The corresponding editor in The Cryosphere
Ref: MS# tc-2014-55

Dear Dr. Eric Larour,

Thank you for your time to handle our manuscript. We have attached the revised manuscript, and the author response to Reviewer#4 and the Editor comments including a marked-up manuscript version. Basically incorporating all of the comments, we revised the manuscript. Below is a summary of the significant changes we made in this revision, and then we show our point-by-point responses to the reviewers. We believe our revised manuscript is improved suitably for the publication in The Cryosphere.

***Figures***

The original Figure 2 in the previous manuscript was moved to the supplementary material, and renamed as a new Figure S6. This is because the original Figure 2 was difficult to demonstrate the winter speed-up signal at Chitina Glacier, which is pointed out by Reviewer#4. However, this figure also shows the active surging at Ottawa Glacier. Thus, we decided to move the figure to the supplementary material. Due to the movement of this figure, some of figure numbers were re-assigned.

We generated the new Figure 2, based on the original Figure 3a, b, and c. This figure is modified by adding three panels that show the temporal changes in ice speed at two distinct sections (lower and upper section at each glacier); this modification was also prompted by Reviewer#4 comment. Moreover, the original Figure 3d (about Logan Glacier) is moved to the supplementary material, adding a graph that shows the temporal change in ice speed. These are assigned as a new Figure S7. This is because the velocity data about Logan Glacier do not necessarily indicate in the quiescent phase, which we consider is not appropriate for the main text.

The original Figure 5 (about Agassiz and Donjek Glaciers) is deleted because the winter speed-up signals are not clearly demonstrated probably due to the coarse temporal resolution compared to those in the new Figure 2.

***Observation results***

We deleted some sentences about the original Figure 2, Figure 3d, and Figure 5 because these figures are now moved or deleted as mentioned above. Moreover, we added some sentences to explain the new Figure 2.

***Discussion***

We added some sentences in order to explain mini-surge and seasonality more clearly.

***Supplementary material***

Due to the movements of some figures, we added some sentences about them. Some of the figures numbers are re-assigned.

## The Point by point responses to the reviewer #4 and the Editor

Below are our responses to the reviewer #4 and the Editor comments. The blue sentences in italics indicate the reviewer and the Editor comments. We indicate in red where the additional explanations are inserted in the revised manuscript.

Reply To Reviewer #4's comments

*The authors have a nice dataset of ice velocities over several glaciers in Alaska and the Yukon. They use this dataset to investigate winter accelerations that occur in the upstream portions of many glaciers in their study area. The authors do highlight interesting velocity patterns, but I found the text hard to follow in many places.*

Thank you for your evaluation. We revised the manuscript to be more clearly, basically incorporating all of your comments.

*Note to authors: Unless it is a TCD requirement (which I don't believe it is), please use continuous line numbering. Your line numbering restarts on each new page, which is slightly annoying as a reviewer.*

This draft was written based on the template of TCD and such line numbering has already set. Our revised manuscript is set in continuous line numbering.

***Main Points:***

*What's the relevance to surge-type?*

*□ The abstract and introduction implies that the fact that the glaciers in your study are surge-type and in their quiescent phase is important. However, this characteristic is not revisited in the discussion, and I'm confused how a quiescent glacier can still move ~200 m/yr in its upper reaches. This seems pretty fast!*

Our data show that the winter speed-up is found every year at many surge-type glaciers, which suggests the winter speed-up may not be a rare phenomenon. Although we consider that the present temporal resolution does not allow us to detect the same signals as Lingle and Fatland, we interpreted our findings, following their hypothesis. We added one sentence at P8L237-238 and two sentences at P9L247-P10L252.

There is no quantitative definition about surge. The flow speed in active and quiescent phases is different at each glacier. We checked these speed data, and the intensity images to examine surface crevasses. Thus we recognized these were not in active phases, but in quiescent phases.

*Timescales and mechanisms:*

 *In many cases it seems like you're describing a seasonal cycle, not a mini-surge. How are you distinguishing between the two?*

Our dataset cannot distinguish repeatedly sporadic speed-up (i.e. mini-surge) from the gradual seasonal speed-up because of the coarse temporal resolution. We added some sentences at P7L195-199.

 *The discussion does a good job describing some mechanisms that could cause fast flow in the winter. However, I found the transition between mini-surge mechanisms and seasonal variability confusing. Perhaps the authors are also confused about these distinctions.*

Thank you. As mentioned above, our dataset cannot distinguish the two. We added some sentences at P7L195-199.

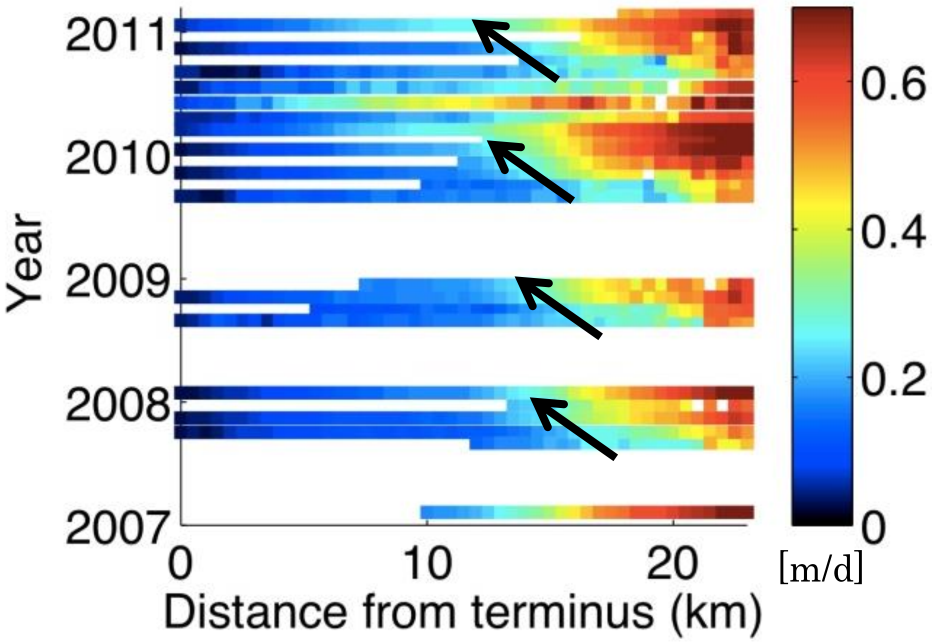
 *If the magnitude of the previous melt season is an important trigger for fast winter flow, can't you investigate this with a simple PDD model?*

Burgess et al. (GRL, 2013) has already studied the relation between volume of melt water and winter velocity with PDD calculation, and they found the negative correlation between them. The magnitude of the previous melt season may be some relations to that of the winter speed-up. However, our data show apparent accelerations in the upstream section from fall winter every year. Thus, we don't need to perform the PDD analysis.

*Propagation direction:*

*□ The velocities are not continuous, so inferring propagation direction and seasonal vs anomalous behavior is tricky.*

The new Figure 2a, which shows the spatial and temporal changes in the ice velocity at Anderson Glacier, is attached here.




The profile data area calculated with 500 m intervals along the flow line. Moreover, the x-label is modified from the original “Distance” to “Distance from terminus” (We think the word “distance” makes it confused to recognize flow direction). Thus, the left side indicates the terminus. The higher speed area (red-color) is clearly expanding toward downstream as winter progresses every year (Black arrows). This indicates the winter speed-up apparently propagates from upstream region to downstream.

We wrote this content at P6L154-158.

*Figure interpretation:*

*□ I had difficulty interpreting the flow direction in Figures 2-5. I assume that the flow is from left to right, but then had trouble following the discussion of up-flow surging and propagation.*

No, the flow is from right to left. We thus modified the labels from “Distance” to “Distance from terminus”.

*Organization:*

 *This paper presents interesting results and I hope the authors will address these points and resubmit the manuscript. The organization and writing throughout the manuscript needs improvement so that it is easier to follow. Observations that are obvious to the authors need to be described clearly for the reader. In addition, distinctions between seasonality and surging, mechanisms and timing need to be more clearly presented.*

Thank you for your valuable comments. We re-vised the manuscript in Observations and Discussions so that readers could easily understand what we would like to deliver. In Observation results, we revised the Figure 2 and related several sentences to clearly demonstrate the winter speed-up at the quiescent surge-type glaciers.

We cannot distinguish winter mini-surges and gradual seasonal speed-up because of the present coarse temporal resolution. However, it is important that our results clearly revealed flow velocity evolution from fall to winter, indicating the increase is not monotonously toward next summer. We added some sentences in Discussion at P7L195-199.

***Abstract**: I suggest rewriting this abstract. It is a bit unclear as it is now.*

We rewrote the abstract to make it clear.

*Line 9-10: Why does the summer speed-up make it difficult to understand the winter surge?*

We apologize for our poor wording. What we would like to describe is winter surge mechanism remains uncertain although the summer speed-up and its mechanism are well-understood. We re-wrote the sentence at P1L9-10.

*Line 10: no question was posed in the previous sentence*

This "question" means what we don't understand about winter surge. We modified the sentence at P1L10-11.

*12: the Yukon*

Done.

*13: "upstream acceleration" is confusing. Is the speed-up just located upstream, or is it migrating upstream?*

This means "acceleration in upstream region". We modified the sentence at P1L13.

*13: title implies all the glaciers are in their quiescent stage*

We would like to focus on the behaviors of surge-type glaciers during their quiescent phase. We thus moved some data during the active phases to the supplementary material.

*14: It's confusing to relate the winter speed-up to the summer seasonal acceleration. I suggest removing the first half of this sentence.*

What we would like to deliver is the propagation direction differs from that of summer speed-up. We deleted the first half of this sentence as you suggest at P1L14.

*15: delete "upstream" – there likely isn't meltwater input anywhere in winter*

Deleted.

*16: does not (not "do")*

Modified.

*17: delete "as winter occurs"*

Deleted.

*18: your findings (or results from models) won't affect future glacier dynamics (but might help us understand them!)*

We agree with you. We modified the sentence at P1L17-18.

***Introduction***

*21: sheets*

Done.

*21: "Ice flow…is typically greatest…"*

Done.

*23: the Zwally reference doesn't fit here (nor is the Bartholomaus one, really)*

OK. We deleted the two citations.

*27-9: I think all you really need is the brief description at the start about seasonality and efficient drainage systems. This part is a bit basic. If you want to keep it in, I suggest the following edits:*

*- delete "more and more" (too colloquial)*

Done.

*- change "that lead" to "causing"*

Done.

*- "These factors" – what factors? Be descriptive*

We modified this sentence to make it clear at P2L34.

*- It is awkward to pose questions in the middle of your introduction. Reword.*

We removed the question, because we discussed the winter speed measurement in the following paragraph.

*P2, line 8: "to be in between" is confusing. Specify that you're talking about the magnitude of ice flow.*

We modified the wording at P2L36.

*10: The Burgess paper is quite relevant here and should be described in more detail. Describe what they found in more specific terms.*

Burgess et al. (Nat. Comm., 2013) reported first velocity map over entire Alaska and the Yukon glacier using radar images. However, they didn't show spatial and temporal changes in ice velocity. We added one sentence about this at P2L42-44.

*12: delete "due to the harsh …"*

Deleted.

*17: Can you reword this to be in an active voice (Cavity closure and water pressure increase caused…)? It is confusing as is.*

We modified the original sentences at P2L48-49. In relation to this, we also added a new sentence at P2L51-54 that explains how the winter slow-down can be theoretically predicted, citing a new reference by Bartholomaus et al. (2011).

*21: reference*

We added a reference (Iken and Truffer, 1997) at P2L51.

*p3, line 3: advances*

Done.

*5: delete "there"*

Deleted.

*6-12: these are results and shouldn't be in the intro*

OK. We deleted these sentences. But, we mentioned that three glaciers were examined in detail at P3L70-72.

***Data sets and analysis method***

*26: Scenes were…*

Done.

