We thank the Poul Cristoffersen, Adrian Luckman, the anonymous reviewer, and Maurie Pelto for their comments. We include below a detailed response to these comments, to which we have appended a changed tracked version of the manuscript.

Below are detailed responses to all comments. An overarching problem seems to be that the reviewers wanted more detailed discussion. Much of this discussion, however, was presented in a 20 page JGR paper. So for many of the comments we so no need to reinvent the wheel and refer interested parties to this work. Instead, this Brief Communication was meant to be an update to the earlier work, largely focusing on recent large speedups.

After responding to the comments below, we did second editing pass and restructured the discussion (largely moving text around) to better address some of the issues.

Reviewer 1 (Cristoffersen)

This manuscript presents new data for Jakobshavn Isbræ, which demonstrate a higher seasonal variability in speed during the last two years compared to the previously established record (1990-2011). As the glacier retreats, summer speedups are becoming more and more pronounced. This is an important finding, as glaciers' seasonal fluctuation is a manifestation of their dynamic capability. Although the manuscript is an extension of the authors' previously published work, the new data comprise an entity of new information, which is both well presented and suitable for a fast-tracked brief communication in The Cryosphere.

Comment appreciated, no action.

My main recommendation is to reduce the description of future evolution of the flow of the glacier, which comes across as speculative in several places (see related comments below). The authors argue that the stability provided by a topographic bedrock high will only be temporary, and that the glacier is likely to continue its retreat even farther inland. While this is indeed a possible future scenario, I suggest adding "will likely", "may" and "potentially" in this context.

Detailed response for the specific comments below. In fact we have gone through the discussion and each and every sentence that is not a direct statement of fact does include such language to convey some level of uncertainty (8 instances of "may" and 5 instances of "likely/unlikely", 2 instances of "appear", 4 instance of "if" and 2 instances of "could", and 1 of "potentially" for a total of 19 qualifiers in 21 sentences).

Speculation is "the forming of a theory or conjecture without firm evidence." We feel our evidence if firm and discussion is more along the lines of hypothesis than speculation.

What the authors do well is show that the potential ten-fold increase of discharge, as hypothesized a few years ago by Pheffer et al. (2008), is not an unrealistic future scenario for Jakobshavn Isbræ. I think this is worth mentioning explicitly in the abstract. I would also welcome a comment by the author in relation to one or more of the statements in recent IPCC report.

> *We do not feel this should go in the abstract as there is the potential for it to be taken out of context. For example, we also conclude "It is unlikely that such retreat could be sustained for more than a few decades because the terminus would rapidly retreat ~50 km to shallower depths" whereas the Pfeffer conjecture assumed a sustained speedup for a century. Hence, the Pfeffer upper bound for the century likely will not be met. Furthermore, as we comment in the conclusion, Jakobshavn is somewhat unique in the extended length of its deep trough, so this statement cannot be generalized to all 200 glaciers in Greenland as in Pfeffer et al (keep in mind they did not say this could happen only that it was the worst case). Since no specific IPCC statement was referenced by the reviewer, we are not sure what the reviewer is after and have not included an IPCC reference.*

Specific comments.
Page 2. Abstract. State absolute magnitude of 'new' speed (mean annual as well as peak), as it is unclear what a percentage of the velocity during 'previous summers' amounts to.

> *We don't feel anything is gained by stating a speed without also providing the location, which is difficult to do. I have seen too much confusion where people compare speeds on glaciers but are referring to the speeds at different points. Furthermore, the speed is fluctuating rapidly with time – what speed do we give the brief peak in 2012, the average speed etc.?*

The last sentence, which includes descriptions such as "... slightly ... moderate ... likely ... a few decades ... rapidly ... end of century", is rather speculative. Rather than this, the authors could simply put forward their key argument, which is that observations from 1990-2013 demonstrate that a ten-fold increase in speed during this century is a plausible and perhaps even likely scenario for Jakobshavn Isbræ.

> *The hypothesis (as opposed to speculation) in this part of the abstract is an important point. That is a hypothesis should be evident from the words "likely", "should", and "potentially". We have shortened the sentence removing the first clause since we were overlength on the abstract.*
>
> *The terminus retreat has averaged about 600 m/yr, the glacier shows no signs of slowing, strong thinning continues, and it is retreating down a deep trough. Therefore, it is not unreasonable to assume that the terminus might retreat 50 km in a century. Of course there may be some stabilizing mechanism, but as of*

yet one has not been put forward. This is certainly no more speculative than what we are being asked to include in the abstract (i.e., a tenfold flux increase).

Page 3.
The description of error is good and probably necessary, but also a bit distracting here. It could, if possible, be moved to a Methods section or Appendix at the end.

There is little need for description since we are using well established methods for which we have provided references. We initially used a fixed (time invariant) DEM, which affected the errors so we felt the need to comment. During the comment period, however, we reprocessed the data, using an updated DEM for each year, which greatly reduced the geometry dependent errors (to what would be expected in cited methods papers). Hence, we now just state that we updated the DEM annually and have greatly shortened the text.

Page 4.
Understanding the dynamic response(s) to calving front proximity as well as water depth is clearly important, yet plotting speeds for a moving location (T09-T13) together with fixed points (M0-M43) on Figure 1 doesn't fully resolve this question. It is also potentially confusing. To resolve the issue, I suggest trying two simple regressions: one with proximity to front as the predictor variable for peak summer (or mean annual) velocity at fixed locations, and another where water depth is the predictor. Judging from Figure 2 and the supplementary figure it seems likely that the second will yield a much higher R-squared value. If meaningful, this would make the analysis more robust and the text could subsequently focus simply on the velocities at fixed locations (which it sort of does already). If the authors retain the analysis as it stand, I suggest plotting T09-13 on Figures 1 and 2 with range of gray tones, so that it becomes clear how location (figure 1) and speed (figure 2) are spatially connected.

We have treated the role of the terminus in modulating seasonal speeds in gory detail in Joughin et al, 2012. There is no need to revisit that analysis here nor perform a new analysis as suggested.

We do feel it of value to show the change in speed both at terminus-fixed and absolute locations and this motivates some of the discussion – it certainly influenced our perception of the results. It is the terminus terminus thickness (both water depth and height above flotation) that drive the much but not all of the variation speed, but this effect decays with distance inland. Hence the speed near the terminus and the speed at a fixed point are both manifestations of the same process – i.e., there is only one predictor, but its influence varies both spatially and temporally as illustrated.

Its not at all clear to us what is meant by the use of gray tones, which surely would not show up against the grayscale image.

Page 5.

Line 1 is a bit awkward. What exactly is meant by "un-buttressed"? (No mélange?) And what are the implications? (Summer only?)

> *Unbuttressed meant with no ice tongue. After "un-buttressed" we inserted "(i.e., post ice-tongue collapse)" to make this point clear. We also completely reworded this sentence to make it less specific to Jakobshavn, since there is another sentence a few lines below that is more Jakobshavn specific. The text now reads "Several studies of outlet glaciers indicate that variation in thickness of an un-buttressed (i.e., no floating section) terminus as it retreats or advances exerts a strong influence on speed within several ice thicknesses of the calving front over time scales ranging from minutes to years."*

The summary of the analysis by Howat et al. (2005) and Joughin et al. (2012) is good, but may be too short to fully convey the dynamics involved. Since it will not be straightforward to all readers, I recommend careful consideration of wording here and a slight expansion of the text if needed.

