The referee's comments are printed in bold (partly re-organized and in summarized form). Our response to each item follows in normal font. We first summarize and address the key issues raised by both reviewers, then respond to each individual comment. Finally, the key changes to the revised manuscript are listed.

SUMMARY OF COMMENTS for both reviewers

1. The study only focuses on the hydro-thermodynamic feedback to surface melt; the proposed mechanism needs to be separated from the general surge mechanics

The main focus of this paper is indeed the role of surface melt in promoting the surge of Basin-3. Our continuous GPS timeseries reveals details of a surge that were, to our best knowledge, never recorded before. The active role of external forcing for glacier surges contrasts the general notion that surges are purely controlled by internal mechanisms.

It was not our aim to exclusively focus on the proposed hydro-thermodynamic feedback to summer melt. We state that Basin-3 was pre-conditioned during a quiescent phase, i.e. it experienced a geometric built-up of a reservoir area and the associated changes in thermal regime and driving stress. This pre-conditioning initiated spatially confined fast flow (phase 1) and can be explained by thermally controlled soft-bed surge mechanisms, suggested earlier in the context of Svalbard glacier surges (Hamilton and Dowdeswell, 1996; Jiskoot et al., 1998; Murray et al., 2000). The hydro-thermodynamic feedback amplifies and spreads the dynamic changes (phase 2 and 3). We consider the hydro-thermodynamic mechanism as an integral part of the surge mechanics, not a separated process. Previous observations of glacier surges relied on archived satellite data. Isolated snapshots of surface motion were derived mainly for the winter season, as surface melt degrades the quality of the derived fields (Murray et al., 2003a; Murray et al., 2003b). Changes during the summer melt season have therefore not been captured. Our continuous GPS timeseries reveals that the multiannual surge initiation of Basin-3 was not gradual, but occurred in discrete steps, coincident with the summer melt period. Based on our observations of surface velocities it is not possible to isolate the effect of surface melt. A numerical model of glacier surges, incorporating both internal mechanisms and surface melt, would allow quantification of the contribution of surface melt to glacier surges. To our best knowledge, such a model does not exist. Its development would be an interesting and challenging follow-up study, however, far beyond the scope of this paper. In the revised manuscript, we tried to clarify the above views better.

2. The paper could be better structured with a stronger focus on Svalbard glacier surges against which to compare the observations of Basin-3

This paper is not meant to represent a review paper on Svalbard glacier surges. Nevertheless, the introduction paragraph on glacier surges has been extended to include theoretical considerations of thermally-controlled soft bed surge mechanism, as well as previous observations of Svalbard glacier surges, adding relevant key publications. Our observations are than discussed in the context to these studies. The information on ice sheet instabilities are removed from the introduction and moved to the discussion, where we consider the implications of our observations from Basin-3 in a wider context.

3. Conclusions of a surging Arctic ice cap cannot be applied to the "non-surging" ice sheets

We believe analogies between glacier surges and partial ice sheet collapses are widespread throughout the glaciological literature (e.g. Clarke et al., 1984; Jiskoot et al., 2000) and, for instance, this year's AGU fall meeting features a session on "Ice Sheet Surging, Meltwater Pathways & Abrupt Climate Change"). We do not expect different physical laws to apply for glaciers, ice caps or ice sheets, while the importance of individual processes and the involved timescales certainly differ. In case of ice sheets, climatic boundary conditions may not be stable over a sufficient time period in order to generate a cyclic behaviour as observed for smaller surge-type glaciers, or the timescales involved in ice sheet instabilities may lay outside scientific records.

4. Some of the GPS data have been published earlier

Dunse et al. (2012) presents the first 2 out of 5 years of the GPS timeseries and discuss the data in the context of seasonal velocity variations. The most important processes became visible only after the initial 2 years, i.e. unstable ice flow and its drivers reported on in the present paper were not yet conceivable (see figures below).

5. The manuscript and its conclusions are too speculative

Our observations are limited to surface processes. Stepwise acceleration, coincident with the annual melt period strongly suggest summer melt as an important driver of the observed changes. Linking ice-surface dynamics to processes at the glacier base remains to some degree speculative by nature. We clearly distinguish between observations (results) and interpretation of the observations (discussion). We think that the discussion of a specific phenomenon in a wider context is important for the scientific progress. This includes in particular the implications of a hydro-thermodynamic feedback to summer melt for the ice sheets in a changing climate, i.e. increasing significance of surface melt, especially also in the background of very recent publications on Antarctica (Mengel and Levermann, 2014) and Greenland (Khan et al., 2014; Lüthi et al., 2014).

6. The proposed hydro-thermodynamic feedback is not well described, and it is not clear how it compares to (thermally-controlled) surge mechanism described earlier, and whether it is a positive or negative feedback.

Glacier surges are generally regarded as internal instabilities, and not driven by external factors (Meier and Post, 1969). The climate is, however, thought to set the boundary conditions, as it influences the glaciers thermal regime, as well as the time period required for building up the reservoir area/depleting the receiving area (Dowdeswell et al., 1995). Our unique continuous in-situ observations of ice surface velocity challenge this common understanding, because our data reveal the importance of summer melt for a stepwise surge initiation. Previous observations of glacier surges were reconstructed from archived satellite radar data, only after a surge was noticed. Snapshot velocities were derived preferably for the winter season, i.e. when surface melt is absent, as liquid water deteriorates the quality of the derived motion maps. Changes during the summer melt season have therefore not been captured and the acceleration was thought to be gradual and uniform (Murray et al., 2003a; Murray et al., 2003b).

On Svalbard, glacier surges are thought to be controlled by a thermally-controlled soft bed surge mechanism (Hamilton and Dowdeswell, 1996; Jiskoot et al., 2000; Murray et al., 2000; Murray et al., 2003b). This theory concerns the slow adjustment of the basal thermal regime and driving stresses in response to geometric changes during the quiescent phase, ultimately leading to a thermal switch from cold to temperate basal conditions (Clarke, 1976; Robin, 1955). Basal melting sets in, subglacial till, if present, is thawed and its shear strength reduced by rising pore water pressure, destabilizing the glacier and initiating the surge (Clarke et al., 1984). Dynamic thinning and reduction in surface slope reduce the driving stress and eventually bring the surge to a halt (Clarke et al., 1984).

The novel aspect of the hydro-thermodynamic feedback proposed here, is that the processes at the glacier base that lead to the surge are driven, at least strongly amplified, by surface melt that reaches the bed within an initiation zone (described in the paper as phase 1). Those processes include cryo-hydrologic warming, which facilitates the thermal switch from cold to temperate basal conditions; basal lubrication of areas where the bed previously was frozen to the bed, and the emerging drainage system is thus not well developed; thawing of underlying frozen till, if present, and its enhanced deformation due to rising pore-water pressure. These processes all result in an enhancement of ice flow and longitudinal extension opens new surface crevasses in regions of the glacier that previously were characterized by supra-glacial drainage. The newly formed crevasse fields provide pathways for meltwater in subsequent summers, subjecting a larger region of the bed to surface melt. This closes the feedback loop.

As with any feedback, whether it is positive or negative depends on both timescales and timing. If a glacier is properly pre-conditioned, i.e. it has built up during a long quiescent phase, the feedback is positive as long as it mobilizes previously stagnant ice regions and as long as the driving stress remains sufficiently high. Once the entire basin is moving by fast basal motion, i.e. the entire base is at pressure melting, the reservoir area has been depleted, the glacier dynamically thinned and its surface flatted out, then, the hydro-thermodynamic feedback is no longer operating.

In the revised manuscript, we tried to clarify the above views by extending the information about glacier surge mechanisms in the introduction and by discussing our observations in the context of these previous studies.

7. The hydro-thermodynamic feedback should be demonstrated on other basins as well, e.g. on Duvebreen which was studied by Dunse et al. (2012). This would help to extract the non-surge contribution of the process.

Glacier surges require a certain pre-conditioning (see above). Preconditioning is different for the individual basins and surge-type behaviour therefore not synchronous. Furthermore, basins with fast flowing outlets are already characterized by temperate beds. In other words, there exists no cold-based marginal ice plug that restricts ice flow (quiescent phase) and that could potentially be weakened by cryo-hydrologic warming. This is the case for Duvebreen. We admit that we do not understand the fixation of the reviewer on “non-surge” contribution. This is a surge, but the details of our interpretation have never been recorded before. We see no reason to believe that the observed stepwise acceleration and the proposed mechanism should not be part of the surge, i.e. an independent overlay over another ice-accelerating process.

Anonymous Referee #1

MAJOR CONCERNS

The contributions from surge dynamics and the proposed hydro-thermodynamic feedback to the observed dynamic behaviour of Basin-3 should be clearly separated. In order to address the surge component, the existing literature on glacier surges in Svalbard should be reviewed. The dynamics of Basin-3 first need to be put in a proper context, before considering the relevance of extending the suggested mechanism to non-surging ice sheets with other properties. While surges arise from an internal imbalance, also involving an excess of mass in the reservoir area, external factors may have a different outcome once a surge is in progress, than on glaciers purely subjected to increased melt water input. The study only focuses on surface melt-driven processes as an explanation to the behavior. It would nevertheless be appropriate to refer some basic literature on the (surface) meltwater influence on dynamics.

In the discussion section we describe three phases of changing glacier dynamcis; P2694 L25 ff: "(1) activation of a spatially confined ice stream in the early 1990's (Dowdeswell et al., 1999); (2) multi-annual acceleration from < 2008 to 2012, along with an expansion of the ice stream; (3) active surge phase following the destabilization of the entire terminus in autumn 2012." Phase 1 acknowledges that the basin was pre-conditioned prior to our observations (i.e. 2008 onwards), and that these dynamic changes could be explained by surge mechanisms proposed in earlier studies, i.e. changes in glacier thermal regime and driving stress, associated with longterm geometric changes during the quiescent phase. This also addresses the "excess of mass in the reservoir area" as pointed out by the reviewer. The current understanding of Svalbard glacier surges is summarized in the term "thermally-controlled softbed surge mechansim", which was mentioned in the introduction. In the discussion we point to previous model experiments of Austfonna that support the concept of a thermally-controlled softbed surge mechansim (Dunse et al., 2011). The proposed hydro-thermodynamic feedback becomes active during phases 2 and 3.

In the revised manuscript we have firstly extended the introduction of glacier-surges and observations of glacier surges on Svalbard, and secondly, we discuss more thoroughly how our observations compare to previous theory of thermally-controlled surges. Further, we have included a schematic illustration of the feedback mechanism and its role within the surge-cycle of Basin-3. We like to stress that the focus of the present paper is the role of surface-generated meltwater and the associated hydro-thermodynamic feedback in promoting the surge, and not on providing a review of Svalbard glacier surges in general. This focus is motivated by the unique GPS timeseries we present. It clearly shows the effect of the surface melt during summer, resulting in a stepwise acceleration. Based on our observations, it is not possible to separate the proposed feedback from the "general surge mechanics". It appears that the hydro-thermal feedback itself is an integral part of the thermally-controlled surge dynamics in the observed case. A numerical model of glacier surges, incorporating both internal mechanisms and surface melt, would allow quantification of the contribution of surface melt to glacier surges. To our best knowledge, such a model does not exist. Its development would be an interesting and challenging follow-up study, however, far beyond the scope of this paper.

The term "thermally-controlled surge mechanism" points at a switch from cold to temperate basal thermal regime that along with sufficient driving stress (sufficient ice thickness and surface slope) activates fast basal motion in regions previously characterized by (slow) ice deformation only. A number of processes determine the temperature distribution within the glacier and at its base, such as heat conduction through the ice, ice advection, strain deformation/heating and frictional heating. The theory on thermally regulated surges focuses on the above mentioned physical processes with the geothermal heat flux and the annual air temperature (plus firn warming) as lower and upper boundary conditions, respectively. Thicker ice leads to a warmer bed and increases the likelihood for a temperate base. Thermal effects by water flow within the glacier have previously been mentioned and considered important (e.g. Clarke, 1976). However, Clarke (1976) neglected cryo-hydrologic warming in thermal models of glacier surges, justified by the assumption that water flow within cold ice is limited. Only recently, has "cryo-hydrologic warming (CHW)" put back in focus (Phillips et al., 2013; Phillips et al., 2010). Phillips et al. (2010) simulates the effect of CHW on ice rheology and hence, ice deformation. Phillips et al. (2013) linked observation of increased velocities in the wet snow zone of Greenland to CHW, also discussing the potential of CHW for changing the basal temperature regime on short timescales that may lead to temperate basal conditions, permitting fast basal motion. We cannot explain our observations using standard theory of glacier surges alone, but incorporating the effect of CHW over an expanding area of the glacier bed provides a good explanation, we believe. The hydro-thermodynamic feedback we propose for the mobilization of the reservoir area of Basin-3, corresponds well to the explanation of enhanced velocities in the wet snow zone of western Greenland, following an increase in ELA (Phillips et al., 2013). Here, we expand the application of CHW to the cold-based marginal ice plug of Basin-3 and suggest that weakening/elimination of the ice plug by CHW initiated the basin-wide surge in autumn 2012. Mobilization of the reservoir area in the prelude of the basin-wide surge is evident from crevasse formation and supported by multi-annual acceleration, indicating increased ice discharge from the reservoir area. The hydro-thermodynamic feedback described here is however not limited to CHW/the thermal component, but also includes the additional hydraulic lubrication effects. Ice regions undergoing a switch from cold to temperate basal conditions were previously characterized by frozen conditions, i.e. absence of water. In the initial stage of basal-hydraulic drainage system development, water input is likely to raise water pressure and enhance basal motion, in line with the established theory on basal lubrication, e.g described by (Schoof, 2010). The revised paper discusses more thoroughly the effects of surface melt on rising pore-water pressure within subglacial sediments. Unconsolidated sediments do likely underlay the marine-grounded ice regions of Austfonna.

In case of Austfonna, or Svalbard in general, surface melt has been a widespread phenomenon throughout most of the Holocene. Therefore, a summer-melt driven hydro-thermal feedback could also have played a role in previous Svalbard glacier surges. The current surge should not be mistaken as a response to recent Arctic warming. The role of surface melt in glacier surging has not been described earlier, to our best knowledge, perhaps simply because of the lack of continuous in-situ data prior and during the surge, such as our GPS timeseries from Basin-3. In the context of continued global warming, surfaces melt and hence, the hydro-thermodynamic feedback may gain importance in destabilizing ice regions outside of Svalbard, with similar pre-conditioning as Basin-3 – including the ice sheets. One such example described in the discussion is the Wilkes basin of East Antarctica. The basin is characterized by sufficient driving stresses and a cold-based marginal ice plug (P 2696 26ff) and has undergone a partial collapse during the Pliocence (Cook et al., 2013). A very recent model study confirms the potential dynamic instability of the Wilkes basin, following the removal of a cold-ice plug (Mengel and Levermann, 2014). In their study, a retreat of the grounding line is forced by oceanic warming, thereby eliminating the cold-ice plug.

Some of the GPS data have been published previously, but it is not clear how the application in this manuscript substantially expands the previous results.

