Answer to reviewer's comments

We would like to thank the three reviewers for their time and constructive comments. We understand and sympathize with the request for more details from all reviewers, but are unable to satisfy all such requests because of the nature of a TC Brief Communication. Having chosen this format, we are restricted to three figures and a maximum of four journal pages as well as only 20 references. Below we address all comments and suggestions (reviewer's comments in black, our reply in blue) and we uploaded a revised version of the manuscript. Within the available space, we have tried to accommodate the request for more details.

Reviewer 1: Ted Scambos

The authors have identified a newly-propagating rift in the southern Larsen C using satellite images. The rift, formerly stable with the rift tip lying just inside a suture zone of marine ice, has grown significantly in 2013-2014 as revealed by Landsat images. The authors describe some scenarios for future growth and eventual calving of a major iceberg from the Larsen C, which they show would adjust the strain field significantly.

The paper requires a table of the Landsat images used. There is a significant change in the imagery between Landsat 7 and Landsat 8, but this is not mentioned or discussed. Improved radiometry could lead to a more sensitive detection of the rift tip, and falsely appear as a rapid growth of the rift. How did they insure that the interpretations were consistent across sensors? Overall, the authors were understandably eager to get this out in front of the community; to do so, they cut short a lot of descriptive details, a lot of analysis of the actual observations, a lot of details of image processing, tables of images, data points, etc. and a lot of other analyses that are straightforward but time-consuming to do.

These are understandable comments but the reasons behind the brief description of the methods is more to do with the format of the paper than any desire for speed. In short we included only what was necessary. We do not believe that the improved radiometric resolution of Landsat 8 over Landsat 7 will have made any real difference in sensitivity of rift tip detection. This will be much more sensitive to spatial resolution (which is identical) and illumination (which is not controlled). We also find no rapid growth of the tip between our use of Landsat 7 and Landsat 8 data. There may be a lot of further analyses that are straightforward but time consuming, but we don't believe that these would alter the results, which are quite clear and unambiguous.We have modified the text in places to clarify some of the points above. We also included a table of data points as supplementary material.

Data that might have been brought to bear: MODIS thermal images (identify date ranges of rapid progression of the fracture, and investigate what might have triggered them); TerraSAR images (same goal). IceBridge data (radar for ice thickness and detailed surface topo). Repeat ice velocity mapping. More analysis of past calvings and rift progressions. Oceanographic data (speed of sub-shelf water flow, from moorings within the ice shelf?) It is likely that the author team is working on some of these things during the review process.

Great suggestions for further work. We are content that the paper is complete as it stands, and lack the space for further work in this manuscript.

I should probably note a potential deal-breaker for the paper's hypothesis up front: Figure 1 and Figure 2 show a fracture in the same new zone, downstream of the current one, which has been there for some time (see http://nsidc.org/data/ iceshelves_images/and http://nsidc.org/MMS/moa/ moamap.html). If a rift has occurred in the same area in the past and not continued to propagate further and cause a calving, then the point of this study is a bit moot. Note the many structural similarities between the downstream'stalled' rift and the new rift. Looking at current maps of flow speed, the downstream rift was in the new rift's position approximately 60 years ago. A check of earlier Landsat images (LIMA, Landsat TM, Landsat MSS) would at least indicate if the downstream rift has been there for decades.

It is correct that there is a surface feature in the Trail flow unit further downstream, but the essential difference is that the propagation of it is stalled on both ends. Landsat imagery indicates that it is not an open rift as the one discussed in this manuscript, but rather the surface expression of a basal crevasse, which can form on the ice shelf (Luckman et al, 2012; McGrath et al., 2012).

The open rift that we describe in this paper reaches from close to the calving front at Gipps ice rise through the suture zone, which is a deviation from the previous pattern of rift propagation in this area. Thus we think that the here described rift and the feature you describe cannot be compared.

P863 L15 – I think 'medium' is subjective, perhaps just say 'at 250 m pixel scale' (note also that pixels are not equal to resolution, picky point but often forgotten).

Corrected

P863-864 L26-L1 – 'minimized by careful control of brightness and contrast' - a less subjective approach would be to high-pass filter the data and then match histograms of the image area of the shelf with a reference image. I admit, it's not likely to change the measurements much, but it sounds better than 'we turned the knobs'.

We have amended the text to clarify the way in which image contrast was handled, and agree that a procedure based on high-pass filtering is highly unlikely to change the measurements.

P864 – it reads as though the selection of the two calving scenarios was also somewhat subjective. More of a discussion here of past calvings of the Larsen C could strengthen the choice. Icebridge data or surface radar would help justify the image-based picks. For Scenario 2, using the ice front as a guide seems very ad hoc. Since you have a numerical model, is there not some indication of where a fracture might propagate?

