates lie between 2-7m/a.

Several processes could be responsible for the high apparent thinning rates in areas of steep or rough topography. If basal crevassing is present in these areas, the observed thinning rate may be a measure of basal crevasse tips propagating upward into the ice shelf. In these areas interpretation is further complicated as the first reflector is seldom from a point directly beneath the radar. For off nadir reflectors the apparent thinning rate will include not only the basal melt and vertical strain rates, but also a component of the horizontal strain rate due to the oblique view angle. However, for typical horizontal strain rates on the tongue (measured by GPS stake networks), the effect is much smaller than the observed thinning rates. Additionally, if horizontal strain effects dominated apparent thinning rates from off-nadir reflectors, high rates of apparent thickening would be expected in horizontal extension directions. No sites surveyed showed rapid thickening.

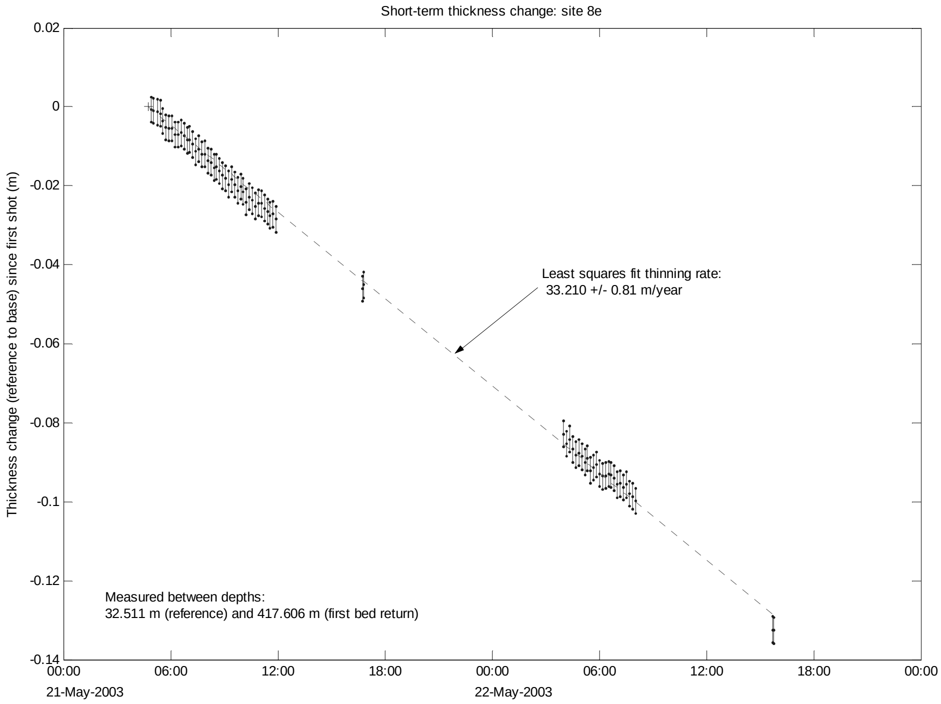

Figure 2. Short term apparent thinning at site 8E. Thickness changes are referenced to the first measurement of the series. Vertical lines indicate individual measurements with error bars. The dashed line indicates least squares fitted apparent thinning rate.

Basal crevasse propagation is more difficult to rule out as a possible cause for the apparent thinning. Horizontal strain rates could be used to rule out crevassing in areas where both principle strains are negative, however although many sites are in net horizontal convergence, one of the principle strains at each site is positive (i.e. extensional). Hyperbola geometry could also be used to assess the sharpness of the basal reflector (as a propagating crevasse tip is likely to be sharper than a melt channel), however this distinction is difficult to make in practice, as the sharpness of a reflection hyperbola in the profile is also dependent on the relative angle of the crevasse and the profile (Jezek, et al. 1979).

Oceanographic arguments can also be used to examine the feasibility of rapid localised basal melting. For the rapid apparent thinning to be melt-induced, water temperature and/or current speed must be higher within channels than on the surrounding areas of flat base. An increase in temperature moving upwards (into a gully) in a sub-ice shelf environment is unlikely. However, an increase in current speed within gullies is plausible given the steep topography. Buoyant melt water plumes may accelerate upwards along the slope if the gullies form part of a continuous drainage network eventually leading to the ice-front. Analysis of surface topography of the glacier suggests that this is possible as depressions are generally linked to major valleys that continue to the ice front.

If the high apparent thinning in channels is melt-induced, then glacier wide average basal melt rates of 20m/a (required for glacier equilibrium) are feasible. If, on the other hand, the high apparent thinning rates are caused by crevasse propagation and basal melt rates in these regions are similar to those in the flat regions (i.e. ~5m/a) then this region is not loosing mass rapidly enough to maintain its current profile, and therefore must be thickening. While recent observations of grounding line retreat in this region of Petermann Gletscher suggest thinning at the grounding line (Rignot, 1998), any non steady-state behaviour such as the advection of thicker pulses down-glacier could cause rapid changes in local mass balances. To improve our understanding of the mass balance of Petermann Gletscher, further work is required to identify whether melt or crevasse opening is responsible for the high apparent thinning rates observed.

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