*30: why were these mods used?*

Only these modes (FBS and FBD) can get high resolution images to be able to measure ice speeds in our study area.

We added some explanations at P3L91-P4L93.

*P4: I found the description of the pixel methodology confusing. What is the approximate pixel size? What is the difference between a search patch and sampling interval?*

One pixel size is about $4.7 \times 3.1$ m$^2$ for FBS and $9.4 \times 3.1$ m$^2$ for FBD. Search patch is a window to search a correlation peak. Sampling interval is a space when the search patch moves.

*9: Specify that this geometry was used for most glaciers.*

OK. We added a phrase "for most glaciers" at P4L102-103.

*13: "range dimension is the same as that of the FBS data"….which is what?*

FBD is a dual-polarization mode, whose range resolution is half of the FBS mode. Thus, we oversampled the FBD data in the range direction to analysis the pair between FBS and FBD data.

We added some explanations at P4L105-106.

*15: delete "That is"*
Deleted.

*16: delete "also"*
Deleted.

*20: "…there remained few topography-correlated artifact offsets" – this needs to be quantified.*
Remained artifact offsets are estimated about 0.3-0.4 m, which is written in the last of this section.

*25: replace thinning with "surface elevation change". If these are quiescent glaciers, why aren't they thickening?*
We replaced "thinning" with "surface elevation changes". Because the present data pair covers only 46 days, we can assume the horizontal displacement are much larger than vertical displacement.

*26-28: I don't understand this sentence at all. How can you average the area over a 1-D flowline?*
We modified the text as P4L121-P5L123.

*29-2: This sentence is awkward. It might be clearer to start the sentence at "The uncertainties of offset tracking are estimated to be between…" "Two data images" sounds awkward – are they data or scenes?*
OK. We modified the sentences to make it clear at P5L125-127.

***Observation results***

*P5, line 5: It's more focused if you reorder the sentence "Here we focus on…., although surging episodes occurred at…"*
We agree with you. We re-wrote the first paragraph at P5L131-137.

*7: Is Hubbard really a surge-type glacier?*
There is a report about the surging in 2009 in the upper tributary at Hubbard Glacier (http://glacierresearch.com/blog/Hubbard-2009-07-22). Thus, we consider it as surge-type. However, as pointed out, the main stream of Hubbard Glacier may not be

surge-type.

*11: "Major 17 glaciers are shown in Figure 1"?????*

We apologize for our mistake. "The names of" major 17 glaciers are shown in Figure 1. We added the phrase at P5L135.

*13: delete "Notice that" – the reader doesn't like to be told what to do!*

We deleted it.

*Figure 2: I had a hard time seeing this trend that you mention. It might be clearer if you show the velocity pattern as a timeseries plot.*

OK. The original Figure 2 is moved to the supplementary material as the new Figure S5. We only use the new Figure 2 in order to explain the seasonal trend at Chitina Glacier.

*18-24: This is speculation/interpretation so should be moved to the discussion*

We agree with you. This part was deleted.

*25-30: I'm confused why the author is focused on fall vs winter speeds. Oftentimes the fall speeds are the slowest of alpine glaciers because of efficient drainage networks.*

This was pointed out by Reviewer #1 and we are aware that the seasonal minimum is in late summer to fall, which is referred in some papers (Iken and Truffer, J. Glacio.1997; Truffer et al., J. Glacio., 2005; Sundal et al., Nature, 2011; Sole et al., GRL, 2013; Burgess et al., GRL, 2013), and the surge "initiation" or, initiation of winter speed-up can be explained by cavity closure and subsequent water pressure increase. However, as explained in the Introduction, it is still an open question why and how the water pressure increase and subsequent speed-up can be maintained without any input of meltwater from the surface. Indeed, Kamb (JGR, 1987) stated in the Introduction of his seminal paper, "*The discussion concentrates on the mechanisms of surging in spring and summer when relatively large amounts of water are available to the basal water conduit system.*" Kamb's theory is based on the observations of the 1982-83 surge at the Variegated Glacier. The figures in Kamb et al (Science, 1985) actually indicate that the flow velocity seems constant during January to March but reveal acceleration only after April. Our dataset is apparently different from those in previous studies, which has already written at P7L200-214.

*- Figure 3: is this distance along the flowline (so 25 km is more downstream?). this is what I am guessing, but was confused by it in the text.*

We apologize for inconvenience. The “Distance’ in the x-label means distance from terminus. Thus, the profiles show the flow speed from the terminus (left side) to the upper area (right). We modified the label in the new Figure 2.

*- 30: It’s hard to tell that the winter speed is >50% greater than the fall speed on Walsh Glacier. The record is pretty spotty. It’s definitely faster than the summer velocity. If this is a big part of your story, I suggest also plotting it as a graph – perhaps with the x-axis as month and y-axis as velocity. Plot each year as a different line.*

Given your suggestions, we generated the new Figure 2 that includes velocity time-series both upstream and downstream (Fig. 2b, d, and f). It is clear that the winter speed is more 50% greater than the fall speed on Walsh Glacier.

*P6, line 1: This writing is awkward. Just state the differences between seasonal trends, don’t ask the reader to do it.*

OK. We modified this sentence at P5L146-147.

*2: for all glaciers? I don’t see that (downstream speeds in summer are faster in winter)*

In the new figure 2b, d, and f, the downstream speeds in summer are faster in winter in 2010. The velocity data in other years could not derived as mentioned at P6L159-161.

*4: This is where I got confused about what is upstream. Is “20-km point upstream” at distance of 5 km in the figure, or 20-km in the figure. If the latter, delete “upstream”.*

We agree with you. We modified this sentence at P5L149-151.

*10: I don’t understand how you infer propagation direction from this data/figure?*

We also apologize for inconvenience. The reply to this comment is written in Propagation direction in Main points.

*14: I also don't understand how this is interpreted as a surging episode?*

The data for Logan is now moved to the supplementary material, because they were not completely during the quiescent phase.

In 2007 and 2008 winter, the speed about 20 km point from the terminus is about 0.4 m/d. However, it is up to 0.8 m/d in 2010 and 2011. The winter speeds appear to increase from one year to the next. This is a clear feature for surging. Thus we consider it as the initiation of a new surging episode. This part is moved to the supplementary material at P3L82-88. Also, we personally learned from Evan Burgess that the Logan Glacier was indeed surging after the analyzed period.

*15-20: I'm confused by this paragraph and the phrase that "glacier dynamics at lower reaches are consistent with previous findings". Maybe start out by saying what the seasonal trends are and then state that your spotty record seems to match this. It's a tough transition from the previous paragraph, which focuses on surging episodes and unique winter velocities, to this paragraph about "typical" seasonality patterns. Which is it?*

OK. We no longer discussed the surging glacier in the previous paragraph. We modified the paragraph at P6L159-165.

*27: So, maybe this is just the seasonal trend, not a surging episode. How are you distinguishing the two?*

As pointed out, the speed in the original Fig4e (in the New Fig. 3e) may be just the seasonal change. Thus we can't distinguish the seasonal change from (mini-)surge. However, it is important that the winter speed is 33%-66% larger than that in previous Aug-Oct "every year". We changed "is most likely" to "may be" at P6L169.

*28: Fragment*

We deleted the original Figure 5 and the following sentences because the winter speed-up signals in the original Figure 5 are not so clear that we consider it hard to explain the winter speed-up.

***Discussions***

*The discussion is actually well thought out and addresses several potential mechanisms for the winter speed-up. It just needs to be better organized so that there is a clear distinction between surges and seasonality.*

Thank you for your comments. We revised the Discussions.

*p7, line 12: What does Variegated have to do with this?*
We agree with you. We deleted this sentence.

*12-15: Again, I don't understand the propagation direction conclusion*
The reply to this comment is written in Propagation direction in Main points.

*16: How did you calculate this?*
Ice speed is proportional to $H^4$ ($H$: ice thickness, Cuffey and Paterson, 2010) and the thickness is about a few hundred meters in this area. Thus, it is clear that the speed-up is not caused by snow accumulation. We added a phrase, "considering that the ice thickness in the area is a few hundred meters or more" at P6L183-184.

*25: pointed out by*
Done.

*17-26: This description of mini-surges only loosely relates to your story here. Your observed speed-ups seem to last longer than 1 day and are more repeatable.*
We can't distinguish sporadic speed-up event from gradual seasonal speed-up because of the coarse temporal resolution of our dataset.

*29: reaching a maximum*
Done.

*p8, 1-10: can't you test this by comparing your speed change with PDD estimates?*
This answer is written in the response against *Main points*.

Reply To the Editor comments

*General remarks:*
*Introduction: very fluid, and introduces the concepts succinctly but very clearly. I agree this is much improved.*
*Data sets and Analysis method: the passage on uncertainty and error estimates is very useful, and is a good addition.*
*Observation results: this section is much more focused indeed, and the move to the Supplementary materials was indeed judicious. It is now clear what the observation's main focus is for the manuscript, and what the message is.*
*Discussion: this section is much less speculative, and has been simplified very well, driving the message across efficiently. The process presented here that could explain the winter speed-up is layed out with the necessary precautions, without excluding other processes such as till deformation for example.*
Thank you for your evaluation.

*Concerns raised by all reviewers:*
*- you correctly address the issue over whether the presented dataset is an original contribution, by stressing the fact that previous work is not extensive in terms of winter speed-up, which is the main contribution of your manuscript.*
*- you also correctly reassessed whether the winter speed-up observations were real signals and could indeed be compared to summer speeds. I believe you have done your due diligence on the dataset, and that the manuscript is now ready to stand the scrutiny of further reads once published. The considerable rework on the citations of previous work by Kamb, Raymond helped in this matter.*
*- considerable work was carried out on the citations, especially to address concerns from reviewer #3, and the flow of the manuscript, and the correct interpretation of the work cited is now much more evident.*
*- in terms of vertical motion, I understand it was neglected, but if you have the velocity maps (in x,y axis), using the divergence of the velocity, you can actually assess what is the expected vertical velocity for a steady-state regime. It would be nice to have such assessment in order to verify that your assumptions on the approximation are valid. A small section on this would be important I believe.*
Thank you for the suggestion. We think it is one of future works.

*Concerns that need to be addressed regarding review #4: apart from the detailed remarks regarding the manuscript, which will need to be addressed before this is pushed for final publication, I would like to following concern addressed thoroughly:*
*- how is the seasonal cycle of a glacier different from potential mini-surges that are here probably captured in the velocity signal.*
*- how can a glacier classified as quiescent be flowing at 200 m/yr.*
*In terms of PDD analysis, I don't believe this to be critical. If the authors would like to carry out such analysis to understand how melt-water from one season can be a trigger for the fast winter flow, I will understand, but I don't see it here as a requisite for publication.*

The reply to the reviewer #4 comments is written in the former part of this letter. I agree with you and we don't carry out the PDD analysis.

*Figures: the figures are very good quality, except maybe for Fig. 2 which has in my opinion too many frames. I would make it a 5x4 array instead of a 8x4 array. It would not take away from the main message of the manuscript, and would allow for a better assessment of the speed-ups in winter.*

The original Figure 2 was moved to the supplementary material, and renamed as the new Figure S5. This is because the original Figure 2 also shows the active surging at Ottawa Glacier, and we consider that it doesn't need to be deleted. In the main text, the new Figure 2 is only needed to explain the winter speed-up.

*Detailed remarks:*

*p3. l14: "the St. Elias Mountains"*

Done.

*p3. l15: due to global warming*

Done.

*p7. l30: reaching a maximum*

Done.

*p9. l12: at the ice-till interface*

Done.

