The corresponding editor in *The Cryosphere*
Ref: MS# tc-2015-187

Dear Dr. Jon Ove Hagen,

Thank you for your time to handle our manuscript, and apologies for the delay in submitting the revision; we have asked for an English-editing service. We have attached the revised manuscript, the response letter including the replies to the two referees and the marked-up revised manuscript, and revised supplementary material as a separate file.

Basically incorporating all of the referees' comments, we substantially re-wrote the manuscript, modified the Fig. 1 and 2, and added the data list of Landsat images in the Supplementary material. Below is a summary of the significant changes comparing with the previous manuscript, 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*.

Introduction

We added more explanations about the detail on the mechanisms of Alaskan and Svalbard-type surging. Moreover, we cited some references in places.

Donjek Glacier

In this section, we mentioned the past surges on Donjek Glacier referring some previous studies.

Results

Some explanations about new Figure 1d (a plot of length v.s. valley width) were inserted in this section. Moreover, we corrected some sentences to make it clearer following the Referees' comments.

Discussion and Conclusion

We added some paragraphs in this section. At first, following the comment by both referees, we mentioned the past surging events at Donjek Glacier, and noted if we could compare with our detected surges in the first paragraph.

Secondly, we re-wrote the new second paragraph about comparison of surge cycle between Donjek and other glaciers.

References

We added some references due to the modifications above. According to this, the number of the references got larger than 20 (this is a basic rule of *Brief Communication*), but these corrections were needed to improve the manuscript.

Added

Bevington, A., and Copland, L.: Characteristics of the last five surges of Lowell Glacier, Yukon, Canada, since 1948, J. Glaciol, 60, 113-123, 2014.

Clarke, G. K. C., and Matthews, W. H.: Estimates of the magnitude of glacier outburst floods from Lake Donjek, Yukon Territory, Canada. Can. J. Earth Sci., 18, 1452-1463, 1981.

Eisen, O., Harrison, W. D., Raymond, C. F., Echelmeyer, K. A., Bender, G. A., Gorda, J. L. D.: Variegated Glacier, Alaska, USA: a century of surges. J. Glaciol. 51, 399–406, 2005.

Johnson, P. G.: A possible advanced hypsithermal position of the Donjek Glacier, Arctic, 25, 302–305, 1972a.

Johnson, P. G.: The mophological effects of surges of the Donjek Glacier , St. Elias Moutains, Yukon Territory, Canada, J. Glaciol., 11, 227-234, 1972b.

Luthcke, S. B., Sabaka, T. J., Loomis, B. D., Arendt, A. A., McCarthy, J.J., and Camp, J.: Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global mascon solution. J. Glaciol., 59, 613–631, 2013.

Post, A.: Distribution of surging glaciers in western North America. J. Glaciol., 8, 229-240, 1969.

Sakakibara, D., and Sugiyama, S.: Ice-front variations and speed changes of calving glaciers in the Southern Patagonia Icefield from 1984 to 2011, J. Geophys. Res. Earth Surf., 119, 2541-2554, 2014.

Yasuda, T., and Furuya, M.: Dynamics of surge-type glaciers in West Kunlun Shan, Northwestern Tibet, J. Geophys. Res. Earth Surf., 120, 2393-2405, 2015.

Figures

In Figure 1, we modified the area map in Fig. 1a to show the other glaciers in the Donjek River Valley due to the comment from the referee#1. In Fig. 1b, the color scale was changed from linear to logarithmic in order to match the scale with Fig. 1c. In Fig.1c, we added some data in 1987, 1988, and 1990. Thus, we can unarguably claim the surging occurred in 1989. Moreover, we generated a new graph (Fig. 1d) about a plot of the width vs. distance, according to the referee#2 comment.

Supplementary material

We added the list of the image pairs using feature tracking (Table S1), and some sentences about the error of feature tracking and the potential effect of seasonal variability.

The Point by point responses to the reviewers

Below are our responses to the two anonymous reviewers. The blue sentences in italics indicate the Referees' comments, followed by our replies. We indicate in red where the additional explanations are inserted in the revised manuscript.

Reply to Anonymous Referee #1's comments

GENERAL COMMENTS This paper provides a summary of the recent changes in area and velocity of Donjek Glacier, with the main finding that the glacier has had a 12-year surge periodicity for its past 3 surges. This information is useful and interesting, but it does not provide the novel information that the authors claim it does. The main problem is that the authors provide poor referencing to previous studies, and miss out many important papers that describe previous surges of this glacier and others nearby. If the results from this previous work are properly incorporated into this study, then the authors could reconstruct the past 6 surges of Donjek Glacier and therefore make much more useful comments about the surge periodicity of this glacier and whether it has been changing over time. Better information is also needed about the potential impacts *of differences in the acquisition time of Landsat imagery on the reported velocity patterns (e.g., whether image pairs capture summer speed up events).*

Thank you for your valuable comments. Although we had known the paper by Johnson (*JG*, 1972), and the suggestions are quite intriguing, no equally quantitative data (e.g., velocity, terminus position…) were presented that allowed us to reconstruct the history of past surges. Moreover, the number of references is limited to less than 20 references in the *Brief Communication* manuscript, and thus we did not refer to them. However, we should have more clearly stated the research history on Donjek Glacier within the introduction. We will comment the previous literatures on surges at Donjek Glacier, clarifying the data sources. Moreover, the detailed list of Landsat images will be added in the supplementary material. We will also mention the seasonal changes in ice speed.

We cited more references in places in the *Introduction* and *Discussion*, adding some sentences. The detailed list of Landsat images were added in the supplementary material as Table S1. We also mentioned the seasonal change in ice speed at P1L20-23 in the material.

Finally, the English language needs to be improved as explanations are difficult to follow in places. I have made some suggestions below to improve the language, but the text needs to be thoroughly read and corrected by a native English speaker prior to publication.

We will re-write the language according your suggestion, and the revised manuscript will be checked by English editing services.

This revised manuscript was modified based on an English editing service.

SPECIFIC COMMENTS (by page and line #) P5944, L7: change 'narrows than up-stream' to 'narrows upstream'

Done.

P5944, L10-16: the explanation of glacier surging needs to be more clearly described, and a distinction made 'Alaskan-type' and 'Svalbard-type' surges and their respective surge and quiescent periods

We will add more explanations of surging in the introduction to make it clear.

We added some explanations of surging in the *Introduction* at P1L27-P2L13.

P5944, L17: change 'called as build-up' to 'called the build-up

Done.

P5944, L20-21: the statement that 'detailed observations of the repeating surge cycles have been extremely limited' isn't really correct. Although there aren't large numbers of such observations, there are several key papers in the study area that reconstruct surges up to the past 100 years for Variegated Glacier: Eisen et al. 2005. Variegated Glacier, Alaska, USA: a century of surges. Journal of Glaciology, 51, 399-406

...and up to the past 65 years for Lowell Glacier: Bevington and Copland. 2014. Characterisics of the last five surges of Lowell Glacier, Yukon, Canada, since 1948. Journal of Glaciology, 60, 113-123.

. . .and similar papers for other regions. These need to be properly reviewed and assessed in the introduction.

Thank you for your suggestion. We will re-write the statement, adding the references.

We re-wrote the statement, adding the references at P2L14-18.

P5945, L2: change 'allowed' to 'allows'

Done.

P5945, L9-10: I would merge these two sentences, so that they read '...derive the spatial-temporal changes in both the velocity field and the terminus area of Donjek Glacier'.

We will re-write the last two sentences as bellow.

"To reveal the long-term evolution of surge-type glaciers in this area, we use Landsat optical images acquired between 1973 and 2014 to derive the spatial and temporal changes in ice speed (1986-2014) and the terminus areas (1973-2014). As a consequence, we here report our findings of three surging events at Donjek Glacier."

We added the below sentences at P2L29-P3L2.

"To reveal the long-term evolution of Donjek and associated surge-type glaciers nearby, we use Landsat optical images acquired between 1973 and 2014 to derive the spatial-temporal changes in ice speed (1986-2014) and the terminus areas (1973-2014).

As a consequence, we report here our findings of three surging events as well as a likely event pre-1985 at Donjek Glacier."

P5945, L13: it would be useful to show the location of these other glaciers in the figure

We modified the new Figure 1a to show the location of the glaciers.

P5945, L15: delete the sentence 'As shown in the result. . .' – this describes results, which should be kept in that section.

We deleted it, and added below instead at P3L8-9.

"Donjek Glacier lies located at an elevation of 1000-3000 m, and the valley width significantly constricts toward downstream at 20 km section from the terminus."

P5945, L19: previous studies on these outburst floods should be referenced here, such as: Clarke and Matthews. 1981. Estimates of the magnitude of glacier outburst floods from Lake Donjek, Yukon Territory, Canada. Canadian Journal of Earth Sciences, 18(9): 1452-1463.

We referred to Clarke and Mathews (1981) at P3L12.

P5945, L20: key references that describe previous surges of Donjek Glacier (in 1935, 1961 and 1969) are missing here, such as: Johnson. 1972. The morphological effects of surges of the Donjek Glacier, St. Elias Mountains, Yukon Territory, Canada. Journal of Glaciology, 11, 227-234 Johnson. 1970. Ice Cored Moraine Formation and Degradation, Donjek Glacier, Yukon Territory, Canada. Geografiska Annaler, 53, 198 ...these previous surges, together with the 1978 surge described by Clarke and Holdsworth (2002) need to be properly described. Indeed, the incorporation of the known dates for these previous surges with the new findings from this paper can enable the reconstruction of surges of the Donjek Glacier back to at least the early 1960s. Doing this would significantly enhance the findings and conclusions of this paper, and enable more meaningful discussion of whether the surge periodicity has changed over time and how it compares to the frequency of other surge-type glaciers in this region.

