1	Self-regulation of ice flow varies across the ablation area in South-West
2	Greenland
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12	Abstract
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14	The concept of a positive feedback between ice flow and enhanced melt rates in a
15	warmer climate fuelled the debate regarding the temporal and spatial controls on
16	seasonal ice acceleration. Here we combine melt, basal water pressure, and ice velocity
17	data. We show using twenty years of data covering the whole ablation area that there is
18	not a strong positive correlation between annual ice velocities and melt rates. Annual
19	velocities even slightly decreased with increasing melt. Results also indicate that melt
20	variations are most important for velocity variations in the upper ablation zone up to
21	the equilibrium line altitude. During the extreme melt in 2012 a large velocity response
22	near the equilibrium line was observed, highlighting the possibility of meltwater to
23	have an impact even high on the ice sheet. This may lead to an increase of the annual
24	ice velocity in the region above S9 and requires further monitoring.
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26 **1 Introduction**

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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 30 increased runoff rates (Van den Broeke et al., 2009, Shepherd et al., 2012, Fettweis et 31 al., 2007) and increased dynamical ice loss (Howat et al., 2007, Joughin et al., 2008, 32 Pritchard et al., 2009, Nick et al., 2013). Therefore, it is of great importance to study 33 the feedback between ice dynamics and surface mass balance changes as this may have 34 important implications for the sensitivity of the ice sheet to a warming climate (Parizek 35 and Alley, 2004, Shepherd et al., 2009, Bartholomew et al., 2011). Of particular 36 interest is the notion that sliding velocity may increase due to an increase in melt, 37 bringing more ice to lower regions where melt rates are usually higher, in turn leading 38 to more melt of ice. On seasonal time scales it has been shown that flow accelerations 39 for land terminating sections of the ice sheet are related to the melt rate, particularly in 40 early summer, suggesting a positive correlation between melt and velocity (Joughin et 41 al., 2008, Zwally et al., 2002, Van de Wal et al., 2008). Later in the ablation season, 42 however, the positive correlation between ice velocity and melt rates breaks down, 43 likely in response to increased subglacial drainage efficiency (Bartholomew et al., 44 2011, Schoof 2010, Fitzpatrick et al., 2013). The leading hypothesis assumes that in 45 early summer, water reaching the bed from the surface initially causes increased 46 storage and higher pressures in a distributed drainage system, after which 47 channelization increases drainage capacity (Bartholomaus et al. 2008), where after water pressure decreases. Crucial to this discussion is the role of subglacial water 48 49 pressure variations in modulating ice flow and to what degree the additional seasonal 50 ice displacement is the integrated effect of several transient accelerations (Schoof 2010, 51 Bartholomew et al., 2012).

52 Here we will use detailed ice velocity data in combination with accurate melt rates 53 derived from automatic weather stations and year round borehole water pressure data, 54 which together form a unique data set allowing further interpretation of ice velocity 55 variation in the marginal zone of Greenland. First we discuss the velocity data (section 56 2) and explain how we calculate melt rates (section 3). In section 4 we combine the 57 velocity and melt rates with the borehole water pressure data on short time scales. 58 Longer time scales are presented in section 5 and wider implications are discussed in 59 section 6

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61 2 Velocities along the K-transect

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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., (Figure 1). Our 21-year-long velocity record encompasses yearly data based on commercially-available single-frequency (L1) receivers prior to 2006 and hourly velocity data over the last 7 years based on L1 GPS instruments developed at IMAU and optimized for measurements on glacier ice (Den Ouden et al. 2010). Weekly (16869 hourly) average positions were calculated, which were used to calculate weekly spaced 70 velocities. Field data from fixed positions in Greenland show a horizontal standard 71 deviation below 0.5 m for these time intervals. The weekly-averaged velocity data for 72 all eight sites are shown in Figure 2. Typically, ice velocities increase rapidly at the 73 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 74 75 variations on a gradually declining velocity pattern in late summer and early autumn 76 (Bartholomew et al., 2010, 2011, 2012, Hoffman et al., 2011). In contrast to the 77 majority of studies that use high-power consumption dual-frequency GPS that 78 shutdown during winter, since 1991 our GPS receivers operated throughout the entire 79 winter. Velocity attains a minimum in late autumn, and thereafter gradually increases 80 during winter, with a maximum increase of 13% at SHR and decreasing to only 6% for 81 S9 from early September to Mid-April. This seasonal pattern is a consistent feature of 82 the record in the lower ablation region despite a gradual increase in ablation over time. 83 This seasonal cycle in the velocity was also observed for the years 2009 and 2013 by 84 Sole et al. 2013, Tedstone et al. 2013 and Fitzpatrick et al. 2013.

