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Self-regulation of ice flow varies across the ablation area in South-West Greenland

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Abstract

The concept of a positive feedback between ice flow and enhanced melt rates in a warmer climate fuelled the debate regarding the temporal and spatial controls on seasonal ice acceleration. Here we combine melt, basal water pressure, and ice velocity data. We show using twenty years of data covering the whole ablation area that there is no strong feedback between annual ice velocities and melt rates. Annual velocities even slightly decreased with increasing melt. Results also indicate that melt variations are most important for velocity variations in the upper ablation zone up to the equilibrium line altitude. During the extreme melt in 2012 a large velocity response near the equilibrium line was observed, highlighting the possibility of rapidly changing bed conditions in this part of the ice sheet that may lead to a doubling of the annual ice velocity.

1 Introduction

The Greenland ice sheet is losing mass at an increasing rate (Rignot and Kanagaratnam, 2006; Van den Broeke et al., 2009; Shepherd et al., 2012). Mass loss is caused by increased runoff rates (Van den Broeke et al., 2009; Shepherd et al., 2012; Fettweis et al., 2007) and increased dynamical ice loss (Howat et al., 2007; Joughin et al., 2008; Pritchard et al., 2009; Nick et al., 2013). Therefore, it is of great importance to study the feedback between ice dynamics and surface mass balance changes as such this may have important implications for the sensitivity of the ice sheet to a warming climate (Parizek and Alley, 2004; Shepherd et al., 2009; Bartholomew et al., 2011). Of particular interest is the notion that sliding velocity may increase due to an increase in melt, bringing more ice to lower regions where melt rates are usually higher, in turn leading to more melt of ice. On seasonal time scales it has been shown that flow accelerations for land terminating sections of the ice sheet are related to the melt rate, particularly in early summer, suggesting a positive feedback between melt and velocity (Joughin

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et al., 2008; Zwally et al., 2002; Van de Wal et al., 2008). Later in the ablation season, however, the positive correlation between ice velocity and melt rates breaks down, likely in response to increased subglacial drainage efficiency (Bartholomew et al., 2011; Schoof, 2010; Fitzpatrick et al., 2013). The leading hypothesis assumes that in early summer, water reaching the bed from the surface initially causes increased storage and higher pressures in a distributed drainage system, after which channelization increases drainage capacity (Bartholomaus et al., 2008), where after water pressure decreases. Crucial to this discussion is the role of subglacial water pressure variations in modulating ice flow and to what degree the additional seasonal ice displacement is the integrated effect of several transient accelerations (Schoof, 2010; Bartholomew et al., 2012).

Here we will use detailed ice velocity data in combination with accurate melt rates derived from automatic weather stations and year round borehole water pressure data, which together form a unique data set allowing further interpretation of ice velocity variation in the marginal zone of Greenland. First we discuss the velocity data (Sect. 2) and explain how we calculate melt rates (Sect. 3). In Sect. 4 we combine the velocity and melt rates with the borehole water pressure data on short time scales. Longer time scales are presented in Sect. 5 and wider implications are discussed in Sect. 6.

2 Velocities along the *K*-transect

Velocity measurements are carried out along a transect in the ablation zone of the western Greenland Ice Sheet ranging from 340 m above sea level (a.s.l.) to 1850 m a.s.l., (Fig. 1). Our 21 year-long velocity record encompasses yearly data based on commercial L1 instruments prior to 2006 and hourly velocity data over the last 7 years based on L1 GPS instruments developed at IMAU optimized for measurements on glacier ice (Den Ouden et al., 2010). Basically 168 h average positions are calculated, which are used to calculate 168 h spaced velocities. Field data from fixed positions in Greenland show a horizontal standard deviation below 0.5 m for these time intervals. The hourly

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velocity data for all eight sites are shown in Fig. 2. Typically, ice velocities increase rapidly at the start of the ablation season, attaining peak values in early summer also called “spring events” and discussed later in more detail. This peak is then followed by weekly variations on a gradually declining velocity pattern in late summer and early autumn (Bartholomew et al., 2011, 2012; Hoffman et al., 2011). Velocity drops at the beginning of winter, and there after gradually increases during winter, with a maximum magnitude of 13 % at SHR and decreasing to 6 % for S9 from early September to Mid-April. This seasonal pattern is a consistent feature of the record in the lower ablation region despite a gradual increase in ablation over time. However, near the equilibrium line at site S9 we observe an exceptionally large peak velocity in 2012, the summer with large melt at high elevation (Fig. 2). This result contrasts with previous work, Tedstone et al., 2013), who noted no specific velocity response to the high melt season of 2012 albeit that this work only covered the lower ablation zone. We argue here that anomalously high melt rates near the equilibrium line yielded a strong local response.