Thank you for the suggestions. As we should have written the previous literatures on the surge at Donjek Glacier, we will refer to Johnson (1972, JG), in which past "surges in 1935, 1961(1962?) and 1969" were mentioned. However, we are wondering if the three episodes before 1970 could be equally compared to our detected surges, because the data sources are entirely different from ours in terms of both quality and quantity. For instance, Johnson (*JG*, 1972) mentioned the 1969 surge in terms of morphological features (push structure and erosion forms), based on a personal communication with Post. Whereas we consider that Post's observations are comprehensive and historically very important, the details of the observations (such as observation frequency) are extremely uncertain. According to Post (1969, JG), it seems that he regarded Donjek as surge-type in view of Table 1 and Figure 1. The 1961(1962?) event might correspond to this, but there were no descriptions on the active phase of Donjek Glacier during 1960s; we could not find what evidences were provided for the 1961(1962?) surges. Regarding the 1969 episode, Johnson (JG, 1972) noted that the terminus advance was less than 500 meters, compared to the earlier surges in 1935 and 1962. It could be likely that mini-surge-like accelerations (so-called pulse) caused the slight advance of the terminus in 1969; we can point out such pulse-like events in our Fig. 1c in 1995 and 2009. Johnson (Arctic, 1972) also wrote, "The history of the glacier from 1935 to the present is well-documented photographically (Wood and Post, personal communications)". Because there were no observations before 1935, we cannot say the surge started in 1935.

First we mentioned the past surging in the *Donjek Glacier*, citing some papers at P3L13-20. After that, we added one paragraph in the *Discussion* at P6L2-15 to compare the historical records and our detected data.

P5946, L2-3: the wording needs to be corrected here: terminus fluctuations were examined from 1973 to 2014, but the flow speed evolution was only examined from 1986 to 2014.

We modified the sentence at P3L23-24.

P5946, L12: no information is currently provided in the main text or supplementary material about the exact dates of the image pairs that were used for velocity derivations. However, this information is crucial to understand whether and how image pairs have been influenced by summer speed ups or winter slow-downs. For example, an image pair from Jun-Aug in the same year would likely show higher velocities (when *standardized to m/day) than an image pair from August one year to June the next year, irrespective of surge conditions. The dates for image acquisitions therefore need to be provided (e.g., in a Table in the supplementary material), and the potential effect of seasonal variability in velocities needs to be discussed.*

We are going to present the exact dates of images and temporal separations of image pairs used in this study as a table in the supplementary material. Temporal separations of image pairs used in this study ranged from 16 to 128 days. These temporal separations were mostly less than 4 months. Thus, some pairs could be influenced by summer speed-up. However, the seasonal amplitude is apparently smaller than that in surging episodes we discuss here.

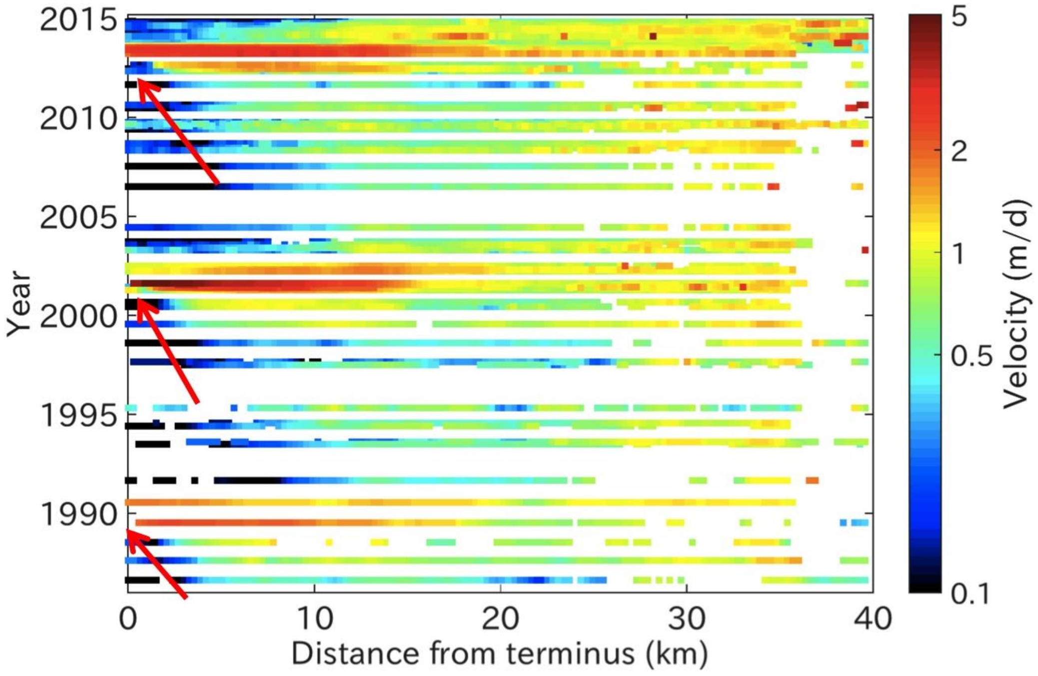
The detailed list of the image pairs used in this study was added in the Supplementary material as Table S1, and we mentioned the potential effect of seasonal variability at P1L20-23 in the material.

P5947, L2-3: the wording here is unclear: it reads as if the 2, 4.5 and 3 m/day values relate to 'other years' (i.e., quiescent years), when they actually relate to surging years.

We re-wrote the sentence as below at P4L15-17.

"In 1989, 2001 and 2013, the speed near the terminus appears much greater, by up to 2 m/d, 4.5 m/d, and 3 m/d, respectively. In contrast, the speed during the other years (i.e. quiescent phases) is about 0.5 m/d or less."

P5947, L8-10: I don't follow the explanation here of what a 'velocity front' is, and how it propagates downstream. Showing these patterns in a figure would be useful, and I would like to see explanation of this point expanded as it can provide useful insight into the propagation mechanism of the surges.



The velocity front we mention here is the boundary between the stagnant and moving part near the terminus. The red arrows indicate the front propagation toward downstream prior to the surging (The figure was updated according to the Referee#2 comments). We will add more explanations about this in the revised manuscript.

We added the explanation about the velocity front in the *Result* at P4L27, and added one sentence, "The active phase seems to initiate when the front reaches the terminus." at P4L29.

P5947, L21-27: this paragraph is missing temporal resolution: please provide months, as well as years, for events. There are frequent repeat images available for the recent surges, so it should be possible to better define them than 'about 1 year'.

We will add the detail of the exact image pairs in the supplementary. We basically used the pairs whose periods were not overlapped each other. Thus, we can discuss the duration of the episode. As pointed out, there are so frequent repeat images only after the 2013 episode (i.e. late 2013-2015), but less frequent before the episode. Thus, we cannot define the exact period (i.e. months) of the active phase.

The detailed list of the image pairs used in this study was added as Table S1 in the Supplementary material. Moreover, we added some statement about the exact period at P5L12-13.

P5948, L1 (and elsewhere): secular is an unusual word to use here. Something like 'gradual' would be better.

We replaced "secular" to "long-term" or "gradual" in places.

P5948, L3: it's a very broad, and somewhat inaccurate, statement to say that the negative trend is due to 'recent global warming'. It's more accurate to say that it's due to 'negative mass balance', and provide some references to studies from this region that indicate that.

OK. We changed the sentence as below and cite two more references at P5L16-17.

"which presumably indicates the negative mass balance trend from recent global warming (e.g., Luthcke et al., 2013; Larson et al., 2015)"

P5948, L6-9: the connection between the surge cycle and 'wax and wane of the terminus area' needs to be better developed. This is a crucial point, as if you can clearly demonstrate that terminus area provides a proxy for surge activity, then it enables the timing of the late 1970s surge to be confirmed (as also suggested by Clarke and Holdsworth, 2002). This would enable the surge record to be extended further back in time.

We will add more explanations about the relation between surge cycle and terminus fluctuation.

We re-wrote the sentences about it at P5L20-25.

P5948, L11: an important question is whether the velocity matching technique could actually capture velocity changes in the accumulation area due to a lack of surface features to track. For example, Bevington and Copland (2014) limited their velocity matching measurements to the lower part of nearby Lowell Glacier for this reason. It therefore needs to be clarified as to whether the observed velocity variations over the lower 20 km of the glacier are simply due to better measurements there, or whether they really reflect glacier-wide changes.

We have confirmed that the orientations of the displacement vectors in the upstream region were identical to the flow direction of the glacier. Hence, the observed velocity variations over the lower 20 km do really indicate the glacier-wide. Moreover, we agree that it is harder to track the surface features in the accumulation area due to its low contrast. Actually, our velocity data in Fig.1c also indicate the poorer coverage in the upstream region (above 35 km from the terminus).

We added some sentences about the measurements above at P1L23-26 in the Supplementary material.

P5948, L21: the recurrence interval is actually very similar to the recent surges of Lowell Glacier described by Bevington and Copland (2014), and not that different to some of the surge periods of Variegated Glacier described by Eisen et al. (2001, 2005).

OK. Here we will change the sentence as below, making both the similarities and differences much clearer.

"The 12-year recurrent interval is as short as the latest interval at Lowell Glacier (Bevington and Copland, 2014). However, in contrast to Lowell and Variegated Glaciers whose average recurrent intervals are 15.25 years (Bevington and Copland, 2014) and 15 years (Eisen et al., 2005), respectively, the recurrent interval at Donjek Glacier is not only shorter on average but also constant and less variable over time."

We added some sentences about above at P6L20-32.

P5948, L23-25: this is a key item that needs to be updated: as discussed above, previous literature indicates that surges of Donjek Glacier also occurred in 1961, 1969 and 1978. This information needs to be incorporated with the text here to provide a better long-term record of the surges of this glacier and their variability over time.

As we mentioned above, we will mention the past surges, and re-write the sentences. As noted above, however, we do not think that the available data would allow us to claim the changes in the recurrence interval since 1960s.

We mentioned the past surges at the first paragraph in the *Discussion* at P6L2-15.

P5949, L3-7, L15: I would remove most of the detailed references to the surges of Medvezhiy Glacier. This is a glacier that is very far away from the study site and in a different climate regime, so I don't think that it makes a good comparison to Donjek Glacier. Instead, a comparison with detailed studies of the repeat surges of glaciers nearby to the Donjek (e.g., Bevington and Copland, 2014; Eisen et al., 2001, 2005) should be the focus here.

While we will discuss a comparison with other nearby surges in the revision, what we'd like to stress in the surge of Donjek Glacier is that the surging area initiated at ~20km point from the terminus, where it significantly narrows downstream; no previous studies on Donjek Glacier have pointed out this observation. This geometry is very similar to that in Medvezhiy Glacier; no such geometry can be found at other glaciers near Donjek Glacier. Although the climate regime at Donjek is similar to that in Variegated and Lowell, we consider that the regularity of the 12-year cycle and the limited surging portion are significant. Thus, we compared with Medvezhiy Glacier in terms of the valley constriction and the active surging area. We will add more explanations to make it clear.