> *We added a few words to make it clear we were talking about the vertical terminus. But a detailed tutorial on force balance is beyond the scope of a brief communication and several references with more detailed descriptions are cited.*

Bottom of page. Can you justify the statement that stability provided by the bedrock high is only transient? Add "may" if needed.

> *Somehow the comments and page refs are not lining up. While not at the bottom of the page, we assume the sentence being referred to is*
>
> *"If Jakobshavn Isbræ's terminus has reached the bottom of an overdeepened region, then the terminus may be able to find a position of transient stability on the high spot farther upstream as retreat to shallower depths yields slower speeds."*
>
> *This sentence already has a "may" (see red underline) in it. We added a reference to the 2012 paper, where a more detailed justification is given.*

Page 6.
Paragraph 1. "... the relatively high slope region." Explain why slope is key here. Re-word if necessary.

> *Inserted ", since it should take more time to thin to near flotation"*

Paragraph 1. "... yielding speeds well above balance velocities". Add 'likely' to be more accurate.

> *Done.*

Paragraph 1. "… extreme velocities". True, but you could leave this argument for the next paragraph.

We feel it makes better sense to leave it as is.

Paragraph 1. Last sentence is a bit contrived as gridding artifact conceivably could work the other way around as well.

Added "Similarly, we cannot rule out that some bed highs may not have been resolved that could provide additional points of transient stability."

Paragraph 2. "… relative to (add: "those observed in") the 1990s."

Inserted "speeds observed in"

Paragraph 2. Explain or summarize briefly what exactly Pfeffer et al. (2008) proposed.

Inserted "the amount a glacier could speed up by that was"

Paragraph 2. Potential twelve-fold speed up at M26. Yes, perhaps, but this number is not directly comparable to the ten-fold speed-up hypothesized by Pfeffer et al., since the latter was a ten-fold increase in the total amount of discharged ice and not a ten-fold increase in flow at a fixed location.

Pfeffer's was a fairly simple assumption designed as a sanity check on how much ice could escape from Greenland; they discuss scaling both velocity and flux and the two are somewhat inseparable because they don't have good thickness data. They don't get into what happens if the terminus thins or retreats, which was entirely appropriate for the level of data they had. Here we discuss in a bit more detail what the complexities are for a rapidly evolving glacier. In particular, what does an X-fold increase mean? Does it mean the speed at the terminus or the speed at a point. We discuss from both points of reference and show why a 10-fold flux increase is plausible, even though the max glacier speed in the future may not approach 10x the past max speed..

Page 7. Conclusions. Observational record. Add: "of velocity on the Greenland Ice Sheet", to be precise.

No we mean the observational record of Jakobshavn (i.e., we are not so naïve as to think that it has not flowed at some point faster in the past millions of years), which should be clear from the sentence. Where we mean the broader record earlier in the paper, we specify the Greenland and Antarctic ice sheets.

"When retreat to shallower depths occurs, ice losses will likely become smaller because… [explain briefly]."

As we state in the prior sentence, which is based on the discussion above in the text and the references cited there in.

"This is a consequence of the fact that retreat into deeper water increases both speed and thickness of the terminus. "

The fact that retreat into shallower water would produce the less loss is simply a statement of the antithesis, which should require no further explanation.

"Unusual". 'Unique' may be a better word here.

Done.

"Sustain (add: 'similar') large increases in ice discharge"

They need not be similar, at least not in magnitude so no change.

Figure 1. It would be quite useful if bed topography contours were added on this figure.

Reviewer 2 already has complained that the figure is hard to read so we have elected not to add further clutter.

Figure 2. Why not show the longer record here? (As in the Supplementary figure.)

The earlier record has already been published. By showing the last 5 years, we can show the record in far more detail (i.e., more zoomed in). For those interested in the complete record, its there in the supplement. Keep in mind this was meant to be a brief communication that extends the record and describes the recent large speedups, not the multi-decadal record, which is describe elsewhere.

Figure 3. Make sure the bed transect shown is indeed the best of alternatives

It's actually quite difficult to find a profile that lines up with the bed, velocity, and imagery. We picked this profile based on our prior analysis. Better profiles may or may not exist, but we have yet to convince ourselves there is a better one. We also are retaining it for comparison with past results using the same profile.

Reviewer 2 (Luckman)

This paper is a welcome update on the dynamic status of Jakobshavn Isbrae, which is significant both in its contribution to sea level rise, and in the insights that it can provide for the future of the Greenland Ice Sheet. The paper is reasonably well written, and the data presented is new and interesting. I have read the comments by Mauri Pelto (interactive) and Poul Christoffersen (referee), agree with everything that has been said, and will repeat their recommendations only where they are

important or further clarification will be helpful. My own recommendations revolve mainly around the understandability of the paper to a wider audience.

> *Thanks and no action taken (addressed below).*

I agree that the discussion is rather too speculative at present and would be improved by being shorter, less speculative in so many respects, and better focused on the potential for a ten-fold increase in discharge from this glacier (Pfeffer), which should also feature in the abstract. In my view the discussion about potential rates of retreat is rather too led by the 1D presentation of the geometry (Fig. 3) and seems to skate over the 3D nature of the glacier – e.g. as the ice front retreats, are we expecting its width tremain constant?

> *While we appreciate this opinion, we tend to disagree in many respects. We do agree the potential for 10-fold increase is important. But just as important is the potential for how long it can be sustained, which is much of what the retreat discussion drives at. The abstract largely focuses on the observations, which were meant to be the main focus of the paper. We are already over length, so we hesitate to expand at this point.*
>
> *With respect to width, the trough is fairly uniform though with some variation. We did modify the text to say "<u>Thus, although there is some variation in trough width (~3.5 to 5.5 km) that could modulate the rate of flow, once into this deepest part of the trough</u>, extreme velocities (>12,000 m a^{-1}) are likely to persist as the terminus rapidly retreats (Thomas et al., 2011)."*
>
> *This is not an unreasonable statement as we merely say that the glacier should exceed the present speeds as it moves into a deeper region. While some regions are narrower, they also tend to be deeper and these differences likely would offset each other. Our definition of extreme, is well below that in the cited Thomas reference. As in the original manuscript, we have qualified the statement with "likely". This is hypothesis rather than speculation.*

Is the hypothesised 50km "rapid" retreat just along this trough (likesome kind of narrow inlet), or would it require retreat or at least considerable thinning of the whole ice sheet in this region? It is this kind of wider conceptual context that is not discussed here and which makes the present discussion too speculative.

> *Some of this discussion is an update to the discussion in Joughin et al., 2012 based on the observations. We added an additional reference where the reviewer can find a more detailed discussion.*

Although this is intended only as a Brief Communication, the paper's size, number of figures, and potential impact might have suited a standard article. Therefore I recommend a more normal structure which should include a methods section between introduction and results.

The paper is intended to be an update to an existing record, which is notable because of the large magnitude of the increased speeds, making it most appropriate for a brief communication.

This section could draw together the beginning of the results section (which is really methods), expand the discussion of errors between satellite tracks (which is currently not easily accessible to a wide audience), and introduce the concept of fixed-position velocities versus ice-front-referenced velocities (which is important in glaciers subject to significant retreat such as Jakobshavn) There are inconsistencies and confusions in the discussion of error. Errors in the feature tracking technique really need to be introduced more fully (perhaps by referring to previous papers) to allow the specific problem of errors between measurements from different satellite tracks, and errors arising from non-coincident DEMs, to be properly explained and given context. At present this aspect is only accessible to experts familiar with such data processing.