Best regards,

Takahiro Abe and Masato Furuya

# Winter speed-up of quiescent surge-type glaciers in Yukon, Canada

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## Abstract

Glacier surges often initiate in winter, but~~ due to the normal summer speed-up, their mechanism remains unclear~~ the mechanism remains unclear in contrast to the well-known summer speed-up at normal glaciers. To better understand the mechanism~~To address this question~~, we used radar images to examine spatial-temporal changes in the ice velocity of surge-type glaciers near the border of Alaska and the Yukon, focusing on their quiescent phase. We found significant ~~upstream~~ accelerations in upstream region from fall to winter, regardless of surging episodes. Moreover, ~~whereas the summer speed-up was observed downstream,~~ the winter speed-up propagated from upstream to downstream. Given the absence of ~~upstream~~ surface meltwater input in winter, we suggest the presence of water storage near the base that does not directly connect to the surface yet can promote basal sliding through increased water pressure~~ as winter occurs~~. Our findings have implications for modeling of glacial hydrology in winter, which may help~~affect~~ us better understand glacier dynamics~~future glacier dynamics~~.

## Introduction

Ice flow on mountain glaciers and ice sheets typically~~ has its~~shows greatest acceleration from spring to early summer, followed by deceleration in mid-summer to fall (e.g., Iken and Bindschadler, 1986; ~~Zwally et al., 2002;~~ MacGregor et al., 2005~~; Bartholomaus et al., 2008~~; Sundal et al., 2011). These speed changes are attributed to subglacial slip associated with water pressure changes, and these changes arise from seasonal variability of meltwater input and the evolution of the subglacial hydraulic system (Schoof, 2010; Bartholomaus et al., 2011; Hewitt, 2013; Werder et al., 2013). From spring to early summer, meltwater from the surface reaches the bed, and develops an “inefficient” drainage system, in which water flow channels are not well developed, producing a high basal water pressure. The high water pressure increases basal slip, which increases the surface velocity. As the amount of meltwater increases, the basal drainage system becomes ~~more and more~~ “efficient” due to the enlarging channels (Röthlisberger, 1972). The larger channels allow a higher meltwater flux with lower water pressure ~~that lead~~causing to a gradual decrease in the surface velocity. In late summer to fall, when the meltwater input terminates, the surface velocity has its yearly minimum. Meltwater input and subsequent evolution of the drainage system apparently~~These factors~~ influence surface ice speeds from spring to fall.~~, but what factors control the ice speeds in winter?~~

Several studies reported that surface ice speeds in winter ~~to be~~were in between the early summer maximum and early fall minimum (e.g., Iken and Truffer, 1997; Sundal et al., 2011; Burgess et al., 2013a). Some recent studies also indicate that the amount of surface meltwater in summer can influence the velocity evolution in winter, in a way that reduces the annual ice flow (Burgess et al., 2013b; Sole et al., 2013). However, ~~Due to the harsh environment and logistic problems, ~~there have been relatively few comprehensive velocity measurements throughout wintertime particularly in the middle-to-upstream regions of mountain glaciers. Although the first velocity map over entire Alaska and the Yukon glaciers was shown by Burgess et al. (2013a), they didn’t show the spatial and temporal changes in ice velocity.

Nevertheless, it is well-known that glacier surges often initiate in winter, exhibiting orders-of-magnitude speed-up and resulting in km-scale terminus advance (Meier and Post, 1969; Raymond, 1987). In order to interpret ~~B~~both the wintertime surge initiation and the intermediate values of winter speed,~~ have been interpreted as being caused by~~ cavity closure and ~~the~~ subsequent water pressure increase are often envisaged, starting with the surge mechanism proposed for the 1982-83 surge at the Variegated Glacier by Kamb et al. (1985). Even in winter, there may be some remnants of summer meltwater that can increase the water pressure (Iken and Truffer, 1997). However, in the absence of meltwater input, the subglacial cavities are increasingly disconnected in winter, resulting in a ‘stickier’ bed even if the water pressure in each cavity becomes locally high (Bartholomaus et al., 2011). Hence, it remains an open question why and how the water pressure increase and subsequent speed-up can be maintained without further input of meltwater from the surface. Do the surface velocities monotonously increase from later summer to the next spring? Such an increase is often assumed, but the process would require some extra sources of water to maintain the higher water pressure. The wintertime dynamics of sub- and englacial water are thus yet to be fully understood. Reaching an understanding requires new continuous measurements.

The St. Elias Mountains near the border of Alaska, USA, and the Yukon, Canada (Fig. 1) contain numerous surge-type glaciers (Meier and Post, 1969). But only a few of these have been studied and reported in the literature (e.g., Clarke et al., 1984; Truffer et al., 2000; Flowers et al., 2011; Burgess et al., 2012). Our understanding of surge-type glacier dynamics is still limited (Raymond, 1987; Harrison and Post, 2003; Cuffey and Paterson, 2010), because few detailed observations have been performed over a complete surge-cycle.

Recent advances in remote sensing techniques allow us to survey the ice-velocity distribution over the entire St. Elias Mountains. Here we present the spatial and temporal changes in the ice velocity for the surge-type glaciers ~~there~~, focusing particularly on the seasonal cycle during the quiescent phases to better understand the wintertime behavior. The three glaciers (Chitina, Anderson, and Walsh) are examined in detail to reveal the speed changes at the upper and the lower regions. On the other hand, the active surging occurred at four glaciers (Lowell, Tweedsmuir, Ottawa, and Logan) in the analysis period, and the details of these glaciers are described in the supplementary material.~~Three glaciers (Chitina, Anderson, and Walsh) significantly accelerate in the upstream from fall to winter, with speeds that are comparable to, and sometimes higher than those in the next spring to early summer. This is apparently in contrast to previously observed winter velocities (e.g., Iken and Truffer, 1997; Sundal et al., 2011) that appeared to be significantly slower than the velocities in spring and early summer. We interpret these observations by speculating the presence of englacial water storage, and discuss its implications for the surge mechanisms.~~

Understanding the dynamics of surge-type glaciers is also important to better simulate future ice dynamics in the St. Elias Mountains. Significant contributions of the Alaskan glaciers' retreat to the possible sea-level rise due to ~~the~~ global warming have been estimated (Radić and Hock, 2011), but projections of glacier mass balance assume non-surge type glaciers whose dynamics are only affected by long-term climate changes. Although the dynamics of surge-type glaciers itself is not directly related to the climate change, there have been several pieces of evidence for the impact of climate change on surge cycle (e.g., Harrison and Post, 2003; Frappé and Clarke, 2007).

## Data sets and analysis method

### ALOS/PALSAR data

We processed phased array-type L-band (wavelength 23.6 cm) synthetic aperture radar (PALSAR) images from the Advanced Land Observation Satellite (ALOS) operated by the Japan Aerospace Exploration Agency (JAXA). Scenes ~~Data was~~were acquired along multiple paths (Fig. 1, Table 1). ALOS was launched on January 2006, and its operation was terminated on May 2011. Thus, the datasets for the study area were acquired only from December 2006 to March 2011. The details of the datasets are listed in Table 1. Only the FBS (fine-beam single-polarization mode) and FBD (fine-beam dual-polarization mode) data are used in this study because their higher spatial resolutions allowed us to reliably measure the flow velocities. We use Gamma software to process level 1.0 data to generate single look complex images (Wegmüller and Werner, 1997) and run pixel-offset tracking analyses. See Table 1 for more detail of the datasets.

### Pixel offset tracking

The pixel-offset tracking (or feature or speckle tracking) algorithms used in this study are based on maximizing the cross-correlation of intensity image patches. The method closely follows that used by Strozzi et al. (2002) and Yasuda and Furuya (2013). We used a search patch ~~–~~of 64 × 192 pixels (range × azimuth) with a sampling interval of 4 × 12 pixels for most glaciers. But, due to its larger size for Hubbard Glacier, we used a search patch of 128 × 384 pixels. We set 4.0 as the threshold of the signal-to-noise ratio and patches below this level were treated as missing data. The FBD data are oversampled in the range direction (i.e., satellite to ground direction) due to the difference of the range dimension so that it~~the range dimension~~ is the same as that of the FBS data.

In the pixel-offset tracking, we corrected for a stereoscopic effect known as an artifact offset over rugged terrain (Strozzi et al., 2002). ~~That is, because of~~ This is caused by the separation between satellite orbital paths, and the effect of foreshortening also generates~~differs~~ ~~in~~ the offsets. We reduced the artifact by applying an elevation-dependent correction, incorporating the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global digital elevation model (GDEM) version 2 data with 30-m resolution. We applied the same method described by Kobayashi et al. (2009) and confirmed that there remained few topography-correlated artifact offsets.

Using both range and azimuth offset data, we derived the surface velocity data (Fig. 1) by assuming no vertical displacements. The studied glaciers are gently sloped at approximately 1-2 degrees, and thus, the vertical component is much smaller than the horizontal component. In addition, we derived the velocity map using image pairs that were temporally separated by at most 138 days. The glaciers' ~~thinning~~ surface elevation change during this period should be negligibly small in comparison to the horizontal movement of the glaciers. To examine the spatial and temporal changes, we first set a flow line at each glacier, and then ~~We~~ averaged the velocity pixel data over the ~350 × 350-m$^2$ area with its center at~~along~~ the flow line. We~~and, from the standard deviation at each area,~~ estimated the measurement error to be below 0.1 m/d~~.~~, from the standard deviation at each area.

Using ~~two data images with ALOS/PALSAR's 46-day intervals acquired at non-deforming areas (Kobayashi et al., 2009), t~~The uncertainties of offset tracking ~~data in the rugged terrain~~ have been estimated to be ~0.3-0.4 m in the rugged terrain, using two images with ALOS/PALSAR's 46-day interval at non-deforming area (Kobayashi et al., 2009). Assuming linear temporal evolution, the errors in the velocity estimate are inferred to be below 0.1 m/d.

## Observation results

~~Although surging episodes occurred at Lowell, Tweedsmuir, and Ottawa, here we focus on winter speed-up signals at surge-type glaciers that were in their quiescent phase during the analysis period. These occurred at seven glaciers (Chitina, Anderson, Walsh, Logan, Hubbard, Agassiz, and Donjek). The Chitina, Anderson, Walsh, and Logan Glaciers, which are the major surge-type glaciers of the Chitina River valley system (Clarke and Holdsworth, 2002),~~

~~could be examined with the highest temporal resolution because of the overlap of multiple satellite tracks. Major 17 glaciers in the region are shown in Figure 1.~~

Here we focus on winter speed-up signals at surge-type glaciers that were in their quiescent phase during the analysis period. The Chitina, Anderson, and Walsh Glaciers are the major surge-type glaciers of the Chitina River valley system (Clarke and Holdsworth, 2002), and could be examined with the highest temporal resolution because of the overlap of multiple satellite tracks. The names of major 17 glaciers in the region are shown in Figure 1. The active surging occurred at four glaciers (Lowell, Tweedsmuir, Ottawa, and Logan), and the details of these glaciers are described in the supplementary material.