We re-organized the second paragraph in the *Discussion* in order to first compare the surge-cycle with Lowell and Variegated Glaciers, and then compare with Medvezhiy Glacier in terms of the shorter cycle and surging area at P7L1-12. While we are well aware of the distinct climate settings, we paid our attention to the similarity in terms of geometric control on the surge dynamics.

P5949, L7-9 & P5950, L11-21: if slope changes and changes in ice thickness are going to be invoked as a causal mechanism for surges, then they need to be properly described and evaluated. At the moment there is no evidence provided to back up any of the statements made here, so they are unconvincing.

We do not consider the thickening of ice and steeper slope as the direct cause of surging. The thickened ice upstream is just a pre-condition prior to surging. The reasons why we have speculated the ice thickening here are 1) the surging initiated around here, 2) the valley significantly narrows 3) the ice speed upstream is larger than here and constant, which indicates that ice is delivered from upstream with a constant rate. Although we have no available data showing the thickening, we speculate that the valley constriction may generate an important pre-condition of the surging at Donjek Glacier. We will add more explanations about this.

We added more explanations about this at P8L4-9.

P5951, L2-3: this last sentence doesn't really say anything. E.g., exactly kind of measurements should be made? Can they be made from space? Or are local field measurements necessary?

What we would like note here is that various data both ground observations and satellite data analysis are needed to reveal the mechanism of these events.

We modified the sentence at P8L24-26.

P5951, L8: change 'grand' to 'grant'

We changed it.

Fig. 1a: need to provide image date in caption. 1b & 1c: The colour scales used in these two figures need to be the same, rather than plotting one as linear and one as logarithmic.

The image date was added in the caption and the color scale was set as logarithmic in the new Figure 1.

Fig. 2a: add numbers to the secondary y axis.

We added the numbers in modified Figure 2

Fig. 3: provide exact image dates, rather than just years

We added the exact image dates in the caption in Figure 3.

Supplementary material P1, L17: the mean error is quoted in m/day, but this isn't very meaningful as the error will vary depending on the time between image acquisitions (greater time separation results in lower error in m/day). This effect therefore also needs to be discussed.

We will add the list of data sets we used in this study. The time separations between image acquisitions were less than about 4 months, and the velocity errors ranged between 0.09 and 0.80 m/d. We also agree that the error is dependent on the time between image acquisitions, and the amplitude of seasonal change is within the error. However, the velocity during the surging is quite larger than the error.

The data list was added as TableS1 in the Supplementary material, adding some explanations about the error of feature tracking at P1L20-23.

P2, L2: 'snapshot s' should be 'snapshots'

Done.

P2, L32 7 L34: reference here should be to Figs. 2a, 2c and 2e

Done.

<u>Reply to Anonymous Referee #2's comments</u>

General Comments The paper by Abe et al. provides a description of the last three surges of Donjek Glacier, which have occurred at twelve-year intervals. Donjek is a well-studied glacier and, like Referee #1, I was surprised the authors did not make much use of previous literature. For example, Johnson (1972, Arctic) describes how the history of the glacier has been well-documented photographically since 1935. While such records may not provide the same velocity data that Abe et al have relied on in the current study, they would certainly provide some better long-term constraints on surge cyclicity. Further, Clarke and Holdsworth (2002, USGS Publication) report about surges in 1974 and 1978. The authors comment on the 1974 surge but, oddly, make no mention of the 1978 one, which would actually lend evidence to the 12-year periodicity argument. Previously reported surges in 1935, 1961 and 1969 however, Discussion Paper don't necessarily support the 12-year periodicity unless it has evolved over the past century (which is no doubt possible!).

Thank you for the valuable comments. We will refer to the previous studies in the revision. However, as we state in the Reply to Referee#1, we cannot consider whether the reported "surges" before the 1960s were truly equivalent to those we report here or like mini-surges, or just advances without speed-up, because the data sources are entirely different from ours in terms of both quality and quantity; no detailed information on the previous observations were available. Although Johnson (1972, Arctic) notes that the history of glacier from 1935 to the present is well-documented, his statement is based on a personal communication with Wood and Post; no documents are accessible at present. Moreover, we had mentioned the first fluctuation of terminus area corresponds to the 1978 surge reported in Clarke and Holdsworth (2002) at P5948, L17-20 of the manuscript, but it seems the explanation was unclear. Thus, we will re-write some sentences to make it clear.

First we mentioned the past surging in the *Donjek Glacier*, citing some papers at P3L8-20. After that, we added one paragraph in the *Discussion* at P6L2-15 to compare the historical records and our detected data.

On the issue of citations, I was surprised that the authors didn't cite more of the classic papers on surge behavior (as described by Referee #1). The authors make substantial inferences based on the apparent 12-year cyclicity but I note that their 1989 surge is based on a single datapoint, and the only datapoint prior to that is from 1986. I was also some surprised that the authors did not provide a list of the 64 images they used.

This is also due to the limited number of references, which is a rule of *Brief Communication*. However, we will re-write the introduction, adding the references on the previous papers on the surge at Donjek Glacier.

Regarding the 1989 surge, we added some velocity data in 1987, 1988, and 1990. Now we can unarguably claim that the surging occurred in 1989. Moreover, we will add the list of the image pairs in the supplementary.

We cited some references in places to make it clearer. Moreover, we added some data in 1987, 1988, and 1990 in Fig. 1 and Fig. 2.

I agree with many of the comments provided by Referee #1 and have tried to avoid duplicating them here. However, I want to point out that Referee #1 seems to be frustrated by the very broad statements made by the current authors, for example about waxing and waning of the terminus area, and links to 'global warming'. I absolutely agree, in that I got the feeling that the authors had made some interesting observations, but failed to put as much effort into coming up with plausible and well-thought out explanations for them. I have not pointed out small typographical or technical errors, but have made comments on passages that I found confusing. I provide below line-by-line suggestions and comments.

Thank you for the detailed comments, which would be helpful to make the manuscript much clearer.

Specific Comments P5944 L6 – On the regularity of the surge cycle at Donjek Glacier, have the authors read the literature about the velocity fluctuations at Black Rapids

Glacier? In the upper parts of that glacier, 50% velocity oscillations have been observed on timescales of 12 years (see for example Heinrichs et al 1998; Nolan 2003, Annals of Glaciol.; USGS Open File; Truffer et al 2005, J. Glaciol.; Shugar et al 2012, JGR).

Thank you for your information. We have known about the oscillations documented by Truffer et al. (2005), and we have read some papers you suggested. However, they are not showing the active surging phase. Instead, Nolan (2003) shows that this oscillation would be the manifestation of slowly propagating waves of till failure and till healing during the quiescent phase. The amplitude of the oscillations is quite different from that in our data.

P5945 L3 – I am not clear what 'acquisition time' refers to in this context. Do the authors mean seasonality?

What we mean here is SAR data acquisition can be done both daytime and nighttime.

One explanation was inserted at P2L24-25.

P5945 L11 – Donjek River 'Valley System' is not a proper noun and so should not be upper case. Further, the Donjek Glacier is in southwest Yukon, not northern Yukon.

We are a bit puzzled with the comment, because Clarke and Holdsworth (2002) wrote "Donjek River Valley System". We will change "northern" to "southwest".

We changed "northern" to "southwest".

P5946 L16 – The sentence 'We calculated the terminus area changes. . .' is somewhat confusing.

We will re-write it as below.

"We calculated changes in area of the terminus lobe using a fixed reference line placed about 5 km from the terminus."

We re-wrote it as below at P4L6-8.

"We calculated terminus area changes using a reference line set upstream to create a polygon representing the edge of the terminus."

P5946 L24 – Why is the colorbar shown in linear scale on one panel but logarithmic on the other?

We considered that linear scale is clearer to show that the surging area is limited to the 20-km section from the terminus. On the contrary, logarithmic scale is clearer to show that upstream speed around 30-km section is faster than lower part in the quiescent phase and nearly constant over time. Thus, we use the linear scale for showing an example speed map associated with the 2001 surging episode and the logarithmic scale for the temporal evolutions. However, as also pointed out by Referee#1, we will set the scale as logarithmic.

We changed the color scale to logarithmic in Fig. 1b.

P5947 L9 – Do the authors mean that there is a distinct slowdown in the 5 years prior to the surges/speedups they observe? This is interesting but there does not appear to be any effort to explain this velocity fluctuation.

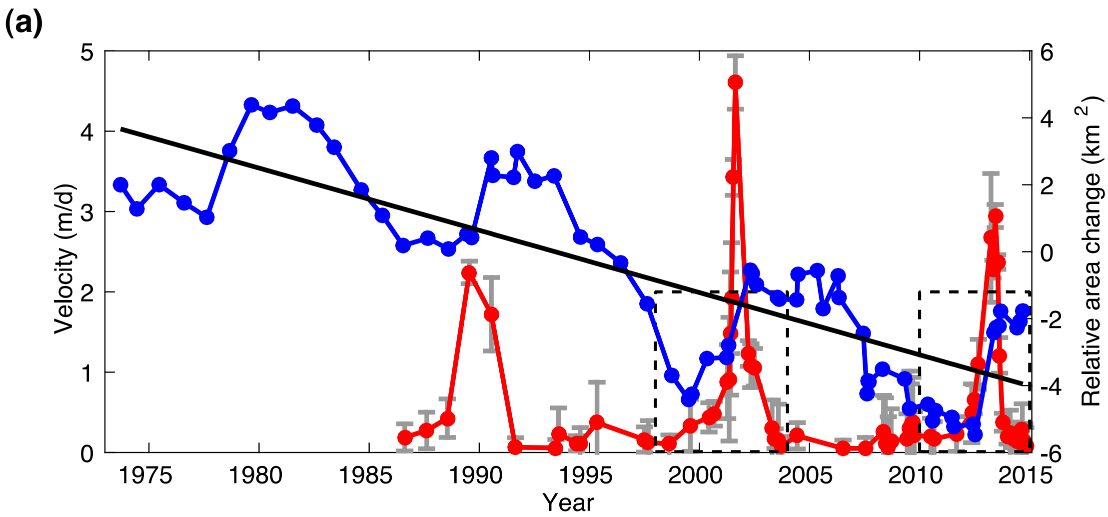
No. What we would like to tell here is the velocity front (about ~0.5 m/d) propagated to the terminus prior to the surging. As also pointed out by Referee#1, we will add some sentences to make it clearer.