The seasonal cycle in the velocity averaged over 7 years is shown in Fig. 3. The relative acceleration is largest at 7 km from the margin at SHR, where we observe a large number of moulins and convergence of ice flow into the outlet glacier. Higher in the ablation area the “spring event” is delayed and of a lower amplitude. After this early summer peak we observe a late summer deceleration. It is somewhat arbitrary at which date to separate early and late summer. In Fig. 3 we used DOY 182, 197 and 212. The deceleration suggest different responses of the subglacial drainage system and bed properties to surface water inputs (Dow et al., 2013), depending on the location with respect to the equilibrium line. The delay of the spring event the higher on the ice sheet is illustrated in Fig. 4 and confirms the idea that the spring event is related to the onset of the melt season. In order to discuss this in more detail we use data from automatic weather stations to estimate the melt rates.

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3 Surface mass balance calculations

We calculate hourly melt energy based on three weather stations at S5, S6 and S9 (Van den Broeke et al., 2008). To calculate the available melt energy we add the net radiative flux to the sensible and latent heat flux. The net-radiation is calculated from the measured components of radiation. The turbulent fluxes are derived using a bulk aerodynamic method. The latter method uses gradients of wind speed, temperature and humidity between a single measurement level (5 m) and the surface. For a melting ice surface these surface values are fixed at $0\,\mathrm{m\,s^{-1}}$, $0\,^{\circ}\mathrm{C}$ and $4.8\,\mathrm{g\,m^{-3}}$, respectively. The bulk aerodynamic method assumes the height for these values to be equal to the aerodynamic and scalar roughness lengths above the underlying ice surface, which we estimated following the results from Smeets et al. (2008a, b) For location SHR and S5, both consisting of a rough hummocky ice surface, we used a representative constant aerodynamic roughness length for the whole ablation season of 0.01 and 0.025 m, respectively. Scalar roughness lengths were calculated using a surface renewal model (Andreas et al., 1987) modified for application over rough ice surfaces as suggested by (Smeets et al., 2008b). The effects of atmospheric stability are corrected for by using an iterative method. Eventually we convert melt energy to melt water production by assuming an ice density of $900\,\mathrm{kg\,m^{-3}}$ and a latent heat of fusion of $335\,\mathrm{kJ\,kg^{-1}}$. It is important to mention that the calculation of melt energy from hourly AWS data yields far better accuracy at daily time scales than the methods based on a (calibrated) degree day method, using only temperature measurements as input, or automated surface height measurements from an acoustic height ranger. Estimated standard deviations for errors in the daily totals of turbulent and radiation fluxes are about 6 and 2 %. As radiation usually dominates melt rates, daily mean errors are estimated to be 5 %. As the region studied is an ablation zone with low accumulation rates and the period of interest is mainly summer we do not distinguish between melt rates and runoff. Refreezing is only a small fraction in this area.

4 Velocities, melt and water pressures on short time scales

Year-round basal water pressure measurements are obtained from a pair of boreholes near SHR (Smeets et al., 2012). The two boreholes, located 5 m apart, yielded almost identical records over the first year of measurements and data indicate a connection to the subglacial system. Further proof of an immediate connection to the active subglacial system was the sudden drop in water level when drilling the first bore hole. It is recognized that subglacial water pressures are very variable in time and space in the ablation zone (Meierbachtol et al., 2013), so caution is necessary when interpreting records from a single location. The data, however, provide the first year-round record of water pressure variations beneath the Greenland Ice Sheet which, in combination with detailed ablation information and GPS data, help to constrain hypotheses about the links between surface meltwater production and dynamic response.

Results presented in Fig. 5 show that at the onset of the ablation season at the beginning of July, there is a short-lived peak in subglacial water pressure above the slowly increasing late-winter values, associated with a sharp rise in ice velocity. This is interpreted as the result of a strong imbalance between melt water supply and drainage capacity, leading to instantaneous over-pressuring of the subglacial drainage system and reduction of bed traction and called the spring event (Bartholomew et al., 2011; Fitzpatrick et al., 2013; Sundal et al., 2001; Cowton et al., 2013). Following the spring event the simultaneous drop in ice velocity and pressure clearly indicate the transition of the drainage system into an efficient network of channels. The rapid increase of melt water supply during early summer enlarges conduits due to wall melting that develop into efficient channels. The increasing transport capacity leads to lowering of the pressure in the hydraulic system in the vicinity of the channels (Schoof, 2010). This is in agreement with our observations in Fig. 5 and confirms that our pressure probes are connected to an active part of the hydrological system in the vicinity of a channel.