The GPS data published in (Dunse et al., 2012) only covered the time period May 2008 to May 2010 (Fig. 1). The timeseries was discussed mainly in the context of seasonal velocity variations. The multi-annual, stepwise acceleration and the strong acceleration since autumn 2012 (Fig. 2) marking the surge of the entire Basin-3 was not yet conceivable.

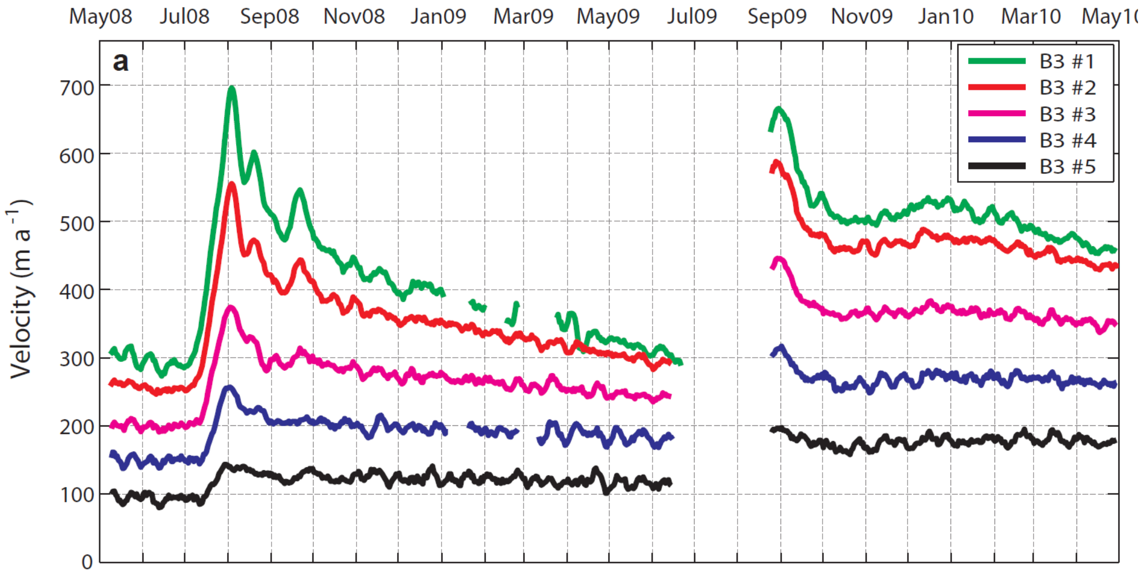

Figure 1. GPS timeseries as published in Dunse et al., 2012

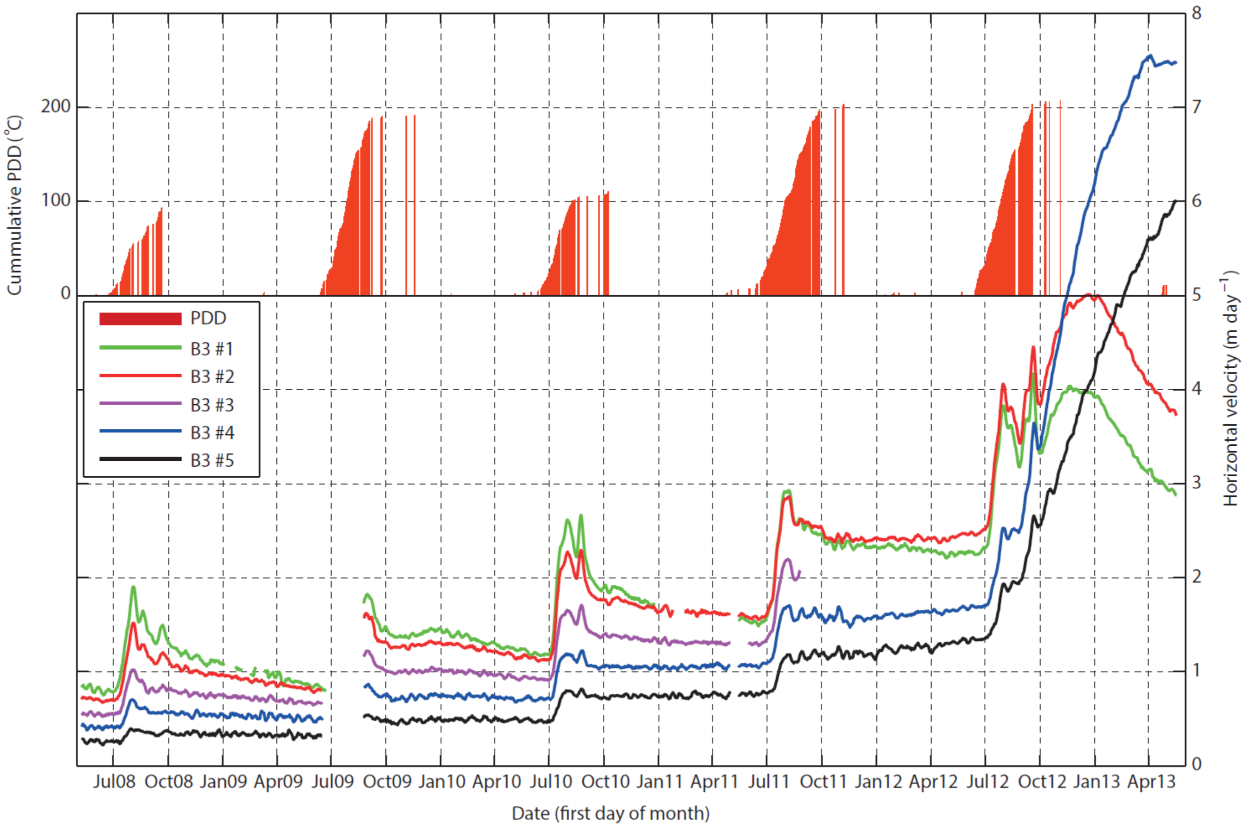

Figure 2. GPS timeseries presented in the present paper

I do not find the hypothesis sufficiently supported and the discussion does not justify the conclusions drawn.

Above we have discussed the integral role of the hydro-thermodynamic feedback in the surge mechanics of Basin-3. The feedback is a contributing factor to thermally controlled glacier surges and does thus not oppose the current/previous understanding of Svalbard glacier surges. In the revised paper we now provide a more detailed background on glacier surges in Svalbard against which we discuss our observations. Our observations are limited to surface processes. Consequently, linking ice dynamics to processes at the glacier base remains to some degree speculative as for most studies on ice dynamics. We have gone through the individual statements, taking care of that interpretations of observations are identified as such. This includes the discussion of possible implications for the ice sheets in a changing climate. We think that the discussion of a specific phenomenon in a wider potential context is important for the scientific progress.

I found the manuscript a bit fragmented and suggest it to be re-organized and aim and objectives of the study to be better defined in the introduction. The manuscript appears a bit fragmented and could do with a better link between the line of thoughts in the introduction and the discussion. Parts of the introduction are not picked up in the discussion. Parts of the results section belongs in the discussion and vice versa.

The background chapter of the revised paper now focuses on glacier surges, as suggested by the reviewers. The aspect of past ice sheet instabilities and abrupt sea-level rise, evident from the geological record, is moved over to the discussion section in which the potential implications of the hydro-thermodynamic feedback for the dynamic stability of the ice sheets are discussed.

The data used in this study have a high temporal resolution for the last six years, however they cover only about half way of the full length of the glacier basin. This should be taken into account. The authors also show that crevasses were formed in the upper part some years before the detailed study of the changes downglacier. Adding the fact that Svalbard surges are known to be long lasting (cf. Dowdeswell et al., 1991 and Sund et al.,2009), an investigating the dynamics at the higher elevations would be appropriate in order to distinguish between the dynamics possibly resulting from processes other than increases in surface melt water.

Are there any possibilities of supplying with data between 1990 and 2008?

Our study employs the GPS timeseries starting in May 2008, and the TerraSAR-X scenes acquired since April 2012. In order to assess the changes prior to 2008 (phase 1) and changes in the upper part of Basin-3, we investigated and presented other available in-situ data, such as annual repeated ground-penetrating radar surveys since 2004 (revealing temporal and spatial crevasse formation; Appendix C) and annual position/displacement of a mass balance stake (P2695 L23-25). Furthermore, we consider previous observations by Dowdeswell et al. (1999) that indicate quiescence of entire Basin-3 until development of a spatially confined fast-flow region in the early 1990s. We distinguish three distinct phases (see Discussion from Page 2694, L24). Phase 1 describes the development of a spatially confined fast-flow region, explained by long-term (quiescent phase) changes of glacier geometry, in line with the current understanding of Svalbard glacier surges. The temporal length of our GPS timeseries misses phase 1. Nevertheless it captures significant changes in the prelude of the surge (phase 2), starting with a strong summer-speed up 2008 and a slow, but gradual approach of the pre-summer values during winter 2008/2009. 60-95% of the velocity increase during summer is reversible, as displayed in the supplementary figure 8, while during the following years an increasing fraction of the summer speedup is of lasting nature, i.e. increased summer velocities are sustained throughout the winter. The fast-flowing region reflects the mobilization of the reservoir area, however, the lateral dimensions of the outlet restricts the outflow from the reservoir area. Increased mobilization of the reservoir area is indicated by the intense crevasse formation observed by repeated radar surveys since 2004 (P2695 L18ff). Multi-annual acceleration of the ice stream further down, as observed with GPS since 2008, provides evidence of increased ice discharge, supporting the hypothesis of an increasingly mobilized reservoir area. Since the unequivocal summer speedup has a lasting effect on background velocities, we conclude that the hydro-thermodynamic feedback had an important contribution to the observed changes, both with respect to the mobilization of the reservoir area and the lateral expansion and speedup of the outlet observed in the lower half of Basin-3. Finally, the GPS timeseries capture the autumn/winter acceleration associated with the start of the basin-wide surge in autumn 2012 (phase 3). Furthermore, we investigated the spatial velocity pattern during the transition from phase 2 to phase 3 by TerraSAR-X.

How does the successive destabilization differ from or resemble the surge development described in previous studies (cf. Murray et al., 2000; 2003 and more recent Sun et al. 2014)? The authors show that the lower parts of a basin of Austfonna experiences multiannual velocity accelerations, but this finding is not particularly surprising given that the basin is also found to be surging. Multiannual velocity accelerations are consistent with previous studies of other surging glaciers in Svalbard (cf. Murray et al., 2003, Sund et al., 2014, and in other areas Burgess et al. 2012). Taking these into account might help to better distinguish the surge contribution of the dynamics from the suggested hydro-thermal feedback.

The hydro-thermodynamic feedback proposed here represents an integral part of thermally and hydrological controlled glacier surges, as explained above. It does not oppose the theory on thermally-controlled (soft-bed) glacier surges, but adds the aspect of a growing area of the glacier bed subjected to surface meltwater and the associated amplification of surge mechanisms, i.e. warming/thermal switch and water pressure/lubrication as well as pore water pressure and sediment deformation, if subglacial sediments are present. Observations of multi-annual acceleration during the active surge phase have indeed been reported earlier, as pointed out by the reviewer. However, studies such as Murray et al. (2003a) and Murray et al. (2003b) rely on snapshots velocities derived from satellite radar and were generally limited to the winter season. Changes in ice dynamics during the summer melt period remained therefor unnoticed. The supplements to our paper contain an analysis of background velocities. The multiannual development of background velocities of Basin-3 alone are in accord with the schematic surge phases as described by Murray et al. (2003b): uniform acceleration over several years in the early surge phase, followed by a strong acceleration over several months. The novel aspect of our study is that we have continuous in-situ observation of ice-surface velocities throughout the development of a surge that helps to pinpoint relevant processes. The multiannual acceleration of Basin-3 did not occur uniformly or gradually, but in discrete steps, each of which coincident with consecutive summer melt periods. Only this temporal continuity of our in-situ data allows us to identify the marked and lasting impact of the summer melt season on the flow of Basin-3.

Following the reviewers advice, the introduction of the revised paper now includes more information on thermally controlled soft-bed surge mechanism and provides a summary of some of the key studies for Svalbard. In the discussion we then compared our observations with those previous studies and point out where our observations can be explained by previous theory and where not.

The work of Solheim (1991) shows a good match between the estimated surge cycle period for Basin-3 and the current surge. This could have been mentioned.

This is added…

Phillips et al. (2013) suggested CHW might facilitate temperature change in the Greenland Ice Sheet due to upward migration of the snow zones, is this case at Basin-3 as well? P2690 L13 states: Over 2002–2008, the climatic mass balance of Austfonna was close to zero (Moholdt et al., 2010a). In addition the fact that Solheim's surge cycle period estimate among other based on total net accumulation matched well, does not seem to point towards a substantial upglacier shift of the ELA.

No, we have no indication of a systematic shift of the ELA. In case of Basin-3, CHW gains significance not because of an expansion of the surface area exposed to melt processes, but because of the first occurrence of surface crevasses, providing pathways for the surface meltwater to enter the glacier and develop moulins that eventually may connect to the glacier bed. First occurrence of crevasses and development of spatially confined fast flow started in the early 1990s as described by Dowdeswell et al. (1999) - we considered this as phase 1 in our description of surge initiation and attribute the dynamic changes to longterm changes in geometry and associated changes in thermal regime and driving stress. Phase 1 entailed an ice flux out of the accumulation area in excess of the balance flux (Dowdeswell et al., 1999) and hence extension and draw down of the reservoir area. Since 2004, we have mapped the first and cumulative occurrence of crevasses along two transects across the reservoir area, areas outside the boundaries of the crevassed and fast-flowing ice stream observed by (Dowdeswell et al., 1999). The estimated surge period of 140-150 years by Solheim (1991) fits surprisingly well with the timing of the renewed surge activity of Basin-3. The figure represents a rough estimate of the time required for the reservoir area to accumulate the mass that corresponds to the surge-lobe volume. The good estimate by Solheim (1991) does in any case not disqualify the proposed hydro-thermal feedback as relevant for the surge initiation, as surface melt on Svalbard is not a phenomenon of recent Arctic warming, but was likely a widespread feature throughout the entire Holocene, and could have played a role for Svalbard glacier surges as much in the past as in the present.

Furthermore, if there is a rise of ELA at basin-3 causing CHW, this would possibly also occur in the other basins as well? It would be nice if the study reflected on why some areas a more affected than others by the proposed feedback. A previous paper covering an additional basin of Austfonna was partly using the same seasonal speed-up data. Why not demonstrate the suggested mechanism on both basins here as well? This possibly makes it easier to extract the non-surge affected contribution to the process.

Glacier surges require a certain pre-conditioning. Basins with fast flowing outlets are already characterized by temperate beds. In other words, there exists no cold-based marginal ice plug that could potentially be weakened by CHW. This is also the case for Duvebreen, the basin referred to by the reviewer. Furthermore, englacial connection must exist to provide pathways for surface meltwater to reach the glacier bed. We admit we do not understand the fixation of the reviewer on “non-surge” contribution. This is a surge, but the details of our interpretation have never been recorded before! We see no reason to believe that the observed stepwise acceleration/ the proposed mechanism should not be part of the surge.