85 However, near the equilibrium line at site S9 we observe an exceptionally large peak 86 velocity in 2012 (Fig. 2), the summer with large melt at high elevations (Nghiem et al. 87 2012). This result contrasts with previous work (Tedstone et al., 2013)), who noted no 88 anomously strong velocity response to the high melt season of 2012, near their close-89 by located site 6. We observe at S9 that anomalously high melt rates near the 90 equilibrium line yielded a strong local response. The mid-summer response near S9 is 91 larger than the early summer speed-up. The fact that this does not show up in other 92 studies may well be explained by a high degree of spatial variability (Palmer et al. 93 2011, Joughin et al. 2013)

94 The seasonal cycle in the velocity averaged over 7 years is shown in Figure 3. The 95 seasonal amplitude is largest at 7 km from the margin at SHR, where we observe a 96 large number of moulins and convergence of ice flow into the outlet glacier. Higher in 97 the ablation area the 'spring event' is delayed and of a lower amplitude. After this early 98 summer peak we observe a late summer deceleration. It is somewhat arbitrary at which 99 date to separate early and late summer. In Figure 3 we used DOY 182, 197 and 212. 100 The deceleration suggest different responses of the subglacial drainage system and bed 101 properties to surface water inputs (Dow et al., 2014), depending on the location with 102 respect to the equilibrium line. The delay of the spring event the higher on the ice sheet is illustrated in Figure 4 and confirms the idea that the spring event is related to the onset of the melt season, an idea which goes back to the earliest measurements of this type in Alpine environments (Iken et al. 1983). In order to discuss this in more detail we use data from automatic weather stations to estimate the melt rates.

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108 **3 Surface Mass Balance calculations**

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We calculate hourly melt energy based on three weather stations at S5, S6 and S9 (Van 110 111 den Broeke et al., 2008). To calculate the available melt energy we add the net 112 radiative flux to the sensible and latent heat flux. The net-radiation is calculated from 113 the measured components of radiation. The turbulent fluxes are derived using a bulk 114 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 115 surface these surface values are fixed at 0 m/s, 0°C and 4.8 g m⁻³, respectively. The 116 bulk aerodynamic method assumes the height for these values to be equal to the 117 118 aerodynamic and scalar roughness lengths above the underlying ice surface, which we 119 estimated following the results from Smeets et al. (2008a, 2008b) For location SHR 120 and S5, both consisting of a rough hummocky ice surface, we used a representative 121 constant aerodynamic roughness length for the whole ablation season of 0.01 and 122 0.025 m, respectively. Scalar roughness lengths were calculated using a surface 123 renewal model (Andreas et al. 1987) modified for application over rough ice surfaces 124 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 125 water production by assuming an ice density of 900 kg/m³ and a latent heat of fusion of 126 127 335 kJ/kg. 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 128 129 mean errors are estimated to be 5%. As the region studied is an ablation zone with low 130 accumulation rates and the period of interest is mainly summer we do not distinguish 131 between melt rates and runoff. Refreezing is only a small fraction in this area.

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133 4 Velocities, melt and water pressures on short time scales

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Year-round basal water pressure measurements are obtained from a pair of boreholes
near SHR (Smeets et al., 2012). The two boreholes, located 5 meters apart, yielded

137 almost identical records over the first year of measurements and data indicate a 138 connection to the subglacial system. Further proof of an immediate connection to the 139 active subglacial system was the sudden drop in water level when drilling the first bore 140 hole. Previous observations of water pressure variations in combination with velocity 141 measurements in Alpine glacier environments (e.g. Iken and Bindschadler, 1986) and 142 in Jakobshavns Isbrae (Iken et al. 1993) revealed insight in the relation between sliding 143 velocity and water pressure. For Greenland first data by Meierbachtol (2013) indicated 144 a very variable pattern in time and space in the ablation zone over summer. Here, we 145 provide the first year-round record of water pressure variations beneath the Greenland 146 Ice Sheet, which in combination with detailed ablation information and GPS data, help 147 to constrain hypotheses about the links between surface meltwater production and 148 dynamic response.