We added the explanation at P4L26-31.

P5947 L17 – The authors describe the peaks in the red lines (Fig 2a) as representing surges. While I don't dispute this at all, I am left underwhelmed by the evidence for the 1989 surge, which is entirely composed of a single datapoint. Indeed, the blue line (changes in terminus area) pattern would suggest a surge, but the more direct evidence is not particularly convincing. Perhaps the authors ought to make more out of the blue line than they do.

As we mentioned above, we added some data in 1987, 1988, and 1990 (new figure is below). Now we can unarguably claim that the surging occurred in 1989. We do never claim, however, that the speed of 1989 surge is lower than 2001 and 2013, because there are fewer data points in late 1980s to early 1990s.

We re-generated the new figure 1 and 2 because the some data in 1987, 1988, and 1990 were added.



P5947 L22 – As mentioned above (and by Referee #1) the authors do not provide sufficient information about the scenes they used. Here, they describe a gradual increase in velocity from 'late 1998-1999' but provide no specifics.

We added the detailed list of Landsat images as Table S1 and some sentences about the error at P1L20-23 in the Supplementary material. Moreover we added the statement at P5L11-13.

P5947 L29 – As above, the authors provide no specifics about the 64 images used.

We consider that it is not necessary because they are basically the same as those used in the velocity mapping.

P5948 L2 – Surely the authors can do better than simply presuming that the change in glacier terminus area is related to global warming. Or at the very least, cite some other papers from nearly glaciers (there are many to choose from) that back those claims up with data.

OK, we will cite some papers and re-write the sentences.

We added some explanations at P5L16-17.

P5948 L6 – The authors state that there are 'a few time lags'. Can they be a little more specific?

We have considered the significant terminus advances occurred a bit after the speed-up, but we cannot quantify the time due to the coarse temporal resolution.

P5948 L8 – The authors state that they cannot derive the glacier speed prior to 1985. Why not? I conducted a 5-minute search on the Canadian Government's NEODF airphoto and satellite imagery search engine and found stereo imagery going back to the late 1940s (incl 1940s, 50s, 70s and 80s). While not the same resolution or timestep as the satellite imagery, these could certainly be used to augment the time series presented by the authors.

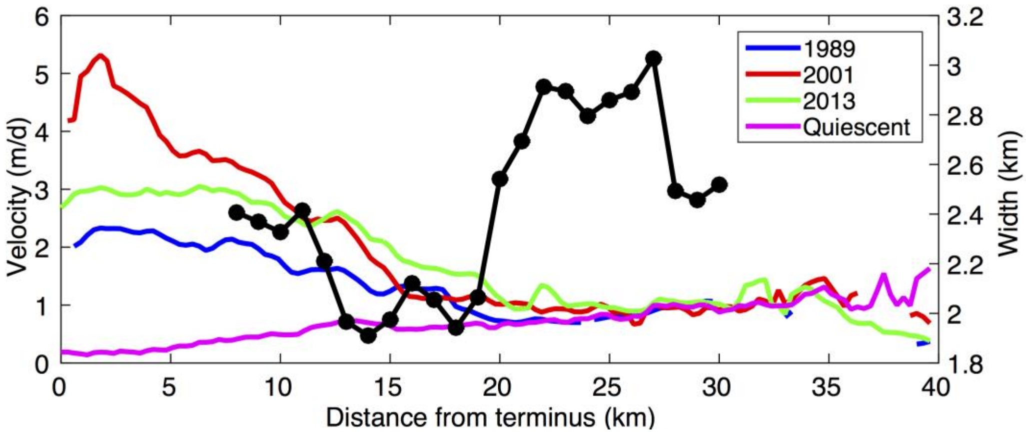
This is due to the low spatial resolution of Landsat 1-3 MSS data, which we have already mentioned in the paper. Although it may be useful to just mention the past surging episodes, the low and coarse resolution images do not augment the "time series" as equally as we have done in the manuscript. The aim of this paper is to inform that the recent three surging episodes occurred at Donjek Glacier with 12-year constant cycle and that they initiated in the narrower valley zone.

Also, thank you for letting us know the NEODF search engine. We tried it, but it turned out that there are only several images could cover the downstream of Donjek Glacier; the temporal resolution was inhomogeneous and coarse.

P5948 L13 - The authors describe the constriction in the glacier width here and elsewhere as being 'at least 35% narrower' [Italics are reviewer's emphasis]. I don't buy this argu- ment. A quick measurement in Google Earth shows it to be at most <30% narrower than upstream, and certainly not for the lower 20km (or whatever ~20km section the authors describe, which is unclear). In fact, there is a relatively short section of <8km that is <30% narrower than upstream, but the glacier then widens again. And in fact, is narrower farther upglacier too. Instead of a local constriction as the authors describe, I would suggest it is perhaps a longitudinally fluctuating width. I would like to see a plot of width vs length here.

We derived one figure showing a plot of width v.s. length in black below calculating every 1 km between 8 and 30 km from the terminus. The velocity profiles associated with the three surging and quiescent averaged between 2003 and 2011 are also shown. As you can see, the section between 18 and 22 km is significantly narrower than upstream, which is about 33% ('At least 35 % narrower' may be a little bit large…). Moreover, the section corresponds to the area where the surging episodes initiated.

We added one figure as fig. 1d and some explanations at P4L20-26 in the *Results*.



P5948 L24 – The authors pin a lot on three surges, here saying: '. . .the recurrent [sic] interval seems to be fairly regular with few variabilities.' With their 1989 surge resting on a single datapoint, I find this statement to be a little too strong. Further, previously published reports of surges in 1961, 1969, 1974 (though a tributary only) and 1978 absolutely must be discussed.

As we mentioned above, we added some velocity data in 1987, 1988, and 1990. Now we can confidently claim that the surging occurred in 1989. Although we have mentioned the surging in 1974 and 1978, we have not stated the surges in 1961, and 1969. As we also discussed in the Reply to Referee#1, we will refer to Johnson (1972) and mention the surge in 1960s.

We mentioned the past surging in the *Donek Glacier*, citing some papers at P2L13-20. After that, we added one paragraph in the *Discussion* at P6L2-15 to compare the historical records and our detected data.

P5949 L8 – The authors again describe the constriction, and suggest that it 'may generate a steep surface slope around the narrowing zone'. This would be incredibly easy to determine in a GIS, yet they have not done it. A figure combining a plot of width vs length and elevation gradient would add some weight to their arguments, in my opinion.

We derived the one figure showing a plot of width v.s. length, as attached above. We could not derive the temporal changes in elevation gradient, because a series of DEMs are not available.

We added the new figure 1d showing a plot of width v.s. length, and the explanations at P4L20-26.

P5949 L12 – The sentences describing the findings of Eisen et al (2001) read a little bit like an undergraduate textbook.

We modified the sentences as below at P6L24-25.

"Eisen et al (2001) attributed the variability in the recurrence intervals to the variable annual mass balance".

P5950 L1 – The first paragraph on this page (starts on 5949) is rather confusing. It jumps around in space and theme, and is as a result hard to follow. I suggest a rewrite.

OK. We will re-write the paragraph to make it clearer to follow.

We re-organized the two previous paragraphs at P6L16-P7L12 to make it easier to follow the next.

P5950 L13 – The authors speculate (their choice of words, L11) that ice locally thickens during quiescence, but they provide no evidence to back this claim up. Analysis of a series of DEMs would allow the authors to state with some confidence, rather than speculate, about ice thickness changes.

It is absolutely true that a series of DEMs would back up the claim, but we have no publicly available data to examine the elevation changes.

P5951 L2 – The authors 'propose to perform detailed observations of not only velocities but also geometric and hydrological changes for the next event' in or around

2025. While this is a nice goal, it reads as if for a grant proposal, not the closing sentence of a peer-reviewed paper.

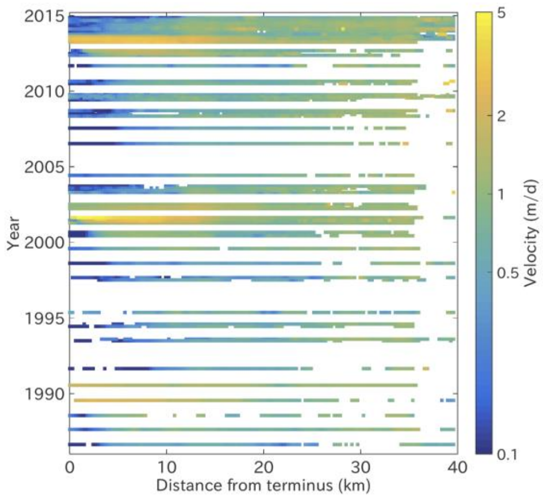
We re-wrote the sentence as below at P8L24-26.

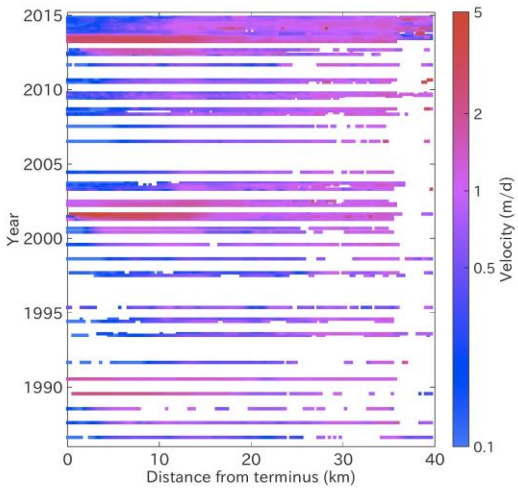
“The detailed observations of not only velocities but also geometric and hydrological changes are needed for the next event in order to reveal the generation mechanisms.”