We chose rift scenarios carefully to minimise subjectivity, but there will always be an element of choice. A model-based projection requires a completely different type of model to the one discussed here.

We chose the first scenario based on the features within the satellite image which is more or less the shortest connection via the weaknesses to the front. The ice bridge data available in this region does not resolve these features, so we cannot say for sure that they are basal crevasses. However, ground based radar surveys in different parts of the ice shelf across similar features proved them to be connected to basal crevasses (Luckman et al, 2012; McGrath et al., 2012).

A previous calving in 1986 followed a similar feature, which can be seen from the shape of the calving front in 1988 as shown in figure 1.The second scenario assumes a more extreme event, which did not happen before in that way. However, there are also rifts visible reaching from the kink in the calving front towards the interior of the ice shelf, and the last large calving which occurred in 2008 was delineated by a similar straight line towards the front at the northern end.

P865 L10-11, please give a quantitative speed to go with ‘modestly’. What is the basis for saying ‘previously appeared to resist transverse fractures’? If you mean that the rifttips terminated in the suture zone, this might not be how you want to say it, because ‘previously’ implies that something changed to permit rift propagation. L12, I think a look at more available data might constrain the timing of a rapid jump more accurately.

Again, what are the quantitative speeds, or lower limits, for all of the time intervals that rift propagation was mapped?

We would prefer not to give rift propagation rates, as we only have discrete measurements in time and therefore only know the mean rate of rift propagation.The instantaneous rates may be much faster than this. The rift has been growing slowly while in the suture zone, and we assume this is due to the warmer and thus softer ice, which can better accommodate stress by ductile behavior (see Kulessa et al. 2014). Furthermore we assume that the fracturing through the Trail inlet has happened more or less instantly, like a calving event would. Thus it is difficult to put rates to the propagation and we changed the wording in the manuscript to better reflect this.

P865 Numerical model. Did you also look at the present-day stresses with the rift in place (but not broken away)? If this is truly a fracture through the ice sheet, it will significantly alter the stress field on either side – this experiment should be run. This brings up a more general question about rift propagation – as a rift moves across a shelf, the ‘lever arm’ of ice that has been set apart by the fracture grows. Wind and ocean stress should concentrate at the propagating tip, accumulating from a wide area (the area of the future berg). I note also that you don’t cite or discuss Joughin and MacAyeal in regards to rift propagation (2005 GRL). This would be a good one to look at, and would point directly to the importance of repeat velocity mapping near the riftzone.

We think that you are right that velocity mapping of the area would be a sensible thing to do and is a good way to monitor the current development of the rift and we will consider doing so in the future.

The numerical model we are using here is a diagnostic model for ice shelf dynamics and we used it to determine the stability of the calving front according to the criterion we defined earlier in Kulessa et al.(2014). We did not plan to model the propagation of the rift, although we agree that this may be done with a different model. We are aware of the Joughin and MacAyeal paper but decided not to discuss it here as our focus is not on modeling rift propagation.

P866 I think it is clear that there is much more that could be said about the results of the numerical model. Was there a flow speed change with the new geometries? Does the shear stress present at Bawden Ice Rise change? Is there support for the guess at the calving front for Scenario I or II? What front shape (of several plausible ones) tends to maximize the amount of low, or high, stress-flow ice at the front?

We have added velocity maps from the model as a figure to this reply (figure R1). The change in flow speed is not spectacular and there is still a large impact of Bawden ice rise on the stress field, which can be seen in the new figure 3 in the revised manuscript, which now also shows the contour line of zero second principal stress.

P866 L23 – ‘development of the rift width – a bit awkward, just say ‘spreading rate’? The following sentence is interesting, and related to a thought I had looking at rifts in Figure 1 – the presence of marine ice in a suture can reduce fracture penetration in that zone, but stress leading to fracture might be propagated on the far side of the suture, causing a ‘leap-frog’ fracture. This seems to be the case downstream of the new rift.

We thought that spreading rate could be misread as propagation, so we would prefer to keep the phrase as it stands.

You are raising an interesting point here, however, even if this is what happened further downstream (the feature you saw as a deal-breaker), there is still the difference that in case of the described rift the suture zone did fail, and that we describe an open rift and not the surface expression of a basal crevasse

Figure 1 – How was the background image produced? It appears to be a shaded relief of the Peninsula (from Alison’s excellent DEM) above the grounding line, and a high-pass filtered MODIS image below that. That is not described.

Yes, we did add the reference forAlison’s data set and altered the figure caption, apologies for the oversight.

Figure 2 – I believe the point labeled Dec 2012 should be Dec 2013? I think it would be important to map this progression better and show the January 2014 point and theAugust 2014 point on the image.An additional figure showing the rift expansion at the 2011 rift tip point would be interesting as well.

