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. We have attached the revised manuscript, the response letter including the replies to the two referees and the marked-up revised manuscript. Basically incorporating all of the referees' comments, we revised the manuscript. We believe our revised manuscript is now suitable for the publication in *The Cryosphere*.

One significant change is the addition of one more figure that shows the slope angle on the surface of the glacier. However, following the rule of *Brief Communication*, the number of figures is limited to three or less. Thus, we added the figure in the supplementary material as Fig. S3.

Below is our response to the two referees' comment.

Reply to Dr. Luke Copland's comments

This paper is much improved from the previous version, and the additional analyses and better referencing to previous work makes the discussion and conclusions much stronger than before. The paper now provides a nice summary of the 3 most recent surges of Donjek Glacier, and new insight into the surge characteristics and periodicity in this region.

Most of my comments below relate to minor technical issues, particularly with respect to English language. The main substantive comment is for P7 L8-10, concerning the statement about changes in surface slope when no evidence is provided to back up these claims. Once these issues have been addressed I believe that the paper is ready for publication.

Thank your for your time to read our revised manuscript. We acknowledge your valuable comments.

*P1 L16: change to '**originating in an area** where the flow width significantly narrows...'*

Done.

*P1 L20: change to 'surge-type glaciers **typically** speed up...', to make it clear that the listed changes don't necessarily occur on all surging glaciers (e.g., some of them see little terminus advance)*

Done.

P1 L23: they can become stagnant across their entire length, not just their downstream part. I would therefore suggest deleting 'in the downstream' from the end of this sentence.

Done.

*P2 L12: change to 'originating **from** the surface meltwater...'*

Done.

P2 L17-18: I don't agree with the statement that 'observations have been too limited to reveal the surging dynamics', as some of the recent papers that you quote actually provide quite detailed information about this. Instead I think that it would be better to change the end of this sentence to: 'but many questions remain about the detailed surging dynamics...'

Thank you for your suggestions. We revised the sentence as you suggested.

P2 L19: the start of this sentence doesn't make much sense as it's not clear what is being referred to. It would be better written as something like 'Recent advances in spaceborne remote sensing can provide insight into surging glacier dynamics.'

Done.

*P2 L27/28: change to 'they **have** revealed long-term changes in terminus positions and velocities of mountain glaciers **around** the world...'*

Done.

P2 L29: add a paragraph break before this sentence 'To reveal...'

Done.

P3 L9: change to 'significantly constricts downstream of 20 km from the terminus.'

Done.

P3 L19: change to 'known as a surge-type ***glacier****...'*

Done.

P3 L2425: explain what the 'resolution problem' is.

We deleted this sentence. Instead, we moved one sentence about the image resolution from the *Results* at P3L24-25.

P4 L2: delete 'image'

Done.

P4 L7: indicate approximately how far upstream this reference line was set.

We added "about 5 km" in the sentence at P4L8.

P4 L13-15: the information in brackets would be better put in the methods section than the results

We moved the sentence to the *Data and Method* at P3L24-26.

P4 L15/16: you say that 'the speed near the terminus appears much greater', but greater than what? It's unclear what you're making a comparison with.

We modified the sentence at P4L15-17.

P4 L20/21: this sentence is awkwardly worded. Please reword to improve English and make clearer.

We modified the sentence at P4L20-21.

P4 L21/22: the information about the colours of the different lines is already given in the figure caption, so this sentence should be deleted.

We deleted the sentence.

P4 L22-24: the wording here is ambiguous as it can be interpreted as saying that the surge initiation occurred upstream of the valley restriction, whereas I think that you mean to say that it initiated ***at*** *the valley restriction. If this is what you mean, then change this sentence to something like 'The initiation of the three surging episodes occurred in the valley section between 18 and 22 km from the terminus, where the valley is about 33% narrower than upstream (Fig. 1c)'.*

Thank you for your correction. We revised the sentence as you mention at P4L21-22.

P4 L27-28: the red arrows that you added to Fig. 1c in the replies to reviewer 1 comments really helped to illustrate this pattern, so I would suggest adding these arrows to the final paper.

Thank you for your suggestion. We added the arrows on Fig. 1c, and the explanation in the caption.

P5 L3-6: wording in this para is awkward, with lots of short, choppy sentences that make the text difficult to follow. Please reword.

We rewrote the paragraph and combined it to the next paragraph at P5L1-10.

P5 L14: change to 'The terminus area changes from 1973 to 2014, with decadal fluctuations...'

Done.

P5 L17: change 'global warming' to 'climate warming'

Done.

P5 L21: change to 'decadal fluctuations ***in terminus area*** *are attributable...'*

Done.

P5 L23: the evidence here seems convincing, so I would delete 'may' from this line

Done.

P5 L26-29: this text basically duplicates what you've already said in the 2nd para in the Results section above. I would therefore delete the text here, and move any relevant information to the 2nd para.

We deleted this para, and some relevant information was moved to the 2nd para at P4L23.

P6 L6: delete 'from'

Done.

P6 L10: you say 'compared to the earlier surges in 1935 and 1961', but you haven't said what you're making a comparison with. Presumably the terminus advance of these earlier surges? Need to specify what this is.

Yes. We agree with that this sentence was unclear. We modified this sentence as "…which was much smaller than about 1-km advances of the earlier surges in 1935, 1961, and the recent three surges in 1989, 2001, 2013" at P6L4-5.