149 Results presented in Figure 5 show that at the onset of the ablation season at the 150 beginning of July, there is a short-lived peak in subglacial water pressure above the 151 slowly increasing late-winter values, associated with a sharp rise in ice velocity. This is 152 interpreted as the result of a strong imbalance between melt water supply and drainage 153 capacity, leading to a water pressure higher than the overburden pressure and reduction 154 of bed traction, called the spring event (Bartholomew et al. 2011, Fitzpatrick et al., 155 2013, Sundal et al., 2001, Cowton et al., 2013, Iken et al., 1983). Following the spring 156 event the simultaneous drop in ice velocity and pressure clearly indicate the transition 157 of the drainage system into an efficient network of channels. The rapid increase of melt 158 water supply during early summer enlarges conduits due to wall melting that develop 159 into efficient channels. The increasing transport capacity leads to lowering of the 160 pressure in the hydraulic system in the vicinity of the channels (Schoof, 2010). This is 161 in agreement with our observations in Figure 5 and confirms that our pressure probes 162 are connected to an active part of the hydrological system in the vicinity of a channel.

163 During the period dominated by channels, there is a clear relation between melt, 164 water pressure and velocities on daily time scales. To highlight this we selected a 165 three-week period in July 2010 to study the diurnal cycle in detail (Figure 6). Water 166 pressure and ice velocity are direct measurements, and melt is calculated from weather 167 station data. All data are from the site SHR. Melt rates attain their maximum during 168 mid-afternoon coinciding with the temperature maximum and just after the maximum 169 in shortwave radiation. This is followed by a maximum in water pressure 2 hours later 170 as the hydraulic system is not capable of handling the maximum melt peak

171 immediately. Coinciding with the maximum water pressure we observe that the 172 velocity increases to 50% above the mean for a short period, subsequently followed by 173 more or less constant values overnight until 10 AM, where after the increase in water 174 pressure and melt leads to a decrease in friction and an acceleration of the ice velocity. 175 Water pressure keeps decreasing overnight as the water input due to melt decreases, 176 but picks up a little later than the onset of the melt in the early morning again once the 177 system is filled again. Hence the capacity of the subglacial drainage system continuously adapts to time-varying water inputs (Schoof, 2010, Bartholomew et al. 178 179 2012). Later in the season, when melt ceases, the channels close, and the clear relation 180 between melt, water pressure and velocity becomes less distinct as the system returns 181 to an inefficient, distributed system in autumn (Schoof, 2010).

182 Around mid summer, melt water production at SHR is at its maximum and water 183 pressure at its minimum indicating the most efficient drainage system (Schoof 2010), 184 (Figure 5). During the second half of summer melt water production slowly decreases 185 and pressure starts to increase while velocity continues to decrease albeit at a more 186 gradual rate. In the autumn, water storage gradually decreases due to reduced surface 187 melt rates while drainage efficiency remains relatively high. This appears to result in 188 high bed traction and minimum ice velocities. It is important to note that absolute 189 water pressure as measured at SHR does not drive velocity variations, as seen by the 190 difference between velocities before and after the melt season, when water pressures 191 are similar, Figure 5. Possibly other temporal sources of water storage impact the 192 relation between water pressure and velocity, but the strong transient drainage capacity 193 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 decrease in 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 dual-frequency 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.

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218 5 Velocities and melt rates on seasonal to decadal time scales

219 An alternative approach to investigating the links between climate and ice dynamical 220 response, circumventing the details of the underlying processes, is to consider the 221 statistical relation between melt rates and velocities during the season. A limitation is 222 that surface mass balance data, based on stake readings, are available only with yearly 223 intervals on all the stations whereas velocity data are available every hour. In order to 224 circumvent these limitations we consider the annual velocity at the different sites over 225 the period y=x, DOY=116 to y=x+1, DOY=116, where y is the year and x running 226 from 2005 to 2011, and DOY the day number. Day 116 is chosen such that it precedes 227 the start of the melt season in all years at all stations. We hypothesise that the velocity 228 increase is caused by the magnitude of the surface mass balance (not the other way 229 around), so we use for the surface mass balance the period y=x-1, DOY=243 to y=x, 230 DOY=243. This yields the annual velocity response to the surface mass balance 231 perturbation over the preceding period. We partition the season into winter and 232 summer. The summer season is defined by the melt considerations and runs from 233 DOY 116 to DOY 243. We additionally divide summer in two periods: early summer 234 velocity and late summer velocity because we observe a different response during 235 different times of the year. It may be noted that the results do not critically depend on 236 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 lowervelocities in late summer.