Again these are updates and the processing methods are well described elsewhere. The main difference with earlier work was that the strong thinning (~100 m) meant that a single DEM introduced large errors because it could not represent the time varying surface. Since the submission, we reprocessed the data with annually updated DEMs. Since the correct elevations are used, errors are now fully consistent with earlier results and the references to processing methods are sufficient. So we removed the geometry induced errors and replaced it with a single sentence describing how we used a different DEM each year.

In particular the use of the word 'precision' in this respect is, I think, inappropriate. The differences in measured velocities are not related to the precision of the technique, but to errors introduced in post-processing

While this text has been removed, we note that prior text was correct in its use of precision. With a single imaging geometry the accuracy was 3%, but that error was common to all estimates (more or less). Hence the repeatability of the measurement was much better than 3% (i.e., if we measured the same speed at different times we would have achieved agreement much better than 3%). In other words the level of precision was much better than the accuracy (recall high school science where precision is how tightly the bullet holes cluster on the target, not whether they hit the bull's eye, which is a measure of accuracy). When we use 2 (or more geometries), we now have different errors but of similar magnitude. So that accuracy is similar, but the precision degraded (ie. we have two (or more) clusters of points similar distances from the bull's eyes). Now that we have improved the DEMs, the precision is much better. For observing changes in speed, we feel that precision can be more relevant than accuracy.

P5463 L1: “the speedup has gradually increased and migrated inland”. This phrase conflates an awful lot of dynamic change information, and is conceptually difficult to grasp. Please clarify the language

The sentence seems fairly self explanatory.

P5463 L25: “the velocity is posted in the wrong location”. I know what you mean, but I think many won’t. Even the term ’posted’ is rather too specialised I think. Please clarify.

This comment no longer applies since we have removed this section of text.

P5465 L8: “plotted the results along the top of”. Stylistically rather weak. I suggest that you just refer to the figure and make sure that the caption explains the figure layout properly.

Changed to “in Figure 2 (top)” Same as one would indicate (a) or (b). The caption is clear on this point.

P5465 L11: “greater importance” -> “greater importance for this glacier”

No this is a general statement that follows from basic theory, and is not meant to only apply to Jakobshavn (e.g., one of the references is from a paper about Helheim).

P5466 L3: “Additional feedbacks”. This is one of two places in which such feedbacks are referred to, so they really need a fuller explanation. What are the feedbacks, what is their impact, and how might they affect the future evolution?

Inserted “(e.g., evolving driving stress, changes in basal water pressure, and margin softening)” A more detailed discussion is beyond the scope of this paper, and the reader should consult the cited references.

P5466 L11: The ’high spot’ is only just discernable (actually looks more like a plateau) on Fig 3 so needs a better introduction, a label in Figure 3, and highlight in Figure 1. In general the presentation of surface and depth height data (see Poul’s comments), as well as velocities only along the profile in 1D limits the readers ability to see the whole problem, and this could easily be improved by additional contours on Figure 1 and/or another figure.

Given the difficulties stated below, we so no reason to further clutter the figures. We agree there is some ambiguity, especially since there are a couple of local maxima on the region. So where we first mention the feature we inserted “(located at ~12 to 17 km in Fig. 3)”, which unambiguously defines the feature in questions.

P5466 L15: "until it again reaches depths". Again a bit confusing – how can a terminus reach a depth? I get the picture but overall the language could do with tightening up for a broader readership.

> ***It seems self explanatory, but to avoid any confusion, we inserted "bed" before "depths"***

P5466 L25: If gridding artefacts are potentially important here, then this needs to be explained in more detail. You haven't said much about the surface (or bed) DEM, its resolution or it potential errors so to introduce this here, only in respect of this 'high spot' is rather confusing. Surely gridding effects can affect each of these data products with potential impact on the rate of retreat either positive or negative. Sorry to be pedantic, but this reads a bit sloppily.

> ***The bed map is not our product and we agree there could be better documentation, but there isn't. Per reviewer 1's suggestion, we added sentence to indicate bumps could be falsely added or missed completely. The surface elevations are straight out of Joughin et al., 2012. We added a citation to the caption explains that they are derived from ATM data.***

P5467 L7: "trough does not narrow substantially". Surely this is testable? Once again, a 2D presentation of the bed DEM (and possibly the surface DEM) would really improve the paper.

> ***This point is addressed where we inserted some language above about the variability of the trough width.***

Figure 1: Labels almost unreadable. So much more could be presented in this figure. Not up to the usual Joughin and Smith high standards!

> ***The original is relatively legible, but we can see that is has been somewhat degraded in the transformation. To improve, we have increased fontsize and markers, increase marker outline widths, and bolded text. This should help substantially.***

Reviewer 3

This is a nice brief paper which adds some rather spectacular (and disturbing) data to the longer term records of ice motion near the calving front of Jakobshavn Isbrae. While the paper could go into a lot more detail in its analysis, the main point of the article (given that it is a short communication) is to get the results in to the public domain. There are no major problems with the paper although it would be good to see a more involved discussion with respect to the predicted retreat scenarios; this discussion is not very detailed and seems to give little attention to

a whole gamut of processes which might affect the retreat history over the coming decades – this point is discussed further under the 'Main Points'.

Comment appreciate, all action deferred to subsequent comments.

Main points

The speed comparisons need amending. Given the issues associated with speed- up of sites as the thinning terminus retreats towards them, the comparison of e.g. M6 velocities between 2012 and 1992 (286% speed-up) is not very informative. A comparison between the velocity values from 1km behind the terminus between 2012 and 1992 would be more useful (and presumably not as extreme as the 286% speed-up quoted).

As our discussion indicates, both are important. The speedup at M6 is somewhat indicative of the increase in discharge (after accounting for thinning). Where as the changes near the terminus are more indicative of the terminus dynamics and speed. We agree, however, more discussion of the terminus was appropriate and have added a couple of sentences in the results section essentially noting the little in the way of a trend and that the 2009 and 2013 mean terminus speeds are identical.

Explanations of the summer velocity variations. You state that "For example, analysis of data from 2009 indicates that the forces associated with the terminus depth variation and height above flotation account for most of Jakobshavn Isbræ's seasonal flow variation (Joughin et al., 2012). Such results are consistent with the large summer speedups in 2012 and 2013 when the terminus appears to have reached the bottom of an overdeepened basin (Fig. 3), which occurred after the terminus retreated more than a kilometer farther inland than previous summers." However, what is therefore the explanation for peak velocities occurring in late summer in 2011, '12 and 13' while the peaks were earlier (about end-June) in 2009 and 2010 – during all this period, the terminus was on a reverse slope so the explanation that has been given should result in the same temporal acceleration to peak velocity each summer. What has changed between the earlier and later summers?

The timing of the peaks and max retreat is generally coincident, especially given that we are using position along at one point along the terminus front as a proxy for the full terminus width. This can be seen in our analysis of the 2009 data in Joughin et al, 2012. In response to this comment, we have added a paragraph that provides more discussion about the seasonal and long term correspondence. We did not augment the discussion to include why the seasonal timing of the terminus position varies substantially. It is beyond the scope of this paper and is the subject of another paper in preparation by another group.

Issue re gridding artefact. The suggestion that "the high spot might be a gridding artifact" seems rather odd. Whatever gridding was used, it should only give a 'high

spot' relative to the lower elevations either side IF there was a high point somewhere within that part of the survey. If this is the case and the high point doesn't in fact exist, then this is a data error (perhaps because it is very hard to sound (Li, 2009)) but this is not a gridding error/artefact.