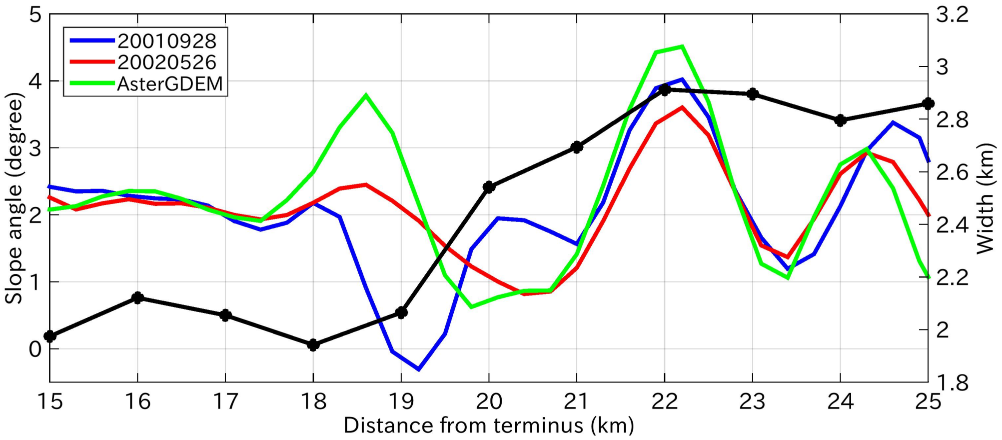
*P6 L30: I would say '**apparently** less variable over time', since your conclusions are based on only the previous 3 surges, compared to 5 or more surges for the periodicities described for Lowell and Variegated glaciers.*

Done.

P7 L8-10: evidence needs to be provided to invoke the surface slope as being a causal factor here. In the replies to reviewer's comments, I know that the authors said that they had no good DEM data to assess whether there a steep surface slope formed in this area during quiescent phases, but without any supporting information they can't make this statement. So either this statement should be removed or reworded to make the lack of data clear, or data should be acquired. A potential source for this data is the ASTER DEM product (AST14DEM), which can now be produced on demand for free from any

ASTER image, of which there should be many available for Donjek Glacier over the past ~15 years.

Thank you for your suggestion. As also pointed out by Dr. Shugar, we collected some available DEMs from Aster, and derived the slope angle on different dates. One figure is attached here.



This figure shows the slope angles along the flow line used in Fig. 1c derived from two Aster DEMs (blue in 28 September 2001, and red in 26 May 2002) and Aster GDEM (green). The Black line shows the width of the valley. Although GDEM is composite DEM and we don’t know the exact date, all the three curves indicate peaks around 18.5 and 22 km point. The former point corresponds the initiation point of S-shape valley, and the latter is that of narrowing valley. These indicate that the valley constriction could generate the slope steepening. Moreover, comparing the blue and red curve especially in the section between 18 and 19.5 km, the slope in 2002 (red) is clearly larger than that in 2001 (blue). This is consistent with our suggestion that the ice had been thickened after the peak speed in the 2001 episode.

We added this as Figure S3 and the explanations in the supplementary material at P2L47-57.

P7 L26-27: you should also mention that it’s very difficult to derive winter velocities using optical image matching due to the lack of identifiable surface features when the glacier is snow- covered.

We added the content at P7L24-25.

P8 L13: I would clarify this wording by saying 'inefficient ***subglacial*** *drainage system...'*

Done.

P9 L16: change to 'known as a surge-type ***glacier****.'*

We deleted this paragraph according to Dr. Shugar's comment.

Reply to Dr. Dan Shugar's comments

General Comments

I was pleased to read the revised version of this manuscript by Abe et al. The authors have made great strides in improving their paper, however I still have reservations about their lack of analysis of glacier surface slopes. First I provide comments on their responses to my own initial criticisms. The line and page numbering described is as used in the original manuscript. I then provide line-by-line comments on the revised manuscript and the page/line numbering refers to the revised manuscript (using the version with response to reviewers for page numbering).

Thank you for your time to read our revised manuscript. We acknowledge your valuable comments.

Specific comments on comments

P5945 L11 re: "Donjek River Valley System noun" The authors describe how Clarke and Holdsworth capitalize the words 'Donjek River Valley System' and how they (Abe et al) are thus surprised that I suggested they make it lowercase. I repeat that 'Donjek River Valley System' is not a proper noun and so 'valley system' should be lower case. The only place that Clarke and Holdsworth use uppercase is in the title of the subsection.

Thank you for your clear explanation. We rewrote the sentences at P3L5-6.

P5948 L6 – re: "coarse temporal resolution" The authors describe how, due to the coarse temporal resolution of their data, they cannot more precisely pin down the dates of terminus advances. Have the authors consulted the ASTER database? Last month, all ASTER data were made freely available. Perhaps by including ASTER data, the authors can reduce the time lag they speak of, at least for the latter two events.

We consulted the ASTER data, which we have known is now freely available. However, there are a few available images that cover Donjek Glacier without cloud. Thus we could not increase the temporal resolution.

P5948 L13 – re: "constriction in Donjek Glacier width" The authors initially described a 35% reduction in width of Donjek Glacier, which I questioned in my initial review. I am pleased that the authors added a panel of glacier width to their Fig 1. I have two further comments. First, it appears that the region of the glacier that sped up in 1989, 2001 and 2013 versus quiescence, is actually a fair bit upstream of the constriction at about km20. Of course, this is somewhat subjective, but it appears that the velocity increases begin at about km25. Second, I was left wanting with respect to the authors' discussion and interpretation of the constriction. They describe how there is likely a "strong control of the valley constriction on the surge dynamics" but expand only briefly on this interesting idea (later, on P31, beginning L31). They imagine that the constriction may generate a steeper surface slope, but as I discuss below, do not test this quantitatively.

As pointed out, Figure 1d shows that the speed-up seems to begin at about 25 km in the 2001 and the 2013 events comparing the quiescent speed. However, these lines show the maximum speed we observed during each event, and do not indicate the initiation. Moreover, the velocity differences between the two events and the quiescence in the section of 20-25 km are small, which are within the errors. Thus, we mention the place of the initiation is around 20 km.