During the period dominated by channels, there is a clear relation between melt, water pressure and velocities on daily time scales. To highlight this we selected a three-week period in July 2010 to study the diurnal cycle in detail (Fig. 6). Water pressure and ice velocity are direct measurements, and melt is calculated from weather station data. All data are from the site SHR. Melt rates attain their maximum during mid-afternoon coinciding with the temperature maximum and just after the maximum in shortwave radiation. This is followed by a maximum in water pressure 2 h later as the hydraulic system is not capable of handling the maximum melt peak instantaneously. Coinciding with the maximum water pressure we observe that the velocity increases to 50 % above the mean for a short period, reaching more or less constant values overnight until 10 a.m., where after the increase in water pressure and melt leads to a decrease in friction and an acceleration of the ice velocity. Water pressure keeps decreasing overnight as the water input due to melt decreases, but picks up a little later than the onset of the melt in the early morning again once the system is filled again. Hence the capacity of the subglacial drainage system continuously adapts to time-varying water inputs (Schoof, 2010; Bartholomew et al., 2012). Later in the season, when melt ceases, the channels close, and the clear relation between melt, water pressure and velocity becomes less distinct as the system returns to an inefficient, distributed system in autumn (Schoof, 2010).

Around mid summer, melt water production at SHR is at its maximum and water pressure at its minimum indicating the most efficient drainage system (Schoof, 2010), (Fig. 5). During the second half of summer melt water production slowly decreases and pressure starts to increase while velocity continues to decrease albeit at a more gradual rate. In the autumn, water storage gradually decreases due to reduced surface melt rates while drainage efficiency remains relatively high. This appears to result in high bed traction and minimum ice velocities. It is important to note that absolute water pressure as measured at SHR does not drive velocity variations, as seen by the difference between velocities before and after the melt season, when water pressures are similar, Fig. 5. Possibly other temporal sources of water storage impact the relation between water pressure and velocity, but the strong transient drainage capacity of the system also contributes to this.

In autumn when surface melt water production stops, daily pressure variations end and the subglacial drainage system quickly reverts to a low-capacity, inefficient state. Remaining water in the system (e.g. basal melt and/or water supplied from reservoirs farther upglacier) is increasingly pressurized, with subglacial effective pressures decreasing asymptotically over the winter season. In tandem, ice velocities slowly increase, suggesting a decreasing bed traction (Fig. 3).

At S4, S5, SHR and S6, the ice velocity records show a similar annual pattern as described in detail for SHR, suggesting a comparable evolution of the hydraulic system. At S7, S8 and S9, a velocity peak is also present in all years, but the subsequent slowdown is of much shorter duration and winter velocities are more constant. We interpret this difference as a response to varying duration of surface water inputs. In the lower ablation zone, high melt rates are sustained for several weeks, and subglacial discharges are high enough to maintain a high-capacity, low-pressure state throughout the ablation season. Consequently, the summer and early winter are characterized by low ice velocities, which are sustained for long enough to offset the short-lived spring event peak. In contrast, at higher elevations the melt season is much shorter, efficient drainage systems have little time to develop, and summer velocity slowdowns are of shorter duration.

At S10 there is neither a seasonal signal nor an increase in annual velocities over time, within the accuracy of our instruments. Recently (Doyle et al., 2014), it was shown, based on differential GPS measurements, that at S10 in Summer 2012 velocities are also slightly higher by 8 % and annual velocities increased by 2 % from 2009 to 2012.

5 Velocities and melt rates on seasonal to decadal time scales

An alternative approach to investigating the links between climate and ice dynamical response, circumventing the details of the underlying processes, is to consider the statistical relation between melt rates and velocities during the season. A limitation is that surface mass balance data, based on stake readings, are available only with yearly intervals on all the stations whereas velocity data are available every hour. In order to circumvent these limitations we consider the annual velocity at the different sites over the period $y = x$, DOY = 116 to $y = x + 1$, DOY = 116, where y is the year and x running from 2005 to 2011, and DOY the day number. Day 116 is chosen such that it precedes the start of the melt season in all years at all stations. We hypothese that velocity surplus is caused by the magnitude of the surface mass balance (not the other way around), so we use for the surface mass balance the period $y = x - 1$, DOY = 243 to $y = x$, DOY = 243. This yields the annual velocity response to the surface mass balance perturbation over the preceding period. We partition the season into winter and summer. The summer season is defined by the melt considerations and runs from DOY 116 to DOY 243. We additionally divide summer in two periods: early summer velocity and late summer velocity because we observe a different response during different times of the year. It may be noted that the results do not critically depend on where the split between the early and late summer is chosen.

By using these subdivisions in season we find for each station separately a negative correlation with ($r > 0.5$, $n = 7$) between melt rate late summer velocity expressing that more melt (a more negative surface mass balance or higher melt rate) leads to lower velocities in late summer.