No it’s really 2012, but the Dec. 2013 position is would appear almost identical on the figure. We chose the points to highlight based entirely on significant jumps in the sequence. Adding further points would simply over-write the ones on the map. Due to space limitation we could not add another figure to the manuscript.

Reviewer 2: Catherine Walker

Using MODIS and LandSat imagery, Jansen and co-authors monitor and report upon the propagation of a rift in the Larsen C Ice Shelf that grew rapidly during 2014 after having been mostly stagnant/stable before that year with its rift tip lying in/near a suturezone likely filled with marine ice. The authors then discuss two possible directions for future propagation, likely calving scenarios, and the associated adjustment of the strain field at the ice front, enabling discussion of future stability. This is a neat and important observation that will be interesting to monitor going forward. The paper highlights the very recent development on Larsen C ice shelf and thus I can understand why it’s been submitted so quickly after the observation! However,while the observation and possible calving scenarios are interesting and noteworthy, the rigorousness with which the event(s) are placed into context, analyzed, and detailed is somewhat lacking. With a few fixes, I think this manuscript will be ready for primetime. In order for significant conclusions to be drawn from this work at this stage,though, it is my feeling that some of this analysis needs to be undertaken in a more rigorous manner. Mostly, I think at this point the authors just need to add more detailto further our understanding of rift propagation and ice shelf dynamics near the front.

Thanks for the supportive comments. We do not detect a specific suggestion within this paragraph to which we can respond. However, we repeat that a lot of the reason for lack of detail lies in the nature of a TC Brief Communication which is limited in length and number of figures. We do not agree that the analysis needs more rigour.

It would be helpful, perhaps coming from my specific point of view, to have a table or list of the observed propagation rates for the rift in recent years so that it's obvious that the rate of propagation increased dramatically. While it's clear from the author's finding that the rift had a large increase in rifting rate, it would be interesting to be able to see the change in rate as it crossed the Joerg Peninsula suture zone and approached the Trail Inlet flow unit. Otherwise all the reader knows about the large change in rift propagation rate is that it covered approx. 20 km in 8 months (or 2.5 km yr-1 between August 2014 and January 2015).

The rift tip is only detectable at sufficient precision in high spatial resolution optical data. Satellite radar suffers from insufficient contrast and MODIS data is too coarse. Thus Landsat is the only source of data available, we have used every available image, and all points are plotted in Figure 2 (graph, not map). Between available images, we cannot know the instantaneous rate of rift propagation because our sampling is not regular nor frequent. Nevertheless, the line joining our observations serves to illustrate the mean rate of rift propagation with clearly does vary, and can be related generally to specific regions of the shelf (see discussion). Nevertheless, this is a reasonable comment, so we have amended both the text and the caption to clarify. We do not think it appropriate to calculate propagation rates, but included the data table as a supplementary file.

How fast is this when compared to other years (as far back as the imagery allows)? What is the background rifting rate? Did it grow rapidly at any other time since its initiation or is this the first time in its history that it has exhibited a large jump in size? Related to this point, how do other rifts behave that are nearbythis rift? Have any of those rifts, which appear to be similar in structure, exhibited this large jump behavior in their past before becoming more stagnant? Is this observation reminiscent of any other rift propagation events on other ice shelves?

The rift tip we investigate in this paper is traveling along a crevasse feature, which has not moved further into the interior of the ice shelf since it has been documented on remote sensing data, which reaches back to the KATE 200 mosaic from 1975 presented in Skvarka et al., (1994). In Glasser et al., (2009), it is also clearly visible that the tip is at the margin of the suture zone.

A more thorough investigation of previous propagation rates of this rift, or a comparison with neighbouring rifts or rifts on other ice shelves would certainly be interesting, but would much more appropriately be the subject of another paper, and would certainly not fit within this limited length paper. The paper here focusses on one particular rift, its recent development, and its potential impact on stability.

P. 863, L. 3: Expand on this? What is the usual pattern? Are there no other instancesof rifts passing through suture zones?

The usual pattern is that they stop at the suture zone. No other rift has been observed penetrating the suture zone. Of course the calving event in 1986 must have gone through it, but that was about 50 kilometers further downstream when it happened.

P. 863, L. 15-22: More description is necessary with regard to the use of the imagery to monitor the rift. How was the MODIS imagery used? Specifically, how was the near-real-time data used to monitor the general propagation and likely future path of the rift? Was the additional length of the rift wide enough to be visible in MODIS imagery? While the authors state that Landsat data at high spatial resolution was used to assess the rift length in all images unobscured by clouds between Nov. 2010 and January2015, how many images exactly were used? What was the temporal resolution of the cloud-free/useable images? Did smaller-timescale changes occur? Perhaps more helpful here than a full-on description (it might make for slightly wordy paragraph), perhaps just a table of the Landsat/MODIS images used would be fine. Additionally, again perhaps from my own point of view, but it would be helpful to understand how the changes between Landsat 7 and 8 might have affected the measurements since both were used in the study.