In terms of the valley constriction, we examined the slope angle in the valley using Aster DEMs, and show the angle in 2001 is clear larger than that in 2002 at the constriction zone. Please also see our response to Dr. Copland's comment.

P5949 L8 – re: "glacier surface slope at constriction: The authors claim to be unable to examine surface slopes. I don't buy this argument. Datasets from the Canadian government(CDED: http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3A537B2D-7058-FCED-8D0B-76452EC9D01F.html), Yukon Government (interpolated 30m DEM: http://www.env.gov.yk.ca/publications-maps/geomatics/data/30m_dem.php) and the ASTER GDEM2 (https://asterweb.jpl.nasa.gov/gdem.asp) are freely available, but seem to simply not have been consulted. At the very least, the authors should look at surface slope changes (e.g. longitudinal/downstream, not necessarily temporal) to confirm whether there is a steepening at the constriction. They conflate my comments here and on P5950 L13 (see below) where I mention the idea of looking at temporal gradient changes.

Thank you for information. We analyzed some Aster DEMs, and added a new figure as Figure S3 and the explanations in the Supplementary material at P2L47-57.
Figure S3 shows the slope angles along the flow line used in Fig. 1c derived from two Aster DEMs (blue in 28 September 2001, and red in 26 May 2002) and Aster GDEM (green). The Black line shows the width of the valley. Although GDEM is composite DEM and we don't know the exact date, all the three curves indicate peaks around 18.5 and 22 km point. The former point corresponds the initiation point of S-shape valley, and the latter is that of narrowing valley. These indicate that the valley constriction could generate the slope steepening. Moreover, comparing the blue and red curve especially in the section between 18 and 19.5 km, the slope in 2002 (red) is clearly larger than that in 2001 (blue). This is consistent with our suggestion that the ice had been thickened after the peak speed in the 2001 episode.

P5949 L12 – re: "recurrence vs recurrent interval" The authors use the term "recurrent interval" in most places, but "recurrence interval" here. Please change all instances to "recurrence".

Done.

P5950 L13 – re: "ice thickening locally" The authors claim that no publicly available elevation datasets are available to examine the elevation changes they expect to have *occurred. I agree with them that an appropriately spaced (in time) set of DEMs is likely not available (e.g. only a couple are available, as I describe above). However, the authors do not even make an attempt to look at elevation in their analysis, yet they pin a lot on those elevation changes happening. I suggest they examine what data are available to see gradient changes with distance down-glacier at the very least.*

Please see my earlier comment.

Figure 1 – re: "jet colorbar vs others" Upon trying my suggestion that they use something other than 'jet', the authors found that the patterns they observed became much less obvious. This was my original point exactly. See here (https://jakevdp.github.io/blog/2014/10/16/how-bad-is-your-colormap/), here (http://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1003833) and here (https://betterfigures.org/2015/06/23/picking-a-colour-scale-for-scientific-graphics/). From the last page: "[jet]...introduce perceived sharp transitions in places where none exist in the data". I agree with Abe et al that the 'Jet' figure is the prettiest of those they provide, but is it the one that most accurately portrays the data?

We understand your concern that "jet" (rainbow) color scale often leads "…sharp transition in places where none exist in the data" and can cheat the readers. This is your point, isn't it?
Comparing the figures with the other color scales as we had attached in our previous letter, we have confirmed the velocity changes did indeed exist. In other words, we cannot find any points/ranges that can cheat the readers, and still believe that "jet" could portray the data most accurately.

Specific comments on revised manuscript (page numbering refers to combined file with author response and revised 'track changes' manuscript) *P23 L12 – In the abstract, the authors describe how "...detailed observations of the evolution cycles [of surge-type glaciers] have been limited...", implying that their own study provides such "detailed observations". I suggest that they tone down this language, as their observations, while interesting, are not particularly detailed. Of course this is a* *subjective statement, but when I think of a detailed study of surge processes, I think of papers like Kamb et al (1995, Science), complete with several lines of in situ measurements and commensurate insights.*

It is indeed subjective, and it would be up to the readers' decision. Kamb et al. (1985, *Science*) is detailed in terms of their multiple observations approaches, but some people will not necessarily think so. We consider our observations are detailed enough because this is the first paper to reveal the long-term evolution for nearly 40 years at Donjek Glacier.

P23 L16 – Here, the authors argue that the width constriction at ~km20 must strongly govern the surge dynamics of Donjek Glacier. This is an interesting observation but without investigating this line of inquiry further, I feel the paper will have much less impact. As I've described already, the authors ought at the very least to examine the available DEMs.

Please see our earlier comment.

*P24 L16 – After the words "Near the border of Alaska and the" were removed, the rest of the sentence is incomplete. ***Note: when I look at the version of the revised manuscript that does not show track changes, these words do not seem to be deleted, so I don't know what's going on with these various versions! This is not the only place this occurs. For example, on P27 L31, the first word of the paragraph ("Figure") is not struck out in the track changes document, but does not appear in the non-track changes document. Another example is on P28 L7, where the sentence (in the track changes document) begins "uations superimposed on a gradual decrease." This makes me wonder whether there was an interim version of the manuscript with more changes that was not uploaded. And it also makes me wonder about the quality of the language editing that the authors contracted out.*

We are so sorry for our mistakes. We found some correction inadequate in the marked-up version. Instead, the revised manuscript was correct. We apologized for the convenience.

P24 L23 – As above, the deletion of part of a sentence rendered the remaining sentence incomplete. The revised sentences read "Recent advances in spaceborne remote sensing. In particular, synthetic aperture radar (SAR) images..." Instead, the authors might consider writing "Recent advances in spaceborne remote sensing, in particular, synthetic aperture radar (SAR) images..."