Figure 1 – I really do like the way the authors have portrayed the velocity time series in panel c. Except I don’t understand why the color scale changes with respect to panel b. These should be the same. Also, there has been much online in recent years about how the ‘jet’ colorscale should be avoided because it draws the viewer’s eye to things that are not necessarily ‘real’. Have the authors tried plotting with a different colorbar to see what it looks like?

As pointed out by the Referee#1, we will set the color scale as logarithmic. Moreover, we generated two figures with different colorbars as below. What do you think? We consider that these colorbars are unclear to show the speed changes, and “jet” would be the best to plot.

We set the color scale as logarithmic using “jet” in Figure 1 and c.





Best regards,

Takahiro Abe, Masato Furuya, and Daiki Sakakibara

Brief Communication: Twelve-year cyclic surging episode at Donjek Glacier in Yukon, Canada

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Abstract

Surge-type glaciers repeat their short active phase and their much longer quiescent phase usually every several decades or longer, but detailed observations of the evolution cycles have been limited to only a few glaciers. Here we report three surging episodes in 1989, 2001, and 2013 at Donjek Glacier in the Yukon, Canada, indicating remarkably regular and short repeat cycles of 12 years. The surging area is limited within the ~20 km section from the terminus, where the flow width significantly narrows ~~than up~~downstream, suggesting a strong control of the valley constriction on the surge dynamics.

Introduction

During their short (1-15 years) active phase, ~~S~~surge-type glaciers speed up by ~~exhibit~~ several-fold to over an order~~s~~-of-magnitude ~~speed-up during the short (1–15 years) active phase~~, resulting in significant thickness changes and km-scale terminus advance (Meier and Post, 1969; Raymond, 1987; Harrison and Post, 2003). In the~~ir~~ quiescent phase~~s~~ (tens to hundreds of years), they flow slowly or become stagnant in the downstream. Meanwhile, ice ~~mass is~~ accumulate~~s~~d in the upstream area ~~for the next active phase~~ and the imbalanced flow causes retreating and thinning in the downstream area, which produces~~develops~~ a steeper glacier surface in the upstream. The~~is~~ part of the~~latter~~ quiescent phase is sometimes called ~~as the~~ build-up phase (Dolgoushin and Osipova, 1975; Jiskoot, 2011). As to the cause of the surge, two generation mechanisms have been proposed: the Alaskan-type and the Svalbard-type (e.g., Murray et al., 2003).

In Alaskan temperate glaciers, the active phase is relatively short, lasting a few months to years, and can have a rapid speed-up and slow-down. The Alaskan-type surge often initiates in winter (Raymond, 1987; Harrison and Post, 2003). The initiation mechanism is thought to be a hydrological transition from efficient tunnel-like drainage to inefficient linked-cavity drainage with a corresponding increase in water pressure (Kamb et al., 1985; Harrison and Post, 2003). In contrast, in Svalbard polythermal glaciers, the speed-up is gradual, leading to years-long active surging. For these glaciers, the active-phase duration and the recurrence interval are much longer than those in the temperate Alaskan-type. Moreover, for Svalbard polythermal glaciers, the surge generation mechanism has been considered to be thermal regulation (e.g., Murray et al., 2003). However, recent observations have shown seasonal modulation in ice speed during the years-long active surging, which indicates the importance of the hydrological process, originating in the surface meltwater, for maintaining a multi-year active phase (Yasuda and Furuya, 2015).

~~Near the border of Alaska and the~~ Yukon, Canada, there are many surge-type glaciers (Meier and Post, 1969; Raymond, 1987; Harrison and Post, 2003). The ~~Nevertheless, detailed observations of the repeating~~ surge cycles in this area have been examined ~~have been extremely limited~~ (e.g., Eisen et al., 2001; 2005; Frappé and Clarke, 2007; Burgess et al., 2012; Bevington and Copland, 2014), but the observations have been too limited to reveal ~~which prevents from better understanding~~ the surging dynamics ~~of surge-type glacier~~ (Raymond, 1987; Harrison and Post, 2003; Cuffey and Paterson, 2010).

~~More extensive observations come from R~~recent advances in spaceborne remote sensing. ~~techniques~~ In particular, synthetic aperture radar (SAR) images have revealed spatial and temporal changes in ice velocity at surge-type glaciers in Alaska and the Yukon~~, using Synthetic Aperture Radar (SAR) images~~ (Burgess et al., 2013; Abe and Furuya, 2015). ~~However, t~~The temporal coverage of spaceborne SAR data is still too short to investigate long-term evolution~~s~~ in ice speed, although SAR allows~~ed~~ us to image remote areas regardless of weather conditions and acquisition time (i.e. SAR data acquisition can be done both daytime and nighttime). Landsat optical images distributed by the United States Geological Survey (USGS) have been available since 1972. While optical images have their limitations in local weather conditions, they revealed the long-term changes in terminus positions and velocities of mountain glaciers in the world (e.g., McNabb and Hock, 2014; Sakakibara and Sugiyama, 2014). To reveal the long-term evolution of Donjek and associated surge-type glaciers nearby, we use Landsat optical images acquired between 1973 and 2014 to derive the spatial-temporal changes in ice speed (1986-2014)~~both the velocity field~~ and the terminus areas (1973-2014). ~~Here we report our findings of three surging events of Donjek Glacier.~~As a consequence, we report here our findings of three surging events as well as a likely surging event pre-1985 at Donjek Glacier.

Donjek Glacier

Donjek Glacier is located in the Donjek River Valley System in ~~northern~~ southwest Yukon (Fig. 1a), which consists of Steele, Spring, Donjek, and Kluane Glaciers; all these are surge-type (Clarke and Holdsworth, 2002). The entire length and area are 55 km and 448 km^2, respectively. Donjek Glacier ~~is located~~lies at an elevation of 1000–3000 m, and the valley width significantly constricts toward downstream 20-km from the terminus.~~ As shown in the result, however, the surging area is limited to the lowermost 20 km, where the flow width becomes significantly narrower than upstream.~~ The terminus spreads out as it flows into the river valley to form a small piedmont lobe. Former surges have caused this lobe to expand to the east against the Donjek Ranges, which blocked the flow in the river (e.g., Clarke and Mathews, 1981). ~~The r~~Recent airborne laser altimetry revealed that the mass balance of Donjek Glacier was –0.29 m w.e. yr^{-1} (Larsen et al., 2015). ~~Although a previous study reported a surge event in 1970s (Clarke and Holdsworth, 2002), there is no report about the recent surges, and the long-term evolution remains uncertain.~~ Previous studies mentioned past surging events in 1935, 1961, 1969, and 1978 (Johnson, 1972a; 1972b; Clarke and Holdsworth, 2002). The earliest three events were recognized using aerial photogrammetry and morphological features. However, the details of the observations (e.g., data source and the observation frequency) and even the duration of the active phase are unclear. Moreover, surges since the 1980s are unreported, and the long-term evolution remains uncertain. ~~The last~~Donjek's last tributary (Fig. 1a) is~~is~~ also known as a surge-type that was active in 1974 (Clarke and Holdsworth, 2002).~~ and 2010 as shown in Fig. 3.~~

Data and method

We used Landsat optical images~~s from 1973 to 2014 were used in order to examine the flow speed evolution and the terminus fluctuation.~~, to examine terminus changes from 1973 to 2014 and flow-speed evolution from 1986 to 2014. The flow-speed examination period is shorter due a resolution problem. These images were acquired by the Landsat 1-5 Multi-Spectral Scanner (MSS), the Landsat 4-5 Thematic Mapper (TM), the Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and the Landsat 8 Operational Land Imager (OLI), all of which are distributed by the USGS (http://landsat.usgs.gov/).

While there are a variety of image matching ~~methods~~ (i.e. feature tracking) methods to derive glacier surface speed (e.g., Heid and Kääb, 2012), we used the Cross-Correlation in Frequency domain on Orientation images (CCF-O) algorithm (Fitch et al., 2002) to derive surface velocity in this study~~,~~ because for Alaskan glaciers, the CCF-O algorithm performs better than ~~is the best performance of all~~ the other methods (Heid and Kääb, 2012). For~~The~~ details of image ~~our~~how we applied this ~~processing~~ method, see~~are described in~~ the supplement~~ary~~.

We also examined the fluctuation of the terminus area ~~fluctuation~~ associated with the surging events using the false color composite images (see the supplement~~ary~~). The spatial resolution of ~~the~~a composite image is 60 m for the MSS images and 30 m for the others~~, respectively~~. ~~We calculated the terminus area changes derived from setting a polygon formed by the terminus lobe and the reference line set in an upstream area~~ We calculated the terminus area changes using a reference line set upstream to create a polygon representing the edge of the terminus.

Results

~~Figure 1a shows the location of Donjek Glacier and the flow line used in our measurement of the velocity distributions.~~ Figure 1b shows the ice speed map for the 2001 surge as an example~~; the velocity map is derived from two images acquired between August and September 2001, and the ice speed is shown in linear scale.~~, and ~~F~~figure 1c indicates the spatial-temporal velocity evolution along the flow line shown in Fig. 1a from 1986 to 2014~~; the ice speed is now shown in logarithmic scale~~. (Because of the lower spatial resolution of the images prior to 1986, we could not derive the velocities ~~during a period~~ between 1973 and

1985, but they images were helpful to examine the terminus changes even in 1970s.) In 1989, 2001 and 2013, the speed near the terminus is apparentlyappears much greater than those in other years, whose velocity reaches, by up to 2 m/d, 4.5 m/d, and 3 m/d, respectively. In contrast, the speed during the other years (i.e. quiescent phases) is about 0.5 m/d or less at the terminus. During the three active phases, the speed-up regions are mostly limited to the ~20-km section from the terminus (see also Fig. 1b), which we associate below with the geometry shape of the glacier.

Consider the possible relation between the width of the valley, and the velocities associated with the three surging episodes. In Fig. 1d, these velocities are blue, red, and yellow-green for the 1989, 2001, and 2013 episodes, respectively, whereas the valley width is black. The valley at the section between 18 and 22 km from the terminus is about 33% narrower than upstream, where we observe the initiation of the three surging episodes (Fig. 1c). Meanwhile, the velocities in the further upstream do not indicate show any significant temporal changes throughout the analysed period, maintaining awhose speed isof about 1.0 m/d (Figs. 1c and d). We Aalso, notice that the velocity front of ~0.5 m/d (i.e. the boundary between the stagnant and moving part near the terminus) propagates toward downstream over for the more than 5-years or longer period prior to the 2001 and 2013 active phases. The active phase seems to initiate when this front reaches the terminus. In addition, the velocities behind the front clearly indicate a gradual acceleration toward the peak active phases. However, wWe cando not identify anany clear timings of the surge initiation and termination season, which could be due to both/either the multi-year precursory acceleration and/or athe lack of temporal resolution in the available data.