However the statistical correlations are not during all parts of the season and for all stations identical. It is only for the upper ablation that we do find a positive correlation between early summer velocities and melt rates. This is shown in Fig. 7, which shows a stacked result of the four upper ablation area stations (S6, S7, S8, S9). It shows that early summer velocities are higher if there is more melt. For the lower region this is not statistically significant. The net effect over summer in this region is the combined effect of early and late summer where the early summer dominates. Secondly we observe that in the upper ablation area there is a negative correlation between melt rate and velocities over winter, i.e. more melt leads to lower winter velocities in the upper ablation area. The net effect of the opposing trends for winter and summer in the upper ablation area is dominated by the longer winter season suggesting that more melt leads to lower velocities in the upper ablation region. For the lower region this is again not statistically significant. Figure 7 indicates that annual velocities typically decrease by a few per cent if the melt increase by 2 standard deviations. Hence we conclude that there are annual variations in the velocity with a coherent pattern but the changes are small and more melt leads to lower velocities in the upper ablation region.

Recently (Sole et al., 2013) showed that in the lower ablation area for a single year with high melt and strong early summer speed up, annual velocities are offset by reduced winter velocities. Here we demonstrate that this is a general feature at least in this area over the last 7 years, Fig. 7. Our high ablation area data show that years with higher than average summer melt and ice velocities (e.g. 2007, 2010 and 2012) are followed by winters with below average ice velocities. In the lower ablation area, however, the annual response to melt rates is not significantly correlated to melt rate. Only the late summer decrease is significantly correlated to melt rates, as has been reported earlier (Sundal et al., 2011). Hence, our results confirm the hypothesis that the melt-induced acceleration is offset by the subsequent slowdown caused by efficient drainage and higher bed traction, hereby providing the solid empirical evidence for earlier postulations that this might be the case (Parizek, 2010).

Our observations also agree with recent tracer studies (Chandler et al., 2013) suggesting the development of an efficient subglacial drainage system over the season up to 40 km from the margin. Superimposed on the gradual decrease of ice velocity during summer, stronger ablation events or lake drainage events (Hoffmann et al., 2011; Das et al., 2008) overpressure the system and lead to high-amplitude but short-lived flow accelerations. Velocity changes in this period are driven by the variability in the melt water input into the system rather than by the absolute melt water volume (Schoof, 2010; Bartholomew, 2012). The positive correlation between ice velocity and melt rate in the early part of the season dominates over the entire summer in the higher parts of the ablation region (Fig. 7). At lower elevations (S4, S5, SHR), however we find no statistically significant correlation between melt intensity and summer velocity between 2005 and 2012.

6 Velocity changes near the equilibrium line altitude

The overarching question arises: will ice flow increase in a future warmer climate? The compensating relation between early summer speed up and a decrease in ice velocities in the following winter suggests that the coupling between ice flow and the subglacial hydraulic system is complex and self-regulates. Long-term correlations between ice velocity and melt rates are limited. For the last 21 years there is no evidence for a strong positive feedback between annual melt rate and annual ice velocities as shown in Fig. 8. It is likely, though, that in warmer years the basal footprint of the ice sheet susceptible to melt water input and basal motion expands as the ablation zone expands to higher elevations along with supraglacial lake drainage (Howat et al., 2013). In order to address that it is useful to consider the equilibrium line altitude.

Based on the mass balance data we can calculate the equilibrium line altitude. For every year we selected the two sites, which enclose the equilibrium line at the end of the ablation season. By assuming a linear gradient with elevation between these two sites we can obtain for most years a fairly accurate estimate of the equilibrium line altitude. This is particularly true as the equilibrium line altitude is often close to S9, requiring only little interpolation. The year 2012 is an exception, as the equilibrium line altitude is above our highest site (S10 at 1850 m a.s.l.), Fig. 9. For this year we estimated the equilibrium line altitude from a linear extrapolation of the mass balance data at S9 and S10. This extrapolation yields a large error, as even the mass balance at S10 was strongly negative −0.74 cm w.e. for this year implying a large extrapolation. With an estimated uncertainty of ±200 m, we cannot exclude that the equilibrium line was above the ice divide, which excludes the presence of an ice sheet at this latitude if it were maintained for a long time period. Despite the large uncertainty it is safe to conclude that in this area the equilibrium line is exceptionally high in 2012.

At the same time we observe that the annual velocity increases with a factor 2 going from S10 to S9. Hence sliding is roughly responsible for half the velocity in this area, as thickness and slope are not varying that rapidly. The crucial point is that Fig. 2 suggests

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that at site S9, located near the equilibrium line (1500 m a.s.l.) the magnitude of the summer acceleration has increased in recent years (Fig. 2). This has to be explained as a direct response to local melt water input, and not longitudinal stress coupling as suggested for some regions (Price et al., 2008), because seasonal velocity variations on the lower parts are more or less similar to previous years. Additionally, the time delay of peak velocities along the transect is in concert with upglacier expansion of the ablation zone (Fig. 4), indicating that local melt water production is the primary forcing.