We rewrote these sentences at "Recent advances in spaceborne remote sensing can provide insight into surging glacier dynamics. In particular…" at P2L19-20.

P24 L27 – Although the authors' are correct saying that SAR does not yet provide a long-enough time series for quantifying surge cycles, a perhaps equally problematic issue is that InSAR is near impossible on temperate glaciers such as Donjek with most satellites due to decorrelation over relatively long repeat times.

Although we agree with that surface decorrelation is an important issue, this technique has started to be commonly used for deriving velocity on mountain glaciers (instead of ice sheets) owing to the recent improvement of spatial resolution of SAR satellite image as well as to the availability of global DEM. Thus, SAR does not yet provide a long time series.

P25 L3 – The authors state here that they investigate not only Donjek Glaier but also other nearby glaciers but those data don't appear in the paper.

What we meant is that we examined the Donjek Glacier and one tributary. Thus, we changed "Donjek and associated surge-type glaciers nearby" to "Donjek Glacier" at P2L30.

P25 L10 – See my earlier comments about "Donjek River Valley System".

Done.

P25 L12 – it is unclear what these length and area figures refer to. Are these for Donjek Glacier only, or the entire 'valley system'?

This is only for Donjek Glacier. We added "of Donjek Glacier" at this sentence.

P26 L18 – Why didn't the authors pan-sharpen their imagery?

Because we conducted the same method as McNabb and Hock (2014) described. Moreover, we considered our result would not change significantly even if we did pan-sharpen analysis.

P26 L24 – This sentence is confusing and should be rewritten – it currently says "The red curve in Fig 2a shows how this speed changes of the years."

We rewrote the sentence at P5L1-2.

P28 L1 – How can the glacier "rapidly increase in late 2000-2001"? Does that mean 2001? Or early winter 2001? I realize the authors claim that the data do not allow monthly or seasonal specificity but annual specificity should be ok, shouldn't it? Saying late 2000-2001 does not make sense. Similar language is used for a variety of time periods in this paragraph.

It means the glacier rapidly speed-up in between the last point on 2000 (mean velocity between 2000/07/30 and 2010/10/02) and the first point on 2001 (2001/03/27-2001/04/28). As you mentioned above, we could not specify the month and the season of the surge initiation due to the coarse temporal resolution. However, we did not use long image pairs and we could identify the timing within a relative time range.

P28 L13 – Larson is misspelled (it should be Larsen).

Done.

P29 L6 – Remove the word "from".

Done.

P29 L10 – The authors argue that the 1960s advances may be better described as pulses rather than surges, but do not provide much supporting evidence. They imply that the small advance of <500m described by Johnson is not sufficient to be called a proper surge. Although Abe et al don't describe terminus advances (aside from areal changes), in their supplement Fig S2 it can be seen that the total range of terminus positions varies by ~1km from 1975 to 2015.

The reviewer seems to adequately our point. Given that our data indicate all the surging events accompany with both ~1km terminus advance (associated areal changes) and speed-up, the 1960s advances may be better described as pulses. Our data suggest such events in 1995 and 2009. We added some explanations at P6L4-5.

P31 L6 – Change the word "evolves" to "involves".

Done.

P31 L10 – The authors here state that there "...seems to be no clear initiation seasons" at Donjek Glacier, but earlier they said that they couldn't determine the seasonality due to the temporal coarseness of their data. These are very different – as written here, the authors state that Donjek Glacier surges occur randomly throughout the year. As written earlier, the authors state that their data does not allow determination of when the surges initiate. The following sentence (L11) clears up the confusion, but the wording in the L10 sentence should be changed.

Yes, we couldn't determine the seasonality because of the coarse temporal resolution. We changed the sentence to "…and we couldn't determine the initiation season" at P7L22.

P32 L5 – Here in the conclusions, the authors state that they use the Landsat data to examine the interaction of one of Donjek's tributaries with the main stem. This came as a bit of a surprise to me, since they do not previously describe the tributary except in passing. Their figure 3 does however, look at the tributary, but is not described until P32 L7, which is in the conclusions section, very close to the end of the paper. I suggest moving this material to earlier in the paper.

OK. We deleted this paragraph, and the contents were divided, and moved to *Data and Method*, *Results*, and *Discussion*.

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, originating in an area where the flow width significantly narrows downstream, suggesting a strong control of the valley constriction on the surge dynamics.

1 Introduction

During their short (1-15 years) active phase, surge-type glaciers typically speed up by several-fold to over an order-of-magnitude, resulting in significant thickness changes and km-scale terminus advance (Meier and Post, 1969; Raymond, 1987; Harrison and Post, 2003). In their quiescent phase (tens to hundreds of years), they flow slowly or become stagnant ~~in the downstream~~. Meanwhile, ice accumulates in the upstream area and the imbalanced flow causes retreating and thinning in the downstream area, which produces a steeper glacier surface in the upstream. This part of the quiescent phase is sometimes called 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~~from 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 surge cycles in this area have been examined (e.g., Eisen et al., 2001; 2005; Frappé and Clarke, 2007; Burgess et al., 2012; Bevington and Copland, 2014), but many questions remain about~~the observations have been too limited to reveal the~~ the detailed surging dynamics (Raymond, 1987; Harrison and Post, 2003; Cuffey and Paterson, 2010).

~~More extensive observations come from recent advances in spaceborne remote sensing~~Recent advances in spaceborne remote sensing can provide insight into surging glacier dynamics. 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 (Burgess et al., 2013; Abe and Furuya, 2015). The temporal coverage of spaceborne SAR data is still too short to investigate long-term evolution in ice speed, although SAR allows 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 have revealed the long-term changes in terminus positions and velocities of mountain glaciers ~~in~~around the world (e.g., McNabb and Hock, 2014; Sakakibara and Sugiyama, 2014).