Consider the ice speed 0–5 km from the terminus. The red curveline in Fig. 2a shows how this speed changes of the years. the temporal changes of the ice speed averaged over the section between 0 and 5 km from the terminus. The tThis speed has three significant peaks in the red . These peaksline correspond to the active phases in 1989, 2001, and 2013 (Figs. 1c and d). While the measured maximum speeds are different from each other, we do not consider the differences to beThe peak magnitudes all differ, but significant, because it could be due to the differences are likely due mainly to the coarse temporal sampling of the velocities.

Figure 2b and 2c show the enlarged views forNow consider the 2001 and the 2013 events in more detail. In the 2001 event (Fig. 2b), the speed startsed to gradually increase in the late

1998–1999, rapidly increaseing in the late 2000-2001, and rapidly decreasinge in 2003. The evolution of the speed for the 2013 event (Fig. 2c) is similar to that for the 2001 event. Namely, the speed startsinitiated to gradually increase in the late 2011–2012, rapidly increasinge in the late 2012 and then terminateds in the late 2013. Although the data do not resolve the exact month or season of the initiationRegarding the rapid acceleration as the surge, the the surge duration of the active phase is about 1 year.

The terminus area also changes from 1973 to 2014, showing decadal fluctuations superimposed on a gradual decrease. The blue line in Fig. 2a shows the temporal changes of the terminus area from 1975 to 2014. In total, we use 64 images to determine the terminus position. Besides the secular decrease in the terminus areas, we can identify decadal fluctuations. The black line in Fig. 2a indicates thea secular long-term rate of decrease of (-0.2 km^2/yr), which presumably indicates the trend negative mass balance trend from recent global warming (e.g., Luthcke et al., 2013; Larson et al., 2015)due to the recent global warming. Moreover, tThe decadal fluctuations in blue show their peaks around 1980, 1991, 2002, and 2014. Comparing those peaks with the speed changes in redwith the speed changes in red, the last three peaks in blue coincide with the last three peakscorrespond to those in the speed data in 1989, 2001, and 2013, with a 0-to-2 yearfew time lags (Fig. 2a). These correspondences indicate that Tthe decadal fluctuations are presumably attributable to the sudden speed-up of a surge event. During a surge, a significant volume of ice must be rapidly transported to the terminus area, and thus the wax and wane of the terminus area may occurassociated with the surge cycle. Although we cannot derive theour speed measurement do not go back data before 1985, such a surge is likely the reason for the temporal increase of the terminus area around 1980 as well is highly likely due to the surge in late 1970s.

Remarkably, the surging area is limited to just the glacial area within the ~20 km section from the terminus instead of the entire glacier (Figs. 1b, and c, and d). Moreover, It is also clear that thise surging area is significantly narrower than the upstream area (red arrow in Fig.1a), which is also an S-shaped valley; that is, the width of the ~20 km section is apparently at least 35 % narrower than upstream. In the three events, the surge seems to have initiated at this constricted area.

Discussion and Conclusion

Post (1969) developed the first comprehensive map of the distributions of surge-type glaciers near the border of Alaska and Yukon, mostly based on aerial photogrammetry. Donjek Glacier was also identified as a surge-type, presumably from its 1961 surge. However, the timing of past surging events at Donjek Glacier from previous studies includes large uncertainties. Those data sources have very different from spatial and temporal coverages than ours, and the active surging was largely judged from morphological observations. For instance, we could not find any descriptions of the activity of the surge at Donjek Glacier in the 1960s. Regarding the 1969 surge, Johnson (1972b) noted that the terminus advance was less than 500 meters, compared to the earlier surges in 1935 and 1961. However, given the recent observations, we may argue that a mini-surge-like acceleration (so-called pulse) could cause the slight advance of the terminus in 1969, a mini event like the pulse-like events in 1995 and 2009 (Fig. 1c). In addition, according to Johnson (1972a), there were no observations before 1935. Thus, we cannot say the surge initiated in 1935. Therefore, we do not merge these past events with our findings.

TThe recurrent intervals between the 1989 and 2001 events and between the 2001 and 2013 events are 12 years (Figs. 1c and 2a). Although we cannot derive the velocity data before 1985, the similar 12-year fluctuation in repeated terminus area fluctuations every 12 yearsthat extends before 1985 strongly suggests that the previous surging occurred in the late 1970s,. Such a surge which is consistent with the previous report of the surge in 1978 at Donjek Glacier –(Clarke and Holdsworth, 2002). The 12-year recurrent interval is as short as the latest interval at Lowell Glacier (Bevington and Copland, 2014). Lowell Glacier experienced five surges between 1948 and 2013, and the surge-cycle recurrent interval (12-20 years) has been shortening over time, which is interpreted as being due to a strongly negative mass balance since the 1970s or earlier (Bevington and Copland, 2014). Variegated Glacier is one of the most famous surge-type glaciers in Alaska, and its surge cycle has been well-studied (Eisen et al., 2001; 2005). Eisen et al. (2001) attributed the variability in the recurrence intervals to the variable annual mass balance. However, in contrast to the Lowell and Variegated Glaciers, whose average recurrent intervals are 15.25 (Bevington and Copland, 2014) and 15 years (Eisen et al., 2005), respectively, the recurrent interval at Donjek Glacier is not only shorter but also less variable over time, which we consider as significant differences despite the three surge-type glaciers sharing a similar climate.

The behaviour of Donjek Glacier is similar to Medvezhiy Glacier in Tajikistan (Dolgoushin and Osipova, 1975, Cuffey and Paterson, 2010), in that both have a short recurrent interval (10-14 years) and both have apparent geometrical control of the surging area. ~~The 12-year recurrent interval is the shortest among the surge-type glaciers in Alaska and the Yukon, and as short as those (10–15 years) of Medvezhiy Glacier in the West Pamir Mountains, Tajikistan (Dolgoushin and Osipova, 1975). Although we have only three solid evidences for the 1989, 2001, and 2013 episodes, the recurrent interval seems to be fairly regular with few variabilities. The short and probably regular recurrence will have important bearings on the dynamics and mechanisms of the surge.~~

~~We compare our observations at Donjek Glacier with those at other glaciers. In terms of the shorter interval and the narrower width of surging region, Donjek Glacier may be similar to Medvezhiy Glacier whose evolution was extensively monitored in the 1960–70s (Dolgoushin and Osipova, 1975).~~ Medvezhiy Glacier lies in the West Pamir Mountains, and its surging activity was extensively monitored in the 1960s–70s (Dolgoushin and Osipova, 1975). Medvezhiy Glacier has a wider accumulation area at an elevation of 4600 to 5500 m, but the surges are confined to the 8-km long ice tongue in the narrow valley, separated by a steep ice fall that drops by 800 m per 1 km (Dolgoushin and Osipova, 1975). Although ~~there are no large~~ the slope changes ~~at~~on Donjek Glacier are smaller, the significant valley constriction may generate a steep surface slope in the quiescent phase around the narrowing zone due to ~~by~~ the mass transport from upstream ~~in the quiescent phase~~. As such, the apparent regularity of the recurrent interval may be due to the rather steady flow speed upstream. ~~At Variegated Glacier, the recurrent interval is about 15 years (e.g., Eisen et al., 2001). Eisen et al. (2001) estimated the cumulative mass balance in the upstream on Variegated Glacier, and showed that the surges were initiated when cumulative annual mass balance reached some critical value. The variabilities in the recurrence interval could be explained by the variable annual mass balance. The apparent regularity of the recurrent interval at Donjek Glacier may be due to the rather steady flow speed in the upstream.~~

At Medvezhiy Glacier, the observed maximum speed exceeds ~~is greater than~~ 100 m/d, and the active phase initiates in winter, lasting about 3 months (Cuffey and Paterson, 2010). At Variegated Glacier, the surge also initiates from fall to winter and the maximum speed is ~~up to~~ 50 m/d during the 1982-1983 surge (Kamb et al., 1985). ~~In~~ At Bering Glacier, ~~the~~ a similar behavior (~~higher~~ speed exceeding~~more than~~ 10 m/d, and winter initiation) is observed in the

2008-2011 surge (Burgess et al., 2012). The recurrent interval is about 18 years. Similar behavior has also been confirmed at Lowell Glacier (Bevington and Copland, 2014). These sudden speed-ups in fall-~~–~~to~~–~~-winter and rapid slow~~–~~-downs in early summer are ~~interpreted~~ thought to arise from the~~by~~ hydrological regulation mechanism.~~,~~ ~~which is a destruction of tunnel-like channel and subsequent change into linked-cavity system and water pressure increase.~~ The ~~hydrological regulation~~ mechanism, which evolves a destruction of tunnel-like channels and subsequent change into a linked-cavity system that increases the water pressure, has been proposed~~,~~ based on ~~the~~ detailed observations of~~n~~ the 1982-1983 surge at Variegated Glacier (Kamb et al., 1985).~~,~~ Thus, ~~and~~ such surges are often termed an Alaskan-type surge. Meanwhile, our observed maximum speed reached at most ~ 5 m/d and there seems to be no clear initiation season~~s~~. It is likely, however, that we have missed much higher speeds and winter initiation due to the coarse temporal resolution in our velocity data. The 12-year recurrent interval is apparently shorter than that in a Svalbard-type surge, whose cycle is thought to be 50 years or much longer (Murray et al., 2003; Jiskoot, 2011). Moreover, the active duration is much shorter than that of~~in~~ Svalbard-type, and the flow speed seems to have rapidly slowed down after the active phase. The observed multi-year acceleration may include small acceleration events or mini-surges that redistribute thickening and thinning (Raymond and Harrison, 1988; Harrison and Post, 2003) during the build-up phase. Thus, we consider that the surge phase of the two events is about 1 year, and that Donjek Glacier presumably~~will probably~~ has the~~belong to~~ Alaskan-type surge.