I found the title a bit misleading since it appears there were changes to ice stream behavior prior to the suggested hydro-thermodynamic feedback; hence the basin was already “triggered”. Also the term ”destabilization” is a bit vague and strange as the authors state there is a surge, which is defined to be short term and with cyclic reoccurrence and accordingly the fast flow is expected “to slow down or come to a halt within a few years”. Finally, what is treated here is only a part of the ice cap.

What changes in ice dynamics represent the trigger point of the surge in time is debatable. Is it the development of a fast flow unit in the early 1990s (phase 1), the annual acceleration by mobilization of the reservoir area (phase 2) or the failure of the marginal ice plug in October 2012 (phase3). We argue for that the hydro-thermodynamic feedback process had a major contribution to both phase 2 and 3, while it is not strictly necessary nor can we confirm (or have stated) its contribution for the initiation of phase 1.

Anyway, we have changed the title from

“Destabilisation of an Arctic ice cap triggered by a hydro-thermodynamic feedback to summer-melt”

to

“Glacier surge mechanisms promoted by a hydro-thermodynamic feedback to summer melt”.

Figures

“a” and “b” and so on, could be indicated on each figure, not just in the caption. Fig.1b. The outline of Basin-3 could be made slightly more visible. The fonts of the current figures could be possibly be slightly enlarged for better readability, but this depends on the final size of the figures.

ok

Specific comments

Specific comments are implemented in the revised manuscript, if not stated otherwise.

P2686 L 5. “Basin-3” or “parts of the“ could be inserted before “Austfonna ice cap” as the data does not cover the entire ice cap.

P2686 L9. I'm a bit confused over this sentence, "By autumn 2012, successive destabilization of the marine terminus escalated in a surge", and I'm not sure if "escalated" is the right word here, considering the long surge development in Svalbard.

We think "escalate" is a good word to describe the continued acceleration after the end of the melt period. The two upper GPS show a 3-fold increase in velocity over the winter months. Nevertheless, we are grateful for suggestions of suitable wording.

P2688 L25. "We propose that cryo-hydrological warming may have a drastic effect on glacier dynamics..." Please consider using another wording than "drastic". This is used several times.

We consider the term "drastic" as appropriate in describing the observed changes. But we are open for suggestions of alternative terms.

P2689 L3. For surge duration it would be more adequate to reference estimates for Svalbard which are years to more than a decade, rather than months, since the surges in Svalbard (cf. Dowdeswell et al., 1991).

Here, we describe surge-type behaviour in general and provide relevant timescales of surge durations both for temperate glaciers (months) and polythermal/Svalbard glaciers (years).

P2689 L7. Strictly speaking I think Hamilton and Dowdeswell, 1991 suggested a deforming bed surge mechanism for Svalbard, while Murray et al., 2000 added the thermal aspect for Svalbard.

More references are included

P2689 L12. MacAyeal, 1993 is not the proper reference here.

(Meier and Post, 1969)

P2689 L13 "provoke" change to "promote".

P2689 L14-17. Please add reference.

(Dowdeswell et al., 1995)

P2690 L2. ice thickness of up to 600m – referred to Lefauconnier and Hagen, 1991, is this right reference? By the way, they suggested that the previous surge might have been larger than the Brasvellbreen surge in 1937-38.

The right reference concerning maximum ice thickness is Dowdeswell (1986)

P2690 L16. It would be useful to get an indication of the approximate length of the

basin, especially as the locations of GPS'es are mentioned with distance from calving front (2692 L 16).

About 60 km

P2692 L20. "High sensitivity and short response time (days) of glacier dynamics to melt periods clearly suggest surface-melt triggered acceleration." Belong in the discussion.

P2694 5 Discussion This section needs a more thorough discussion and comparison with previous findings on Svalbard and elsewhere (cf. Solheim, 1991; Murray 2000; 2003; Sund 2009; 2014; Burgess 2012; Tangborn, 2013). I suggest first discussing the elements caused by surge dynamics. Then explain how additional factors and mechanisms such as CHW can be found, extracted and separated from the surge dynamics, and finally how these constitutes a possible hydro-thermodynamic feedback.

P2694 L6. How long time is considered to be within "prior to"? It is referred to Fig. 4b. This only shows data from April 2012.

C981

P2694 L18. The last part of this paragraph belongs in the discussion section. While showing the large increases due to surge during a short period, it would also be appropriate to mention the possible influence during the long quiescent phase.

P2694 L25. Dowdeswell et al., 1999 attribute the increase in flow to be a surge or mini-surge and the following three phases outlined appears to have similarities with those outlined by Sund et al., 2009. This should be considered in the discussion.

P2695 L7. Parts here resemble other studies on Svalbard surges.

P2695 L8. Please be more specific about what you mean by "the current understanding", to make it easier for the reader to follow.

P2695 L10. Fig 8 does not exist.

P2695 L1.9 "Ground-penetrating radar (GPR) surveys reveal first occurrence of surface crevasses from 2004 onwards (Appendix C; Fig. 7)." This belongs in the results section.

2695 L24. This stake is not mentioned before, should be in the result section.

2696 L4. Maybe add a reference for “sticky spots”?

(Alley, 1993)

2696 L4. Please cf. Murray et al., 2000 to cover further aspects.

2696 L19. Other references on surge termination could be preferentially be added.

(Clarke et al., 1984)

2696 L24. Add “in Svalbard” after “drainage basins”. There are surge-type glaciers in other areas that are temperate.

2696 L21 and onward. The text jumps forth and back between surge-type glaciers and ice sheets with no observed surge history. If the authors believe the situations can be compared, they need to explain why the surge context can be ignored.

P2697 L20. Please consider another phrasing than “enormous”, or simply skip. This sentence doesn’t really bring any new information.

References

C982

G.S. Hamilton (Referee #2)

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This manuscript describes a recent surge-like event of the southern margin of the Austfonna ice cap, Svalbard, which the authors apparently link to a feedback mechanism involving increased surface meltwater production leading to enhanced basal motion over an ever-expanding area. The GPS observations of ice motion have been described in an earlier paper (Dunse et al., 2012) (updated here) but the velocity maps from satellite radar images are new, as is the description of the 2012-2013 surge event affecting Basin-3. There is certainly enough new information to warrant publication in The Cryosphere but, as currently written, I find much of the manuscript to be a bit too speculative and I’m not sure the conclusions are really supported by the observations. I encourage the authors to rethink a lot of the interpretation and discussion, and come back with a suitably revised manuscript.

One of my main concerns is the proposed feedback mechanism. The authors don’t really describe the mechanism in detail so it difficult to tell how it differs from (or is similar to) the various thermal mechanisms proposed for glacier surges, or to the cryo-hydrologic and other melt-induced mechanisms proposed for Greenland.

Dunse et al. (2012) presented the first two out of five years of the GPS timeseries presented here. Multi-annual acceleration culminating in a surge of Basin-3 was not yet conceivable (see response to reviewer 1). Previous studies of surge initiation mainly relied on achieved satellite radar data from which snapshots of ice-flow velocity were derived. The required phase coherence for satellite radar interferometry is generally only achieved in the absence of summer melt, and ice-flow maps were mainly derived for the winter months (e.g. Murray et al., 2003a; Murray et al., 2003b). Winter snapshots do not reveal changes associated or coincident with the summer melt-period. For the first time, to our best knowledge, we have obtained continuous in-situ velocity observations during glacier surge initiation. This enabled us to identify the lasting effect of consecutive summer-melt seasons on the multi-acceleration of Basin-3. Changes in basal thermal regime and basal hydraulic drainage system are widely recognized as controls of glacier surges. The novelty of our study lies in identification of the role of surface-melt driven processes in promoting glacier surges, which are generally regarded as arising from internal instabilities, with only their surge period being determined by climate (mass balance and build-up of a critical geometry). The hydro-thermodynamic feedback to surface melt, proposed here, affects (surge) dynamics as a consequence of changes in basal thermal regime and hydrology. CHW has been discussed in the context of englacial ice temperatures and ice rheology (Phillips et al., 2010), as well as its importance for basal sliding, if CHW would spread inland, following the upward migration of the ELA in the wet snow zone of western Greenland (Phillips et al., 2013). Here, we point at its role in eliminating a cold-based marginal ice plug that prevents inland ice to quickly drain into the ocean.

Two missing pieces, in particular, stand out. One is the exact nature of the feedback, i.e., is it positive or negative. It seems to me that the mechanism as outlined would tend to be self-limiting (negative). Increased ice flux from the interior would gradually thin the ice column and promote refreezing of the bed (I think this type of feedback is similar to thermal mechanisms of surging).

As with any feedback, it is a matter of both timing of the underlying processes and the timescales these processes operate on. With regards to the surge initiation of Basin-3, the feedback is clearly positive, i.e. surface meltwater is routed to the bed and enhances ice flow; extensional flow opens surface crevasses in regions previously characterized by surface run-off, subjecting an increasing area of the bed to surface melt; further flow enhancement and spread of the active zone promotes the surge. We have stated that we expect the surge to be of temporary nature, i.e. that it will likely come to a halt within a few years, after dynamic thinning has occurred, the driving stress is greatly reduced and temperate conditions at the base can no longer be maintained.

Alternatively, and this leads to the second missing piece, the subglacial drainage system gradually evolves to a more efficient state under continuing high meltwater inputs and surface velocities actually drop. This type of negative feedback has been inferred quite convincingly for the western margin of the Greenland Ice Sheet, yet the authors do not really explore the reasons why their observations are seemingly inconsistent with the Greenland story.

Our conclusions do not contradict the current understanding of the positive and negative effects of meltwater input into the basal hydraulic drainage system (Schoof, 2010). In line with Phillips et al. (2013) we point at the potential of CHW and the thermo-hydrological feedback in mobilizing more inland ice regions and thereby increase ice discharge through existing outlet glaciers. The most obvious difference between Basin-3 and the outlet glaciers of western Greenland is the presence of a cold-based ice plug that, until autumn 2012, restricted drainage from the reservoir area. In case of fast-flowing Greenland outlet glaciers, the thermo-dynamic feedback would lead to a gradual acceleration of lasting nature as long as the ELA continues migrating upglacier, rather than leading to surge-type behaviour.

Some reorganization of the paper would definitely help. For example, much of the introduction strays into material that is not directly relevant to the present study (e.g., oceanic triggers for outlet glacier changes, ice shelf (in)stability in West Antarctica, or post-LGM Heinrich events). A better way to introduce the paper would be to summarize current state-of-the-art in thermal mechanisms for glacier surging and maybe meltwater-induced speed-ups of the West Greenland ice margin. Reviewing this background material would allow the authors to frame their current study in a more meaningful way, and might also help the authors refine the details of their proposed feedback mechanism in a way that builds on existing ideas and is supported by their observations.

OK - the introduction of the revised paper will have more focus on glacier surging and less on ice sheet instabilities. In the discussions, we then compare our results with previous studies of (Svalbard) glacier surges. The paragraph on ice sheet disintegration is moved from the introduction to the discussion chapter, where we discuss the implication of our results for the ice sheets (see also response to reviewer 1).

I have a few additional comments that I hope are useful to the authors.

Specific comments are implemented in the revised manuscript, if not stated otherwise.

P2685 L3: Delete the hyphen in “summer-melt” in the title.

C1684

P2686 L6: no hyphen in “summer-melt”

P2686 L16: change “glacier wastage” to “mass loss”

P2686 L22: change “not only the...but also the ice sheets” to “both glaciers and ice caps (Kaser et al., 2006) and ice sheets”

P2686 L26: delete the sentence “Recently, the West Antarctic...”...not sure of its relevance to a paper about Svalbard.

P2687 L4: too much disparate information in one sentence...separate the ideas about basal lubrication and oceanic forcing. As written, there is an implication that the two mechanisms are linked.

P2688 L17: start a new paragraph at “The effect of surface...”

P2689 L1: rewrite slightly “...variations in glacier flow, and is...”

P2690 L7: change “ground” to “bed”

P2690 L8: change “intersperse” to “embedded within”

P2690 L12: change “to some extent” to “partially”

P2690 L21: write out acronyms on first usage (“SAR”)

P2690 L25: “lineations” plural

P2691 L1: change “years” to “time”

P2691 L6: need a short paragraph here to set the stage for the work that follows. So far you’ve provided a general introduction, but now you need to describe the motivation for the present study.

P2691 L6: delete “GPS”

P2691 L6: the section on GPS analysis needs to be expanded a bit for clarity. I know the most of the details were written up in an earlier paper (Dunse et al., 2012) but readers will benefit from a brief overview here. For example, you say “single-frequency code receivers (L1 band)” which could mean two things – you used the C/A code modulated on the L1 frequency, or you use the L1 phase measurements. Position qualities will be different for either approach. I suspect you used C/A code because you go on to mention “geographical positions were logged”, implying onboard processing without ephemeris information. But please clarify to reduce reader confusion.

We use the term “CODE receiver” to indicate that the receiver uses the code information of the L1 band and not the phase. To be clearer, we now use “single-frequency code receivers (L1 band, C/A code only)”

P2692 L2: where does the ice thickness information come from???

P2692 L6: change “was” to “has”

P2692 L15: delete sentence “In spring 2008...” which is an exact repeat from section 3.1

P2692 L21: change “periods” to “events”

P2692 L25: not clear what you mean by “progressively irreversible”. Is that even possible??

Increasing degree of irreversibility

P2693 L9: change “further” to “farther” because you are talking about distance.

P2693 L10: unclear what you mean by the sentence “Consequently, ...”

P2693 L12: change order of words, "also displayed"

P2693 L15: instead of inferring the lack of basal motion, you could actually estimate how much of the observed motion is due to internal deformation (using glacier geometry)

P2693 L24: re-order the sentence, "Fast flow of Basin-3 (Table 2) continued at least until the end of 2013."

P2694 L1: calving flux estimates require information on ice thickness. Do you know that? Where do the data come from??

The appendix describes in detail how the calving flux was calculated.

P2694 L10: change "as opposed to stable front position" to "compared to the stable

C1686

Key changes to the revised manuscript

As part of the major revision, we have edited the text throughout the entire manuscript. Only the key changes are listed here:

1. Title

We have changed the title from "Destabilisation of an Arctic ice cap triggered by a hydro-thermodynamic feedback to summer-melt" to "Glacier surge mechanisms promoted by a hydro-thermodynamic feedback to summer melt".

2. Introduction

We have extended the background on theory and observation of glacier surges, especially Svalbard glacier surges, adding numerous key references.

3. Discussion

The hydro-thermodynamic feedback is now better described and put in context with previous studies of Svalbard glacier surges to point out similarities and differences with the established theory. To this end we have also added a schematic illustration of the feedback (new Fig. 5).

4. Structure

We have moved content from the results to the discussion, and vice versa, in order to better distinguish between observed facts and our interpretation of the observations. Furthermore, comments on ice-sheet instabilities are moved from the introduction to the discussion.