To reveal the long-term evolution of Donjek~~ and associated surge-type~~ ~~g~~Glacier~~s 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 surging event pre-1985~~ at Donjek Glacier~~.

2 Donjek Glacier

Donjek Glacier is located in ~~the Donjek River Valley System in~~ southwest Yukon (Fig. 1a).~~, which consists of~~ Steele, Spring, ~~Donjek,~~ and Kluane Glaciers are major surge-type glaciers located around Donjek~~; all these are surge-type~~ (Clarke and Holdsworth, 2002). The entire length and area of Donjek Glacier are 55 km and 448 km^2, respectively. Donjek Glacier lies at an elevation of 1000–3000 m, and the valley width significantly constricts ~~toward~~ downstream of 20 ~~-~~km from the terminus. 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). Recent airborne laser altimetry revealed that the mass balance of Donjek Glacier was –0.29 m w.e. yr^{-1} (Larsen et al., 2015). 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. Donjek's last tributary (Fig. 1a) is also known as a surge-type glacier that was active in 1974 (Clarke and Holdsworth, 2002), but there is no recent report of this tributary's surge.

3 Data and method

We used Landsat optical images, to examine terminus changes from 1973 to 2014 and flow-speed evolution from 1986 to 2014. Because of the lower spatial resolution of the images prior to 1986, we could not derive the velocities between 1973 and 1985, but the images were helpful to examine the terminus changes even in 1970s. ~~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 (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 the other methods (Heid and Kääb, 2012). For details of ~~image~~ how we applied this method, see the supplement.

We also examined the fluctuation of the terminus area associated with the surging events using the false color composite images (see the supplement). The spatial resolution of a composite image is 60 m for the MSS images and 30 m for the others. We calculated the terminus area changes using a reference line set about 5 km upstream to create a polygon representing the edge of the terminus. Moreover, we investigated the behavior of the tributary and examined the interaction of it to the main stream by the composite images.

4 Results

Figure 1b shows the ice speed map for the 2001 surge as an example, and F~~f~~igure 1c indicates the spatial-temporal velocity evolution along the flow line shown in Fig. 1a from 1986 to 2014. ~~(Because of the lower spatial resolution of the images prior to 1986, we could not derive the velocities between 1973 and 1985, but the images were helpful to examine the terminus changes even in 1970s.)~~ 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, than~~. In contrast,~~ that~~the speed~~ during the other years (i.e. quiescent phases), which is about 0.5 m/d or less. 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 shape of the glacier.

We compare~~Consider the possible relation between~~ the width of the valley ~~, and~~with the velocities associated with the three surging episodes (Fig. 1d). ~~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 initiation of the three surging episodes occurred in the ~~T~~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), which is also an S-shaped valley. Meanwhile, the velocities further upstream do not show any significant temporal changes throughout the analysed period, maintaining a speed of about 1.0 m/d (Figs. 1c and d). Also, the velocity front of ~0.5 m/d (i.e. the boundary between the stagnant and moving part near the terminus) propagates downstream for the 5-year or longer period prior to the 2001 and 2013 active phases (red arrows in Fig. 1c). 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, we cannot identify a clear timing of the surge initiation and termination season, which could be due to the multi-year precursory acceleration or a lack of temporal resolution in the available data.

~~Consider the ice speed 0–5 km from the terminus.~~ The red curve in Fig. 2a shows the temporal changes of the ice speed averaged over the section between 0 and 5 km from the terminus.~~how this speed changes of the years.~~ This curve ~~speed~~ has three significant peaks, which~~. These peaks~~ correspond to the active phases in 1989, 2001, and 2013 (Figs. 1c and d). The peak magnitudes all differ, but the differences are likely due mainly to the coarse temporal sampling of the velocities.

~~Now consider the 2001 and 2013 events in more detail.~~ In the 2001 event (Fig. 2b), the speed starts to gradually increase in late 1998–1999, rapidly increasing in late 2000-2001, and rapidly decreasing in 2003. The evolution of the speed for the 2013 event (Fig. 2c) is similar to that for the 2001 event. Namely, the speed starts to gradually increase in late 2011–2012, rapidly increasing in late 2012 and then terminates in late 2013. Although the data do not resolve the exact month or season of the initiation, the duration of the active phase is about 1 year.

The terminus area also changes from 1973 to 2014, ~~showing~~with decadal fluctuations superimposed on a gradual decrease. The black line in Fig. 2a indicates a long-term rate of decrease of -0.2 km^2/yr, which presumably indicates the negative mass balance trend from recent ~~global~~climate warming (e.g., Luthcke et al., 2013; Larse~~o~~n et al., 2015). The decadal fluctuations in blue show peaks around 1980, 1991, 2002, and 2014. Comparing those peaks with the speed changes in red, the last three peaks in blue coincide with the last three peaks in the speed data, with a 0-to-2 year time lag (Fig. 2a). These correspondences indicate that the decadal fluctuations in terminus area are 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~~ occur with the surge cycle. Although our speed measurement do not go back before 1985, such a surge is likely the reason for the temporal increase of the terminus area around 1980 as well.

There are many looped moraines on the main stream induced by the tributary’s surge (Fig. 3a). During the period between 1973 and 2014, we observed the two surge events, in 1973–74 (Fig. 3b) and 2009–10 (Fig. 3e), and couldn’t identify any surges between 1974 and 2009.~~Remarkably, the surging area is limited to just the glacial area within ~20 km from the terminus (Figs. 1b, c, and d). Moreover, this 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 narrower than upstream.~~

5 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, which was much smaller than~~compared to~~ about 1-km advances of the earlier surges in 1935, ~~and~~ 1961, and the recent three surges in 1989, 2001, 2013. 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.