241 However the statistical correlations are not during all parts of the season and for all 242 stations identical. It is only for the upper ablation that we do find a positive correlation 243 between early summer velocities and melt rates. This is shown in Fig. 7, which shows 244 a stacked result of the four upper ablation area stations (S6, S7, S8, S9). It shows that 245 early summer velocities are higher if there is more melt. For the lower region this is not 246 statistically significant. The net effect over summer in this region is the combined 247 effect of early and late summer where the early summer dominates. Secondly we 248 observe that in the upper ablation area there is a negative correlation between melt rate 249 and velocities over winter, i.e. more melt leads to lower winter velocities in the upper 250 ablation area. The net effect of the opposing trends for winter and summer in the upper 251 ablation area is dominated by the longer winter season suggesting that more melt leads 252 to lower velocities in the upper ablation region. For the lower region this is again not 253 statistically significant. Figure 7 indicates that annual velocities typically decrease by a 254 few percent if the melt increase by 2 standard deviations. Hence we conclude that there 255 are annual variations in the velocity with a coherent pattern but the changes are small 256 and more melt leads to lower velocities in the upper ablation region.

257 Recently (Sole et al. 2013) showed that in the lower ablation area for a single year 258 with high melt and strong early summer speed up, annual velocities are offset by 259 reduced winter velocities. Here we demonstrate that this is a general feature at least in 260 this area over the last 7 years (Fig. 7). Our data from the upper ablation area data show 261 that years with higher than average summer melt and ice velocities (e.g. 2007, 2010 262 and 2012) are followed by winters with below average ice velocities. In the lower 263 ablation area, however, the annual response to melt rates is not significantly correlated 264 to melt rate as noted by Sole et al. 2013 as well. Only the late summer decrease is 265 significantly correlated to melt rates, as has been reported earlier (Colgan et al. 2011, 266 2012; Sundal et al., 2011). Hence, our results confirm the hypothesis that the melt-267 induced acceleration is offset by the subsequent slowdown caused by efficient drainage 268 and higher bed traction, hereby providing the solid empirical evidence for earlier 269 postulations that this might be the case (e.g. Truffer et al. 2005; van de Wal et al., 270 2008, 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 273 up to 40 km from the margin. Superimposed on the gradual decrease of ice velocity 274 during summer, stronger ablation events or lake drainage events (Hoffmann, et al., 275 2011, Das et al., 2008, Doyle et al., 2013) overpressure the system and lead to high-276 amplitude but short-lived flow accelerations. Velocity changes in this period are 277 driven by the variability in the melt water input into the system rather than by the 278 absolute melt water volume (Schoof, 2010, Bartholomew et al., 2012). The positive 279 correlation between ice velocity and melt rate in the early part of the season dominates 280 over the entire summer in the higher parts of the ablation region (Fig. 7). At lower 281 elevations (S4, S5, SHR), however we find no statistically significant correlation 282 between melt intensity and summer velocity between 2005 and 2012.

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284 **6 Velocity changes near the equilibrium line altitude**

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286 The overarching question arises: will ice flow increase in a future warmer climate? The 287 compensating relation between early summer speed up and a decrease in ice velocities 288 in the following winter suggests that the coupling between ice flow and the subglacial 289 hydraulic system is complex and self-regulates. Long-term correlations between ice 290 velocity and melt rates are limited. For the last 21 years there is no evidence for a 291 strong positive correlation between annual melt rate and annual ice velocities as shown 292 in Figure 8. It is likely, though, that in warmer years the basal footprint of the ice sheet 293 susceptible to melt water input and basal motion expands as the ablation zone expands 294 to higher elevations concomitant to the inland expansion of supraglacial lakes (Howat 295 et al. 2013, Fitzpatrick et al., 2014, TC). Along the K-transect the equilibrium line is 296 often close to S9, but can not precisely be determined from year to year as we have no 297 information on refreezing. We do however know that 2012 is an extreme year as the 298 equilibrium line altitude is above our highest site (S10 at 1850 m. a.s.l.). If we estimate 299 the equilibrium line altitude from a linear extrapolation of the mass balance data at S9 300 and S10 we arrive at an elevation above the ice divide, which excludes the presence of 301 an ice sheet at this latitude if it were maintained for a long time period. Despite the 302 obvious large uncertainty it is safe to conclude that in this area the equilibrium line is 303 exceptionally high in 2012 as the SMB has never been so negative at S10 over the last 304 20 years.