We speculate ~~the following scenario for~~Based on these findings, we argue that the cyclic surging at Donjek Glacier occurs as follows ~~episode~~. In the quiescent phase, ice delivered from the upstream area ~~is~~ stores~~d~~ up at the highly~~significantly~~ narrowed area (Fig. 1a), causing ~~and the ice~~ local~~ly~~ thicken~~s~~ing. The ice thickening generates a steeper ~~geometry~~ slope with a corresponding higher driving stress. When the ice thickness reaches a critical value, the glacier ~~initiate~~starts to speed-up. We do not claim, however, that th~~e~~ise driving stress itself is high enough to initiate the surging~~.~~; that is, the thickening of ice and steeper slope are not the direct cause of surging. Rather, thickened ice upstream is just a pre-condition prior to surging. But a~~A~~s the ice thickness increases, the volume of englacial water storage will also increase, which can supply~~will assist~~ a greater basal water flux and increase its pressure, thereby allowing the higher speed during the surging event (Lingle and Fatland, 2003; Abe and Furuya, 2015). During the surge, the inefficient drainage system and the ~~enough~~sufficient englacial water volume can maintain~~keep~~ higher velocity. After the mass re-distribution terminates, the thickness in the reservoir zone will again increase for the next event.

The last tributary at Donjek Glacier (Fig. 1a) is also known as a surge-type, with~~and the~~ a previously studied surge that occurred in 1974 (Clarke and Holdsworth, 2002). We used Landsat images to examine~~d~~ the interaction of th~~e~~is tributary to the main stream~~, using Landsat images~~. There are many looped moraines on the main stream induced by the tributary's surge (Fig. 3a). Although we observed only two tributary~~'s~~ surge events, being in 1973–74 (Fig. 3b) and 2009–2010 (Fig. 3e), ~~it turns out that the interval is~~their separation indicates an interval of 36 years. This interval ~~It~~ is much longer than that ~~in~~for the main stream~~ surging~~, indicating that the tributary's surge is independent from the main stream's ~~surging~~.

The next event of Donjek Glacier is ~~highly~~ likely to occur around 2025. ~~In order to better understand the surge dynamics, we propose to perform detailed observations of not only velocities but also geometric and hydrological changes for the next event.~~To test the model proposed here, we need detailed observations of not only ice velocities but also the associated geometric and hydrological changes.

Acknowledgements

Landsat images were downloaded from http://earthexplorer.usgs.gov. Glacier outlines were downloaded from the Randolph Glacier Inventory version 4.0 http://www.glims.org/RGI/rgi40_dl.html. We acknowledge JSPS-KAKENHI grant~~d~~ number 24651001 (M.F.) and Grant-in-Aid for JSPS Fellows (T.A.:15J01952 and D.S.:14J02632) for supporting this study.

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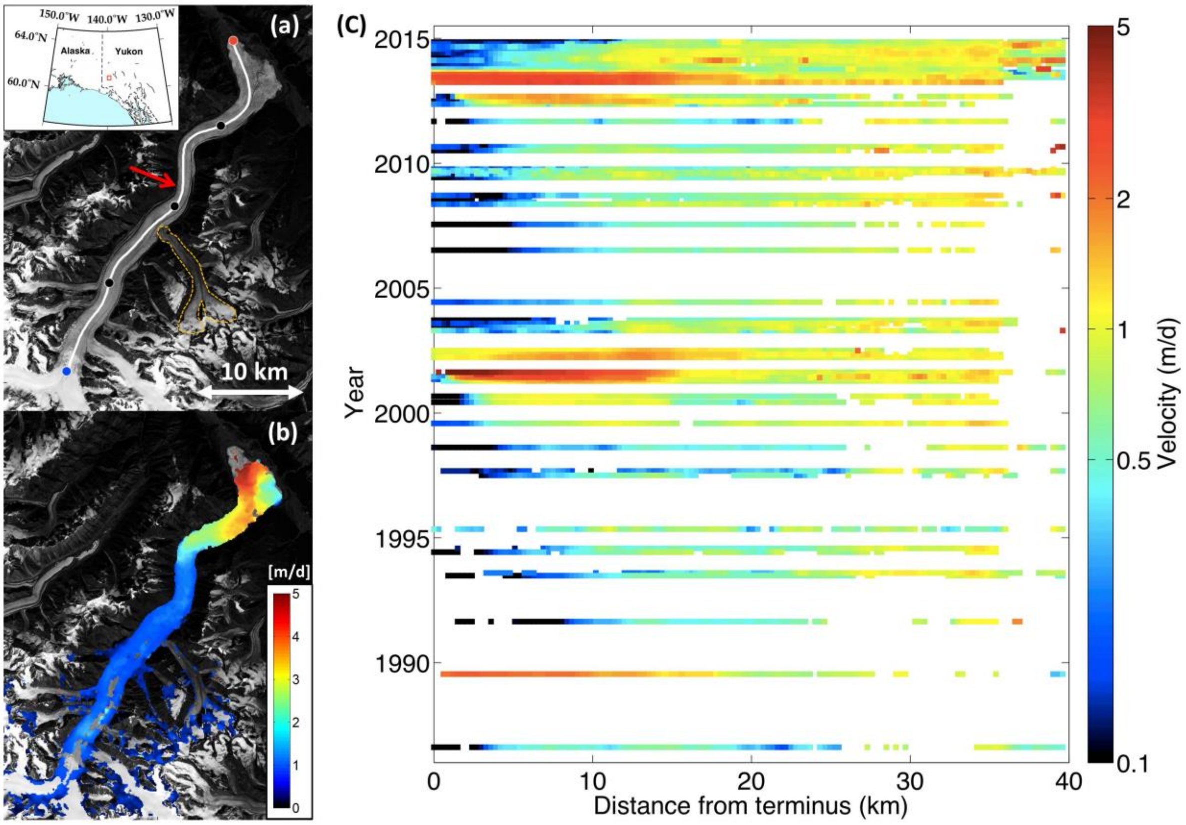
Figures and captions



~~Figure 1. (a) Location of Donjek Glacier and a flow line used in (c). The red and blue dot shows the start and end point of the flow line. The black dots are plotted every 10 km interval. The length of the flow line is close to 40 km. The red arrow indicates the significantly narrowing area of the valley. The dotted orange indicates the last tributary. (b) A sample ice speed map derived from two images acquired on August and September, 2001. The color scale is shown in linear scale. (c) Spatial-temporal velocity evolution along the flow line in (a) from 1986 to 2014. The color scale is shown in logarithmic scale.~~

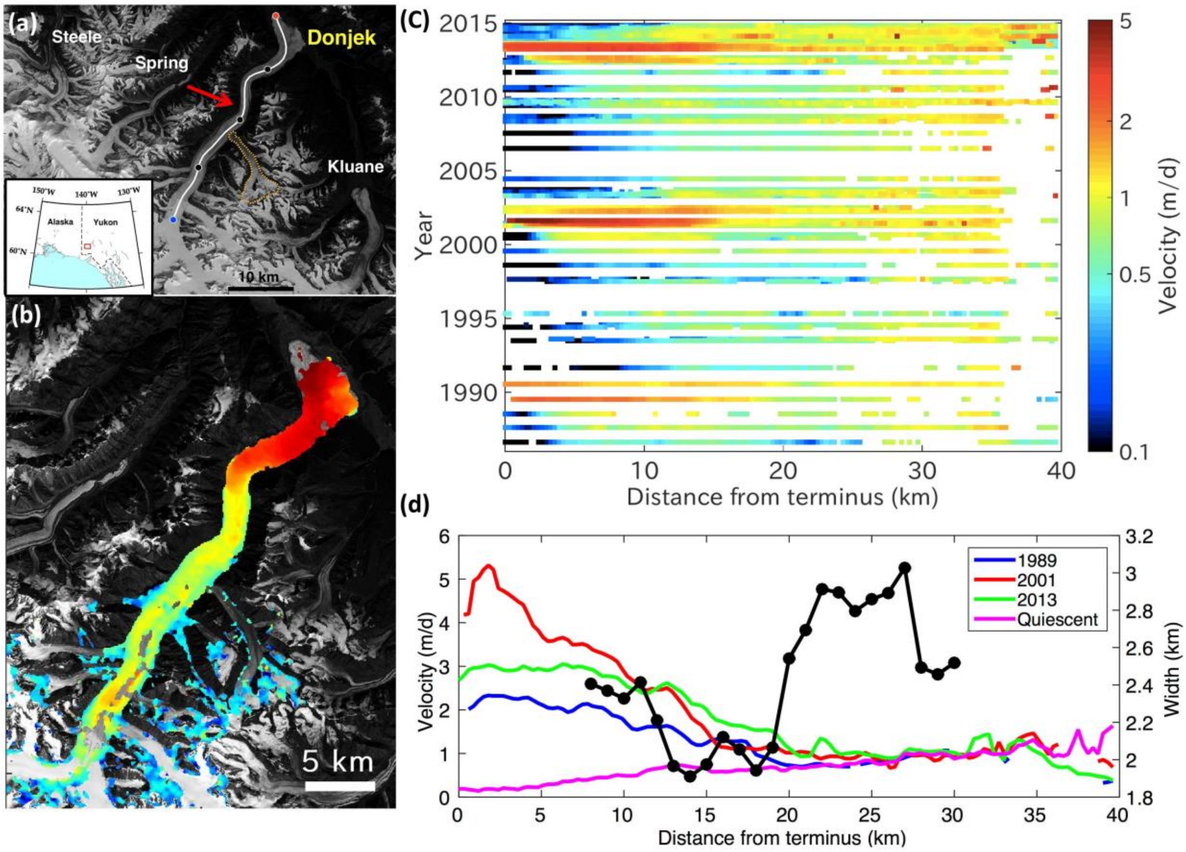
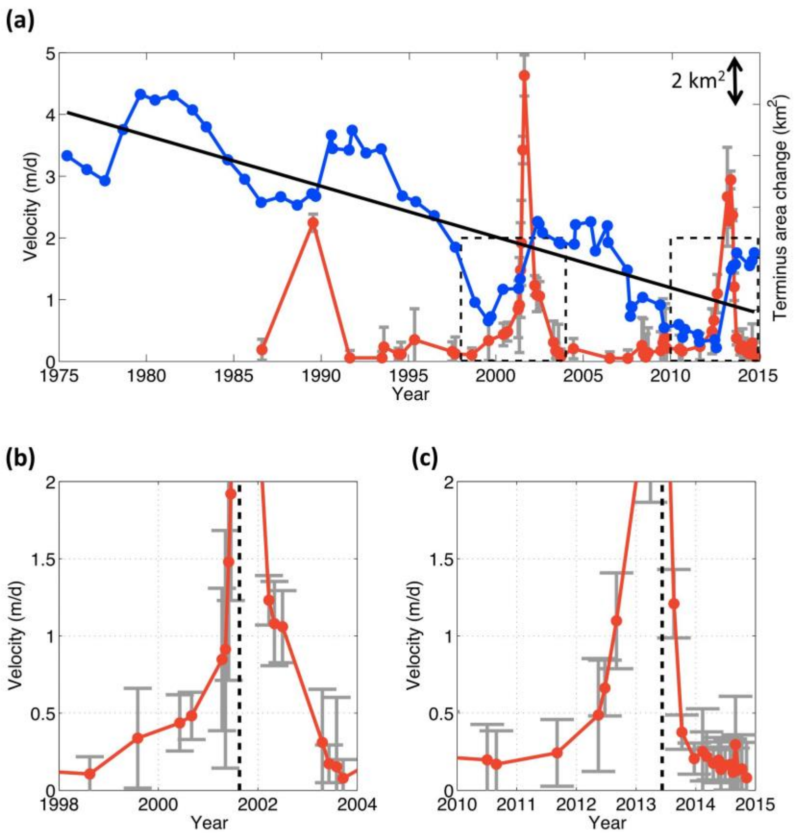