~~Figure 2 shows flow velocity at Chitina Glacier from oldest at top left to most recent at bottom right. Notice that the flow velocity in the upstream gradually increases from fall to winter every year (Fig. 2c-f, g-j, k-o, u-z). Starting in fall 2009, the velocity increases at the confluence between Chitina and Ottawa Glacier (Fig. 2l). On Feb-Mar 2010, it speeds up to 4 m/d at Ottawa Glacier (Fig. 2p-q), which we regard as a glacier surge (see the supplementary material). At the same time, the velocity in the upstream region of Chitina Glacier gradually increases as winter approaches (Fig. 2k-o). In contrast to the surge, the winter speed-up occurs every winter, which thus indicates that the wintertime acceleration in the upstream of Chitina Glacier is independent of the surge at Ottawa Glacier. Moreover, the winter speed in the upstream region is comparable to and sometimes higher than that in spring/early summer in 2010 (Fig. 2s), which we believe had not been observed before. The higher speed in the middle to downstream (Fig. 2q-t) may have been triggered by the surge at Ottawa Glacier. Similarly high winter speeds were also detected at other surge-type glaciers.~~

~~Figure 3 shows the spatial-temporal evolution of ice velocity of four glaciers along their flow lines. At Chitina Glacier, the winter velocities in the upstream region exceed 0.5 m/d, which is significantly greater than the fall velocities of ~0.3 m/d regardless of the surge signal at Ottawa glacier (Fig. 2l-t, Fig. 3a). At the 20-km point upstream on Anderson Glacier (Fig. 3b), the winter speed is more than double the fall speed. Along the upstream segment on Walsh Glacier (Fig. 3c), the winter speed is more than 50% greater than the fall speed.~~

~~Consider the distinction between upstream and downstream seasonal trends. Although the downstream speeds in early summer are faster than those in winter, the upstream speeds in winter are comparable to, and sometimes faster than those in early summer. For instance, at the 20-km point upstream on Anderson Glacier, the velocity is ~0.5 m/d in early summer~~

~~2010 but exceeds 0.7 m/d in winter of 2009/2010 and 2010/2011. Similarly, at 20-25 km upstream on Walsh Glacier, the velocity is 0.3-0.5 m/d in early summer 2010 but 0.6-0.8 m/d in winter. Moreover, in contrast to the upglacier propagation of summer speed-up observed in the ablation zone of glaciers in Greenland (Bartholomew et al., 2010), here the higher-velocity area expands from upstream in fall to downstream in winter. This downglacier propagation is clearest at Anderson Glacier (Fig. 3b). These trends apply to longer glaciers as well. Logan Glacier, with nearly twice the length of the above three glaciers, has a broad segment in the middle that accelerates from fall to winter (Fig. 3d). In addition, the winter velocities appear to increase from one year to the next, indicating the initiation of a new surging episode (Fig. 3d).~~

Figures 2a, 2c, and 2e show the spatial-temporal evolution of ice velocity at the three glaciers (Anderson, Chitina and Walsh) along their flow lines shown in Figure 1. At the 20-km point on Anderson Glacier (Fig. 2a), the winter speed is more than double the fall speed. At Chitina Glacier (Fig. 2c), the winter velocities at the 20-km point exceed 0.5 m/d, which is significantly greater than the fall velocities of ~0.3 m/d regardless of the surge signal at Ottawa glacier in 2010 (Black circle in Fig. 2c). At the 20-km point on Walsh Glacier (Fig. 2e), the winter speed is more than 50% greater than the fall speed.

Figure 2b, 2d, and 2f are time-series plots averaged over the downstream (blue) and upstream (red) section in Figs. 2a, 2c, and 2e, respectively. We can recognize the distinct seasonal trends in the upstream and downstream. Although the downstream speeds (blue) in early summer are faster than those in winter, the upstream speeds (red) in winter are comparable to, and sometimes faster than those in early summer (Fig. 2b, d, and f). For instance, over the 18-21 km section on Anderson Glacier, the velocity is ~0.5 m/d in early summer 2010 but exceeds 0.7 m/d in winter of 2009/2010 and 2010/2011 (Fig. 2b). Over the 18-21 km section on Chitina Glacier, the velocity is ~0.5 m/d in early summer 2010 but is also in winter of 2009/2010 and 2010/2011 (Fig. 2d). Similarly, over the 21-24 km section on Walsh Glacier, the velocity is 0.4 m/d in early summer 2010 but 0.6 m/d in winter (Fig. 2f). Moreover, in contrast to the propagation toward upstream region of the summer speed-up observed in Greenland outlet glacier (Bartholomew et al., 2010), the higher-velocity area expands from upstream in fall to downstream section in winter. This propagation toward downstream is most clearly observed at Anderson Glacier (Fig. 2a).

~~Although we could not obtain quality summer velocity data for each year due to large intensity changes associated with surface melting, the glacier dynamics at lower reaches is consistent with previous findings. For example, Figure 3 shows summer speed-up signals in 2010 in the lower to middle reaches of each glacier. In addition, compared to the gradual downglacier propagation of the winter speed-up noted above, the summer speed-up in the lower reaches appears to occur primarily over a shorter period.~~ We could not obtain quality and much summer velocity data for each year due to large intensity changes associated with surface melting and due to the data availability problem except the year 2010. Figure 2 shows summer speed-up signals in 2010 in the lower middle reaches at each glacier. In addition, compared to the gradual propagation of the winter speed-up toward downglacier noted above, the summer speed-up in the lower reaches appears to occur primarily over a shorter period. The glacier dynamics at lower reaches thus seems to be consistent with previous findings.

For Hubbard Glacier, the only tidewater glacier in the study area, the ~15 km-length section in the midstream region has velocities in January and February that are ~33-60% greater than the velocities of the previous August to October (Figs. 3~~4~~a, d, e, and h). The significant speed-up during the 2009 winter may be ~~is most likely~~ associated with a small surge in the upper tributary (Fig. 3~~4~~e). The much smaller tributary in the upper reach of Malaspina Glacier (Fig. 1) also exhibits greater velocities in winter, ~~as does Agassiz and Donjek Glacier (Fig. 1, Fig. 5),~~ suggesting that the winter speed-up mechanism is independent of the glacier's size.

~~Consider Agassiz and Donjek Glacier. At Agassiz Glacier, the winter midstream speed-up and downglacier propagation occur from fall to winter in the 2007-2008, 2009-2010, and 2010-2011 seasons (Fig. 5a). Moreover, the winter velocities in 2008 and 2011 are clearly greater than the fall velocities in the corresponding years. The greater velocities in the summer 2010 indicate a summer speed-up. The greatest seasonal fluctuations occur near 10 km, outlined in black in the figure. At Donjek Glacier, the black-squared segment mid-glacier (Fig. 5b) shows winter velocities that are greater than the fall velocities. However, the downglacier propagation is not clear in the Donjek case.~~

## Discussion

According to the average air temperature at Yakutat Airport provided by The Alaska Climate Research Center data (http://akclimate.org), the monthly average temperature from 2006-2011 is about 0.2 ℃ in November, and about -2 ℃ for December, January, and February. Almost all of our study area is above 1000 m a.s.l.~~, except Agassiz Glacier, which extends from 450 to 1100 m a.s.l.~~ Thus, the wintertime temperature is significantly below freezing, so there should be little surface meltwater during winter. ~~Moreover, each glacier's location in this study is much higher than that at Variegated Glacier, which is a temperate glacier.~~ Under such circumstances, it is likely that the mechanisms of winter speed-up and its downglacier propagation are different from those of the summer speed-up that usually propagates upglacier. Also, the detected annual winter speed-up in the upstream is up to 100% too high to be explained by snow accumulation, considering that the ice thickness in the area is a few hundred meters or more~~.~~

The observed winter speed-up in the upstream region may be regarded as a "mini-surge" (Humphrey and Raymond, 1994). However, not all previously reported mini-surges occurred in winter. For instance, the mini-surges prior to the 1982-1983 surge at Variegated Glacier occurred in summer (Kamb et al., 1985; Kamb and Engelhardt, 1987). A mini-surge defined in Kamb and Engelhardt's paper indicates dramatically accelerated motion for a roughly 1-day period, which occurred repeatedly during June and July in 1978-81. Although Kamb et al. (1985) noted an anomalous increase in wintertime velocities since 1978, the measurements were done only once in September and once in June (Raymond and Harrison, 1988), and thus they may include the spring speed-up signals as pointed out by Harrison and Post (2003). To the best of our knowledge, no comprehensive wintertime velocity observations have been done in upstream regions. However, even if sporadic speed-up events repeatedly occur from fall to winter, we cannot distinguish them from gradual seasonal speed-up because of the present coarse temporal resolution. Nevertheless, it is important that our results clearly revealed flow velocity evolution from fall to winter, indicating the increase is not monotonously toward next summer.~~No comprehensive wintertime velocity observations have been done upstream.~~

~~We~~ now compare our findings to previous studies. Iken and Truffer (1997) found a gradual speed-up from fall to winter at the ~2-km-long downstream section of the temperate Findelengletcher in Switzerland, where the speed continues to increase, reaching a~~s~~ maximum in summer. In contrast, our observed winter speed-up occurs in the upstream region, and speed does not continue to increase after winter. Sundal et al. (2011) examined how ice speed-up and meltwater runoff are related at land-terminating glaciers in Greenland. The ice speed-up is affected by the amount of surface runoff each year, which differs between high and low melting years. The results indicate that the ice speed in a high melting year gradually increases from fall to winter. However, the ice speed does not accelerate in low melting years. Moreover, they did not report the spatial distribution of speed during winter, and the maximum speed is apparently observed in early spring to summer. Our velocity data do not simply indicate the gradual speed-up from fall to next spring. The winter speed-up initiates upstream, and the maximum speed in winter is comparable to that in early summer. As some of the glaciers could not be examined with a high temporal resolution, it is likely that there are other winter speed-up glaciers.

How can we explain the observed winter speed-up signals? First, we argue that the mechanism proposed by Kamb et al. (1985) for the Variegated Glacier does not apply here. In that mechanism, the efficient tunnel-shaped drainage system, which is present in summer, may provide a less efficient distributed system in early winter due to depletion of surface meltwater and the destruction of conduits by creep closure. Thus, the subglacial water pressure may greatly increase. For our observed winter speed-up to be explained by this mechanism, there would have to be an efficient drainage system. Although such an efficient drainage system is often observed near the terminus (Raymond et al., 1995; Werder et al., 2013), the winter speed-up is observed upstream, far from the terminus. In addition, even if there exist~~s~~ meltwater remnants in the upstream region, it is unclear how the subsequent speed-up can be maintained without further input of meltwater from the surface. In the absence of meltwater input, subglacial cavities will be increasingly disconnected (Bartholomaus et al., 2011). Thus, we need to consider a mechanism that can trap water in the upstream in winter so that the subglacial water pressure can be maintained high enough to generate basal slip.

One such mechanism was proposed by Lingle and Fatland (2003). In that study, using the few ERS1/2 tandem radar interferometry data with the 1-3 day’s observation interval, they similarly detected a faster speed in winter than in fall at the non-surging Seward Glacier in the St. Elias Mountains. They also found localized circular motion anomalies at both surging and non-surging glaciers that indicated local uplifting and/or subsidence caused by transient subglacial hydraulic phenomena. Combining their observations with earlier glacier hydrological studies, they proposed a model of englacial water storage and gravity-driven water flow toward the bed in winter that applies to both surge-type and no~~t~~n surge-type glaciers. Lingle and Fatland (2003) suggested that the size of englacial water storage would determine if a given glacier is surge-type or not.

Few winter speed-up observations have been made since Lingle and Fatland (2003), but our data suggests that winter speed-up may not be a rare phenomenon. Each local uplift and/or subsidence event in the Lingle and Fatland study must be a transient short-term process, episodically occurring in places. We could not observe such localized signals in our offset-tracking displacements because our observation interval, at least 46 days, is much longer than the 1-3 days in Lingle and Fatland (2003). Nevertheless, we propose that both Lingle and Fatland's and our observations are caused by the same physical processes. This is because the locally increased basal water pressure could increase basal sliding and contribute to larger horizontal displacements. Following Lingle and Fatland's hypothesis, our finding of winter speed-up signals at the quiescent surge-type glaciers seems to indicate the presence of sizable englacial water storage whose water volume will not only change seasonally but also evolve secularly until the next active surging phase. Considering that the observed glaciers are surge-type but during their quiescent phase, we speculate that total englacial water volume may not yet be large enough to generate the active surging phase.

Till deformation is another mechanism to cause glacier surge (e.g., Cuffey and Paterson, 2010), and some glaciers in Alaska and the Yukon have till layers. For example, Truffer et al. (2000) examined surface velocity and basal motion at the ice-till interface at Black Rapid Glacier in the Alaska Range, finding that the large-scale mobilization of subglacial sediments plays a dominant role in the surge mechanism. However, based on Coulomb-plastic rheology for the till deformation (e.g., Clarke, 2005), substantial till deformation requires a high basal water pressure. So, regardless of the presence of till layer, the mechanism for winter speed-up should include a process in which a high basal water pressure can be kept during wintertime.