> *Actually troughs gridded from sparse flightlines often have such artifacts, which are often termed "string of beads." Per the other reviewers request, we noted the gridding could either add a false bump or fail to resolve a bump.*

The rather bleak domesday scenario for retreat and acceleration would benefit from a caveat. You state in the introduction that the previous initial speed-up was "likely in response to increased basal melting (Holland et al., 2008; Motyka et al., 2011) and to weakened ice mélange in the fjord (Amundson et al., 2010; Joughin et al., 2008)." Does your retreat scenario assume that weakened ice mélange and increased basal melting can now be assumed as inevitable in decades to come? If not, and given the complexity of tidewater glacier dynamics, then you should at least add something about other processes that might slow (or indeed increase) the rate of flow and retreat.

> *Short of a major cooling that allowed readvance, its likely to some extent the retreat is decoupled from climate (although moderate cooling or warming could still modulate the rates) since the dynamics of the deep terminus are driving much of the change. Capturing this subject in detail is beyond the scope of this paper, but we did add the underlined clause in the following. "As the large drawdown since the 1990s indicates, this could happen over the span of a few decades or less (Joughin et al. 2012), absent a period of extended (several years to decades) cooling."*

At the moment, the discussion seems overly simplistic in simply saying that accelerating retreat is inevitable. In addition, since the thrust of the retreat argument is really based on the reverse bedslope marine instability theory, it would be good to reference some early work that has alluded to the concept (e.g. Weertman, 1974). Furthermore, given that you say the bed topography is very hard to sound (and thus the bed data are presumably poor?), how confident are you that there aren't a lot of potential pinning points inland of your transect or to either side of the transect?

> *The bed data does tend to improve with distance inland. There could be some bumps as we modified the text in response to the other comments to indicate. While there is much in common with the marine ice sheet instability, I think once the bed reaches a certain depth, strong stretching will yield continued near-terminus thinning and retreat. Nonetheless, we have included a reference to Weertman where we added several other tidewater specific references in the first sentence of the discussion.*

Minor issues

P5462, L18 – over the last decade and A half

Done.

P5462, L23 – suggest adding actual velocity behavior to clarify text: 'the glaciers speed has varied seasonally SLOWING as its terminus advanced in winter and ACCELERATING DURING retreat in summer'

Done.

P5462, L24 – "This seasonal variation of the terminus.." – best to say variation in what I,e, velocity and position.

Done.

P5464, L5 – M23 and M43 locations not shown

Done.

P5464, L23 - as it moves increasingLY close

Done.

P5465, L3 - relative to the 1992 PEAK?

There was no peak but we see the problem changed to "relative to the speed in 1992".

P5465, L3 - The statement 'While terminus position has often been correlated with terminus retreat' is meaningless as written and needs amending (with rates perhaps) to give the correct context.

Complete typo on our part. It now says "While terminus position has often coincided with terminus speed"

P5466, L11 – "While the high spot above the basin" is very imprecise. Could say "While the high spot behind the basin at km 12.5 (Fig. 3). . . " (or whatever the correct distance is)

Left as is here, but in response to another reviewers comment a few sentences earlier the text says "transient stability on the high spot farther upstream (located at ~12 to 17 km in Fig. 3)"

P5466, L16 – amend to make point clearer "(~1300m below sea level and~15km upglacier from its current position (Fig. 3).

Done.

"Once past the high spot" – again, very imprecise. Do you mean the one at ~12.5km or the higher one at ~17km – this could be expressed more clearly

Since it was define above, it should be clear we mean the full region between 12 and 17.

Figures

Fig. 1. The orange and purple labels are almost impossible to see. Keep the circles coloured but make the lettering black or white (and larger if necessary) so they are legible

In response to another reviewer's comments the font size and weights have been increased.

Fig 3 – indicate the time period recorded by the terminus position in the caption (as the annual cycles over~4 years around kms 7-12 are clear but not sure how long the rapid 8 km retreat took hence it needs clearer labelling (presumably from 2009 given top plot but it would help to state start and end of that multi-colour time series))

We don't quite understand the confusion since the axis on the right side does given the range and we explicitly call it out in the text "...time (right y-axis)" and this goes from 2009 through 2013. We did add "(see also same data in Figure 2)" to make it clear the data are the same.

Interactive(Pelto)

Joughin and Smith (2013) provide an interesting and important update to the velocity variation of Jakobshavn Isbrae. The glacier has experienced a further increase in speed and greater summer acceleration. The comments below are all minor and just suggest additional information what would more strongly convey the spatial and temporal changes in velocity of this important glacier.

Comment appreciated, no action required.

5462-19: It would extend the unique nature of the velocity change that began in the 1990's if you cited data on velocity back to 1964 from Table 1 (Pelto et al, 1989) that indicated consistency from 1964-1986, which then remained unchanged into the 1990's when your analysis begins. "Measurement of surface velocities at the calving front in July of 1964, 1976, 1978, 1985, and 1986 yielded a mean velocity of 20.6 m/d, variation in mean velocity from year to year is less than I m/d." Not suggesting this need be plotted as location specific comparison not possible.

I had never seen this paper, but was glad to find out about it. I added to the introduction (underline) "After a period of multi-decadal relative stability (Pelto et al, 1989), speedup began in the late 1990s when Jakobshavn's Isbræ's floating ice tongue began to weaken and break up." I also added a citation where we cited Echelmeyer et al for seasonal stability since this paper shows *only small seasonal variation. I hesitate to do more since it gets beyond the scope of the paper.*

5463-2: This paper focuses on the main trunk of the Jakobshavn, which is at the southern side of the current terminus. There should be brief mention in the introduction of the rest of the rest of the terminus and its response. The entire terminus should also be visible in Figure 1. The northern terminus is important to generating the ice mélange that plugs the fjord for much of the year and has also retreated substantially. To put the two in context either the flux or the distance of the trough inland could be used to illustrate the lesser importance of the northern branch.

We have modified the figure to show the north branch and have included a time series plot (updating our 2008 plot) for the north branch in the Supplement. We don't really discuss the north branch beyond this, but it is good to have the complete record available.

5464-14: Given the shortness of this paper and number of figures, I recommend including the supplemental figure in the regular paper at this point.

We feel the supplement is appropriate since much of that record has been already published and the focus is largely on the last few years.

5464-21: Add perspective by identifying the percentage of summer acceleration prior to 2012. This is well shown for 2009 and 2010 in Figure 5 Joughin et al (2012). With Figure 2, an additional figure is not needed.

I think giving too many percentages will bog down the text. The numbers you mention should be self evident from the figure.

5463-13: A figure that displays the velocity variation and the bedrock high in a map view similar to Joughin et al (2008) Figure 2, extending further inland would be quite useful for the coming discussion.

This one of the reasons we put the terminus variation on both figures 2 and 3. We didn't have any bed data in the 2008 paper.

5466-7: Figure 3 indicates the length along the main flow line of this high spot, how consistent across the width is this high spot, is it even wider or higher or not toward the northern and southern margins of the ice stream. This maybe unknown, if it is known than it is worth mentioning.

I am not sure that the bed data are good enough to support such an analysis. The fact that we state "we can't rule out that some or all of the high spot might be a gridding artifact" should be sufficient to convey the uncertainty in the bed data.

5467-1: This 12 fold speedup would represent approximately how much volume flux, given changes in thickness and width of the ice stream at M-26? If this cannot be quantified, qualitatively state likely change.