Hence the transition between cold-based and warm-based conditions may occur rapidly following penetration of surface water to the bed, due to latent heat release during refreezing, a process sometimes called cryo-hydrologic warming (Philips et al., 2010). As a consequence ice speed-up by sliding may therefore occur rapidly in response to increased surface melting at high elevations. During the exceptional melt extent of 2012, when melt occurred over (98.6 %) of the ice sheets surface area (Nghiem et al., 2012) and the ELA attained an unprecedented elevation (Fig. 9), S9 accelerated to over double its previous velocity maximum in 2010. This remarkably fast response to additional water input suggests that even in a zone where there is firn and refreezing, water rapidly penetrates to the bottom of the ice sheet yielding reduced basal traction and enhanced velocities. Our observations therefore support the short time scales of cryo-hydrologic warming (Philips et al., 2010).

7 Conclusions and outlook

The data along the transect show a subtle pattern of response with respect to the position of the equilibrium line. In particular in the higher ablation area annual velocities decrease near the equilibrium line. This suggests that the feedback between melt rates and velocity increases is of limited importance for decadal time scales. On the other hand we observed a strong response near the equilibrium line in 2012. Hence further detailed subglacial temperatures and water pressure data near and above the equilibrium line are needed to understand the importance of this observation.

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It is therefore too early to conclude that melt rates are not important for the ice dynamics, as has been suggested (Shannon et al., 2013). However we suggest to shift research efforts from lubrication enhanced flow in the ablation region towards water penetration induced expansion of the sliding area having much more potential to yield an acceleration of the annual ice flow.

Author contribution. R. S. W. van de Wal performed the interpretation and wrote the analysis together with C. J. P. P. Smeets. M. Stoffelen, R. van Kampen assisted with the dataprocessing. All other co-authors contributed to the fieldwork and commented on the manuscript.

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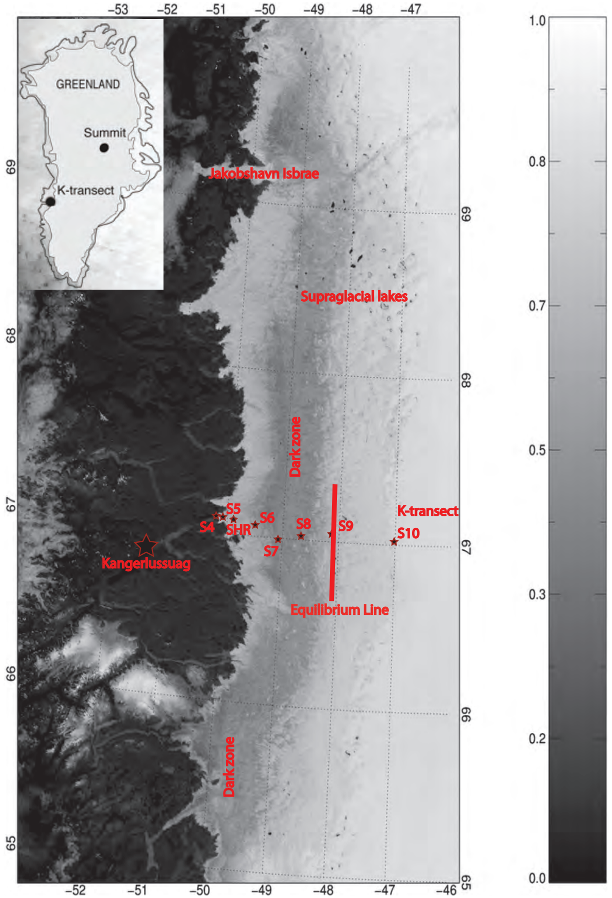

Figure 1. MODIS daily reflectance (band 620–670 nm) indicated by the colour bar on the right hand side from 21 August 2012 including the sites of the K-transect relative to the ice margin, the dark zone with lower surface albedo and supraglacial lakes. Flow direction is from East to West. The region is characterised by a lack of lakes at the end of the summer season.