Figure 1. Glacier flow speeds and glacier extent. (a) Location of Donjek Glacier. Background is a Landsat 8 image acquired on 22 July 2014. White line is the flow-line used in (c) and (d). The red and blue dots show the start and end points, whereas the black dots mark 10-km intervals. The red arrow indicates a significantly narrower area of the valley and the dotted-orange curves outline the last tributary. (b) A sample ice-speed map derived from two images acquired on August and September, 2001. The color scale (logarithmic) is the same as that in (c). (c) Spatial-temporal velocity evolution along the flow line in (a) from 1986 to 2014. (d) The black line shows the change in the valley width between 8 and 30 km along the flow-line. The blue, red, and yellow-green lines show the ice velocity associated with surging episode in 1989, 2001, and 2003, respectively. The pink line is the averaged velocity between 2003 and 2011 (i.e., the quiescent phase).


(a)
2 km^2
Velocity (m/d)
Terminus area change (km^2)
Year
(b)
Velocity (m/d)
Year
(c)
Velocity (m/d)
Year

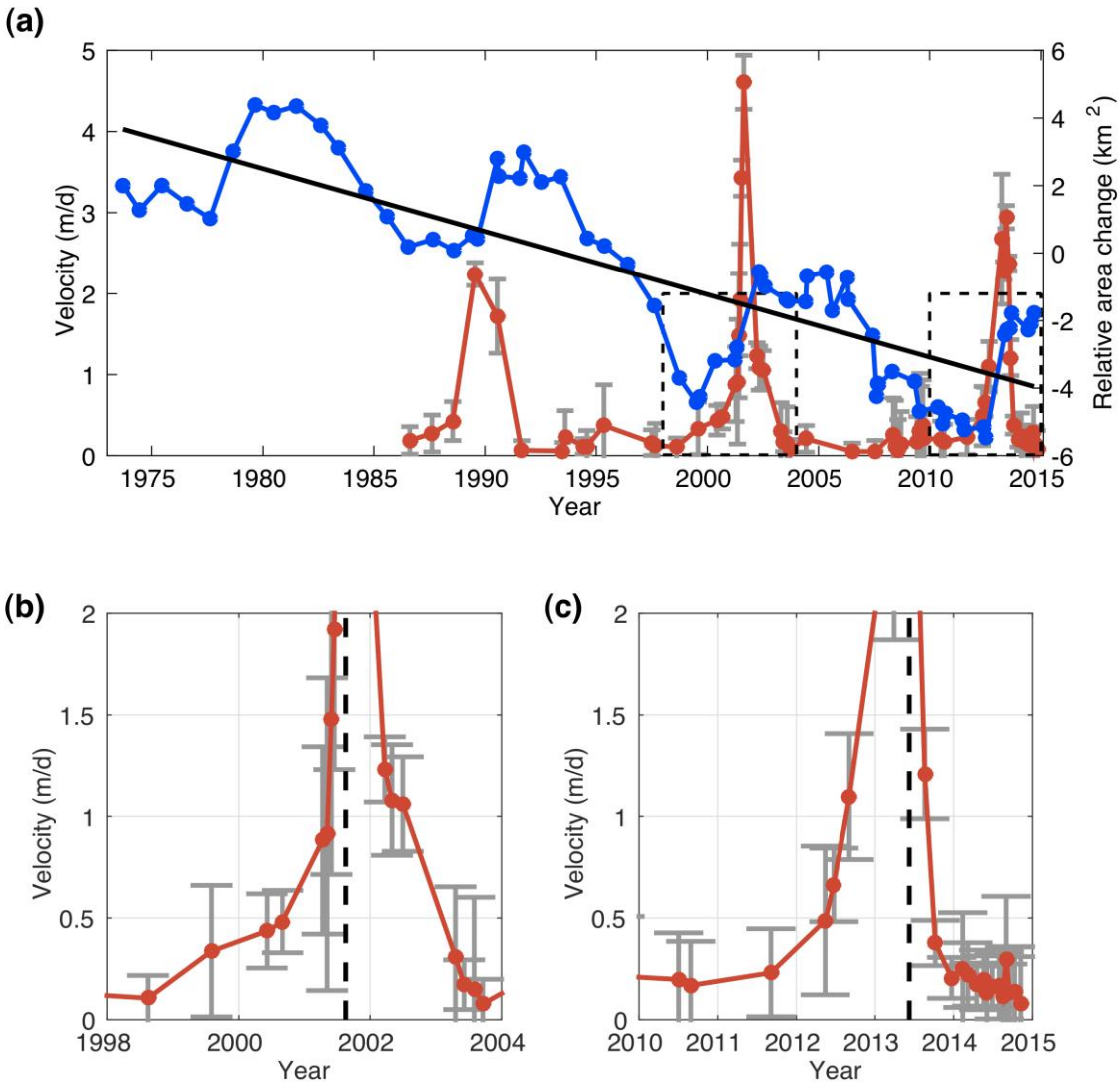


Figure 2. Ice speeds and area near the terminus. (a) Temporal changes of the ice speed (red) and the terminus area (blue). The ice speed data are averaged over the section between 0 and 5 km along the flow line shown in Fig. 1a. The error-bars indicate the mean speed in the non-glacia~~ted~~l region. The black line indicates the ~~secular~~ long-term change of the terminus area. ~~The one tick of the right axis stands for 2 km^2.~~ The dotted-line boxes mark~~indicate~~ the areas shown in (b) and (c). (b) ~~Enlarged t~~Temporal change of the ice speed associated with the 2001 event.~~ and~~ (c) Same as (b) except ~~one~~ for the 2013 event~~, respectively~~. The black-dotted line marks~~indicates the time of~~ the peak in ice speed during each event.

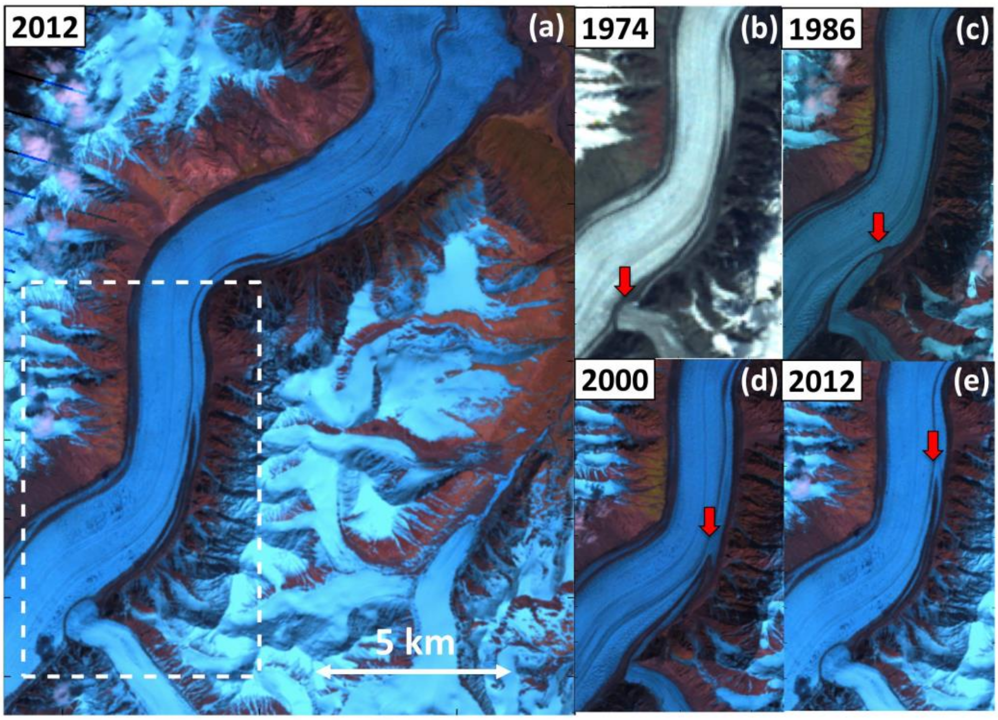


Figure 3. Spatial patterns of the looped moraines induced by the tributary surges shown in the Landsat images. (a) The near-terminus region of Donjek Glacier shown in Landsat 7 ETM+ false color composite image acquired ~~in~~on 6 June 2012. The white-dotted box shows the enlarged areas shown in ~~the~~ (b)~~-~~–(e). (b)~~ (e) show s~~Snapshots on 19 July 1974 of the moraine movements (red arrow) generated by the 1973~~-~~–1974 tributary's surge. (c) Same as (b) except 25 July 1986. (d) Same as (b) except 7 July 2000. (e) Same as (b) except 6 June 2012.