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~~Destabilisation of an Arctic ice cap triggered~~ Glacier-surge mechanisms promoted by a hydro-thermodynamic feedback to ~~summer-melt~~summer melt

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Abstract

Mass loss from glaciers and ice sheets currently accounts for two-thirds of the observed global sea-level rise and has accelerated since the 1990s, coincident with strong atmospheric warming in the Polar Regions. Here we present continuous GPS measurements and satellite synthetic aperture radar based velocity maps from ~~the~~ Basin-3, the largest drainage basin of the Austfonna ice cap, Svalbard~~, that~~. Our observations demonstrate strong links between surface-melt and multiannual ice-flow acceleration. We identify a hydro-thermodynamic feedback that successively mobilizes stagnant ice regions, initially frozen to their bed, thereby facilitating fast basal motion over an expanding area. By autumn 2012, successive destabilization of the marine terminus escalated in a surge of ~~the ice cap's largest drainage basin,~~ Basin-3. The resulting iceberg discharge of $4.2 \pm 1.6\,\mathrm{Gt\,a^{-1}}$ over the period April 2012 to May 2013 triples the calving loss from the entire ice cap. ~~After accounting for the~~ Accounting for the seawater displacement by the terminus advance, the related sea-level rise contribution ~~of~~ amounts $7.2 \pm 2.6\,\mathrm{Gt\,a^{-1}}$ ~~matches the recent~~. This rate matches the annual ice-mass loss from the entire Svalbard archipelago ~~. Our study highlights the~~ over the period 2003–2008, highlighting the importance of dynamic ~~glacier wastage and illuminates mechanisms that may trigger a sustained increase in dynamic glacier wastage or the disintegration of ice-sheets in response to climate warming, which~~ mass loss for glacier-mass balance and sea-level rise. The active role of surface melt, i.e. external forcing, contrasts previous views of glacier surges as purely internal dynamic instabilities. Given sustained climatic warming and rising significance of surface melt, we propose a potential impact of the hydro-thermodynamic feedback on the future stability of ice-sheet regions, namely at presence of a cold-based marginal ice plug that restricts fast drainage of inland ice. The possibility of large-scale dynamic instabilities such as the partial disintegration of ice sheets is acknowledged but not quantified in global projections of sea-level rise.

1 Introduction

Glacier mass loss constitutes the largest contributor to global mean sea-level rise (SLR), followed by ocean thermal expansion (Church et al., 2011). Over the last two decades, ~~not only the~~ both glaciers and ice caps ~~(?) , but also the~~ (Gardner et al., 2013) , as well as ice sheets have lost mass at accelerating rates (AMAP, 2011; Shepherd et al., 2012). These ice mass changes coincide with atmospheric warming that causes record summer temperatures and glacier melt in the Arctic (Gardner et al., 2011) and across the Greenland ice sheet (Tedesco et al., 2013). ~~Recently, the West Antarctic ice sheet has been reported as one of the world's fastest warming regions (?) .~~ In addition to mass loss by melting, glacier dynamics have the potential to significantly amplify glacier response to climate change by altering the ice discharge to the ocean. ~~Outlet-glacier, respectively ice-stream acceleration is~~ Acceleration of outlet-glaciers of the Greenland ice sheet are generally attributed to hydraulic lubrication and ~~oceanic-warming induced destabilization of floating ice tongues in the case of the Greenland ice sheet and~~ marine terminus destabilization by oceanic warming and calving (Nick et al., 2009; Bartholomew et al., 2010; Moon et al., 2014) . West Antarctic ice-stream acceleration is generally attributed to reduced buttressing by thinning or loss of ice shelves ~~in the case of the West Antarctic ice sheet (WAIS)~~ (Shepherd et al., 2012). Recent observations of sustained ice flow and mass loss from Northeast Greenland and West Antarctica are also reported as evidence of a marine ice-sheet instability (Khan et al., 2014; Mouginot et al., 2014). The phenomenon, also known as tidewater-glacier instability, refers to glacier speed-up due to terminus retreat into deeper water (Meier and Post, 1987; Pfeffer, 2007).

To date, glacier-dynamic feedback processes remain poorly constrained and are therefore not yet incorporated in global projections of future glacier ~~wastage~~ mass loss (Stocker et al., 2013). SLR projections released with the IPCC Fifth Assessment Report range from 0.26 to 0.82 m over the 21st century (Stocker et al., 2013). The projections include ice discharge from the ice sheets into the ocean, however, based on current discharge rates and not accounting for a future dynamic response to climate change. The IPCC acknowledges, but is not able to quantify the probability of significantly higher SLR, such as associated with disintegration of marine-based sectors of the Antarctic ice sheet (Stocker et al., 2013). ~~Rapid marine ice-sheet~~

~~disintegration is evident from geological records both in the Northern and Southern Hemisphere and typically associated with air temperatures similar or warmer than those predicted for the end of the 21st century (Cook et al., 2013; Deschamps et al., 2012) . Ice-rafted debris distributed across the North Atlantic ocean floor provide evidence of substantial calving associated with the rapid disintegration of the Laurentide ice sheet, so-called Heinrich events (Bond et al., 1992) . Paleoclimatic records suggest rates of sea-level change much larger than currently observed or projected for the 21st century, e.g. 3.5 to 5SLR per century (35–50mm) at the end of the last glacial maximum, ~14.5ka ago (Deschamps et al., 2012) .~~

Variations in glacier flow and hence ice discharge, encompass wide ranges of time-scales and magnitudes, from diurnal velocity fluctuations to century-scale surge-type behaviour, and are mainly attributed to changes in basal drag (Clarke, 1987). ~~Seasonal~~ Cyclic surge-type behaviour is thought to arise from internal instabilities (Meier and Post, 1969) , whereas seasonal velocity variations are externally controlled by surface-melt induced acceleration through basal lubrication ~~(?) . The~~ (Iken and Bindschadler, 1986; Schoof, 2010; Hewitt, 2013) . Basal water pressure, and therewith basal drag, is controlled by the rate of water supply to the glacier bed and the capacity of the subglacial drainage system to accommodate increased discharge ~~regulate the basal water pressure and therewith basal drag~~ (Schoof, 2010). Increased meltwater supply may thus accelerate, but also slow down ice flow, if it facilitates the establishment of a hydraulically efficient drainage system (Schoof, 2010). Several recent studies therefore suggest that hydraulic lubrication alone has a more limited effect on the future net mass balance of the Greenland ice sheet (Nick et al., 2013; Shannon et al., 2013) than previously anticipated (Zwally et al., 2002). However, these assessments do not account for changes in the extent of the basal area subjected to hydraulic lubrication (Nick et al., 2013) or ~~the associated~~ do not quantify changes in calving loss (Shannon et al., 2013).

The effect of surface meltwater on the thermal structure of glaciers has only recently been considered in modelling studies ~~(Phillips et al., 2010) . The process of latent heat release and~~ and was termed cryo-hydrological warming (CHW; Phillips et al., 2010, 2013) . CHW includes latent heat released during refreezing of meltwater, as well as direct heat transfer ~~from water in glaciers was termed cryo-hydrological warming (Phillips et al., 2010) .~~

~~Cryo-hydrological warming~~ between water and ice. CHW has the potential to change englacial and basal temperatures within years (Phillips et al., 2010) , whereas changes in ~~the~~ basal thermal regime by heat conduction alone would require decades to centuries (Phillips et al., 2010). ~~Present~~ Phillips et al. (2010) regard CHW as a phenomenon specific for the ablation area and suggest that more areas of the Greenland Ice Sheet will be subjected to CHW in case of sustained climate warming and thus upward migration of the equilibrium-line altitude (ELA). CHW has the potential to enhance ice deformation through the temperature dependency of the ice viscosity (Phillips et al., 2010) , as well as basal motion, if it would increase the extent of the basal area at pressure-melting point (Phillips et al., 2013) . It has previously been suggested that present outlet glaciers may accelerate significantly, if meltwater drainage to the bed would spread inland ~~and thaw areas of the bed that are currently frozen (Alley et al., 2008) . We propose that cryo-hydrological warming may have a drastic effect on glacier dynamics by weakening cold-based marginal ice regions that obstruct outflow of inland ice regions with basal temperatures already at or near the pressure melting point~~(Alley et al., 2008; Bartholomew et al., 2011) . Phillips et al. (2013) simulated ice dynamics within the wet snow zone of western Greenland and achieved a best fit with observed increased wintertime velocities, if both increased ice deformation and an increase in the extent of basal temperate conditions, allowing for fast basal motion, was considered.

Cyclic surge-type behaviour is an extreme example of variations in glacier flow, and characterized by long quiescent phases (decades to centuries) with slow ~~flow velocities~~ ice flow followed by short-lived active phases (months to years) with orders-of-magnitude increases in flow velocities ~~(Raymond, 1987) .~~ (Raymond, 1987; Dowdeswell et al., 1991) . Resistance to sliding during the quiescent phase leads to build-up of an upper reservoir (Clarke et al., 1984) . During a surge, mass is transferred from ~~an upper~~ the reservoir area to a lower receiving area, often associated with kilometre-scale advances of the terminus and greatly enhanced calving flux, in the case of tidewater glaciers ~~. A thermally controlled soft-bed surge mechanism has been proposed for the polythermal glaciers of Svalbard (Hamilton and Dowdeswell, 1996) . When thawed, unconsolidated, water-saturated sediments lack shear strength and have the potential to efficiently destabilize the overlying ice (Tulaczyk et al., 2000) . Surge-type behaviour is~~

~~generally considered independent of climatic forcing. Internal mechanisms may be sufficient to drive cyclic instabilities (?) . Changes in glacier geometry during the quiescent phase provoke corresponding changes in driving stress and basal thermal regime (Clarke, 1976) .~~ (Murray et al., 2003a) . Glacier surges are generally regarded as internal instabilities, and not thought to be driven by external factors (Meier and Post, 1969) . Nevertheless, the climatic mass balance influences the build-up of the reservoir area and therewith ~~the surge periodicity~~surge occurrence and periodicity (Dowdeswell et al., 1995) . In addition, external factors may drive feedback processes that lead to amplified dynamic response, pushing the glacier towards an instability threshold.

~~Here we presentobservations of multiannual ice-stream acceleration of a large Arctic ice cap, culminating in a surgeand drastically enhanced ice discharge~~On Svalbard, glacier surges are thought to be controlled by a thermally-controlled soft bed surge mechanism (Hamilton and Dowdeswell, 1996; Jiskoot et al., 2000; Murray et al., 2000, 2003b) , as previously proposed for surges of polythermal glaciers in subpolar environments (Robin, 1955; Clarke, 1976; Clarke et al., 1984) . This theory concerns the slow adjustment of the basal thermal regime and driving stresses in response to geometric changes during the quiescent phase, ultimately leading to a thermal switch from cold to temperate basal conditions, permitting for fast basal motion. Basal melting sets in, subglacial till, if present, is thawed and its shear strength reduced by rising pore water pressure, destabilizing the glacier and initiating the surge (Clarke et al., 1984; Tulaczyk et al., 2000) . Dynamic thinning and reduction in surface slope reduce the driving stress and sliding rates, eventually bringing the surge to a halt (Clarke et al., 1984) .

Thermal models of glaciers generally account for heat conduction through the ice, heat transfer by ice advection, strain heating and frictional heating. The geothermal heat flux and the annual air temperature (plus firn warming) form the lower and upper boundary conditions, respectively. Thermal effects by water flow within glaciers have previously been mentioned and considered important (e.g. Clarke, 1976) , but only recently, has ”cryo-hydrologic warming (CHW)” put back in focus (Phillips et al., 2010, 2013) . Clarke (1976) neglected CHW in thermal models of glacier surges, by assuming that water flow within cold ice is limited.

However, recent studies suggest meltwater connections from the surface to the bed through cold ice of substantial thickness (e.g. Das et al., 2008; Clason et al., 2014) .

Direct observations of ice dynamics during glacier surges are scarce. The evolution of several surges on Svalbard was reconstructed from archived satellite radar data, only after a surge was noticed. Snapshot velocities were derived preferably for the winter season, i.e. when surface melt is absent, as liquid water deteriorates the quality of the derived motion maps using satellite interferometric radar (Luckman et al., 2002; Murray et al., 2003b,a) . Changes in ice dynamics specifically during the summer melt season have therefore not been captured. Based on the available motion snapshots, Murray et al. (2003b) proposed that Svalbard glacier surges are characterized by gradual acceleration over several years, at a higher rate during the months towards the peak of the surge, and followed by multiannual, gradual slow-down. Murray et al. (2003a) states that seasonal velocity variations are negligible compared to the multiannual acceleration (and deceleration), i.e. there exist no evidence of short-lived or seasonal velocity variations during Svalbard surges.

Here, we present a 5 year record of continuous GPS measurements (May 2008 to May 2013) and satellite synthetic aperture radar based velocity maps (since April 2012) from Basin-3, a marine terminating drainage basin of the Austfonna ice cap on Svalbard. Our observations demonstrate strong links between surface-melt and ice-flow acceleration~~. We propose a~~, culminating by October 2012 in a surge and drastically enhanced ice discharge. To date (autumn 2014), the surge continues. We propose a hydro-thermodynamic ~~feedback that efficiently weakens the basal drag in initially frozen areas and facilitates enhanced basal motion over an expanding temperate basal area. By identifying the hydro-thermodynamic~~ feedback ~~to summer meltas a trigger for the mobilization of initially slow-moving ice regions, our study contributes to~~ mechanism to surface melt, subsequently mobilizing the ice within the reservoir area and weakening cold-based marginal ice that restricts inland ice to drain into the ocean. Finally, we discuss possible implications of the ~~understanding of dynamic glacier wastage and disintegration mechanisms of the ice-sheets in a warming climate(Alley et al., 2008; Joughin and Alley, 2011) , i. e. characterized by more widespread and intense occurrence of surface melt.~~ proposed mechanism for the stability of marine ice-sheet regions, if exposed to significant surface melt in a warming climate.

2 Austfonna, Basin-3

At $\sim 7800\,\mathrm{km}^2$, Austfonna is the largest ice cap in the Eurasian Arctic (Fig. 1a). The ice cap consists of a main dome with an ice thickness of up to $600\,\mathrm{m}$ that feeds a number of drainage basins, some of them known to have surged in the past ~~(Lefauconnier and Hagen, 1991)~~ (Dowdeswell, 1986) . Austfonna has a polythermal structure. In the ice cap's interior basal temperatures are likely at pressure melting point (Zagorodnov et al., 1989), while the thinner ice-cap margins are cold and frozen to the ~~ground~~bed, except for distinct fast flowing outlets that are dominated by fast basal motion and ~~intersperse~~ imbedded within the generally slowly deforming ice cap (Dowdeswell et al., 1999). The south-eastern basins are to a large extent grounded below sea level, and form a continuous, non-floating calving front towards the Barents Sea (Dowdeswell et al., 2008). The regions grounded below sea level are ~~to some extent~~ at least partially underlain by marine sediments (Dowdeswell et al., 2008). Over 2002–2008, the climatic mass balance of Austfonna was close to zero (Moholdt et al., 2010a). Yet, the ice cap was losing mass due to calving and retreat of the marine ice margin that accounted for $2.5\,\mathrm{Gt\,a}^{-1}$ or $33 \pm 5\,\%$ of the total ablation (Dowdeswell et al., 2008).