Schoof et al. (2014) recently reported wintertime water pressure oscillations at a surge-type glacier in Yukon, and interpreted them as spontaneous oscillations driven by water input from englacial sources or ground-water flow. But without flow velocity data, they could not correlate the wintertime drainage phenomenon to glacial dynamics. The present observations though are consistent with the englacial water storage model of Lingle and Fatland, and thus may help explain our observed upstream glacier speed-ups in winter.

Although the englacial water storage model may explain the winter speed-up, the specific water-storage system remains unknown (Fountain and Walder, 1998). One plausible form of englacial water storage is the basal crevasses observed by Harper et al. (2010) at Bench Glacier, Alaska. Such crevasses have no direct route to the surface, yet can store significant volumes of water near the bed. Thus, water in the basal crevasses may generate high pressure when they become constricted due to creep closure in winter.

The formation of basal crevasses in grounded glaciers requires a high basal-water pressure that may approach the ice overburden pressure and/or longitudinally extending ice flow (van de~~e~~r Veen, 1998). Although such crevasses have not been detected in this area, their restrictive conditions might explain our observations of uncommon winter speed-up signals and the distribution of surge-type glaciers in the area.

## Conclusions

In this study, we applied offset tracking to ALOS/PALSAR data on glaciers near the border of Alaska and the Yukon to show their spatial and temporal velocity changes in 2006-2011. ~~Surging episodes occurred at three glaciers (Lowell, Tweedsmuir and Ottawa).~~ For many of the quiescent surge-type glaciers around the St. Elias Mountains, upstream accelerations occurred from fall to winter and then propagated toward downstream. The winter speeds in the upstream regions were comparable to, and sometimes faster than those in spring to summer. Combining the absence of upstream surface meltwater input in winter with insights from some previous studies, we speculate that sizable water storage may be present near the bottom of glaciers, not directly connected to the surface, yet can enhance basal sliding by increased water pressure as they constrict in winter. Further observational and theoretical studies are necessary to decipher the winter speed-up mechanisms and determine if such water storage systems exist.

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Table 1. Data list of the ALOS/PALSAR.

| Sensor/Path | Frame | Master | Slave | Mode | #Bperp (m) | Span (day) |
|---|---|---|---|---|---|---|
| PALSAR/241 | 1190–1210 | 20070829 | 20071014 | FBD–FBD | 597 | 46 |
| | | 20080114 | 20080229 | FBS–FBS | 796 | 46 |
| | | 20090116 | 20090303 | FBS–FBS | 529 | 46 |
| | | 20100119 | 20100306 | FBS–FBS | 756 | 46 |
| | | 20100306 | 20100421 | FBS–FBS | 353 | 46 |
| | | 20100421 | 20100606 | FBS–FBD | 104 | 46 |
| | | 20100606 | 20100722 | FBD–FBD | 122 | 46 |
| | | 20100722 | 20100906 | FBD–FBD | 332 | 46 |
| PALSAR/243 | 1200 –1220 | 20061230 | 20070214 | FBS–FBS | 1342 | 46 |
| | | 20070817 | 20071002 | FBD–FBD | 425 | 46 |
| | | 20071002 | 20080102 | FBD–FBS | 627 | 92 |
| | | 20080102 | 20080217 | FBS–FBS | 1041 | 46 |
| | | 20080819 | 20090104 | FBD–FBS | 1779 | 138 |
| | | 20090104 | 20090219 | FBS–FBS | 652 | 46 |
| | | 20090822 | 20091007 | FBD–FBD | 566 | 46 |
| | | 20091007 | 20100107 | FBD–FBS | 726 | 92 |
| | | 20100107 | 20100222 | FBS–FBS | 794 | 46 |
| | | 20100825 | 20101010 | FBD–FBD | 505 | 46 |
| PALSAR/244 | 1200–1220 | 20070116 | 20070303 | FBS–FBS | 1554 | 46 |
| | | 20070903 | 20071019 | FBD–FBD | 474 | 46 |

continued

| | | | | | | |
|---|---|---|---|---|---|---|
| | | 20071019 | 20080119 | FBD-FBS | 799 | 92 |
| | | 20080905 | 20081021 | FBD-FBD | 672 | 46 |
| | | 20081021 | 20090121 | FBD-FBS | 874 | 92 |
| | | 20090908 | 20091024 | FBD-FBD | 419 | 46 |
| | | 20091024 | 20100124 | FBD-FBS | 960 | 92 |
| | | 20100124 | 20100311 | FBS-FBS | 722 | 46 |
| | | 20100911 | 20101027 | FBD-FBD | 504 | 46 |
| | | 20101027 | 20110127 | FBD-FBS | 997 | 92 |
| | | 20110127 | 20110314 | FBS-FBS | 840 | 46 |
| PALSAR/245 | 1200-1220 | 20070920 | 20071105 | FBD-FBS | 655 | 46 |
| | | 20071105 | 20071221 | FBS-FBS | 86 | 46 |
| | | 20071221 | 20080205 | FBS-FBS | 884 | 46 |
| | | 20080807 | 20080922 | FBD-FBD | 1027 | 46 |
| | | 20080922 | 20081223 | FBD-FBS | 596 | 92 |
| | | 20090810 | 20090925 | FBD-FBD | 671 | 46 |
| | | 20090925 | 20091226 | FBD-FBS | 776 | 92 |
| | | 20091226 | 20100210 | FBS-FBS | 690 | 46 |
| | | 20100210 | 20100328 | FBS-FBS | 532 | 46 |
| | | 20100328 | 20100513 | FBS-FBD | 169 | 46 |
| | | 20100513 | 20100628 | FBD-FBD | 122 | 46 |
| | | 20100628 | 20100813 | FBD-FBD | 486 | 46 |
| | | 20100813 | 20100928 | FBD-FBD | 470 | 46 |
| | | 20100928 | 20101229 | FBD-FBS | 614 | 92 |
| | | 20101229 | 20110213 | FBS-FBS | 790 | 46 |

# Bperp stands for the orbit separation distance perpendicular to the radar line of sight.

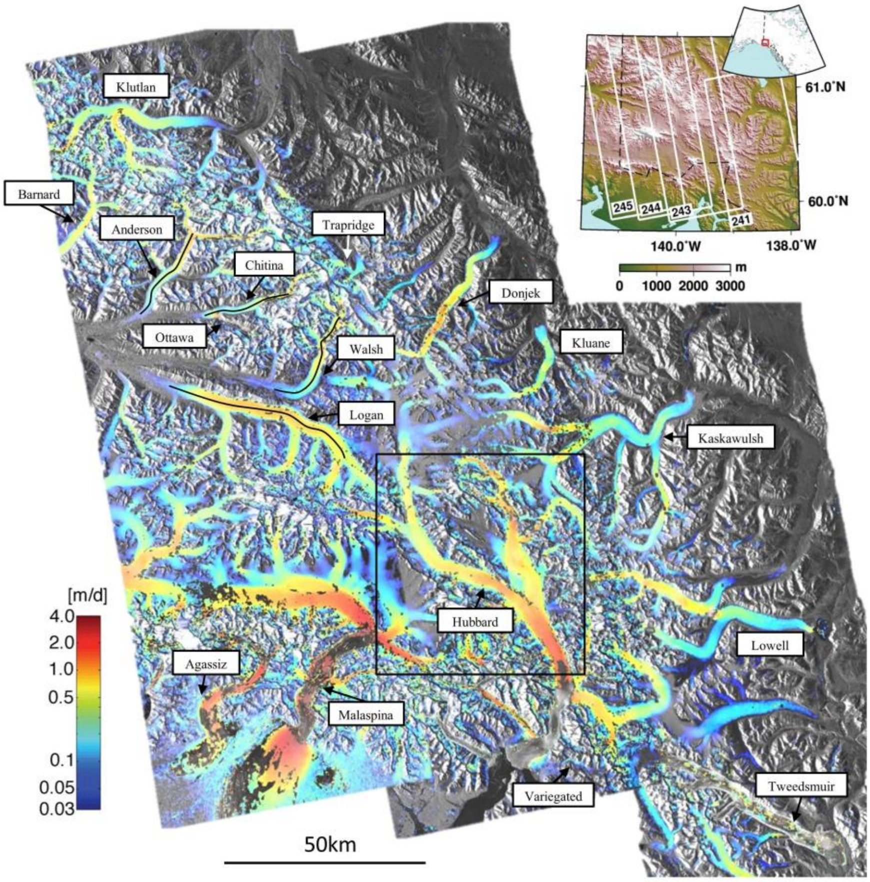
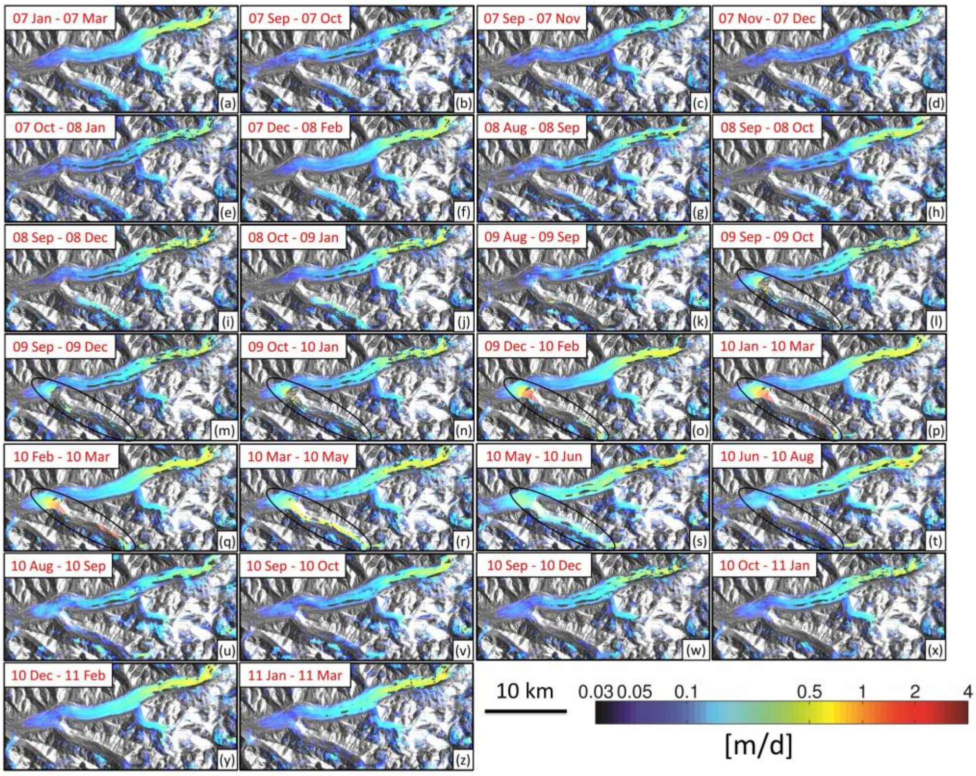
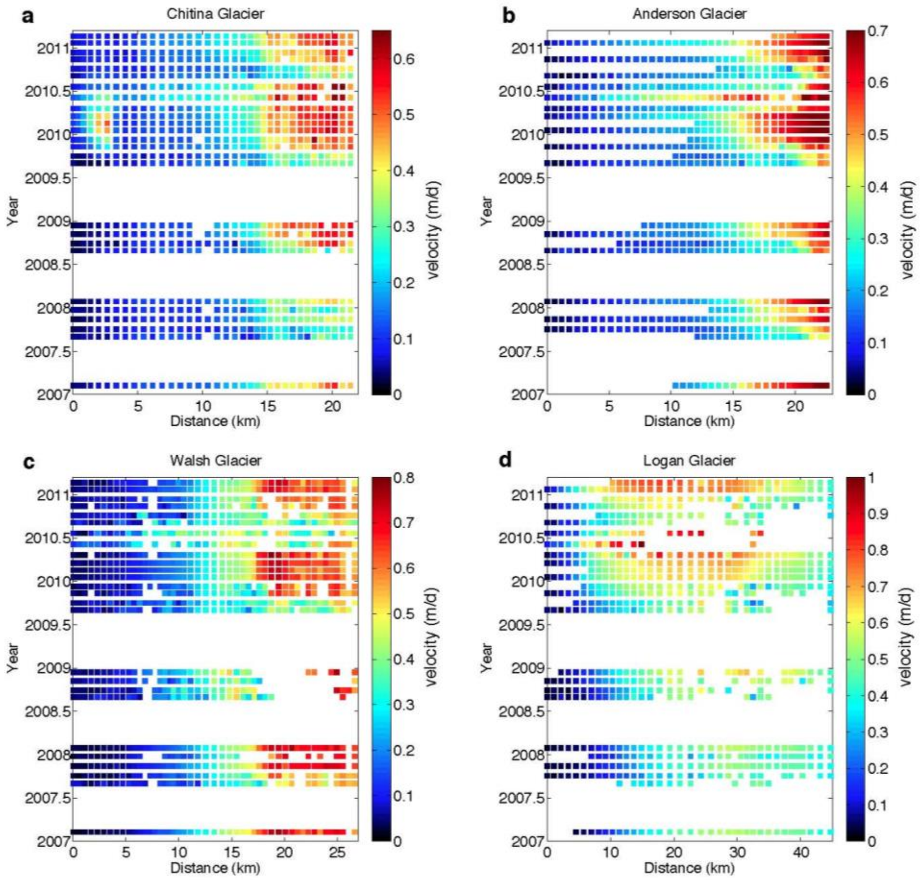