> ***Simply scaling by 12 thicknesses in at M26 in 1990s vs thinning to flotation yields 8.5, which is what we meant by close to ten-fold. Given the back of the envelope nature of this calculation, which is meant to be illustrative rather the predictive, I am not sure whether it improves the text to include this number. Nonetheless, we added after ten-fold in parentheses "(~8.5 based on simple scaling by the ratio of thickness at flotation to 1990's thickness)".***

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Brief Communication: Further Summer Speedup of Jakobshavn Isbrae

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Abstract

We have extended the record of flow speed on Jakobshavn Isbræ through the summer of 2013. These new data reveal large seasonal speedups, 30 to 50% larger than previous summers. At a point a few kilometres inland from the terminus, the mean annual speed for 2012 is nearly three times as large as that in the mid 1990s, while the peak summer speeds are more than a factor of 4 greater. These speeds were achieved as the glacier terminus appears to have retreated to the bottom of an over-deepened basin with a depth of ~1300 meters below sea level. The terminus is likely to reach the deepest section of the trough within a few decades, after which it could rapidly retreat to the shallower regions ~50 km farther upstream, potentially by the end of this century.

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1 Introduction

The speeds of many of Greenland glaciers have varied dramatically over the last two decades (Howat et al., 2008; Moon et al., 2012), which has contributed to the ice sheet's increasingly negative mass imbalance (Rignot and Kanagaratnam, 2006; Shepherd et al., 2012; van den Broeke et al., 2009). Nowhere are such changes more evident than on Greenland's fastest glacier, Jakobshavn Isbræ (Fig. 1), which sped up more than twofold over the last decade and a half (Joughin et al., 2012b). After a period of multi-decadal relative stability (Pelto et al., 1989), speedup began in the late 1990s when Jakobshavn Isbræ's floating ice tongue began to weaken and break up (Joughin et al., 2004; Luckman and Murray, 2005; Thomas et al., 2003), likely in response to increased basal melting (Holland et al., 2008; Motyka et al., 2011) and to weakened ice mélange in the fjord (Amundson et al., 2010; Joughin et al., 2008). Since the loss of this ice tongue, the glacier's speed has varied, seasonally slowing down with terminus advance in winter and speeding up with terminus retreat in summer (Joughin et al., 2012b). This seasonal variation of the terminus position may be driven by seasonal changes in the rigidity of the ice mélange, which appear to reduce winter calving (Amundson et al., 2010). Over the past several years, the speedup has gradually increased and migrated inland due to a number of feedbacks as the glacier has thinned and retreated (Joughin et al., 2012b; Van der Veen et al., 2011). Largely as a consequence of this speedup, Jakobshavn Isbræ alone has contributed nearly 1 mm to global sea level over the period from 2000 to 2011 (Howat et al., 2011).

A record of Jakobshavn Isbræ's variation in speed from the mid 1990s through mid 2011 was published recently (Joughin et al., 2012b). Since then, the summer speedups in 2012 and 2013 were in excess of those observed in previous summers. Thus, here we provide a Brief Communication to extend the record of flow speed to include events through 2013.

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2 Results

Since 2009, we have mapped the speed of Jakobshavn Isbræ regularly using data from the German Space Agency's (DLR) TerraSAR-X synthetic aperture radar (SAR). To do this, we applied a set of well established speckle-tracking techniques (Joughin, 2002) to pairs of TerraSAR-X images separated by 11 days. Figure 2 shows a time series of speeds extracted from these velocity maps. These speeds typically have slope-dependent errors of up to ~3%, which also are a function of the particular imaging geometry. One complication with Jakobshavn Isbræ is that surface elevations near the terminus are lowering rapidly (~15 m/yr) (Joughin et al., 2008; Krabill et al., 2004), which can increase slope errors and introduce geolocation errors. To reduce such errors, we used an updated digital elevation model (DEM) for each calendar year determined using a combination of, ASTER-stereo (Howat et al., n.d.), WorldView-1/2-stereo, and TanDEM-X elevation data.

The speeds plotted in Figure 2 are from the locations along the glacier's main trunk that are shown in Figure 1 (M26 and M43 locations not shown). The colored circles correspond to fixed points such that the name (e.g., M6) indicates the distance from the late 2003 ice front. Because these points are fixed in space, the changes in speed reflect both the influence of proximity to the terminus and variation in terminus thickness, both of which vary with terminus advance and retreat. To help separate these effects, we also plotted the speed at a point (T09-T13) 1-km behind the location of where the terminus reaches its point of maximum summer retreat for the corresponding calendar year. As a result, speed at these points is largely influenced by near-terminus conditions (e.g., thickness) rather than by diminishing proximity to the terminus.

Figure 2 shows the change in speed on Jakobshavn Isbræ since 2009, extending a satellite-derived record that reaches back to 1992 (see Figure S1 in Supplement) (Joughin et al., 2012b). Although our focus is on the main branch, for completeness, Figure S2 provides a record of variation in speed along the north branch (points N6-N15 in Fig. 1). Following the near doubling of speed near the terminus of the main branch in the late 1990s to early 2000s (Joughin et al., 2004; Luckman and Murray, 2005), Jakobshavn Isbræ sped up more moderately at rates of 2.6-to-4.4% per year from 2004 through 2011,

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coincident with a strong seasonal variation in speed (Joughin et al., 2012b). Our data show that in the last two years this pattern has altered, beginning with the increase in the peak summer speed at M6 by 50% from 2011 to 2012 (11,300 to 17,000 m a^{-1}). Some of this change can be attributed to the terminus having a greater influence on speed as it moves increasingly close to M6 each summer (<1km in 2013). Just above the terminus (orange triangles Figure 2), peak speeds increased by 31% from summer 2011 to 2012 (13,300 to 17,100 m a^{-1}). From 2012 to 2013, peak summer speeds near the terminus (M6 & M9) appear to have declined slightly, but increased at points farther inland (M13-M46). The TerraSAR-X satellite was inoperative for a brief period in early August 2013, so that we missed acquisitions near the time of the 2013 peak. As a result and because the peak in 2012 was brief, we can't rule out the possibility of a similarly brief peak in 2013 with a similar or even greater magnitude than 2012. The summer 2012 peak at M6 represents a 420% increase in speed relative to the speed in 1992, which corresponds to a period with little observed seasonal variation (Echelmeyer and Harrison, 1990; Pelto et al., 1989). Thus, a more direct comparison is that of the mean annual speed at M6 in 2012 (11,600 m a^{-1}), which yields a 1992 to 2012 speedup of 286%. Winter near terminus speeds (T9-T13) show little increase.

To evaluate terminus retreat, for each TerraSAR-X image we digitized the location where the terminus intersects the white profile shown in Figure 1 and plotted the results in Figure 2 (top). Since there are geolocation errors associated with rapidly changing topography as described above, this yields position errors of ±100 m. While terminus position often appears to influence terminus speed (Howat et al., 2008), of greater importance is whether the terminus is retreating into deeper water (Howat et al., 2005; Thomas, 2004). To examine the relationship of retreat to surface and bed geometry, Figure 3 illustrates the glacier geometry, corresponding to the white profile shown in Figure 1, along with the position of the terminus through time. We have aligned this profile to follow the deepest part of the gridded bed map, which differs from the points where we have plotted speeds.