Basin-3 ($\sim 1200\,\mathrm{km}^2$ and a length of ~ 60km) is the largest drainage basin of Austfonna and topographically constrained by a subglacial valley that extends from south of the main dome eastwards towards the Barents Sea (Fig. 1b). About one third of the ice base is grounded below sea level down to a maximum depth of $\sim$ ~~155~~150 m within an overdeepening in the central terminus region (Fig. 1b; Dowdeswell et al., 1986; Dunse et al., 2011) . A previous velocity map based on ~~interferometric SAR~~ satellite radar interferometry from data acquired in the mid-1990s revealed an ice stream in the northern lower reaches of Basin-3 with flow velocities $\leq 200\,\mathrm{m\,a}^{-1}$ (Dowdeswell et al., 2008). The ice stream was topographically constrained by a subglacial mountain to the north (Isdomen) and near-stagnant ice, likely frozen to its bed, to the south. The absence of surface ~~lineation~~ lineations (e.g. crevasses) as late as 1991, identified the ice stream of Basin-3 as a recent feature (Dowdeswell et al., 1999). During the 1990s, the front retreated on average by $70 \pm 10\,\mathrm{m\,a^{-1}}$, accounting for two thirds of the calving flux of $\sim 0.4\,\mathrm{Gt\,a^{-1}}$ (Dowdeswell et al., 2008). Basin-3 is known to have surged some ~~years~~ time prior to 1870 (Lefauconnier and Hagen, 1991), and the advancing terminus created a pronounced surge lobe nearly 25 km in width. The terminal moraine associated with the last surge lies $\sim 8\,\mathrm{km}$ from the present-day position of the calving front (Robinson and Dowdeswell, 2011). Based on lobe volume and accumulation rate, the duration of the quiescent phase ~~has been~~ of Basin-3 was estimated to last ~~200–500~~130–140 years ~~(Dowdeswell et al., 1991)~~ (Solheim, 1991) , a very good estimate considering the basin's renewed surge activity since autumn 2012, reported on here.

3 Methods

3.1 ~~GPS velocity~~ Velocity timeseries

In spring 2008, five GPS receivers were deployed along the mid-1990's central flowline, 5 to ~~16~~21 km upglacier from the calving front (Fig. 1; Dunse et al., 2012). We used GPS single-frequency code receivers (L1 band, C/A code only). Geographical positions were logged at hourly intervals, every third hour for instruments installed after May 2011, at an accuracy typically better than 2 m (den Ouden et al., 2010). Filtering in the time domain was applied to reduce random errors, i.e. a 7-day running mean was applied to the daily mean position, velocities were computed, and finally, the velocity was smoothed by applying another 7-day running mean (Dunse et al., 2012).

3.2 Velocity maps from synthetic aperture radar

Velocity maps of Basin-3, Austfonna, were produced from ~~20~~ 24 2 m resolution ~~TerraSAR-X~~ TerraSAR-X (TSX) scenes acquired between April 2012 and ~~May~~ November 2013, and provided by the German Aerospace Center (DLR). Displacement fields were derived by using cross correlation between two consecutive acquisitions (Strozzi et al., 2002) and geocoded using a DEM of Austfonna (Moholdt and Kääb, 2012). Appendix A provides more detailed information on the TSX data and processing. Calving front outlines were digitized from geocoded backscatter images (Appendix B). The calving flux of Basin-3 was derived by the ice flux through a fixed fluxgate upglacier of the calving front and the area change downglacier of that fluxgate, multiplied by an average ice thickness. The ice thickness was derived by differencing of a bedrock map (Fig. 1b; Dowdeswell, 1986; Dunse et al., 2011) and a digital elevation model (Moholdt and Kääb, 2012) .

3.3 Additional data

To approximate timing and magnitude of surface-melt periods, cumulative positive-degree days (PDD) were computed from the temperature record of an automatic weather station. The station ~~was~~ has operated since April 2004 on the western flank of Austfonna at 22°25′12″ E, 79°43′48″ N and 370 m a.s.l. ~~(?)~~ (Schuler et al., 2014) . Surface crevasses were identified and mapped using ground-penetrating radar (Ramac GPR; Målå Geoscience) at a centre frequency of 800 MHZ, providing structural information from the glacier surface down to a depth of $\sim 12\,\mathrm{m}$ (Dunse et al., 2009, Appendix C). GPR profiles were annually repeated since 2004 and geolocated using a kinematic Global Navigation Satellite System (GNSS; GPS and GLONASS).

4 Results

4.1 ~~Multi-annual~~ Multiannual ice-flow acceleration

~~In spring 2008, five GPS receivers were deployed along the mid-1990's central flowline, 5 to 16upglacier from the calving front (Fig. 1; Dunse et al., 2012) .~~ Winter velocities observed by GPS in May 2008, were significantly higher than in the mid-1990s (Fig. 2). The GPS time series also reveal considerable overall acceleration, occurring in pronounced steps, each of which coincides with the summer melt period, as indicated by the temperature record of an automatic weather station ~~(Fig. 2; ?) . High sensitivity and short response time (days) of glacier dynamics to melt periods clearly suggest surface-melt triggered acceleration.~~

(Fig. 2; Schuler et al., 2014) . The 2008 summer speed-up is followed by a gradual winter deceleration~~, returning to pre-summer velocities only before the onset of the 2009 summer speed-up (maximum not captured due to instrument-power loss~~. 60-95% of the velocity increase during summer is reversible (Appendix D). However, during subsequent years ~~, the summer speed-ups were progressively irreversible, resulting in elevated winter velocities (Appendix D,~~ an increasing fraction of the summer speedup is of lasting nature, i.e. increased summer velocities are sustained throughout the winter although surface melt had ceased.

Multiannual changes in ice dynamics are also evident from within the reservoir area, higher up on Basin-3. The annual position change of a mass-balance stake close to the ice divide (Fig. ~~8) . In autumn 2012, strong acceleration continued although surface melt had ceased.~~1) revealed strong acceleration from 11 $\mathrm{m\,a^{-1}}$ between 2004 and 2007 to 28, 43 and 114 $\mathrm{m\,a^{-1}}$ for the period 2010–2013. In addition, annually repeated GPR surveys reveal first and cumulative occurrence of surface crevasses from $\sim$2004 onwards, between $\sim$2004 and 2007 along the western profile, and between 2008 and 2012 along the eastern profile (Fig. 1a; Appendix C).

4.2 Mobilization of stagnant ice regions

The drastic acceleration during autumn 2012 coincided with the expansion of the fast-flowing region across the entire basin, as revealed by a time series of ice-surface velocity maps based on intensity tracking of repeat-pass TerraSAR-X satellite radar images (Fig. 3; Appendix B). ~~Ice-stream velocities~~ Velocities in April 2012 were up to 3 $\mathrm{m\,d^{-1}}$, one order of magnitude larger than in the mid 1990's (Fig. 3a). In April 2012, the ~~ice stream extended further~~ fast-flow region extended farther inland and had widened southward to a width of $\sim$6–8 km, as compared to $\sim$5–6 km in the mid-1990s. ~~Consequently~~As a result of southward expansion, the GPS receivers were located $\sim$1 km north from the central flowline and did not capture fastest flow velocities. In contrast to the mid-1990s, the south-eastern corner of Basin-3 ~~displayed also~~ also displayed fast motion, at velocities of up to 1 $\mathrm{m\,d^{-1}}$. These two distinct fast-flow regions were completely separated by almost stagnant ice, notably including the calving front. Low ice velocities, $< 0.1\,\mathrm{m\,d^{-1}}$, indicate the absence of considerable basal motion, and suggest frozen-bed conditions in this region. In August 2012, i.e. at the end of the summer melt season, velocities had increased significantly, up to $6\,\mathrm{m\,d^{-1}}$ for the northern and $4\,\mathrm{m\,d^{-1}}$ for the south-eastern fast-flow region, along with further lateral expansion of the fast flowing areas. Consequently, the slow moving ice region in-between had decreased in size (Fig. 3b) and disappeared by October 2012, when ice flow escalated into a surge comprising the entire width of the basin, reaching velocities $>10\,\mathrm{m\,d^{-1}}$ (Fig. 3c). Velocities increased further until January 2013, reaching a maximum of $20\,\mathrm{m\,d^{-1}}$ (Fig. 3d~~; Table 2~~). Between January and May 2013 the maximum velocities decreased to $15.2\,\mathrm{m\,d^{-1}}$, while the upglacier regions continued to accelerate (Fig. ~~5b~~6b). By the end of 2013, fast flow of Basin-3 continued (~~Table 2~~Appendix A).

4.3 Calving flux

The TSX data allowed calculation of the calving flux components, i.e. (i) the ice flux through a fixed fluxgate near the calving front, and (ii) the mass change of the terminus downglacier of that fluxgate, accounting for front position changes (Fig. 4; Appendix B). The observed ice flux peaked at a rate of $13.0\pm4.2\,\mathrm{Gt\,a^{-1}}$ in December 2012/January 2013, after which it decreased slightly (Fig. 4a). Prior to October 2012, the position of the entire calving front of Basin-3 was remarkably stable (slight retreat; Fig. 4b), indicating that the entire ice flux was balanced by iceberg calving. After November 2012, the southern and central parts of the front, advanced by $>1\,\mathrm{km}$, reducing ice mass loss through calving by 61 %, as ~~opposed~~ compared to a stable front position.

Direct conversion of calving mass loss to SLR contribution is only meaningful for a static calving front. Glacier surges are typically accompanied by significant terminus advances. An advancing terminus reduces the mass loss from the glacier, however, the submerged part of the terminus replaces sea water instantaneously, causing an instantaneous sea-level rise. We therefore distinguish between a glacier-mass balance and a sea-level perspective on the calving flux (~~Table 1;~~ Fig. 4c; Table 1). From 19 April 2012 to 9 May 2013, calving mass loss [yearly rate] from Basin-3 accounted for $4.4\pm1.6\,\mathrm{Gt}$ [$4.2\pm1.6\,\mathrm{Gt\,a^{-1}}$], an order of magnitude increase compared to 1991–2008 (Dowdeswell et al., 2008), nearly tripling the calving loss from the entire Austfonna ice cap. The related sea-level rise contribution of $7.6\pm2.7\,\mathrm{Gt}$ [$7.2\pm2.6\,\mathrm{Gt\,a^{-1}}$], is as large as the total glacier mass change from the entire Svalbard archipelago for the period

2003 to 2008, estimated to $-6.6 \pm 2.6\,\mathrm{Gt\,a^{-1}}$ (Moholdt et al., 2010b). Rates of sea-level rise contribution are expected to decline once the surge of Basin-3 has terminated, i.e. the ice flux diminished and the terminus advance come to a halt. Nevertheless, iceberg calving and hence, ice mass loss will be maintained, dependent on future rates of marine-terminus retreat.

5 Discussion~~of hydro-thermodynamic feedback mechanism~~

The dynamic changes that have been observed at Basin-3 over the last two decades can be separated into three phases: (1) activation of a spatially confined ~~ice stream~~ fast-flow region in the early 1990's (Dowdeswell et al., 1999); (2) ~~multi-annual acceleration~~ multiannual acceleration and expansion of the fast-flow region from $<$ 2008 to 2012~~, along with an expansion of the ice stream~~; (3) active surge phase following the destabilization of the entire terminus in autumn 2012.

~~The activation of a spatial confined ice stream in the~~

5.1 Phase 1: Initiation of spatially confined fast flow

Spatially confined fast-flow was initiated in the northern part of lower Basin-3 in the early 1990's~~(phase 1) can~~, and interpreted as a temporary flow instability (Dowdeswell et al., 1999) . Activation of fast flow within this region could be explained by internal mechanisms, ~~e.g.~~ i.e. by gradual changes in basal thermal regime and driving stress~~(Dunse et al., 2011) , following the geometric build-up of the glacier over~~ , associated with longterm geometric changes during the quiescent phase (e.g. Clarke, 1976; Clarke et al., 1984) . Numerical simulations of Austfonna support the concept of a thermally-controlled softbed surge mechansim (Dunse et al., 2011) , as proposed earlier for Svalbard glacier surges (Hamilton and Dowdeswell, 1996; Jiskoot et al., 2000; Murray et al., 2000, 2003b) . Spatially confined fast flow since the early 1990's entailed an ice flux in excess of the balance flux (Dowdeswell et al., 1999) and thus a draw down of the reservoir area. Extensional flow within the reservoir area is expected to form crevasses (van der Veen, 1999) , as indeed observed by

GPR since $\sim$ ~~120of quiescence. The multi-annual, stepwise acceleration in the prelude of the present surge (phase 2~~2004 (Fig. 1a; Appendix C).

5.2 Phase 2: Mobilization of the reservoir; multiannual, stepwise acceleration

The multiannual acceleration of Basin-3, observed by GPS since 2008~~) coincides with successive annual summer speed-ups~~ , occurred in discrete steps, each of which coincident with consecutive summer melt periods (Fig. 2). High sensitivity and short response time (days) of glacier dynamics to melt events clearly suggest surface-melt triggered acceleration. Short-lived acceleration during the melt season is consistent with current understanding of hydraulic lubrication (Schoof, 2010). In contrast, the ~~multi-annual~~ multiannual acceleration of background velocities (~~Fig. 8~~Appendix D) cannot be explained by this mechanism and suggests a fundamental change in dynamics.

Enhanced post-summer velocities sustained throughout the winter can be explained by successive activation of previously stagnant ice regions during the previous summer melt period. Mobilization of increased ice volumes within the reservoir area lead to increased ~~ice-stream~~ velocities and discharge. A widening of the ~~ice stream~~ fast-flow region itself, allows for higher centre-line velocities due to the increased distance from the lateral shear margin, analogue to the behaviour of Antarctic ice streams (Joughin and Alley, 2011).

Mobilization of the reservoir area is evident from the surface-crevasse formation within the upper accumulation area of Basin-3 ~~. Ground-penetrating radar (GPR) surveys reveal first occurrence of surface crevasses from~~ since $\sim$2004 ~~onwards (Appendix C;~~ (Fig. ~~7~~1a; Appendix C). Crevasses are a manifestation of longitudinal extension and evidence of upglacier migration of the fast-flowing region. This is in line with the upglacier expansion of the ice stream revealed by TSX and the ~~annual position change of a~~observed strong acceleration of the mass-balance stake ~~close to the ice divide~~ within the reservoir area (Fig. 1)~~, subjected to strong acceleration from 11between 2004 and 2007 to 28, 43 and 114for the period 2010–2013~~. The first occurrence of crevasses signify the development of potential meltwater routes to the glacier bed, subjecting an increasing region to ~~hydraulic basal lubrication and cryo-hydrologic warming~~CHW and basal hydraulic lubrication. Similarly, meltwater reaching the bed beneath the heavily crevassed shear margin of the fast-flow region efficiently weakens the basal drag that balances the lateral drag, which in turn regulates ice ~~stream~~ velocities (Joughin and Alley, 2011). ~~Cryo-hydrologic warming~~ CHW and increased frictional heating both act to enhance this ~~positive feedback~~mechanism, weakening the flow resistance exerted by the lateral shear margins and ~~initially~~ possibly cold-based ice patches acting as “sticky spots” (Alley, 1993) . The interplay between ~~cryo-hydrologic warming~~ CHW and the emergence of basal hydraulic lubrication over an expanding area of the ice base constitutes a hydro-thermodynamic feedback. Unconsolidated subglacial sediments underneath the marine-based ice of Basin-3 ~~would~~ act to further enhance this feedback~~, and when thawed,~~ . Input of surface meltwater during consecutive summers progressively rises the pore-water pressure within the sediment, reducing its shear strength and favour rapid destabilization ~~(Hamilton and Dowdeswell, 1996; Tulaczyk et al., 2000)~~ (Clarke et al., 1984; Tulaczyk et al., 2000) .

