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Discussions

Interactive comment on "Reduced glacier sliding caused by persistent drainage from a subglacial lake" *by* E. Magnússon et al.

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Authours reply to comments by D. Benn

Comment 1:
A curious feature of the velocity difference maps in Figure 2b-e is that the upper extremity of the zone of decreased flow does not coincide with the channel (as indicated in Fig. 2a), but veers off to the north-west. The authors should comment on this anomaly, since it is not what should be expected if low water pressures in the leakage zone are the sole cause of the observed slowdown.

The reason why we do not see any clear velocity decrease along the uppermost part of

the channel is that the ice motion was simply negligible small at this location before the Gjálp eruption. The explanation why the area northwest from the channel slows down is not as trivial. This area is a part of a relatively fast moving glacier section which ~5 km down-glacier joins the leakage path from Grímsvötn. Given the short distance and the extensive impact of the continuous leakage along the channel, the subglacial water pressure underneath this area may have been affected as well. One might also argue that reduced basal sliding above the channel from Grímsvötn may have hindered ice motion few km up-glacier along the ice flow direction.

Comment 2:
567-8: The discussion of the cause of the glacier slowdown invokes steady state hydraulic theories, which posit contrasting pressure-discharge relationships for distributed and channelized drainage systems. However, it should be recognized that recent work on glacial drainages has shown that systems fed from the surface undergo large fluctuations in both pressure and discharge, and that pressure-discharge relationships can differ widely from those predicted by steady state theory. For example, work by Hubbard et al. (J Glac. 41, 572-583) on Arolla Glacier shows that, water pressure in a surface-fed subglacial conduit is higher than in the surrounding bed at times of rising recharge, and lower at times of falling recharge. This results in a reversal of the hydraulic gradient at different times of the day. Furthermore, observations and modelling work have demonstrated that, during 'spring events', the glacier speeds up over the channel axis and for a short distance on either side (Hubbard et al., J Glac. 44, 368-378).
Now, given that there are seasonal variations in water accumulation at Grimsvötn (568.9), we might expect that flow conditions along the leakage route will be nonsteady, and that pressure-discharge relations may vary throughout the year. All of the velocity maps (Figure 2) are for mid-winter. Are there any data for the summer months? It would be interesting to see if there were any seasonal variations in the flow field. Does

the ‘slowdown effect’ apply for the whole year? Or only parts of the year? If such data are available, they should be included to provide a better picture of the relationship between lake drainage and glacier flow. In any case, the authors should acknowledge the limitations of steady state glacier hydraulic theory, and consider the implications of fluctuating discharges, citing the papers mentioned above.

We agree that we should acknowledge the limitations of steady state hydraulics in our paper. In case of short term variations in the subglacial water flow, such as diurnal variations during the melting period or events of intense rainfall/melting, the discharge-pressure relation for tunnel flow at steady state (Röthlisberger, 1972) is not applicable. We however believe that our observations and conclusions do not contradict those of Hubbard et al. (1995), which were carried out in the ablation area of a glacier during late summer. The rather stable leakage from Grímsvötn is the basis for the referred discharge-pressure relation to be valid. It is unlikely to be violated for the presented winter velocities. It may however be questioned for the few summer observations presented in Figure 3, with broken lines. This, as D. Benn points out, warrants more consideration than in the current version of our paper.

The InSAR data, obtained before the Gjálp eruption, indicate gradual seasonal changes in the water inflow to the lake Grímsvötn between ~6 m^3 s^{-1} and ~30 m^3 s^{-1}. The water accumulation in Grímsvötn after the Gjálp eruption was also seasonal, indicating that the increased inflow during summers was not compensated by increased leakage. Diurnal variations in the water inflow to Grímsvötn during the surface melting season are less than in the ablation area of the glacier since the drainage basin of Grímsvötn is within the accumulation area of the Vatnajökull ice cap. The snow pack buffers water drainage from the surface to the bed, damping diurnal variations. The high water accumulation rate observed in Grímsvötn during late autumn also indicates slow drainage in the accumulation area. Since the water inflow to Grímsvötn is rather

steady we expect short term variations in the leakage from Grímsvötn to be small, apart from small jökulhlaup events, which occurred during our study period (these events were however not monitored with InSAR). Except for the jökulhlaup events, we expect greater short time variations in water drainage from the surface in the path of the leakage than in the leakage from Grímsvötn.

The velocities observed from InSAR at cross-section I (Figure 3), in the accumulation area of the glacier, show little or no seasonal variation neither before nor after the Gjálp eruption. The observed summer and winter velocities are near $\mathbf{V}_{ref}$ before the Gjálp eruption and remain ~0.5*$\mathbf{V}_{ref}$ after it. This may be because the snow pack in the accumulation area buffers the water flow from the surface to the base, maintaining stable water flow and pressure at the bed. We propose that the different velocity fields observed before and after the Gjálp eruption indicate that high basal water pressure was maintained by distributed drainage system before the Gjálp eruption both during summers and winters, while after the Gjálp eruption the leakage from Grímsvötn preserved tunnel flow at low water pressure throughout the year.

At cross-section II (Figure 3), which is below the equilibrium line of the glacier, some seasonal variations were observed in the ice motion before the Gjálp eruption. We have one velocity observation from 30-31 July 1997 in this area. At that time the fastest part of the cross-section flows at ~0.25 m d^{-1} compared to a typical winter velocity of ~0.4 m d^{-1} in 1995-1996, which may be referred to as the minimum velocity at this location before the Gjálp eruption; summer velocities are normally higher (Figure 3). We also have two observations from the summer 1999, which show similar velocities as observed during the winter 1995-1996 (Figure 3). Since the summer velocity is normally higher than the winter velocity at this location it is possible that the drainage from Grímsvötn was still affecting the subglacial water pressure at that time, hence the basal sliding.

We know from discrete GPS measurement on the Grímsvötn floating ice cover that the average water accumulation in Grímsvötn from 26 July to 24 August 1997 was $\sim$25 m^3 s^{-1}. Given rough estimates of the inflow component to Grímsvötn (explained in our paper) it is unlikely that the total inflow to Grímsvötn exceeded 60 m^3 s^{-1} during mid summer 1997. This puts a maximum on the leakage at $\sim$35 m^3 s^{-1}. We estimate a likely value for the water drainage from the surface, passing cross-section II at that time, between 200 and 300 m^3 s^{-1} (see answer to a comment by M. Pelto).

For simplification we may divide the water drainage, passing cross-section II, in three components; a) water transferred through distributed drainage system b) non-varying (in a time scale of few days) drainage through tunnel and c) diurnal variations in the tunnel flow. In order to maintain low water pressure in this area a significant part of the water flow must contribute to the non-varying tunnel drainage at cross-section II. We cannot see how increasing b) by <35 m^3 s^{-1}, can have such an impact on the water pressure in a drainage system with total discharge between 200 and 300 m^3 s^{-1}. We suggest that the low pressure tunnel formed by the leakage drained water from the distributed drainage system in the vicinity of the leakage path, causing positive feedback in the non-varying tunnel drainage. Component b) at cross section II was therefore higher than the sum of the leakage and the non-varying tunnel discharge at cross section II prior to the onset of the leakage.

References

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