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3 Discussion

Several studies of outlet glaciers indicate that variation in thickness of an un-buttressed (i.e., no floating section) terminus as it retreats or advances exerts a strong influence on speed within several ice thicknesses of the calving front over time scales ranging from minutes to years (Howat et al., 2005; Joughin et al., 2012a; Nick et al., 2009; Thomas, 2004; Weertman, 1974). This means that as the terminus retreats into deeper water, the pressure boundary condition at the near-vertical terminus face produces a force that must be balanced upstream by longitudinal stress gradients, which are produced through increased stretching (i.e., speedup). This stretching should produce thinning that contributes to further retreat. In response, additional feedbacks (e.g., evolving driving stress, changes in basal water pressure, and margin softening) contribute to the overall variation a glacier's speed as it geometry evolves in response (Joughin et al., 2012b; Van der Veen et al., 2011).

Analysis of data from 2009 indicates that the forces associated with the terminus depth variation and height above flotation account for most of Jakobshavn Isbræ's seasonal flow variation (Joughin et al., 2012). Such results are consistent with the large summer speedups in 2012 and 2013 when the terminus appears to have reached the bottom of an overdeepened basin (Figure 3), which occurred after the terminus retreated more than a kilometer farther inland than previous summers. While the correspondence between seasonally varying terminus position and speed is relatively strong, there are some notable differences. For instance, peaks in speed tend to be sharper in time than corresponding peaks in terminus retreat, which, in addition to the nonlinearity of the ice dynamics, likely reflects the glacier's rapid evolution. As an example, if the terminus maintains roughly the same location for a period of weeks (e.g., relatively flat peak in late summer 2011), then the terminus should continue to thin by several meters over the same period. Since speed is sensitive to height above flotation, this thinning is likely to reduce the peak speed even with no change in terminus position.

Over the 5-year period of our observations, the correspondence between terminus depth and speed is less clear. The greatest mean annual speeds do occur in 2012 when the terminus is near what appears to be an overdeepening and subsequently decline in 2013

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as the terminus retreats to higher ground. By contrast, the 2009 mean speed was faster (11,130 m a^{-1}) than the 2011 (10,590 m a^{-1}), despite a more advanced 2009 terminus position. This difference likely reflects that fact that at these time scales that the other processes and feedbacks mentioned above have a substantial influence on flow (Joughin et al., 2012b; Van der Veen et al., 2011).

If Jakobshavn Isbræ's terminus has reached the bottom of an overdeepened region, then the terminus may be able to find a position of transient stability on the high spot farther upstream (located at ~12 to 17 km in Fig. 3) as retreat to shallower depths yields slower speeds (Joughin et al., 2012b). The relatively high surface slope region above the basin, where the present heights are tens to hundreds of meters above flotation, may further slow retreat, since it should take more time to thin to near flotation. By contrast, low surface slopes and heights near flotation (Figure 3) likely facilitated the rapid retreat since 2009. While the high spot above the basin may slow flow, the terminus would still be grounded on a bed at least 900 meters below sea level, likely yielding speeds well above balance that would maintain strong, although potentially diminished, thinning. As a consequence, the terminus likely will continue to retreat, albeit perhaps more slowly in the near term, until it again reaches bed depths similar to summer 2012 (~1300 m below sea level) at ~15 km farther upstream (Fig. 3). As the large drawdown since the 1990s indicates, this could happen over the span of a few decades or less (Joughin et al., 2012b), absent a period of extended (several years to decades) cooling.

Once past the high spot, the trough extends roughly 50 km farther inland at depths below sea level of ~1200 m and greater before eventually reaching shallower depths. Thus, although there is some variation in trough width (~3.5 to 5.5 km) that could modulate the rate of flow, once into this deepest part of the trough, extreme velocities (>12,000 m a^{-1}) are likely to persist as the terminus rapidly retreats (Thomas et al., 2011). Furthermore, without the ability to seasonally advance up a relatively steep bed slope as in the past several winters, such high speeds may be sustained year round. Because the deep trough of Jakobshavn is extremely difficult to sound (Li, 2009), we can't rule out that some or all of the high spot might be a gridding artifact, in which case retreat may occur even more rapidly. Similarly, we cannot rule out that some bed highs may not have been resolved that could provide additional points of transient stability.

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The transient summer speeds we observe for 2012 (>17,000 m a^{-1}) appear to represent the fastest observed speed for any outlet glacier or ice stream in Greenland or Antarctica. This yields a transient peak speed a factor of four larger than the speeds observed in the 1990s, while the mean annual speedup is by just under a factor of 3. If, as the glacier recedes up the trough, it is able to maintain the peak speeds year round, then a sustained speedup of the terminus by a factor of 4 of 5 is conceivable based on recent behavior, which is about half of the ad hoc tenfold upper limit on the amount a glacier could speed up by that was proposed by Pfeffer et al. (2008). Nevertheless, these speeds would occur in a trough roughly twice as deep as prior to the speedup. Hence, a tenfold increase in ice flux may be possible for Jakobshavn Isbræ if the trough does not narrow substantially with distance upstream. Equivalently, while the increase in terminus speed and the glacier's overall maximum speed may remain under a factor of five, as the terminus retreats farther inland where the speeds now are comparatively slow, the relative speedup is much greater (e.g., if the terminus retreated to M26 with a speed of 16,000 m a^{-1}, this would represent a twelve-fold speedup). Thinning by hundreds of meters to a terminus near flotation, however, would yield something closer to a ten-fold flux (~8.5 based on simple scaling by the ratio of thickness at flotation to 1990's thickness) increase. It is unlikely that such retreat could be sustained for more than a few decades because the terminus would rapidly retreat ~50 km to shallower depths (Joughin et al., 2012b).

4 Conclusions

Our results show that Jakobshavn Isbræ has accelerated to speeds unprecedented in its observational record as its terminus has retreated to a region where the bed is ~1300 m below sea level. While the current increase in annual discharge flux remains less than a factor of three, the increase plausibly could reach or exceed a factor of 10 within decades. This is a consequence of the fact that retreat into deeper water increases both speed and thickness of the terminus. Conversely, where retreat to shallower depths occurs, losses will be far more moderate. Hence, a tenfold increase in discharge is likely only to be sustained in the few decades before rapid thinning would cause the terminus to retreat out of the deep trough. Thus, the potential for large losses from Greenland is likely to be determined by the depth and inland extent of the troughs through which its outlet glaciers

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drain. These features are only beginning to be well resolved by international efforts such as NASA's Operation IceBridge. The relatively sparse data collected thus far indicate that, with its great depths and inland extent, Jakobshavn's Isbræ is somewhat unique (Bamber et al., 2013), suggesting that it may be difficult for the majority of Greenland's outlet glaciers to produce or to sustain large increases in ice discharge.

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Acknowledgements

The contribution to this work by I.J. was supported National Science Foundations Office of Polar Programs (NSF-OPP) through the Center for Remote Sensing of Ice Sheets (CReSIS) (NSF ANT-0424589). The contribution to this work by B.S. was supported by the National Aeronautics and Space Administration's (NASA) Earth Science Division (NNX09AE47G). Support for the SAR data processing was from NASA's MEaSUREs Program (NNX08AL98A and NNX13AI21A). The TerraSAR-X data were provided by the German Space Agency (DLR), project HYD0754. The bed elevation data were provided by CRESIS and the surface elevation data were provided by NASA's Airborne Topographic Mapper (ATM) Program. NASA's Operation IceBridge and its predecessor campaigns provided the instrument platform for both the bed and elevation data collection. Comments by P. Christoffersen, A. Luckman, M. Pelto, and an anonymous reviewer improved the revised manuscript.