The recurrence~~t~~ 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 terminus area that extends before 1985 strongly suggests that previous surging occurred in the late 1970s. Such a surge is consistent with the previous report of the surge in 1978 (Clarke and Holdsworth, 2002). The 12-year recurrence~~t~~ 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 recurrence~~t~~ 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 recurrence~~t~~ intervals are 15.25 (Bevington and Copland, 2014) and 15 years (Eisen et al., 2005), respectively, the recurrence~~t~~ interval at Donjek Glacier is not only shorter but also apparently 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 recurrence~~t~~ interval (10-14 years) and both have apparent geometrical control of the surging area. 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 the slope changes 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 the mass transport from upstream (see the supplement). As such, the apparent regularity of the recurrence~~t~~ interval may be due to the rather steady flow speed upstream. Moreover, we consider that the surge is independent from the tributary's surge. This is because the interval of the tributary's surge is 36 years, which is much longer than that of the main stream's.

At Medvezhiy Glacier, the observed maximum speed exceeds 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 50 m/d during the 1982-1983 surge (Kamb et al., 1985). At Bering Glacier, a similar behavior (speed exceeding

10 m/d, and winter initiation) is observed in the 2008-2011 surge (Burgess et al., 2012). The recurrence~~t~~ 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 thought to arise from the hydrological regulation mechanism. The mechanism, which in~~e~~volves a destruction of tunnel-like channels and subsequent change into a linked-cavity system that increases the water pressure, has been proposed based on detailed observations of the 1982-1983 surge at Variegated Glacier (Kamb et al., 1985). Thus, such surges are often termed an Alaskan-type surge. Meanwhile, our observed maximum speed reached at most ~ 5 m/d and we couldn't determine the~~there seems to be no clear~~ initiation season. It is likely, however, that we have missed much higher speeds and winter initiation due to the coarse temporal resolution in our velocity data and difficulties for optical image matching caused by the lack of identifiable surface features when the glacier is snow-covered. The 12-year recurrence~~t~~ 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 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 has the Alaskan-type surge.

Based on these findings, we argue that the cyclic surging at Donjek Glacier occurs as follows. In the quiescent phase, ice delivered from the upstream area stores up at the highly narrowed area (Fig. 1a), causing local thickening. The ice thickening generates a steeper slope (Fig. S3) with a corresponding higher driving stress. When the ice thickness reaches a critical value, the glacier starts to speed-up. We do not claim, however, that this 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 as the ice thickness increases, the volume of englacial water storage will also increase, which can supply 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 subglacial drainage system and the sufficient englacial water volume can maintain 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 a previously studied surge that occurred in 1974 (Clarke and Holdsworth, 2002). We used Landsat images to examine the interaction of this tributary to the main stream. There are many looped moraines on the main stream induced by the tributary's surge (Fig. 3a). Although we observed only two tributary surge events, being in 1973–74 (Fig. 3b) and 2009–2010 (Fig. 3e), their separation indicates an interval of 36 years. This interval is much longer than that for the main stream, indicating that the tributary's surge is independent from the main stream's.~~

The next event of Donjek Glacier is likely to occur around 2025. To test the model proposed here, we need detailed observations of not only ice velocities but also the associated geometric and hydrological changes.

Acknowledgements

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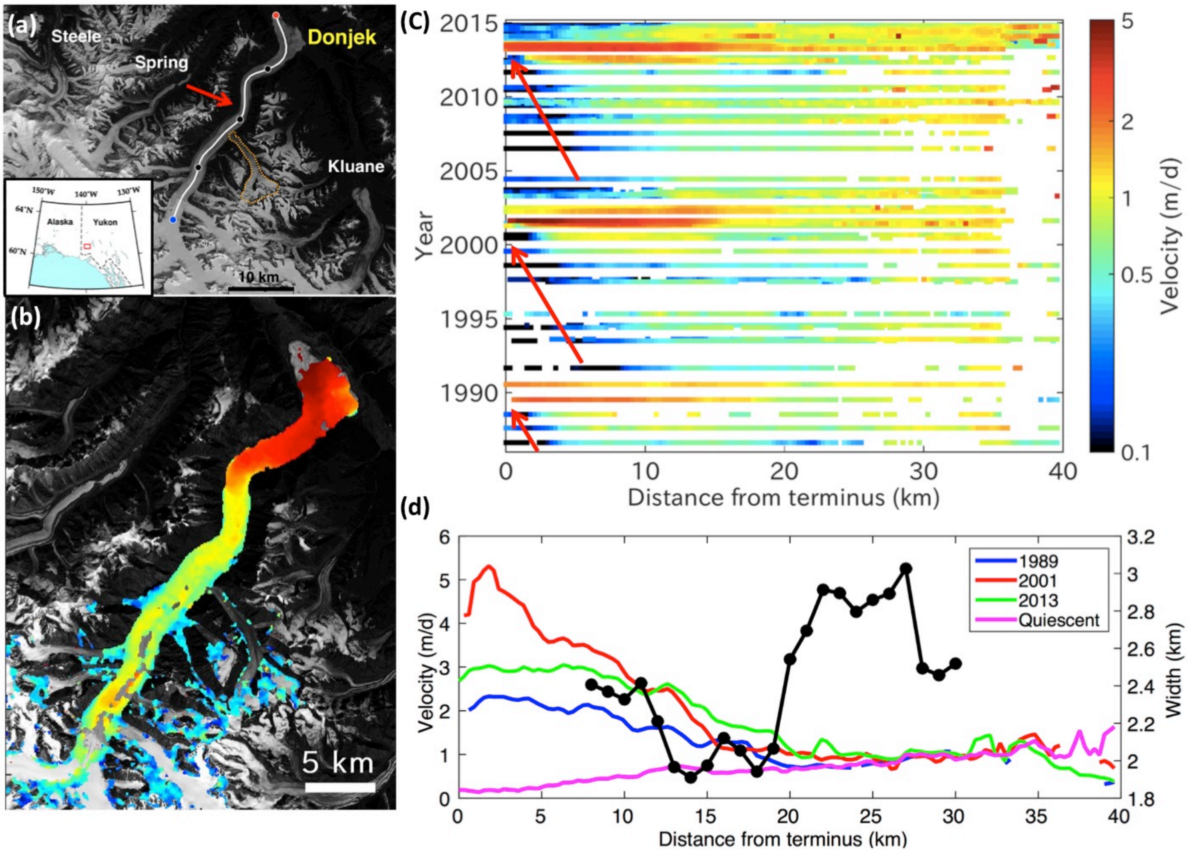
Figures and captions