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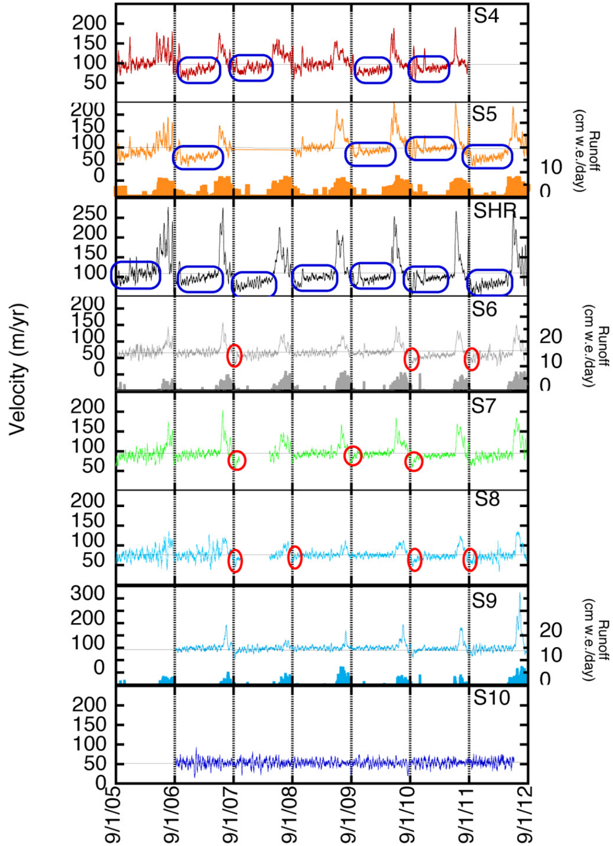

Figure 2. Velocity records from the 8 sites on the *K*-transect with 7 years of data. Data are plotted with respect to their mean values (grey line) and sorted from the ice margin (top) to the accumulation area (bottom), 150 km from the margin. Note some similar patterns, increase in winter velocity encircled blue, and dip in autumn velocity encircled red. For S5, S6 and S9 melt based on AWS data is shown for reference on the right axis.

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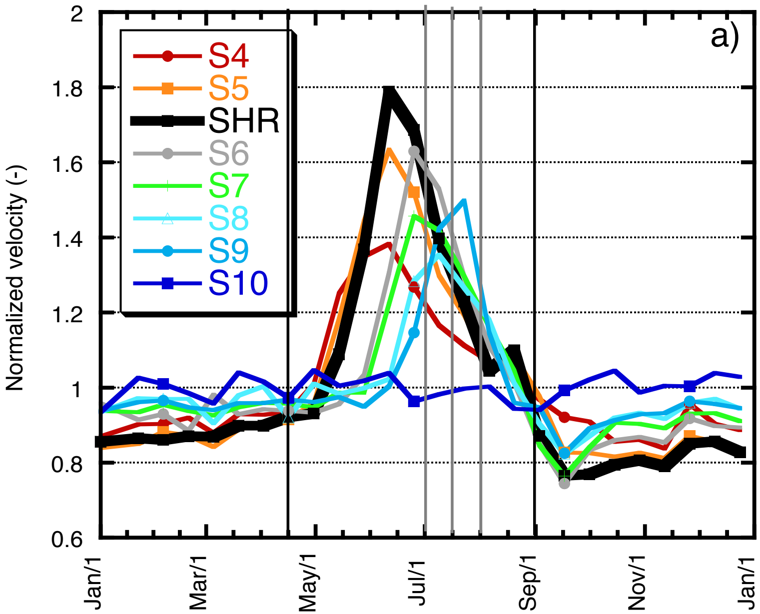

Figure 3. The average seasonal cycle of the velocity at stations S4–S10 over the last seven years. Data are normalized with their mean over the entire period with data available. Note the progressive increase in velocity over winter at SHR. Higher frequency cycles after the summer peak are smoothed by a two-week-long period filter. The grey lines show the arbitrary range in the separation between early and late summer. Qualitative conclusions are not affected by the arbitrary choice of this date.

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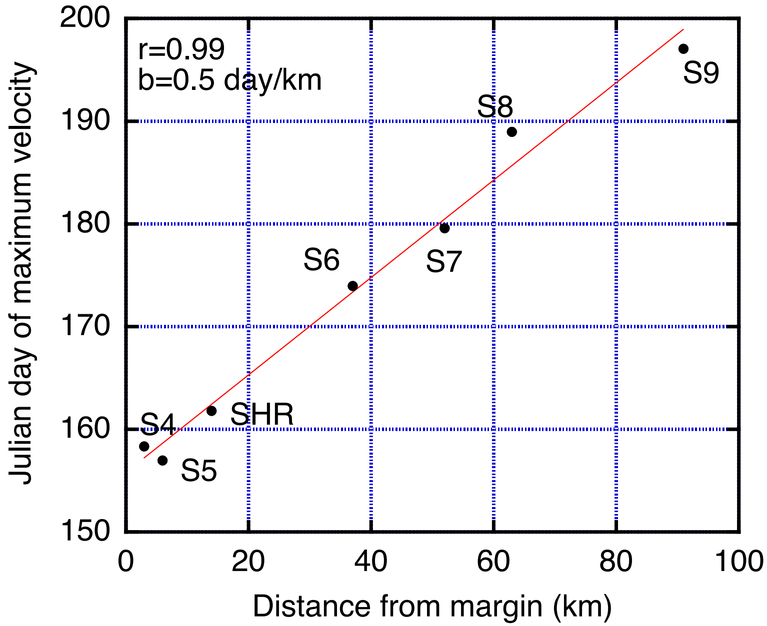

Figure 4. The progression of the early spring event upglacier. Data are averaged over the period 2005–2012.