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Figures

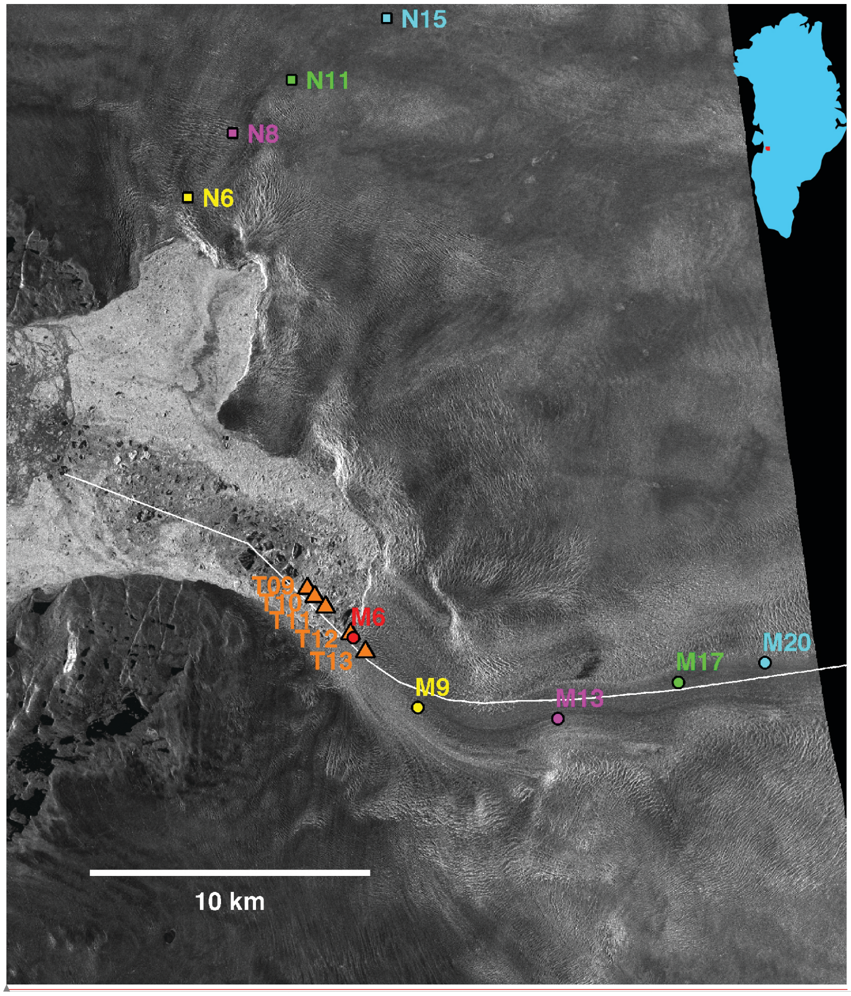

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Figure 1. TerraSAR-X image acquired September 20 when the terminus was near the point of maximum retreat in the summer of 2013. Markers M6-M20 and T09-T13 show the locations of points plotted in Figure 2. The white profile indicates the location of the profile plotted in Figure 3. TerraSAR-X image copyright DLR, 2013.

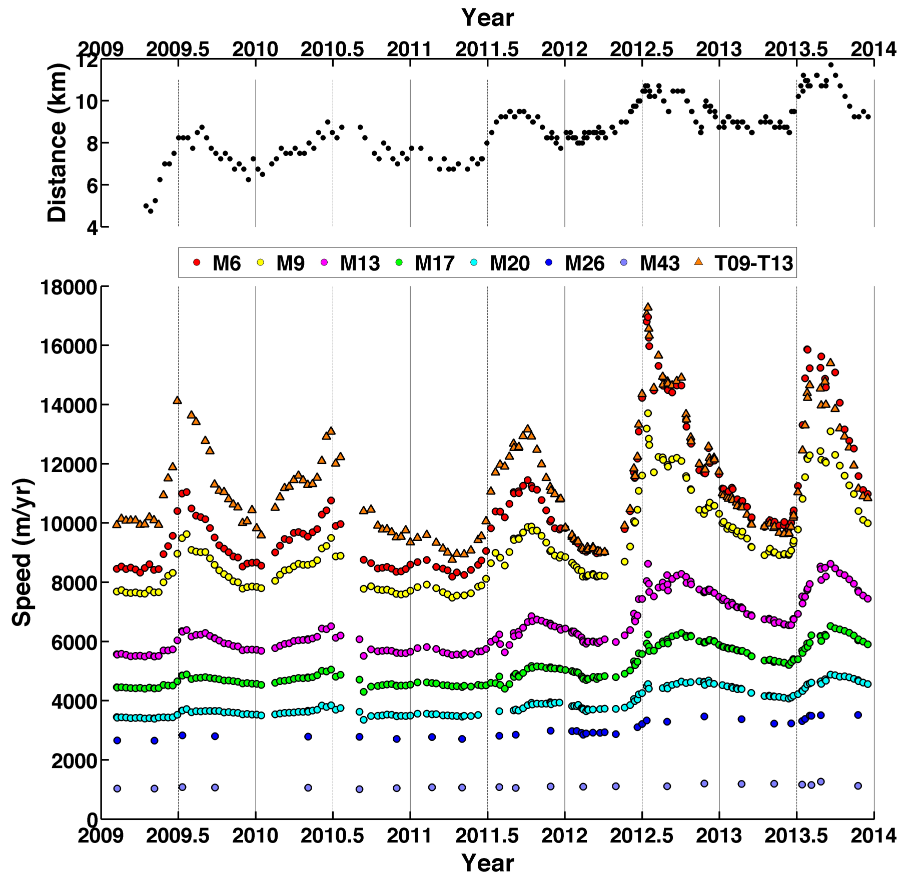

Figure 2. Plots of (top) terminus position and (bottom) speed through time for Jakobshavn Isbræ determined from TerraSAR-X data collected from 2009 to 2013. Terminus position was digitized where it intersects the white profile shown in Figure 1. The color circles (M6-M43) show the speed at several points along the glacier's main trunk at the locations shown in Figure 1 (M26 and M43 locations not shown; see Joughin et al., (2008)). Each point's numerical designation (e.g., M6) gives the approximate distance in kilometres from glacier terminus in late summer 2003 and these points are used for consistency with earlier records, (Joughin et al., 2008; 2012b). Additional markers, T09-T13 (orange triangles) (locations shown in Figure 1), are each situated 1-km upstream of the terminus at its position of

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maximum retreat for the years 2009-2013. Each year, speeds are plotted for the corresponding point (T09-T13).