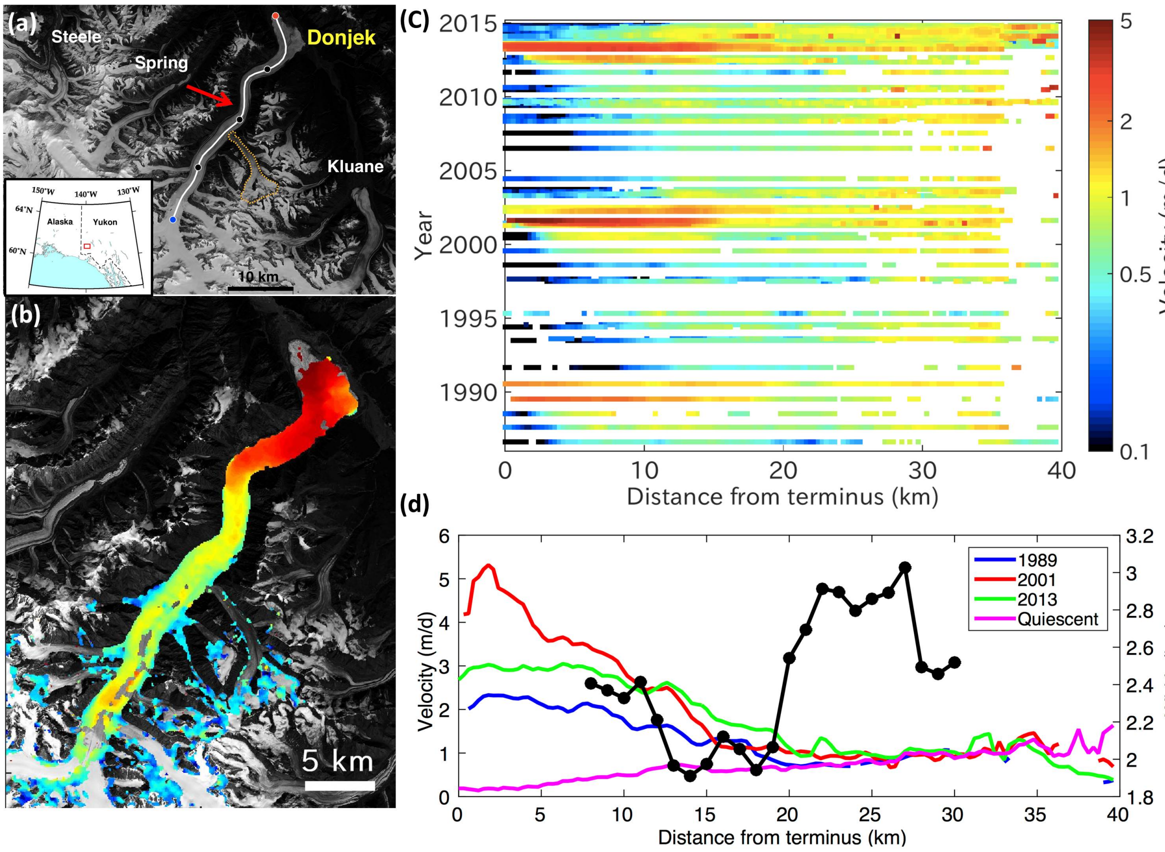


Figure 1. Glacier flow speeds and glacier extent. (a) Location of Donjek Glacier. Background is a Landsat 8 image acquired on 22 July 2014. White line is the flow-line used in (c) and (d). The red and blue dots show the start and end points, whereas the black dots mark 10-km intervals. The red arrow 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. The red arrows indicate the propagation of the velocity front. (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).