5.3 Phase 3: Destabilization of the marginal ice plug; basin-wide surge

A surge comprising the full width of Basin-3 and the subsequent advance of the terminus followed the mobilization of the remaining ~~slow moving~~ stagnant ice regions, notably including the calving front~~(phase 3).~~ . Water flow may have accessed the cold-ice base through partially unfrozen subglacial sediments, as suggested in case of Trapridge Glacier, Yukon (Clarke et al., 1984) . Field measurements of thermal structure and ice flow during a surge of Trapridge Glacier do not indicate that the cold ice below the surge front acts as a thermal barrier to water flow. Clarke et al. (1984) observed very high temperature gradients in the cold basal ice below a surge front, about 10 times larger than expected from geothermal heat flux, and attributed this to water flow through an unfrozen substrate beneath the cold ice. The abrupt onset of fast flow in previously stagnant regions of Basin-3 suggests sheer tearing of the glacier from its bed~~, after the remaining sticky spots have been sufficiently weakened by the hydro-thermodynamic feedback outlined above .~~ . This activation was possibly related to a combination of warming of the glacier bed through CHW and mechanical stress transfer from active ice further upstream. During the fieldwork in spring 2012, large ice blocks were observed to be pushed upward above the glacier surface near the lower shear margin, an indication of strong longitudinal stresses.

While fast flow continued by the end of 2013, it is expected to slow down or come to a halt within a few years. Massive ice redistribution from the reservoir into the receiving area and towards the calving front efficiently lowers the driving stress. Eventually, temperate basal conditions underneath the dynamically thinned and decelerating terminus are expected to be no longer maintained, at which time the base of the ice will start to refreeze to its bed ~~(Dunse et al., 2011)~~ (Clarke et al., 1984; Dunse et al., 2011) .

~~To what extent can present dynamics of an Arctic ice cap like Austfonna shed light on the future dynamic behaviour of ice sheets?~~

5.4 Hydro-thermodynamic feedback mechanism

We cannot explain our observations using standard theory of glacier surges alone (e.g. Clarke et al., 1984) . The multiannual acceleration did not occur uniformly or gradually, as previously thought characteristic for Svalbard glacier surges (Murray et al., 2003b,a) . Incorporating the effect of CHW over an expanding area of the glacier bed provides a good explanation of our observations, we believe (Fig. 5). The hydro-thermodynamic feedback proposed here, is not limited to CHW, but also includes the additional hydraulic lubrication effects. Ice regions undergoing a switch from cold to temperate basal conditions were previously characterized by frozen conditions, i.e. absence of water. In the initial stage of basal-hydraulic drainage system development, water input is likely to raise water pressure and enhance basal motion, in line with the established theory on basal lubrication, e.g described by (e.g. Schoof, 2010) . In addition, thawing of underlying frozen till and rising pore-water pressure lead to enhanced sediment deformation. These processes all result in an enhancement of ice flow. Longitudinal extension opens new surface crevasses that provide englacial pathways for meltwater in subsequent summers, subjecting a larger region of the bed to surface melt. Eventually, the entire drainage basin is sufficiently destabilized, initiating the surge. Once the entire basin is moving by fast basal motion, i.e. the entire base is at pressure melting, and driving stresses are decreasing, the hydro-thermodynamic feedback is no longer operating.

We like to stress that the hydro-thermodynamic feedback proposed here does not oppose, but can be understood as an integral part of the theory of thermally-controlled soft-bed glacier surges, as illustrated in Fig. 5. An increasing fraction of the glacier bed is subjected to surface melt, and basal processes conductive for surge behaviour are amplified. Basal processes include in particular, (1) CHW that leads to a switch from cold to temperate basal conditions, permitting for fast basal motion; (2) expansion of the area subjected to basal lubrication; (3) rising pore water pressure and sediment deformation. The feedback requires an initiation zone in which surface meltwater can access the bed, such as the spatially confined fast-flow region described in phase 1. Alternatively, supra-glacial lake drainage may establish full ice-thickness meltwater pathways (Das et al., 2008) . Our observations of Basin-3 suggest a significant contribution of the hydro-thermodynamic feedback on the mobilization of the reservoir area, on one hand, and weakening of the flow resistance within the receiving area, on the other hand.

5.5 Implications for the future stability of ice sheets

Surface melt has likely been been a widespread phenomenon on Svalbard throughout most of the Holocene. The current surge of Basin-3 should therefore not be mistaken as a response to recent Arctic warming. The hydro-thermal feedback could also have played a role in previous Svalbard glacier surges. Given continued global warming, characterized by more widespread and intense occurrence of surface melt, we hypothesize that the hydro-thermodynamic feedback may gain importance in other glaciated regions, including the ice sheets.

Rapid marine ice-sheet disintegration is evident from geological records both in the Northern and Southern Hemisphere and typically associated with air temperatures similar or warmer than those predicted for the end of the 21st century (Cook et al., 2013; Deschamps et al., 2012) . Ice-rafted debris distributed across the North Atlantic ocean floor provide evidence of substantial calving associated with the rapid disintegration of the Laurentide ice sheet, so-called Heinrich events (Bond et al., 1992) . Paleoclimatic records suggest rates of sea-level change much larger than currently observed or projected for the 21st century, e.g. 3.5 to 5 m SLR per century (35–50 $\mathrm{mm\,a^{-1}}$) at the end of the last glacial maximum, $\sim$14.5 ka ago (Deschamps et al., 2012) .

Analogies between glacier surges and partial ice sheet collapses are widespread throughout the glaciological literature (e.g. Clarke et al., 1984; Jiskoot et al., 2000) . Analogue to the ice sheets, ice caps like Austfonna consist of slow moving inland ice interspersed by faster flowing outlet glaciers and ice streams that deliver inland ice towards the calving front. Drainage basins of Austfonna in their quiescent phase are characterized by margins frozen to their bed (Dowdeswell et al., 1999). Similarly, the coastal margins of the Antarctic ice sheet contain large regions of cold-based ice (Pattyn, 2010) that may currently prohibit efficient drainage of warm-based interior ice towards the ocean – e.g. in the Wilkes Basin, East Antarctica, that is known to have been dynamically active during the Pliocene warmth (Cook et al., 2013). ~~In~~ A very recent model study confirms the potential dynamic instability of the Wilkes basin, following the removal of a cold-ice plug (Mengel and Levermann, 2014) . In their study, a retreat of the grounding line is forced by oceanic warming, thereby eliminating the cold-ice plug.

Our proposed mobilization of the reservoir area of Basin-3 is in line with (Phillips et al., 2013) pointing at the potential of CHW, in mobilizing more inland ice regions of the Greenland ice sheet, thereby increasing ice discharge through existing outlet glaciers. An obvious feature that distinguishes Basin-3 from Greenland outlet glaciers is the presence of a cold-based ice plug that, until autumn 2012, restricted drainage from the reservoir area. In case of fast-flowing Greenland outlet glaciers, the thermo-dynamic feedback would therefore lead to gradual acceleration, as long as the ELA continues migrating upglacier, rather than leading to surge-type behaviour. In southwest Greenland, further acceleration of Jacobshavn Isbræ followed the 2012 record summer melt season (Joughin et al., 2014). Although the authors attribute the acceleration to terminus retreat into a bedrock depression, the occurrence of pronounced summer speed up at higher elevations may also reflect inland migration of surface melt and the effect of associated hydraulic feedbacks on glacier dynamics (Alley et al., 2008; Meierbachtol et al., 2013; Phillips et al., 2013). Similarly, the hydro-thermodynamic feedback may play a role in the sustained mass loss recently reported from northeast Greenland and mainly attributed to sea-ice decline due to regional ~~waming~~ warming (Khan et al., 2014).

6 Summary and conclusion

~~Our observations of multiannual acceleration of an Arctic ice cap indicate successive enhancement of basal motion driven by meltwater supply and shed light on a destabilisation mechanisms of Polar land ice~~For the first time, to our best knowledge, we have obtained continuous in-situ velocity observations during glacier surge initiation. Our observations from Basin-3 of Austfonna, reveal details of a surge that were never recorded before. Unlike proposed earlier for Svalbard-glacier surges (Murray et al., 2003b,a) , multiannual acceleration during surge initiation of Basin-3 was not gradual, but occurred in discrete steps, coincident with successive summers. We propose a hydro-thermodynamic feedback mechanism, triggered by surface melt reaching a growing fraction of the glacier bed. Intrusion of surface melt to the glacier bed provides an efficient heat source through ~~cryo-hydrological warming and initiates~~ CHW, facilitating a thermal switch from cold to temperate basal conditions, permitting for basal motion. Initiation of hydraulic lubrication, ~~weakening the resistance to~~ along with rising pore-water pressure within subglacial sediments, further enhance basal motion, ~~especially in initially cold-based iceregions. During the summer melt season, slow moving ice regions are successively mobilized through lateral and inland expansion of regions dominated by fast basal motion~~eventually destabilizes the overlying ice. These processes have earlier been summarized as thermally-controlled softbed surge mechanism (e.g. Clarke et al., 1984; Murray et al., 2003b) . However, the active role of surface-melt and the associated hydro-thermodynamic feedback mechanism contrast the previous understanding of glacier surges as purely internal instabilities.

The recent calving flux of Basin-3 ~~is enormous and~~ has strong implications for the mass balance of the ice cap and its contribution to sea-level rise. From 19 April 2012 to 9 May 2013, the calving flux [yearly rate] of Basin-3 amounted to $4.4 \pm 1.6\,\mathrm{Gt}$ [$4.2 \pm 1.6\,\mathrm{Gt\,a^{-1}}$], an order of magnitude increase compared to 1991–2008 (Dowdeswell et al., 2008). Accounting for the terminus advance, the related sea-level rise contribution of $7.6 \pm 2.7\,\mathrm{Gt}$ [$7.2 \pm 2.6\,\mathrm{Gt\,a^{-1}}$] equals the total annual glacier-mass loss from the entire Svalbard archipelago for the period 2003 to 2008, estimated to $6.6 \pm 2.6\,\mathrm{Gt\,a^{-1}}$ (Moholdt et al., 2010b).

Given continued climatic warming and increasing surface melt, we hypothesize that the hydro-thermodynamic feedback ~~to surface melt will gain significance for the destabilisation~~

~~of Polar land ice~~may gain significance in other glaciated areas, including the ice sheets. In light of recent record melt and rising ELA of the Greenland Ice Sheet, the proposed mechanism has the potential to lead to a long-term enhancement of outlet-glacier discharge and calving loss, as earlier proposed by Phillips et al. (2013) . Our expectation contrasts recent studies that indicate limited effects of surface-melt induced acceleration on the future net-mass balance of the Greenland ice Sheet (Nick et al., 2013; Shannon et al., 2013). Surface melt in Antarctica is presently mainly constrained to the ice shelves (Comiso, 2000). Given strong continued warming, surface melt will increasingly occur over coastal areas of Antarctica, making the grounded ice-sheet margins vulnerable to the hydro-thermodynamic feedback.

Our study of the Austfonna ice cap highlights the importance of dynamic ~~glacier wastage for the mass balanceof Polar land ice~~ice-mass loss for glacier mass balance. Current model projections of future SLR (Stocker et al., 2013) still do not account for the dynamic response of glaciers to continued global warming and might need to be revised upward after incorporating mechanisms such as CHW and the hydro-thermodynamic feedback.

Appendix A TerraSAR-X velocity maps

20 TerraSAR-X (TSX) satellite synthetic aperture radar scenes of $\sim 2\,\mathrm{m}$ ground resolution (TSX Stripmap mode) were acquired between April 2012 and ~~December~~ November 2013 (Table 2), providing information on the spatial evolution of the surge (Fig. 3). For each pair of consecutive acquisitions, displacements were determined using cross-correlation of the intensity images (Strozzi et al., 2002) and ~~19~~ 21 velocity maps produced by accounting for the respective repeat-pass period (Table 2). The size of the matching-window was adjusted according to the expected maximum displacements during the repeat pass cycle, 300×344 pixels in range and azimuth direction in case of 11 days or 599×688 pixels for 22 days or longer. Displacements were measured in discrete steps of 50×57 pixels in range and azimuth to achieve a resolution of $\sim 100 \times 100\,\mathrm{m}$. Velocity maps were calculated from displacement maps by accounting for the time interval between the two underlying TSX images (t_1 to t_{19}, Table 2) and geocoded using a DEM of Austfonna (Moholdt and Kääb, 2012). Velocities larger than a carefully es-

timated maximum (Table 2) were classified as mismatches and removed. To estimate the ice flux (Appendix B), obvious erroneous velocities remaining in the vicinity of a fixed fluxgate were manually removed and the maps interpolated using inverse distance weighting to provide continuous velocity profiles along the fluxgate (Fig. ~~5a~~6a). A comparison between TSX and GPS velocities for each GPS station and all repeat-pass periods, revealed that TSX underestimated local velocities at the GPS stations by $0.3\,\mathrm{m\,d^{-1}}$ (Fig. ~~6~~7). We explain this small bias by large horizontal velocity gradients within large matching windows, which could lead to the average velocities within a matching window being typically smaller than the strictly local GPS velocity. Consequently, more stable areas produce best matches.

Appendix B Calving flux

The calving flux, q, of Basin-3 was calculated based on TSX velocity maps and changes in extend of the glacier by $q = q_{\mathrm{fg}} + q_{\mathrm{t}}$, with q_{fg} being the ice flux through a fluxgate near the calving front, and q_{t} the volume change of the terminus downglacier of that fluxgate due to advance or retreat of the calving front. Here, we defined a spatially fixed fluxgate approximately perpendicular to the ice flow, typically 1–$3\,\mathrm{km}$ upglacier from the actual calving front (Fig. ~~5a~~6a), and where ice surface velocities could be inferred from all TSX-image pairs. The ice-flux can be written as

$$q_{\mathrm{fg}} = H_{\mathrm{fg}} \cdot w_{\mathrm{fg}} \cdot v_{\mathrm{fg}}$$

where $H_{\mathrm{fg}} = zs_{\mathrm{fg}} - zb_{\mathrm{fg}}$ is the ice thickness along the fluxgate, with zs_{fg} and zb_{fg} surface and bedrock elevation, respectively, w_{fg} is the width of the fluxgate and v_{fg} the velocity across the fluxgate. We assume plug flow, i.e. depth averaged velocities equal surface velocities, because at the high flow velocities observed, ice deformation is negligible compared to basal motion (Clarke, 1987). Position changes of the calving front are addressed by changes in areal extent of the glacier downstream from that fluxgate per repeat-pass period

$$q_{\mathrm{t}} = H_{\mathrm{t}} \cdot \frac{\Delta A_{\mathrm{t}}}{\Delta t}$$

where $H_\mathrm{t} = zs_\mathrm{t} - zb_\mathrm{t}$ is the ice thickness at the terminus in vicinity of the calving front, where zs_t represents a typical height of the calving front and zb_t is the mean bedrock elevation for the area encompassed by the observed maximum and minimum glacier extent. ΔA_t is the areal change of the terminus over the repeat-pass period Δt between successive TSX acquisitions. The uncertainty in the calving flux estimate is associated with uncertainties of the input variables listed in Table 3. If the variables are derived from several independent components, their uncertainties can be summed by the root of the sum of squares (RSS) of the uncertainty of the components.