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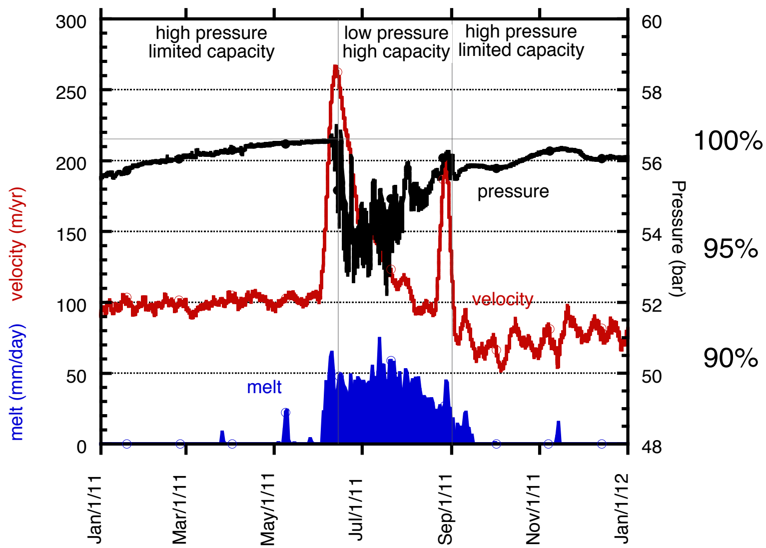

Figure 5. Seasonal cycle of water pressure, melt and velocity at SHR starting in January 2011. Note how the onset of significant melt leads to high magnitude acceleration and a short period of water pressure in excess of the overburden pressure (horizontal grey line), which infers floatation. Later in the ablation season variability in the water pressure remains visible, but the amplitude is diminished. During the ablation season the hydraulic system of channels develops, phase 1, and closes once the melt decreases, phase 3 in the figure. Note that even in autumn and early winter, single melt events affect water pressure and ice velocity. Ablation rates are linearly from zero to 8.5 cm w.e. day^{-1}. The percentages indicate the pressure scaled by the overburden pressure.

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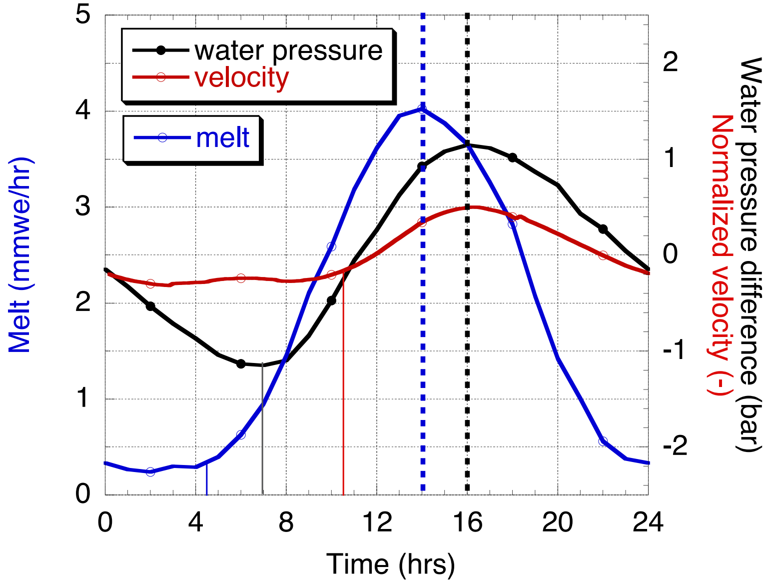

Figure 6. The average daily cycle for a period of 3 weeks in July 2010. Melt production peaks in the afternoon and ceases overnight. Vertical dashed lines indicate peak values and vertical solid lines indicate timing of acceleration in the morning.