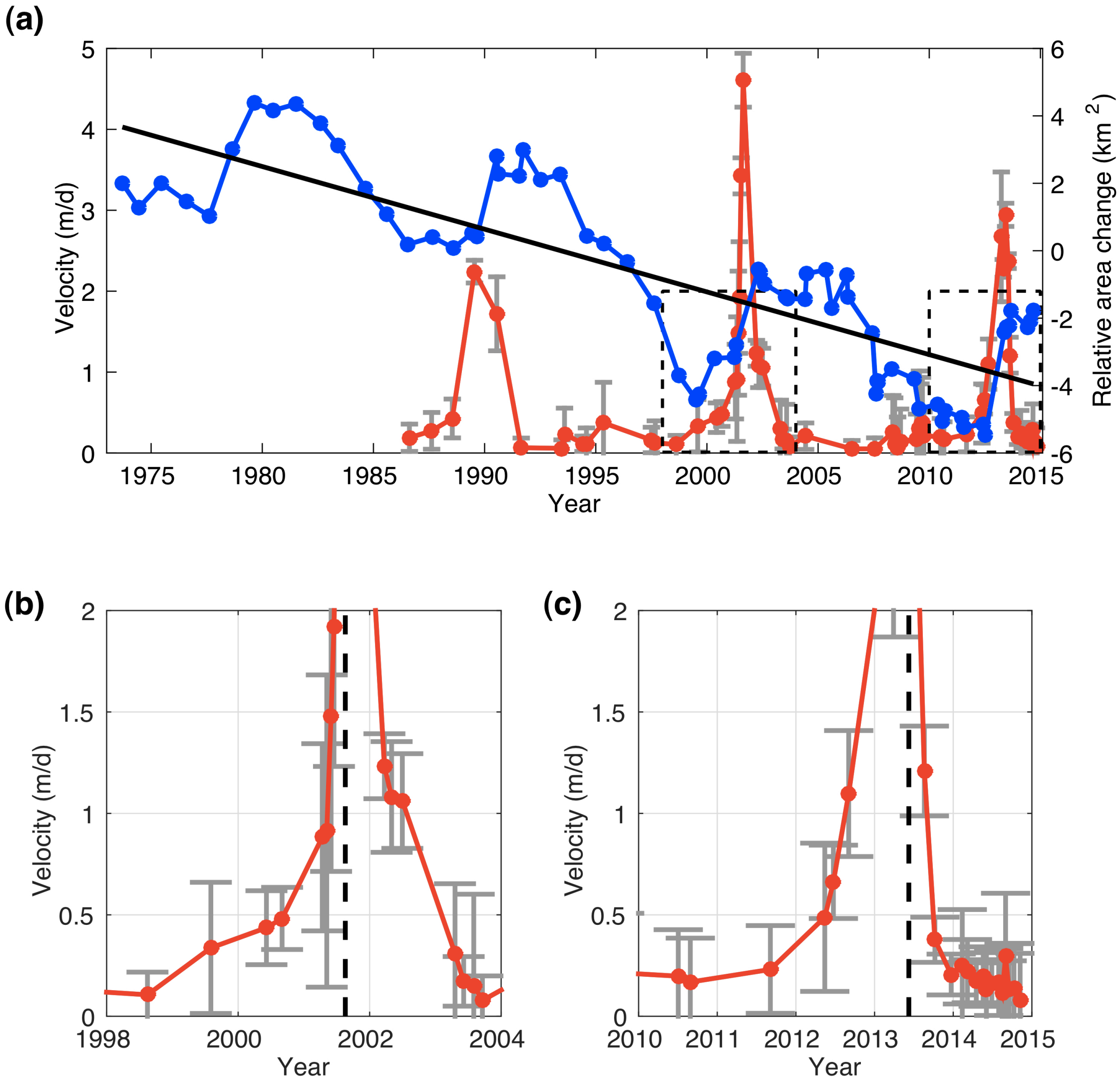


Figure 2. Ice speeds and area near the terminus. (a) Temporal changes of the ice speed (red) and the terminus area (blue). The ice speed data are averaged over the section between 0 and 5 km along the flow line shown in Fig. 1a. The error-bars indicate the mean speed in the non-glacial region. The black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

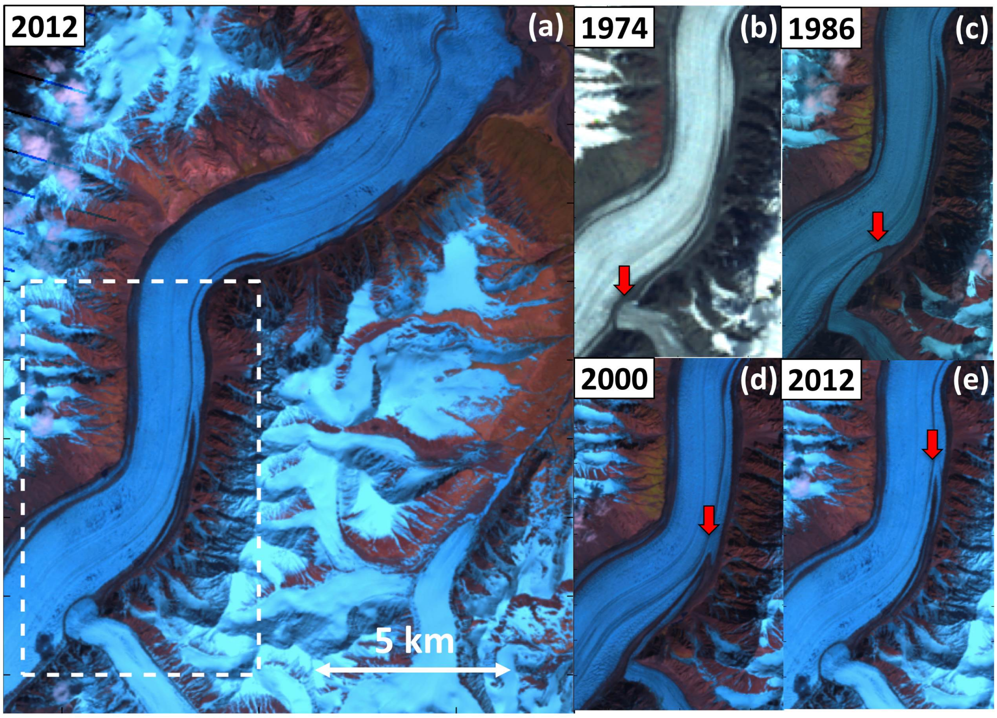


Figure 3. Spatial patterns of the looped moraines induced by the tributary surges shown in the Landsat images. (a) The near-terminus region of Donjek Glacier shown in Landsat 7 ETM+ false color composite image acquired on 6 June 2012. The white-dotted box shows the enlarged areas shown in (b)–(e). (b)Snapshot 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.