B1 Ice flux

To calculate the ice flux $q_{\mathrm{fg},i}$ for each repeat pass period t_i (Fig. 4a), the ice flux through 617, 50 m-wide fluxgate segments was integrated, accounting for local ice thickness and velocity. Ice volume is converted to mass using an ice density $\rho_\mathrm{ice} = 917\,\mathrm{kg\,m^{-3}}$. The cumulative ice flux over the period 19 April 2012 to 9 May 2013 is derived by summing up the ice flux over 19 successive TSX repeat-pass periods, weighted by their time duration (Fig. 4b),

$$q_\mathrm{fg} = w_\mathrm{fg} \cdot \sum_{t_i=1}^{19} \sum_{n=1}^{617} H|_{\mathrm{fg},n} \cdot v|_{\mathrm{fg},i,n} \cdot \rho_\mathrm{ice}$$

To derive continuous velocity profiles along the fluxgates, the velocity maps were interpolated horizontally in the vicinity of the fluxgate where mismatches occurred. The velocity maps associated with long repeat pass periods, t_3 and t_6, suffer from large gaps, only 51 and 46 % of the fluxgate segments hold sound velocity estimates. In case of t_3, the available data aligns with the previous velocity profile for t_2, a factor x relation was determined and the gaps filled by piecewise polynomial interpolation so that $v(t_3) = x \cdot v(t_2)$. In case of t_6, the velocity profile was constructed by using the mean of the previous and following repeat-pass cycle, $v(t_6) = \frac{1}{2} \cdot (v(t_5) + v(t_7))$ (dash-dotted lines in Fig. ~~5a~~6a). The accuracy of the resulting velocity profiles were evaluated by comparing the constructed velocity profiles and the available reliable matches, revealing a standard deviation of 0.21 and 0.25 $\mathrm{m\,d^{-1}}$ and a negligible mean offset of 0.03 and 0.04 $\mathrm{m\,d^{-1}}$, in case of t_3 and t_6, respectively.

The uncertainty in the ice-flux term, Δq_{fg}, is derived according to the law of propagation of uncertainty

$$\Delta q_{\mathrm{fg}} = w_{\mathrm{fg}} \cdot \sum_{t_i=1}^{19} \sum_{n=1}^{617} \sigma(q_{\mathrm{fg}})_{i,n}$$

with $\left(\frac{\sigma(q_{\mathrm{fg}})}{q_{\mathrm{fg}}}\right)^2 = \left(\frac{\sigma(H_{\mathrm{fg}})}{H_{\mathrm{fg}}}\right)^2 + \left(\frac{\sigma(v_{\mathrm{fg}})}{v_{\mathrm{fg}}}\right)^2$, omitting indexes i and n.

B2 Position changes of calving front

Similarly, the calving-flux term related to position changes of the calving front can be expressed by the volume change of the terminus in vicinity of the calving front, q_{t}:

$$q_{\mathrm{t}} = H_{\mathrm{t}} \cdot \sum_{t_i=1}^{19} \frac{\Delta A_{t,i}}{\Delta t_i} \cdot \rho_{\mathrm{ice}}$$

The calving front outlines of Basin-3 were digitized from geocoded TSX intensity images. Due to layover and shadow effects along the calving front a systematic error in the order of twice the height of the calving front of 30 m is assumed (Moholdt and Kääb, 2012). The digitizing accuracy is conservatively estimated to 4 pixels, i.e. $\pm 8\,\mathrm{m}$.

Analog to the ice-flux term, the uncertainty in the terminus-change term, Δq_{t}, is determined by the law of propagation of uncertainty:

$$\Delta q_{\mathrm{t}} = \sum_{t_i=1}^{19} \sigma(q_{\mathrm{t}})_i \cdot \rho_{\mathrm{ice}}$$

For each repeat-pass period $\sigma(q_{\mathrm{t}})$ is determined by $\left(\frac{\sigma(q_{\mathrm{t}})}{q_{\mathrm{t}}}\right)^2 = \left(\frac{\sigma(H_{\mathrm{t}})}{H_{\mathrm{t}}}\right)^2 + \left(\frac{\sigma(\Delta A_{\mathrm{t}})}{\Delta A_{\mathrm{t}}}\right)^2$, omitting index i.

Appendix C Crevasse formation

Ground-penetrating radar (GPR) profiling was performed on Austfonna on an annual basis since spring 2004 (Dunse et al., 2009). The GPR was operated at a centre frequency of 800 MHZ and provides information over a depth range of about $\sim 12\,\mathrm{m}$. The data allows for identification of individual surface crevasses. Survey profiles initially focused on the accumulation area. Since 2008, also the flowline along which GPS receivers are deployed, was repeatedly surveyed. In the accumulation area, crevasse formation took place between 2004 and 2007 (Fig. ~~7a and b~~8a and 8b) and 2008 and 2012 (Fig. ~~7c and d~~8c and 8d), for the western and eastern profile, respectively. The monitored flowline towards the terminus was already heavily crevassed at the time of the first GPR survey (Fig. ~~7c~~8c).

Appendix D Background GPS velocities and summer speed-up

Our five-year GPS record from Basin-3 shows that the annual velocity minimum typically occurs in June, just prior to the onset of summer speed-up (Dunse et al., 2012). Since 2008, the mean velocity in June has increased dramatically, with values in 2012 3 to 5 times higher than in 2008 at lowest (GPS B3 #1) and highest elevation (B3 #5), respectively (Fig. ~~8a~~ 9a and b). The strong acceleration results from flow velocities remaining above their pre-summer values after the annual summer speed-up. In particular, the reversible fraction of the summer speed-up decreases with time and diminishes in 2013, when the entire basin is surging (Fig. ~~8c~~9c). While the two upper GPS stations (B3 #4 and B3 #5) experience further drastic acceleration (factor 24 and 18 increase in June 2013 compared to June 2008, respectively), the lower GPS stations (B3 #1 and B3 #2) only show moderate velocity increases, because the locations are close to the lateral shear margins of the surging basin (Fig. 3c and d).

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TSX processing. T.V.S. analysed AWS data. C.H.R. provided GPS instruments and access to quality-controlled data set. All co-authors assisted in data interpretation and commented/edited the paper.

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Table 1. Estimate of calving flux components and total calving flux over the TSX observation period from 19 April 2012 to 9 May 2013.

Calving Flux components	(Gt)	($\mathrm{Gt\,a^{-1}}$)
Ice flux, Q_{fg}	8.3 ± 2.8	7.8 ± 2.7
Terminus change, Q_{t}	3.8 ± 1.2	3.6 ± 1.1
Terminus-seawater displacement, Q_{tsd}	3.2 ± 1.1	3.0 ± 1.0
Total calving flux		
Mb perspective, $Q_{\mathrm{mb}} = Q_{\mathrm{fg}} - Q_{\mathrm{t}}$	4.4 ± 1.6	4.2 ± 1.5
SLR perspective, $Q_{\mathrm{sl}} = Q_{\mathrm{mb}} + Q_{\mathrm{tsd}}$	7.6 ± 3.9	7.2 ± 2.6

Table 2. TerraSAR-X acquisitions of Basin-3 and repeat-pass period and maximum velocities of inferred velocity maps.

ID of period	Repeat pass period (days)	Start and end-date (dd mm yyyy)	Maximum velocity ($\mathrm{m\,d^{-1}}$)
t_1	11	19 Apr 2012–30 Apr 2012	4.5
t_2	11	30 Apr 2012–11 May 2012	4.5
t_3	88	30 Apr 2012–7 Aug 2012	4.5
t_4	11	7 Aug 2012–18 Aug 2012	6.4
t_5	11	18 Aug 2012–29 Aug 2012	6.8
t_6	44	29 Aug 2012–12 Oct 2012	8.4
t_7	11	12 Oct 2012–23 Oct 2012	13.6
t_8	11	23 Oct 2012–3 Nov 2012	13.6
t_9	22	3 Nov 2012–25 Nov 2012	15.9
t_{10}	11	25 Nov 2012–6 Dec 2012	18.2
t_{11}	22	6 Dec 2012–28 Dec 2012	18.4
t_{12}	11	28 Dec 2012–8 Jan 2013	20.0
t_{13}	22	8 Jan 2013–30 Jan 2013	18.6
t_{14}	11	30 Jan 2013–10 Feb 2013	18.6
t_{15}	22	10 Feb 2013–4 Mar 2013	17.5
t_{16}	11	4 Mar 2013–15 Mar 2013	17.3
t_{17}	22	15 Mar 2013–6 Apr 2013	16.1
t_{18}	11	6 Apr 2013–17 Apr 2013	16.4
t_{19}	22	17 Apr 2013–9 May 2013	15.2
t_{20}	11	16 Aug 2013–27 Aug 2013	15.5
t_{21}	11	12 Nov 2013–23 Nov 2013	12.5

Table 3. Calving flux input variables – values, sources and uncertainties.

Variable	Value/Source	Uncertainty	Explanation
zs_{fg}	40 m (constant)	$\pm 30\,\mathrm{m}$	The chosen values allow for elevations from flotation height of 10 m as lower limit and mean DEM height of 67 m as upper limit. The DEM originates from prior to surge initiation. GPS data since 2008 indicates extensional flow, and hence, dynamic thinning.
zb_{fg}	Local bedrock map values along fluxgate	$\pm 30\,\mathrm{m}$	Twice the accuracy in ice thickness measurement of $\pm 15\,\mathrm{m}$ used to derive the bedrock map (Dunse et al., 2012), thereby accounting for uncertainties introduced by gridding of spatial inhomogeneous measurements.
H_{fg}	$zs_{\mathrm{fg}} - zb_{\mathrm{fg}}$	$\pm 42\,\mathrm{m}$	RSS of errors in zs_{fg} and zb_{fg}.
zs_{t}	30 m (constant)	$\pm 20\,\mathrm{m}$	Allows for calving front heights down to flotation and significantly larger than typical front height of 30 m (Moholdt and Kääb, 2012).
zb_{t}	-87 m (constant)	$\pm 30\,\mathrm{m}$	Value represents the mean bedrock elevation within the observed range in front position with an uncertainty analogue to the one of zb_{fg}.
H_{t}	$zs_{\mathrm{t}} - zb_{\mathrm{t}}$	$\pm 36\,\mathrm{m}$	RSS of errors in zs_{t} and zb_{t}.
v_{fg}	Local value from TSX velocity maps	$\pm 0.37\,\mathrm{m\,d^{-1}}$ (0.42 for t_3 and 0.44 for t_6)	Uncertainty based on standard deviation (std) of TSX and GPS velocities, yielding a $0.37\,\mathrm{m\,d^{-1}}$; for the long repeat cycles t_3 and t_6, additional uncertainty is added based on a comparison of the available data (51 and 46 % coverage) and reconstructed velocity profile, resulting in a std of 0.21 and $0.25\,\mathrm{m\,d^{-1}}$.
Front position	2 m resolution TSX backscatter image	± 8 m (4 pixels)	Digitizing error of calving front position results in uncertainty of ΔA_{cf}, determined by RSS of deviation from minimum and maximum extent of A_{cf} at times $t_{i,\mathrm{start}}$ and $t_{i,\mathrm{start}}$.

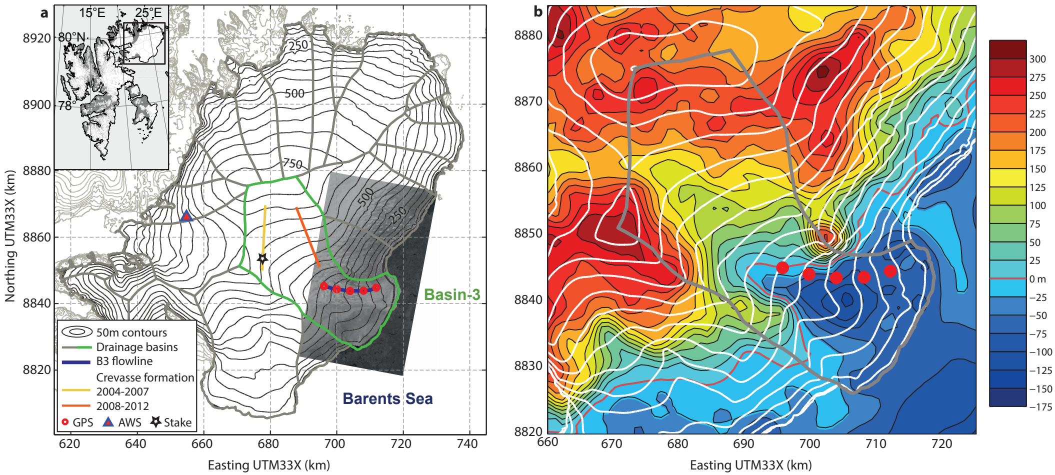

Fig. 1. Surface and bedrock topography of Austfonna/Basin-3. **(a)** Surface elevation contours at 50 m interval (solid black), overlain on a TerraSAR-X backscatter image (30 April 2012). The insert provides the ice cap's location within the Svalbard archipelago. Drainage basins are outlined in solid grey, solid green for Basin-3. Position of five GPS receivers and one stake on Basin-3, as well as the automatic weather station (AWS) are marked. Repeat-GPR profiling revealed crevasse formation in upper reaches of Basin-3 between 2004–2007 and 2008–2012 (Appendix D). **(b)** Bedrock contours (black, color-filled) are at 25 m intervals, with the bedrock sea-level contour highlighted in red and 50 m surface elevation contours superimposed (white).

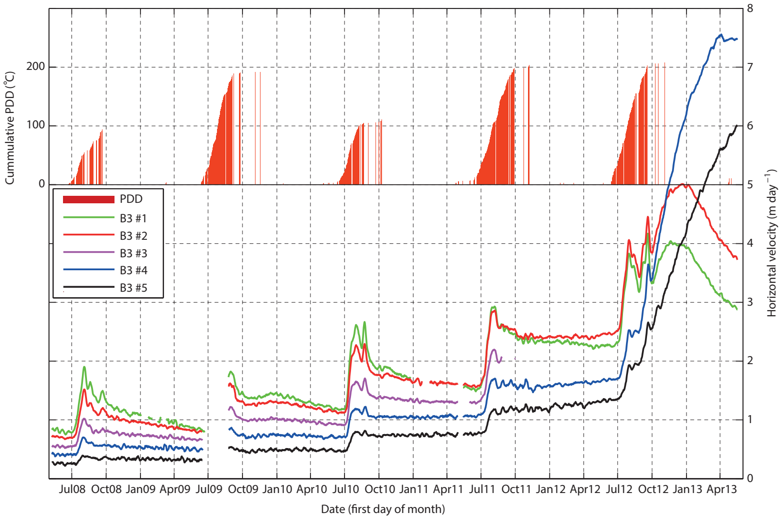

Fig. 2. Flow velocities along the centreline of the ~~ice stream~~ fast-flow region of Basin-3, Austfonna, between May 2008 and May 2013. GPS stations are numbered from 1 at lowest to 5 at highest elevation (Fig. 1). Red bars (upper panel) indicate potential melt days and cumulative positive degree days (PDD) for each summer, inferred from the temperature record of an automatic weather station.