Figure 1. Composite ice-speed map of the study area. The individual maps for the study area were derived by intensity tracking between two PALSAR images. The left, middle and right velocity maps are derived from images pairs from 10 February 2010 and 28 March 2010 of Path 245, 30 December 2006 and 14 February 2007 of Path 243, 14 January 2008 and 29 February 2008 of Path 241, respectively. The square region around Hubbard Glacier is shown in Fig. 4. Black lines in some glaciers show the flow line. The upper right panel indicates the location and topography of the study area as well as the satellite's imaging areas.




~~Figure 2. Surface velocity time-series (from upper left to lower right) at Chitina Glacier. Images are arranged in the order of middle date between the first and second acquisitions for each pair. The color scale is logarithmic. The black ovals mark a surge from autumn 2009 to summer 2010 on Ottawa Glacier. Details of the surge are in the supplementary material.~~




~~Figure 3. Time evolution of ice velocity profiles along the flow lines of Chitina, Anderson, Walsh, and Logan Glaciers. The flow lines are marked in Fig. 1.~~

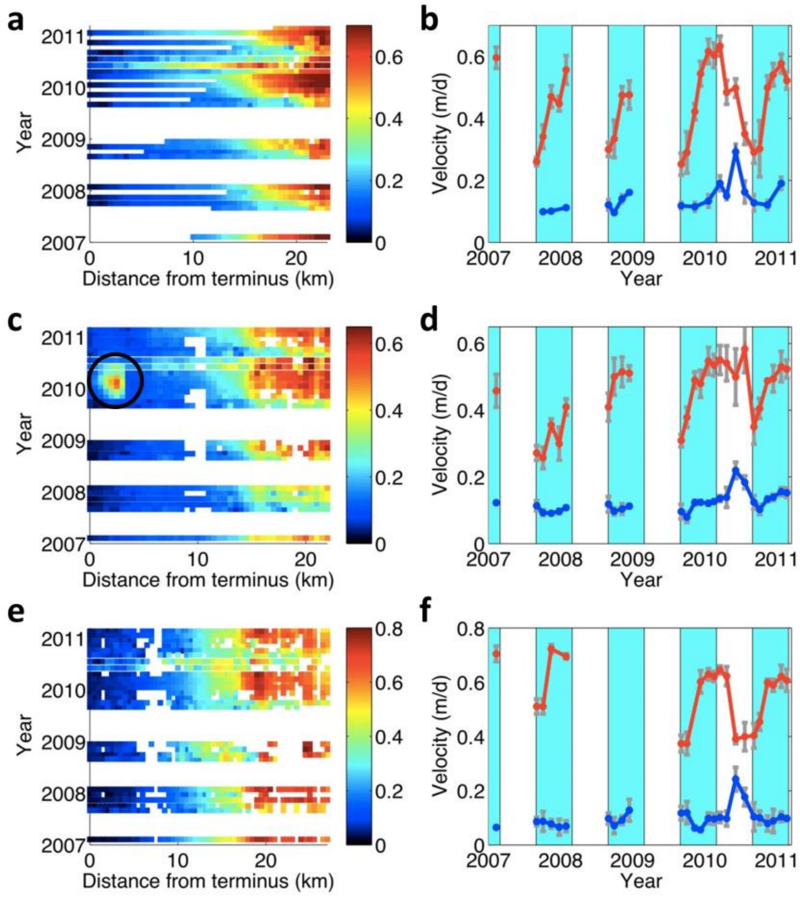



Figure 2. Left panels: Spatial and temporal changes in ice velocity along the flow lines of (a) Anderson, (c) Chitina, and (e) Walsh Glaciers. The profiles are plotted with 500 m intervals along the flow lines shown in Fig. 1. Black circle indicates the speed-up signal caused by Ottawa Glacier (a tributary of Chitina Glacier, and here is the confluence.). Right panels: Averaged time-series plots at two distinct sections derived from Fig. 2a, c, and e, respectively. Red line shows upper region (b: 18-21 km of, d: 18-21 km, f: 21-24 km) and blue line do lower region (b: 5-8 km, d: 5-8 km, f: 4-7 km). Cyan shades stand for winter season (Sep - Feb).

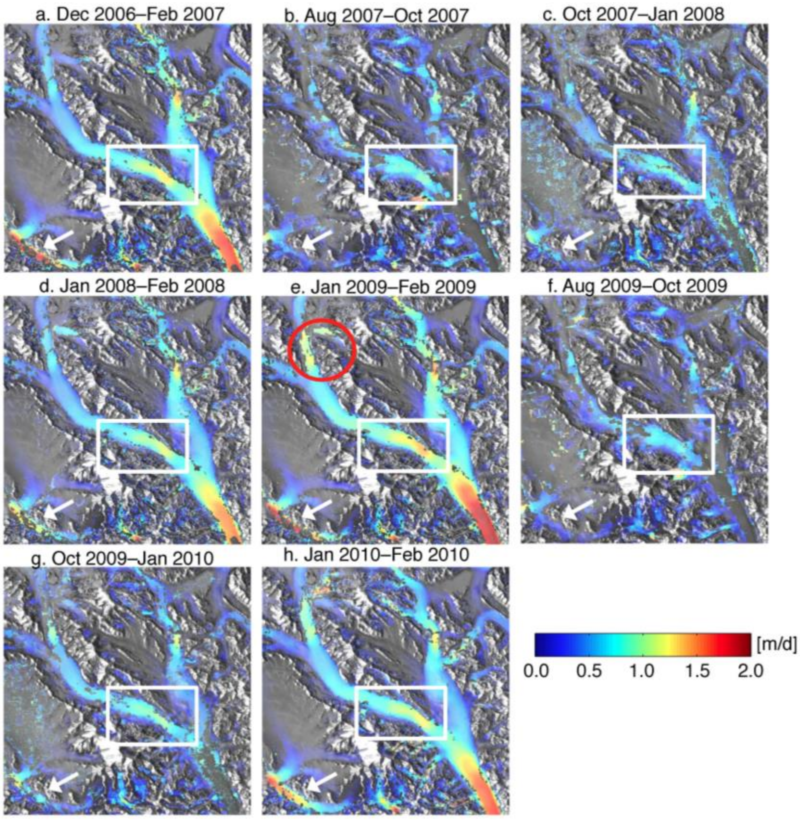
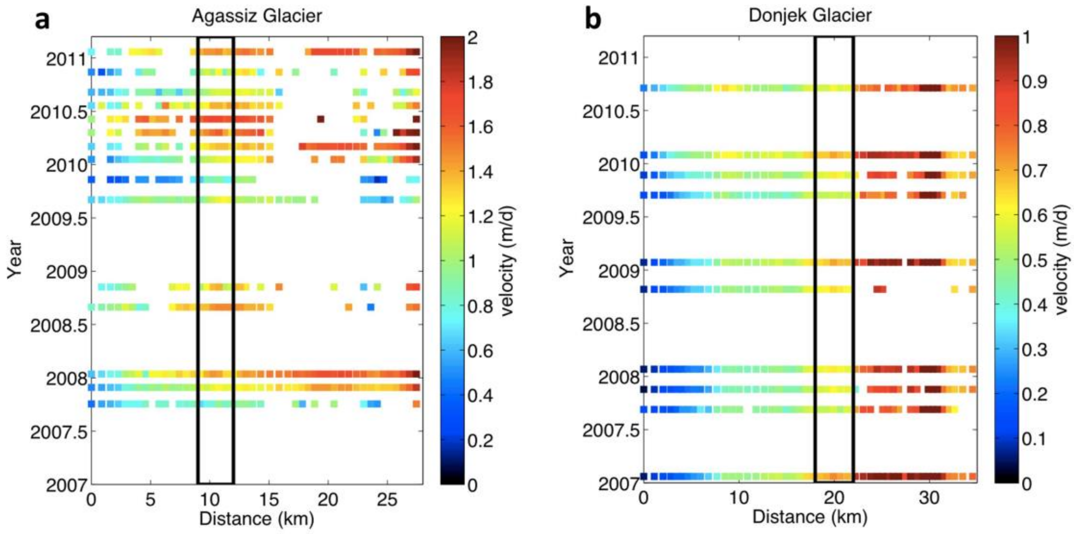



Figure 34. Spatial-temporal evolution of ice velocity at Hubbard Glacier and an upper tributary of Malaspina Glacier. The flow direction of Hubbard Glacier is from north to south. The white square marks a region in which the velocity in winter (a, d, e, h) exceeds that of late summer and fall (b, c, f, g). The red circle in (e) marks a “mini-surge-like” signal in the upstream region during January-February 2009. The white arrow in that image shows a winter speed-up of an upper tributary of Malaspina Glacier.




~~Figure 5. Temporal evolution of ice velocity profiles along the flow lines of Agassiz and Donjek Glaciers. The black box indicates the section showing clear seasonal changes.~~

# Supplementary material of “Winter speed-up of quiescent surge-type glaciers in Yukon, Canada” by T. Abe and M. Furuya

This supplementary material documents the surging episodes at four~~three~~ glaciers (~~,~~ Lowell, Tweedsmuir, ~~and~~ Ottawa Glacier, and Logan). We show radar intensity changes associated with the opening and closing of crevasses due to the surge; the intensity changes were derived by the RGB method (Yasuda and Furuya, 2013). We also describe the spatial-temporal changes in the ice velocity at the ~~three~~ glaciers and terminus advances during their active phases.

## 1. Surface crevasse formation revealed by SAR intensity analysis

Due to the sudden speed-up, a glacier surge generates new crevasses that will dramatically change the surface roughness and hence enhance the SAR scattering intensities (Yasuda and Furuya, 2013). By co-registrating two temporally separated SAR intensity images and assigning the older image (master) with cyan [(R~~r~~ed, ~~g~~Green, ~~b~~Blue) = (0%, 100%, 100%)] and the newer image (slave) with red [(Red, Green, Blue) = (100%, 0%, 0%)], the composite image tells us where the scattering intensity has remarkably changed. This is called the RGB method, which has also been employed in identifying the emerged/subsided small islands after the 2004 Sumatra Earthquake (Tobita et al., 2006). In the composite image, the cyan shows areas having an intensity increase, whereas the red shows with a decrease. The RGB method allows us to clearly visualize the intensity changes that can be attributed to the initiation of glacier surge. Although the SAR intensities can change by other processes such as surface melt in summer and snow accumulation in winter, we apply this method to the intensity images before and after a significant speed-up event (i.e., surge episodes), which occurred at Lowell, Tweedsmuir and Ottawa Glacier (Fig. 1). We have confirmed that there are few changes except surging glaciers (i.e., non-surging glaciers and off-ice area). Thus, all the intensity changes we show below are attributed to glacier surge.