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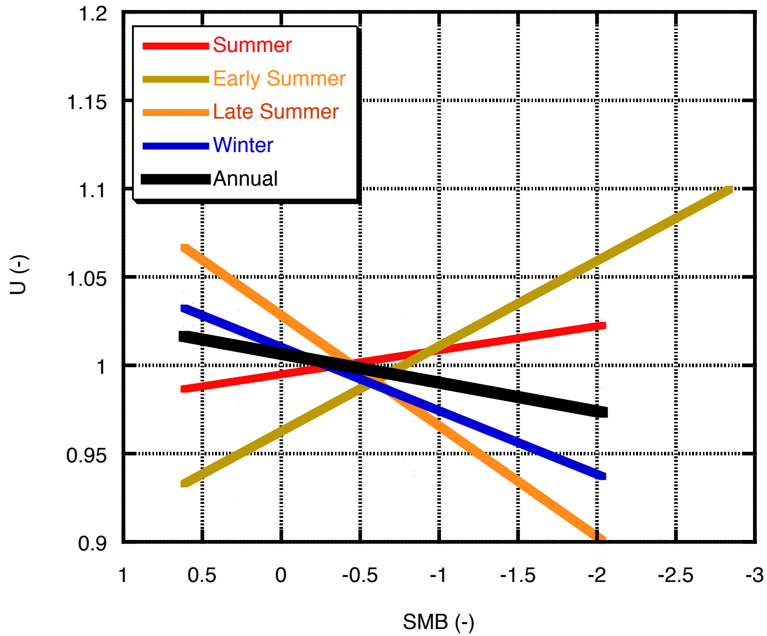

Figure 7. Relation between velocity and surface mass balance (SMB) for different seasons averaged over the upper ablation area (S6–S9). SMB data of different years are normalized with the mean over the period 1990–2010 and divided by the standard deviation. Velocity data are normalized with their mean over the corresponding season and then averaged. Data for velocity and mass balance refer to the period 2005–2012. All fits are statistically significant (minimum $r = 0.79$; maximum $r = 0.96$, $n =$ minimum 5 years, $n =$ maximum 7 years).

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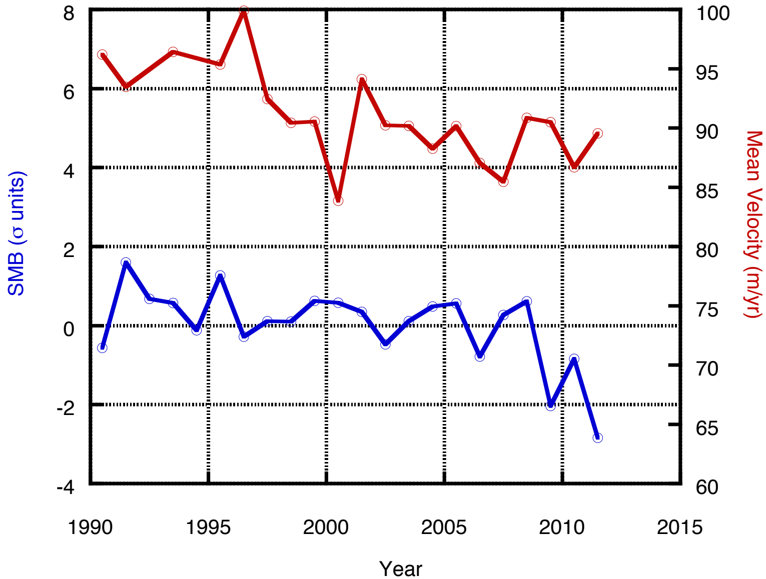

Figure 8. Decadal trends in SMB and velocity from 1990–2012. Data (Van de Wal et al., 2012) suggest a gradual decrease in SMB with superimposed large interannual variability and a decrease in velocity over time. Data for SMB and velocity are weighted mean values over the entire ablation area (19), where the individual sites are weighted proportional to the area they cover along the transect.

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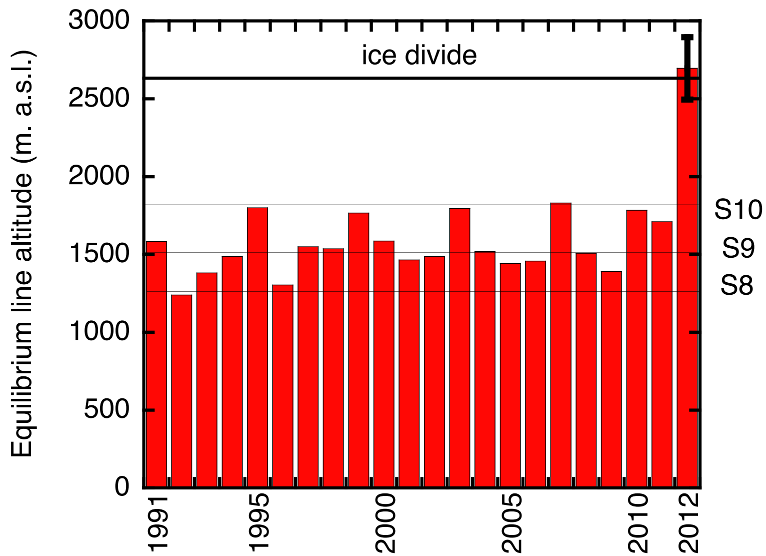

Figure 9. Equilibrium line altitude as function of time over the period 1990–2012. Likely the equilibrium line was above the ice divided in 2012.

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