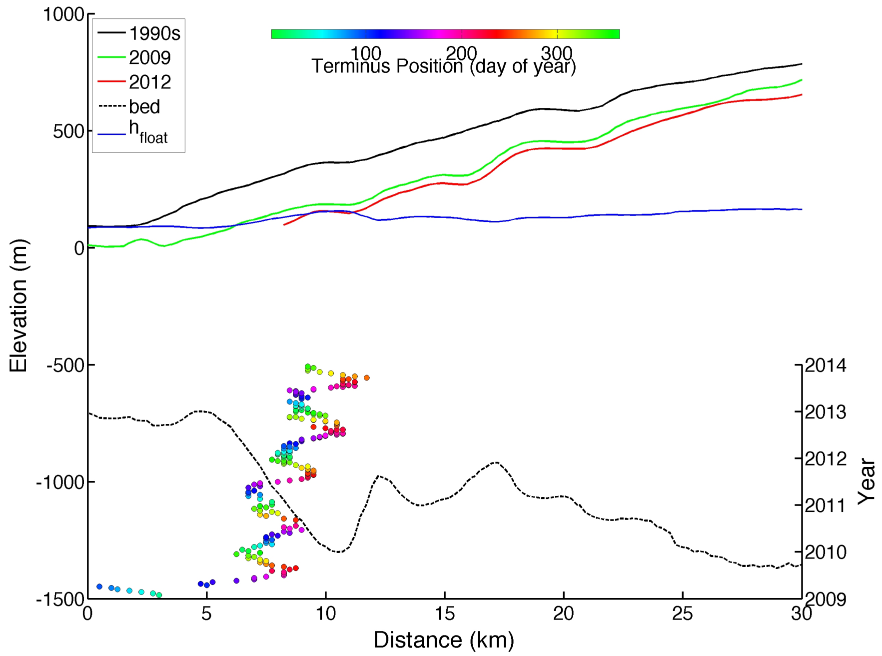

Figure 3. Surface and bed elevations in the near-terminus region of Jakobshavn Isbræ along the profile shown in Figure 1. Terminus position (x-axis) is shown as a function of time (right y-axis) with color to indicate day of year (see also same data in Figure 2). Surface elevations were determined (Joughin et al., 2012b) by interpolating data collected by NASA's Airborne Topographic Mapper (ATM) in the 1990s, 2009, and 2012 as part of Operation Icebridge and its predecessor missions (Krabill et al., 2004). Bed elevations were interpolated from a gridded map of radar depth soundings produced by the Center for Remote Sensing of Ice Sheets (CReSIS)(Li, 2009; Van der Veen et al., 2011). Multiple versions of the DEM exist, but based on comparison with other data sets our preferred version is the one located at (ftp://data.cresis.ku.edu/data/grids/old_format/2008_Jakobshavn.zip).

Supplement to

Brief Communication: Further Summer Speedup of Jakobshavn Isbræ

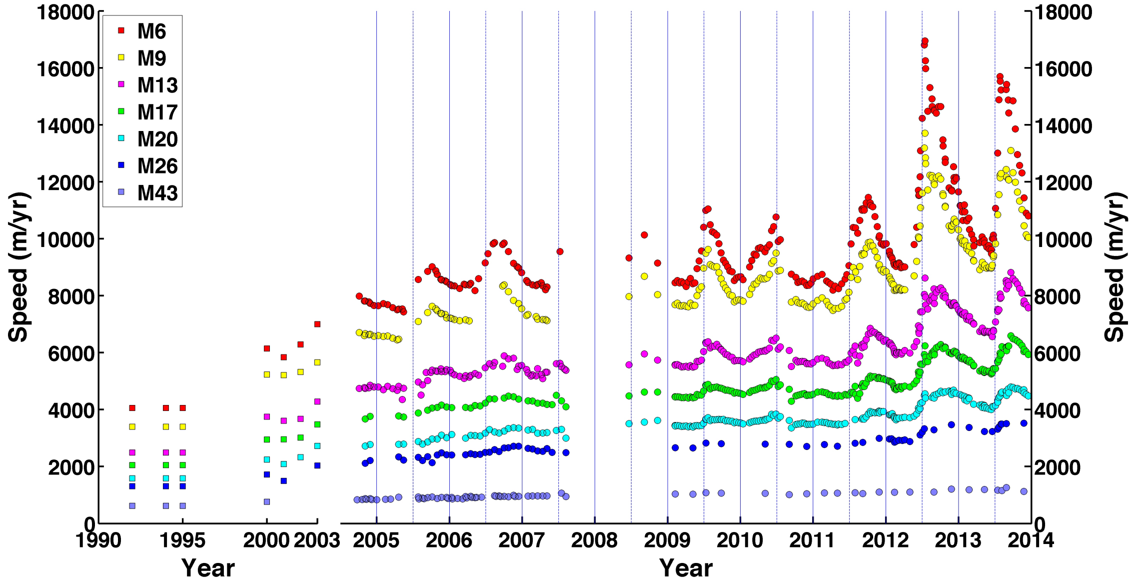

Figure S1. Plots of speed through time for the main branch of Jakobshavn Isbræ determined from TerraSAR-X data collected from 2009 to 2013, RADARSAT data collected from 2000, and 2004 to 2007, LandSAT data collected from 2001 to 2003, and ERS-1/2 data collected from 1992 to 1995 (Joughin, Abdalati, & Fahnestock, 2004; Joughin et al., 2008; 2012). The colour circles (M6-M43) show the speed at several points along the glaciers main trunk at the locations shown in Figure 1 (M43 location not shown; see Joughin et al., (2008)). Each point's numerical designation (e.g., M6) gives the approximate distance in kilometres from glacier terminus in late summer 2003.

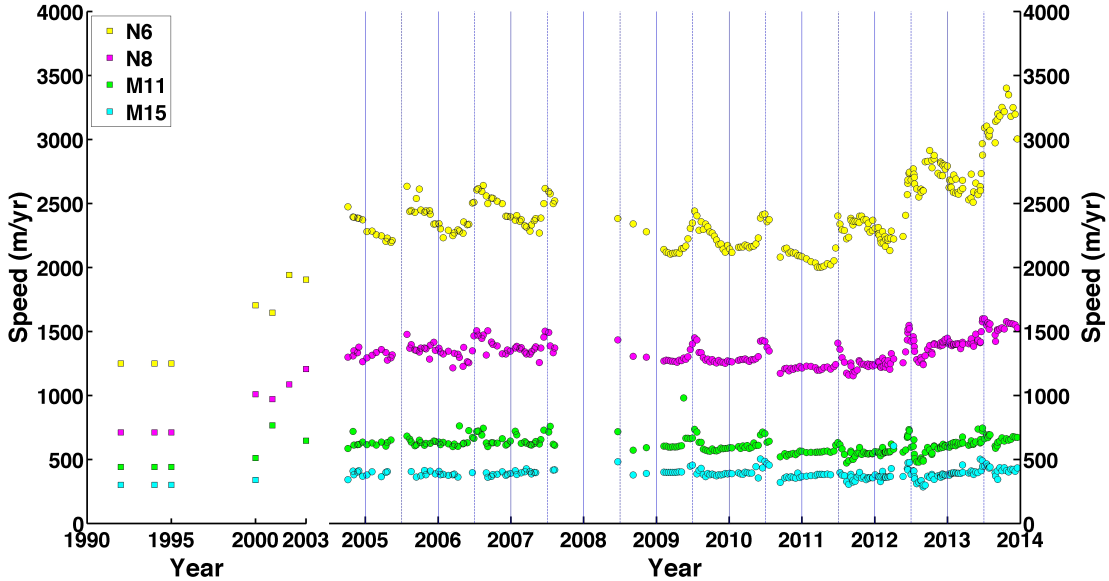

Figure S2. Plots of speed through time for the north branch of Jakobshavn Isbræ determined from TerraSAR-X data collected from 2009 to 2013, RADARSAT data collected from 2000, and 2004 to 2007, LandSAT data collected from 2001 to 2003, and ERS-1/2 data collected from 1992 to 1995 (Joughin et al., 2004; 2008; 2012). The colour circles (N6-N15) show the speed at several points along the glaciers main trunk at the locations shown in Figure 1. Each point's numerical designation (e.g., N6) gives the approximate distance in kilometres from glacier terminus in late summer 2003.

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