## 2. Spatial and temporal variability of surging glaciers

### 2.1 Lowell Glacier

Lowell Glacier is a famous surge-type glacier located in Kluane National Park near the eastern edge of the St Elias Mountains. According to the Yukon Geological Survey (YGS), Lowell Glacier has surged 5 times in the last 70 years (YGS, 2011). The latest surge began in late 2009 and continued until late 2010 (YGS, 2011; Bevington and Copland, 2014). Pre-surge, the ice velocity was at most ~1 m/d (2007- 2009), it exceeded 5 m/d in the data pair of January and March 2010 (Fig. S1). This is consistent with the YGS report. The ice velocity slowed down in July and September 2010, but a lack of data prevents us from determining exactly when the surge ended.

Figure S2a shows that the terminus advances by up to 4 km from early 2009 to July 2010. The RGB method shows how the radar intensity increases after surge begins (Fig. S2b), and how it decreases after the surge ends (Fig. S2c). We interpret the intensity changes as being due to changes in the roughness of the ice surface that are attributable to the opening and closing of crevasses at the start and end of the surge.

### 2.2 Tweedsmuir Glacier

Tweedsmuir Glacier is 50-km south of Lowell Glacier in the St. Elias Mountains. According to the United States Geological Survey (USGS), the last surge began around 2007 summer and terminated in 2008 (USGS, 2010). Figure S3 shows the ice velocity evolution, which exhibits a greater velocity with ~6 m/d during the period from August to October 2007, but slows down in January to March 2009. In 2010, we find a summer speed-up, but the velocity magnitude is ~0.3 m/d, which is an order of magnitude slower than that during the surge in 2007.

Figure S4a shows the terminus location changes, which expands several hundreds of meters from the summer in 2007 to 2009. The RGB-method images in Figs. S4b and S4c, analogous to those in Fig. 2 show the surge at its beginning and end.

### 2.3 Ottawa Glacier - A tributary of Chitina Glacier -

Chitina glacier is a major surge-type glacier that forms the Chitina River Valley system. Although surging episodes have been inferred from satellite image analyses (Clarke and Holdsworth, 2002), we know of no ground-based monitoring at this glacier.

~~Figure 2l shows that the velocity at the confluence of Ottawa and Chitina increases in fall 2009. At the same time, the radar scattering intensity also increases (Fig. S5a). Later, in summer 2010, the flow velocity changes (Fig. 2t). This indicates that Ottawa Glacier underwent a surging episode that terminated around summer 2010.~~

~~The RGB-method images in Figs. S5a and S5b, analogous to those in Fig. 2 show the surge at its beginning and end.~~

Figure S5 shows flow velocity at Chitina Glacier from the oldest at the top left to the most recent at the bottom right. Starting in fall 2009, the velocity increases at the confluence between Chitina and Ottawa Glacier (Fig. S5l). On Feb-Mar 2010, it speeds up to 4 m/d at Ottawa Glacier (Fig. S5p-q), and we regard it as the active surging phase. Meanwhile, the velocity in the upstream region of Chitina Glacier gradually increases as winter approaches (Fig. S5k-o). In contrast to the surge, the winter speed-up occurs every winter, which thus indicates that the wintertime acceleration in the upstream of Chitina Glacier is independent of the surge at Ottawa Glacier. Moreover, the winter speed in the upstream region is comparable to and sometimes higher than that in spring/early summer in 2010 (Fig. S5s), which we believe had not been observed before. The higher speed in the middle to downstream (Fig. S5q-t) may have been triggered by the surge at Ottawa Glacier.

The increase of radar scattering intensity coincides with the surge initiation (Fig. S6a). Later, in summer 2010, the flow velocity changes (Fig. S5t). This indicates that Ottawa Glacier underwent a surging episode that terminated around summer 2010. Figure S6b shows the surge at the end.

## 2.4 Logan Glacier

Logan glacier is also a major glacier that consists of the Chitina River Valley system. Figure S7a shows the spatial and temporal changes in the velocity. In 2007 and 2008 winter, the speed at 20 km point from the terminus is about 0.4 m/d. However, it is up to 0.8 m/d in 2010 and 2011. The winter speeds appear to increase from one year to the next. This is a clear feature for surging. Figure S7b also shows the velocity increase year to year. Thus we consider it as the initiation of a new surging episode.

## References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The United Nations Geological Survey: http://ak.water.usgs.gov/Projects/Tweedsmuir/index.php, last access: 25 June 2013, 2010.

Yukon Geological Survey: http://www.geology.gov.yk.ca/821.html, last access: 24 May 2013, 2011.

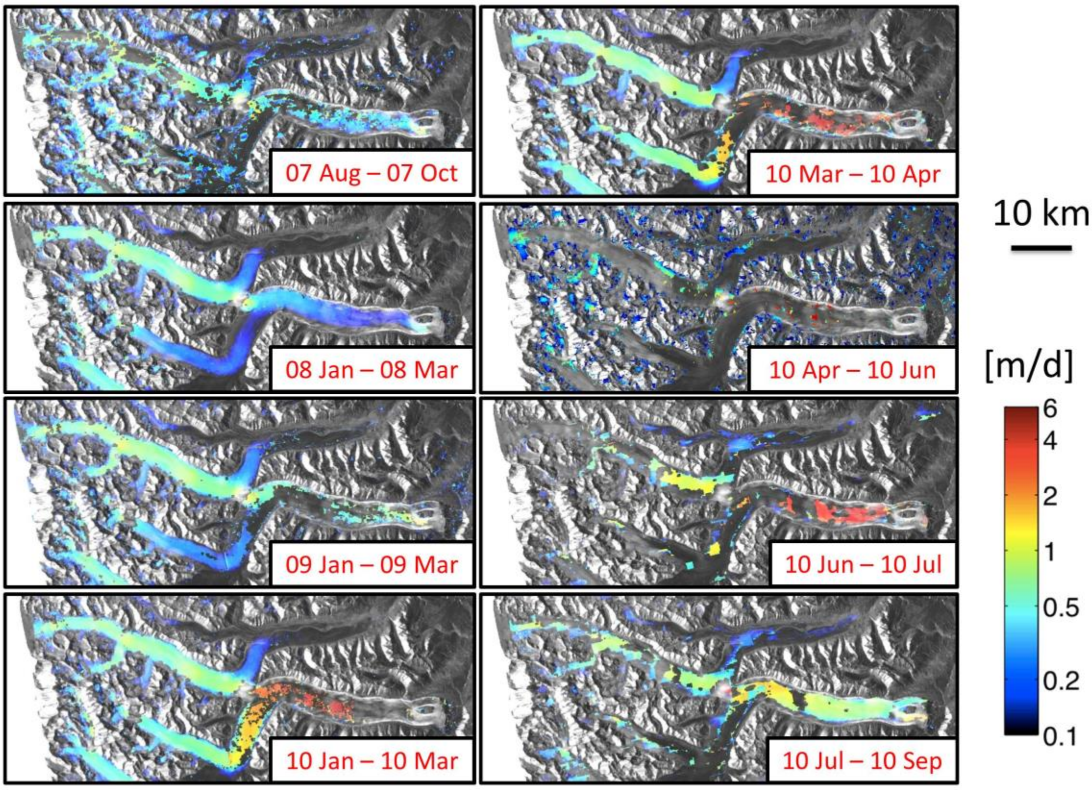


Figure S1. Surface velocity evolution on Lowell Glacier. The color scale is logarithmic.

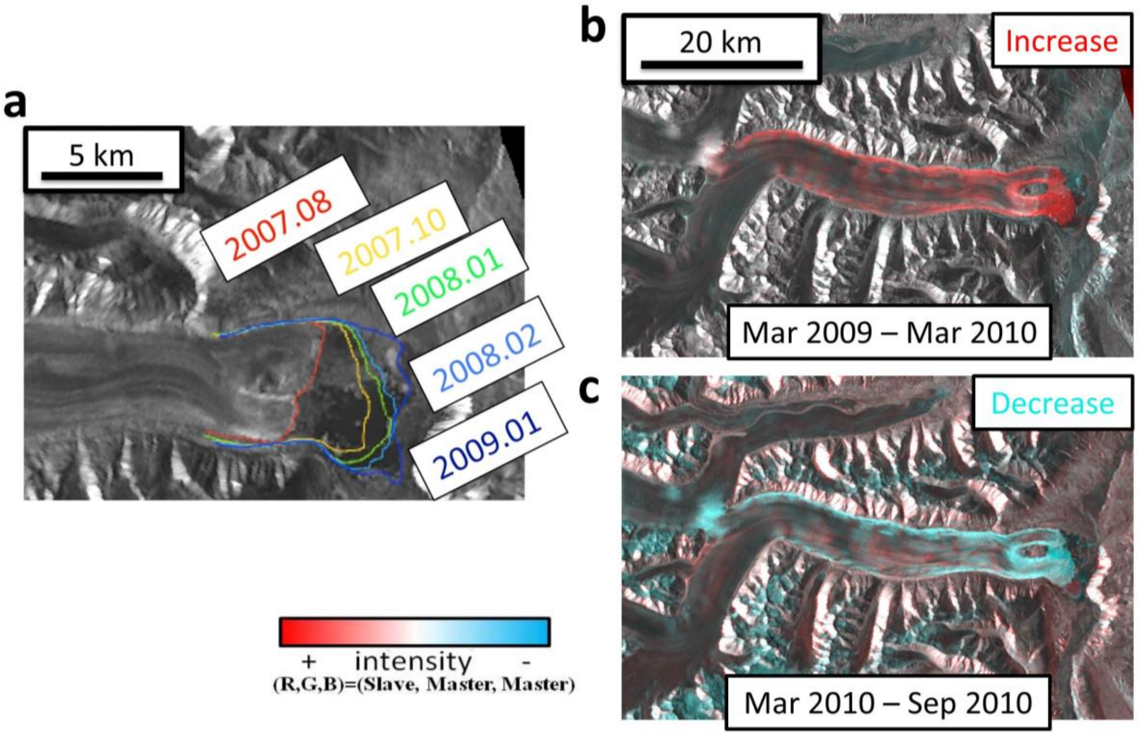


Figure S2. Surging event on Lowell Glacier. (a) Terminus locations based on PALSAR intensity images. (b) An RGB composite image derived from the images on 3 March, 2009 and 6 March, 2010. The red region indicates where the scattering intensity has increased. (c) A composite image derived from the images on 3 March, 2010 and 10 September, 2010. The cyan region indicates where the scattering intensity has decreased.

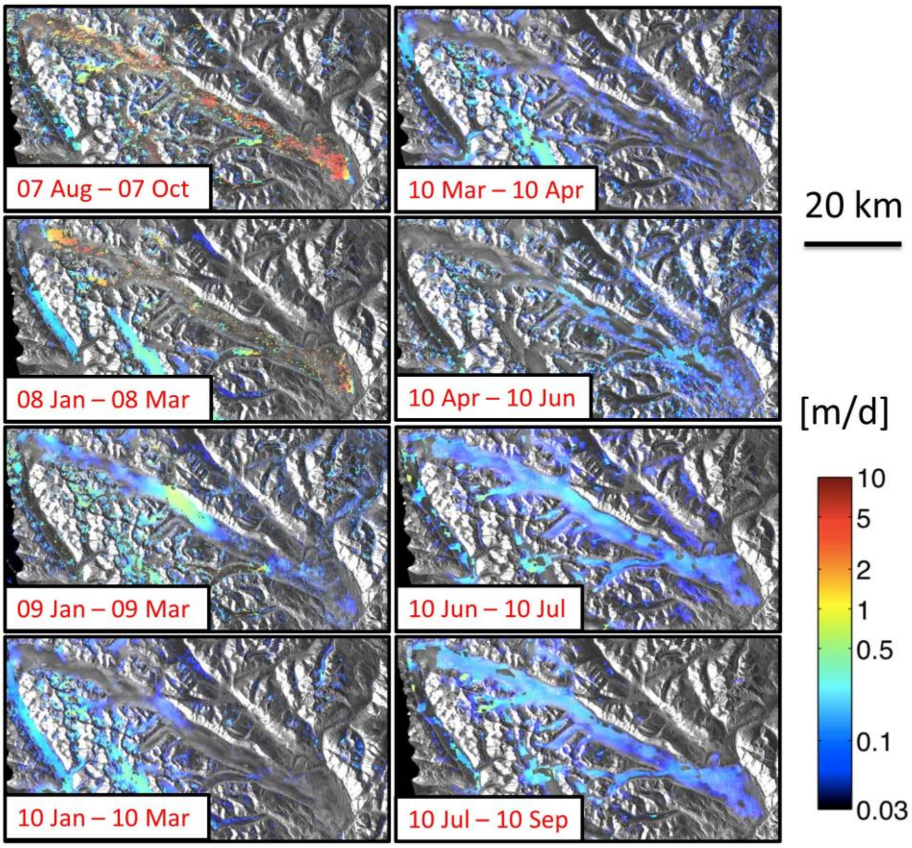


Figure S3. Surface velocity evolution on Tweedsmuir Glacier. The color scale is logarithmic.