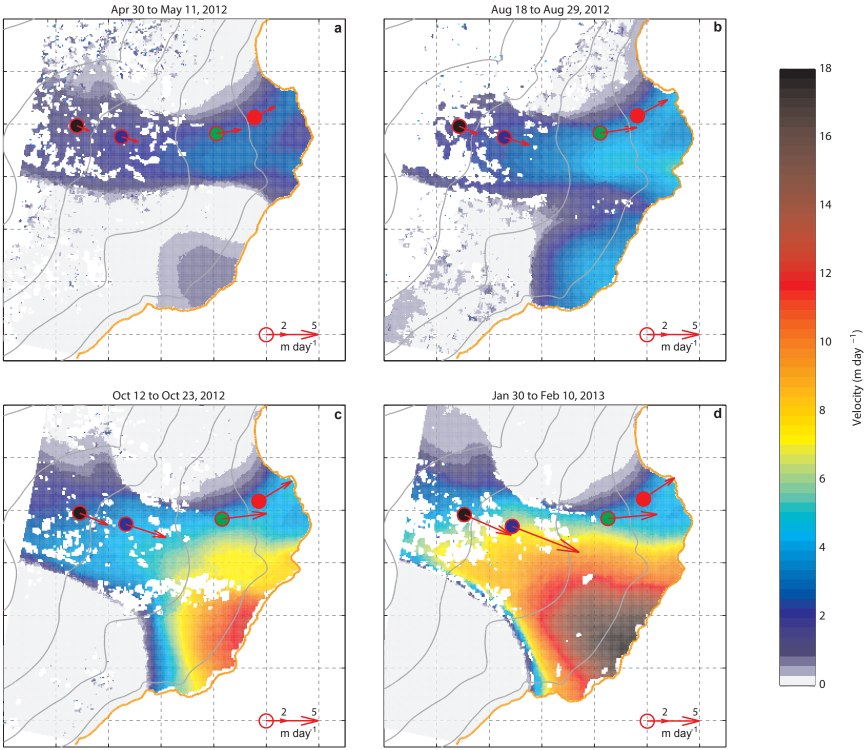

Fig. 3. Surface velocity fields of Basin-3, Austfonna, derived from TerraSAR-X feature tracking; **(a)** April/May 2012; **(b)** August; **(c)** October; and **(d)** January/February 2013. Red circles represent mean position of GPS receivers over the particular repeat-pass period, fillcolor according to color-coding of receivers in Fig. 2. The red arrows indicate associated GPS velocity vectors. Glacier elevation contours plotted in grey at 100 m intervals, front position at time of repeat pass in orange.

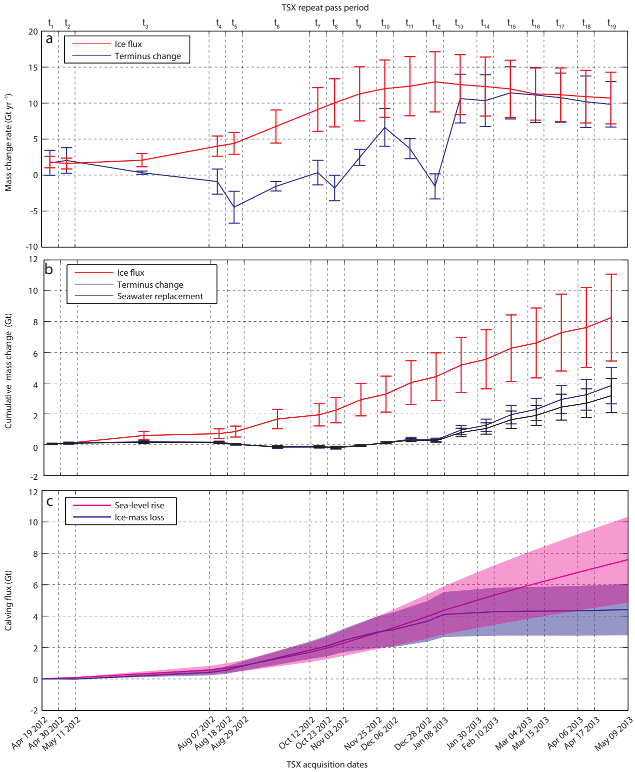

Fig. 4. Calving-flux from Basin-3, Austfonna, April 2012 to May 2013. Calving components are expressed in terms of the instantaneous **(a)** and cumulative mass change **(b)** and allocated to the effect on glacier mass balance and sea-level (**c**; see Sect. 4.3). Whiskers **(a, b)** indicate uncertainty bounds calculated using propagation-of-uncertainty analysis and shaded areas **(c)** upper and lower bounds given maximum or minimum ice thickness.

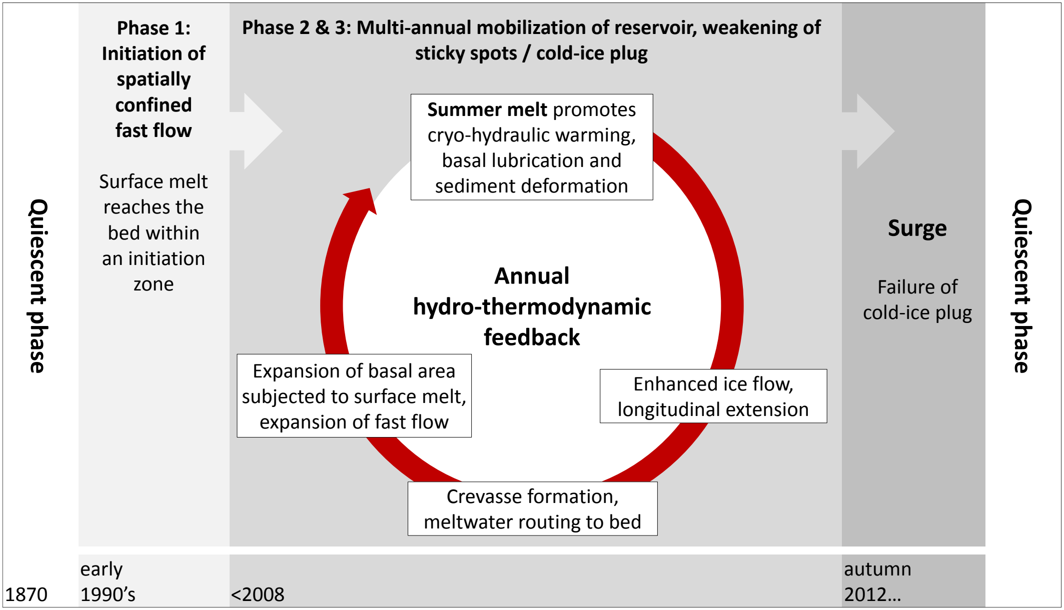

Fig. 5. Schematic illustration of the proposed hydro-thermodynamic feedback to summer melt, imbedded within the surge cycle of Basin-3, Austfonna. The approximate start of each phase is indicated at the bottom. Phase 1 follows from long-term changes in glacier geometry, i.e. built-up of a reservoir, and associated changes in driving stress and basal thermal regime. The hydro-thermodynamic feedback loop operates over several years during phase 2 and 3, each loop coinciding with consecutive summer melt periods. Successive mobilization and destabilization initiates the surge. Dynamic thinning, reduction in driving stress and basal heat dissipation eventually terminate the surge.

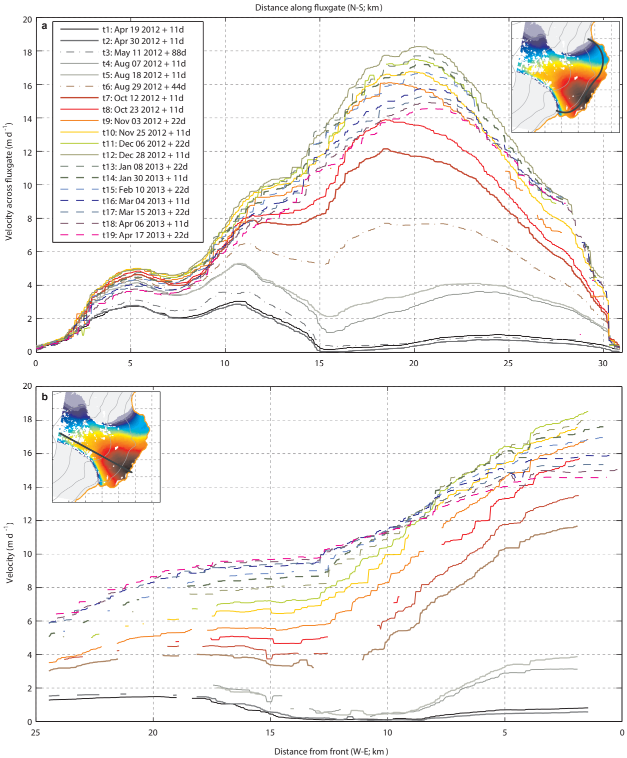

Fig. 6. Evolution of ice-flow velocities across a calving fluxgate **(a)** and along a central flowline of Basin-3 **(b)**. Velocity profiles extracted from TerraSAR-X velocity maps April 2012 to May 2013 and median filtered to remove outliers. The insert shows the location of the profiles overlain onto the velocity map of t_{14}. Fluxgate velocities are used to compute the calving ice flux. Velocities for long repeat passes t_3 and t_6 have been constructed as described in B2.

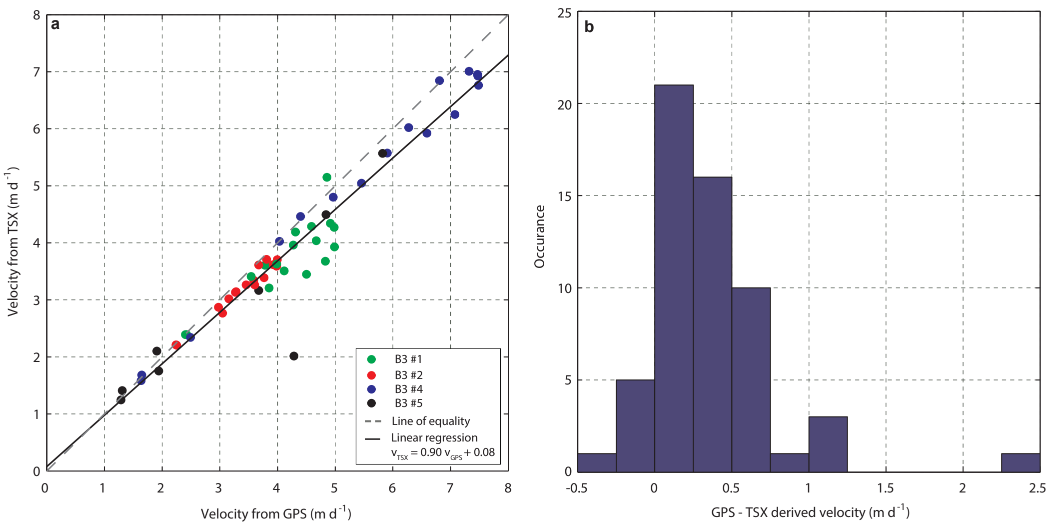

Fig. 7. Comparison of TSX and GPS velocities at GPS locations and for each repeat-pass period. **(a)** Linear regression (solid black; $R^2 = 0.94$) predicts 94 % of the variance in TSX velocities ($0.14\,\mathrm{m\,d^{-1}}$). **(b)** TSX velocities typically slightly underestimate local (sub-pixel scale) velocities measured at the GPS stations by $0.3\,\mathrm{m\,d^{-1}}$.

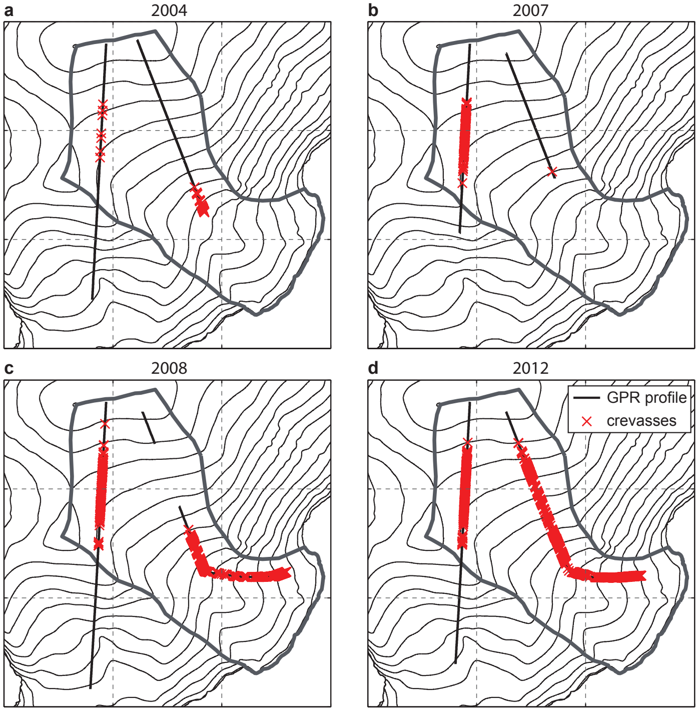

Fig. 8. Crevasse formation on upper Basin-3 in 2004–2012, inferred from GPR. GPR profiles are plotted in solid black, detected crevasses are marked by a red cross. The outline of Basin-3 is shown in dark grey.

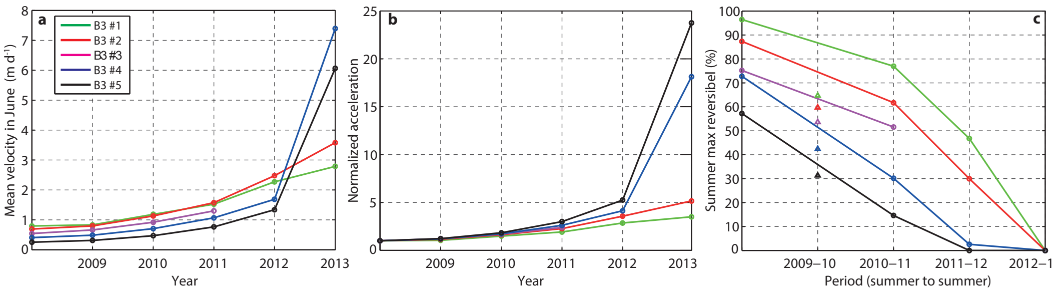

Fig. 9. GPS-velocity evolution along a central flowline of Basin-3; **(a)** annual velocity minimum defined as the mean value in June 2008 to 2013 and **(b)** normalized to mean-June velocity 2008; **(c)** reversibility of summer speed-up defined as the ratio of the velocity increase from pre-summer minimum (mean June) to maximum summer velocity and subsequent velocity decrease to pre-summer velocity of subsequent year. In 2009, summer maximum velocities were not captured due to GPS power loss. The triangles only indicate a minimum estimate for 2009–2010, based on elevated late-summer velocities measured after maintenance of GPS receivers in end of August.