305 At the same time we observe that the annual velocity increases with a factor 2 going 306 from S10 to S9. No detailed vertical distribution of the horizontal velocity is available, 307 hence we roughly estimate sliding to be responsible for half the velocity in this area, as 308 thickness and slope are not known accurately enough to conclude anything else. The 309 crucial point is that Figure 2 suggests that at site S9, located near the equilibrium line 310 (1500 m a.s.l.) the magnitude of the summer acceleration has increased in recent years 311 (Fig. 2). This has to be explained as a direct response to local melt water input, and not 312 longitudinal stress coupling as suggested for some regions (Price et al., 2008), because 313 seasonal velocity variations on the lower parts are more or less similar to previous 314 years. Additionally, the time delay of peak velocities along the transect is in concert 315 with upglacier expansion of the ablation zone (Fig. 4), indicating that local melt water 316 production is the primary forcing.

317 Nevertheless, the transition between cold-based and warm-based conditions may occur rapidly following penetration of surface water to the bed, due to latent heat 318 319 release during refreezing, a process sometimes called cryo-hydrologic warming 320 (Philips et al. 2010). As a consequence, it cannot therefore be excluded that ice speed-321 up by sliding may occur rapidly in response to increased surface melting at high 322 elevations. During the exceptional melt extent of 2012, when melt occurred over 323 (98.6 %) of the ice sheets surface area (Nghiem et al., 2012) and the ELA attained an 324 unprecedented elevation, S9 accelerated to over double its previous velocity maximum 325 in 2010 (Fig. 2). This remarkably fast response to additional water input suggests that 326 even in a zone where there is firn and refreezing, water rapidly penetrates to the bottom 327 of the ice sheet yielding reduced basal traction and enhanced velocities. Our 328 observations therefore support the short time scales of cryo-hydrologic warming 329 (Philips et al., 2010). However, up to now we do not observe a significant trend in the mean winter velocities in this region (Fig. 2), which mainly determine the annual 330 331 velocities and what is what determines the ice flux to the lower regions.

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333 7 Conclusions and outlook

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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 sub- and englacial temperatures and water pressure measuremnets near and above the equilibrium line are needed to understand the importance of thisobservation.

343 It is therefore too early to conclude that melt rates are not important for the ice 344 dynamics, as has been suggested (Tedstone et al., 2013, Shannon et al. 2013). However 345 we suggest to shift research efforts from lubrication enhanced flow in the ablation 346 region towards water penetration induced expansion of the sliding area having much 347 more potential to yield an acceleration of the annual ice flow.

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479 Figure Captions

Figure 1: MODIS daily reflectance (band 620-670 nm) indicated by the colour bar
on the right hand side from 21st of August 2012 including the sites of the Ktransect 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.

- 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.
- 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.
- Figure 4. The progression of the early spring event upglacier. Data are averagedover the period 2005-2012.
- 501 Figure 5. Seasonal cycle of water pressure, melt and velocity at SHR starting in 502 January 2011. Note how the onset of significant melt leads to high magnitude 503 acceleration and a short period of water pressure in excess of the overburden 504 pressure (horizontal grey line), which implies floatation. Later in the ablation 505 season variability in the water pressure remains visible, but the amplitude is 506 diminished. During the ablation season the hydraulic system of channels 507 develops, phase 1, and closes once the melt decreases, phase 3 in the figure. Note 508 that even in autumn and early winter, single melt events affect water pressure and 509 ice velocity. Ablation rates are linearly from zero to 8.5 cm w.e. per day. The 510 percentages indicate the pressure scaled by the overburden pressure.

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511 Figure 6. The average daily cycle for a period of 3 weeks in July 2010. Melt 512 production peaks in the afternoon and ceases overnight. Vertical dashed lines 513 indicate peak values and vertical solid lines indicate timing of acceleration in the 514 morning.

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).

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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Velocity (m/yr)



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