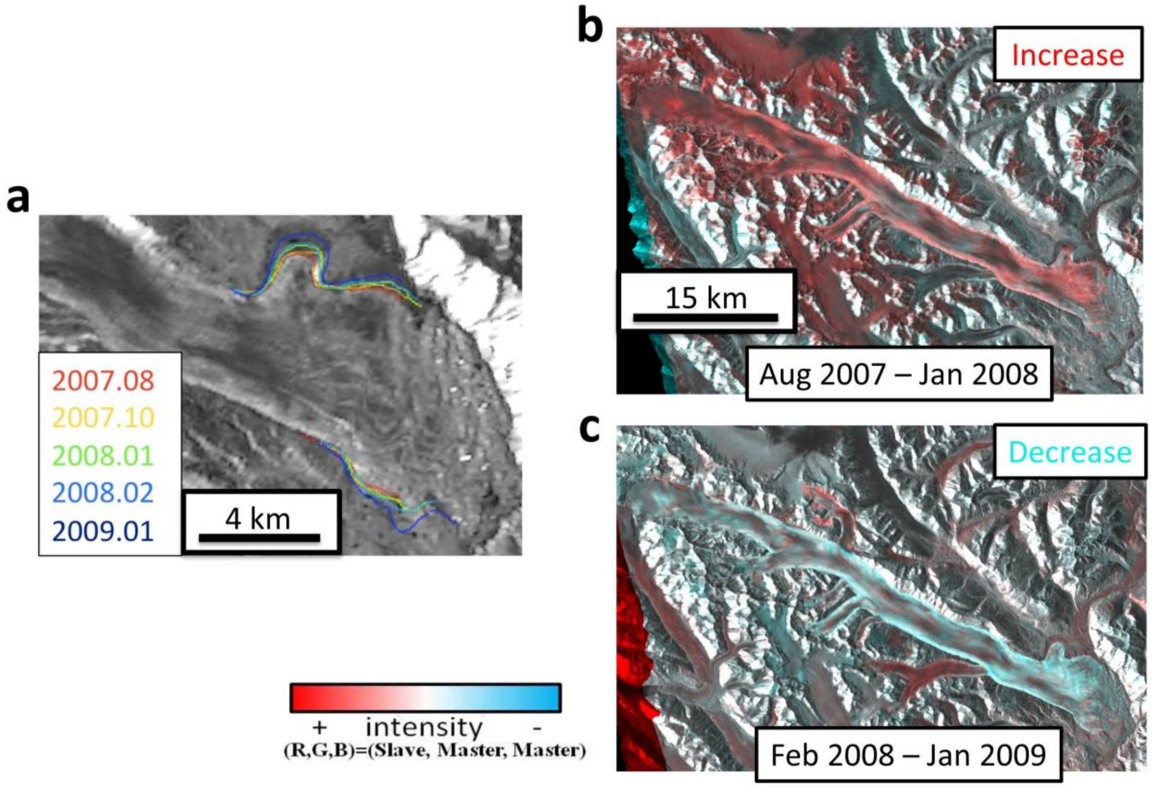


Figure S4. (a) Terminus locations on Tweedsmuir Glacier based on PALSAR intensity images. (b) An RGB composite image derived from the images on 29 August, 2007 and 14 January, 2008. (c) A composite image derived from the images on 29 February, 2008 and 16 January, 2009.

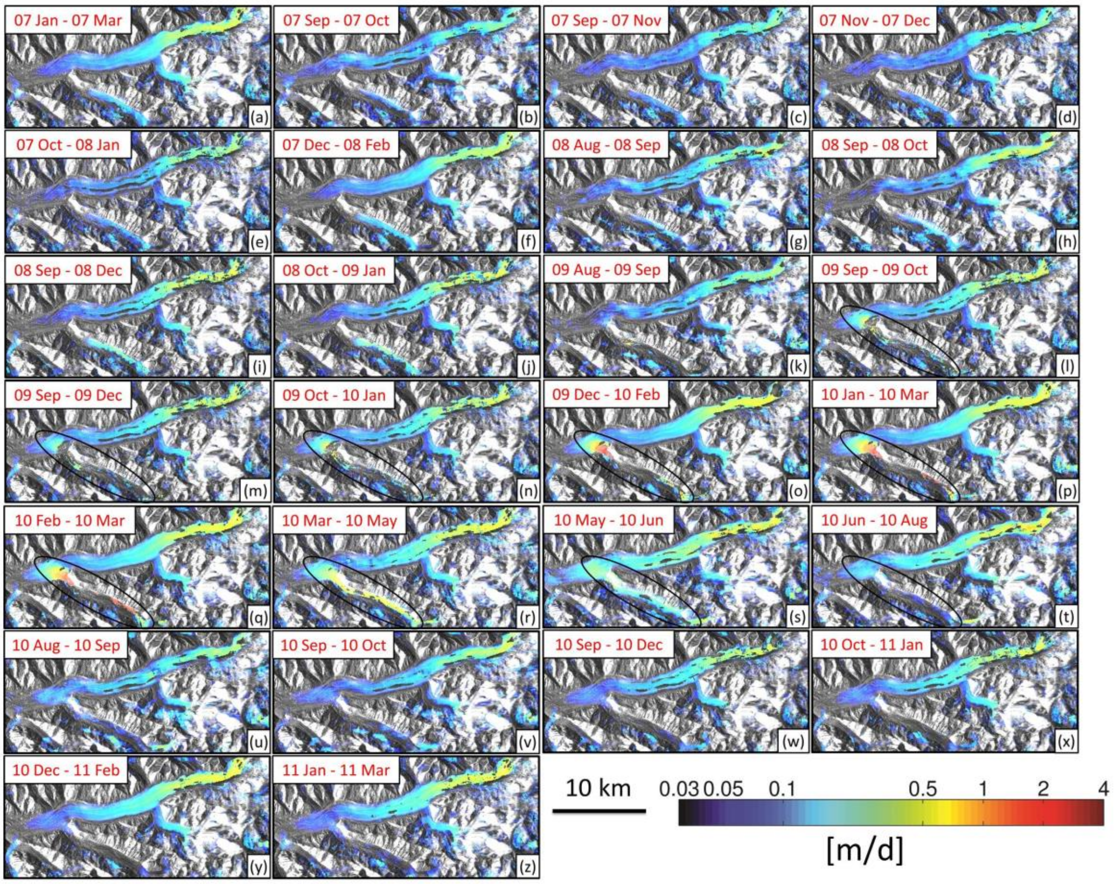


Figure S5. Surface velocity time-series (from upper left to lower right) at Chitina Glacier. Images are arranged in the order of middle date between the first and second acquisitions for each pair. The color scale is logarithmic. The black ovals mark a surge from autumn 2009 to summer 2010 on Ottawa Glacier.

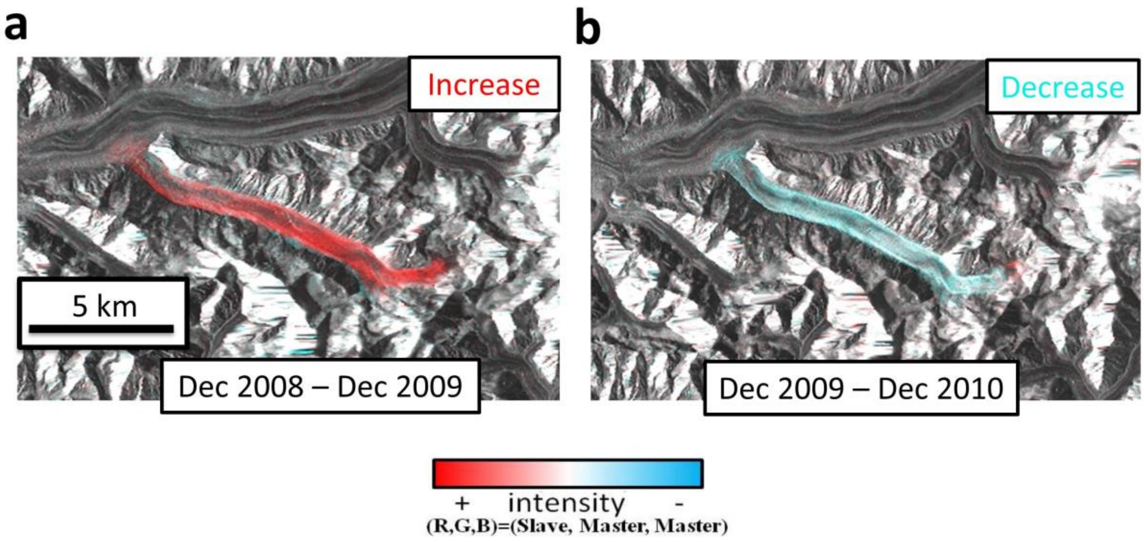


Figure S6~~5~~. Composite images on Ottawa Glacier. The larger glacier at the top is Chitina Glacier. (a) An RGB composite image derived from the images on 23 December, 2008 and 26 December, 2009. (b) A composite image derived from the images on 26 December, 2009 and 29 December, 2010.

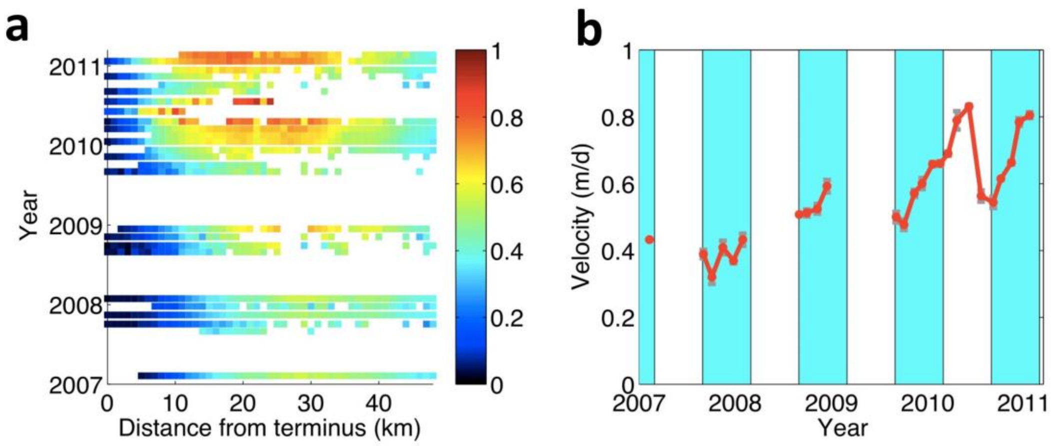


Figure S7. (a) Spatial and temporal evolution of the ice velocity profile along the flow lines of Logan Glacier. The flow lines are marked in Fig. 1. (b) Averaged time-series plot at the section between 18 and 21 km. Cyan shades stand for winter season (Sep - Feb).