We agree that a table of Landsat images would be a good idea and have included it as supplementary material. For the comparability of the sensors please see above in the reply to reviewer 1. As stated in the text, the MODIS data was used only to monitor the general propagation of the rift and predict where it might go. The spatial resolution is not sufficient to add to the rift propagation series (Figure 2). We have clarified this point in the text. We provided the link to the NRT archive simply because this was our source of data and stating it would allow others to repeat the analysis. As we have stated in previous responses, only 15 cloud free images were available and we used all of them. The text has been clarified on this point. The table shows that the transition between Landsat 7 and 8 did not affect our measurements.

How was the starting point of Nov. 2010 selected? Since the rift was first observed prior to 2010, why was it deemed not relevant to track its propagation back to its earliest observation? This probably won't change the overall outcome of this particular paper, but in general if you want to discuss changes in the behavior of a rift, why not start at the beginning? The reasoning behind starting in 2010 (rather than its earliest observation) isn't clear.

The paper focusses on the recent rift propagation and its impact. We chose November 2010 to show three years of data before the recent more rapid propagation. The text has been amended to clarify this point.

P. 863, L. 26- P. 864, L. 1: How were the brightness and contrast controlled? Were there limits set for detectability? What imagery software was used? This may have been mentioned elsewhere, but it should be included here in this section regarding satellite observations.

We have amended the text a little to clarify this point for reviewer 1. However, we don't think this issue is particularly important. Using any image processing software it is possible to optimize contrast at the rift tip. We have no reason to believe that this issue would have impact on the results beyond the stated estimate error of a few tens of meters.

P. 864, L. 5-6: How do you differentiate between surface features and basal crevasses? Was radar used to determine the orientation of the basal crevasses?

Features like these were mapped in other regions of the ice shelf: Surface and basal crevasses are distinguishable due to their spatial scales, please see Luckman et al. (2012) or McGrath et al. (2012) and the answers to reviewer 1. We assume that the surface features are the surface expression (troughs) of basal crevasses. The rift has been so far propagating along such a feature which originated from Kenyon Peninsula.

P. 864, L. 8-11: Could you expand on the determination of the two Scenarios? Are there any other scenarios? Why are these the most likely? Here it would be relevant to discuss, perhaps, previous calving patterns of Larsen C. These scenarios are described as if they are test cases, but perhaps with more explanation of how they were determined, it would be more clear as to why these were chosen as the two likely scenarios.

As stated in the reply to the reviewer 1 above, both scenarios are based on visible zones of weakness (most likely basal crevasses) and previous calving events followed a similar patterns, only further downstream.

P. 865, L. 10-22: Because this is a paper reporting the recent development of a rift, I would expect a longer results section describing the rift activity and history, placing the current development into context. This paragraph highlights the point that I wanted to make above - it would greatly improve the manuscript as an observation paper to describe the actual observations in detail, rather than just giving a few quantitative values (e.g., 40 km yr-1 widening rate or 20 km in 8 months. . . what are these when placed in context?). Specifically in Line 11, what does ‘modestly’ mean? What observation led you to the conclusion that the rift ‘previously appeared to resist transverse fractures’? This isn’t clear. In Line 12, what quantitatively constitutes “dramatically”? Overall this section and the entire manuscript needs to be more focused on quantitative values -while the qualitative observation of it growth and the numerical modeling results are an interesting snapshot, it would be relevant to present these observations and modeling results in the context of quantitative observations.

We agree that the history of the rift is not described in great detail, as we are focusing on the current processes. We do not agree that more numbers would improve the paper. The rates are based on sporadically available imagery, and more numbers would just give a false sense of accuracy. The focus of this paper is the obvious change in the pattern, that the rift penetrated the suture zone, in contrast to all observations made before, and the stability of the calving front after possible calving scenarios.

P. 866: It would be great to enhance the discussion of the numerical model results as it appears to yield very interesting results! With such a model, many different scenarios could be investigated and discussed. Especially, though, it would be great to know more about the set up for the scenarios and the outcomes. Can/does the model show a change in velocity after calving in Scenario I/II/both? Is there any scenario where the velocity of the flow did not change? How does the stress around the rift itself appear? Does it change? Thinking about it from a non-modeling perspective, I would expect the rift to alter the stress field. Does it have any effect on the outcome in Scenario I or II?

We added a summary figure of the calculated flow velocities for both the reference run and both scenarios to this discussion (figure R1), but unfortunately there’s no room for this in the manuscript.

Of course the rift is altering the stress field, but this is not relevant for the results with the new calving fronts, where the former rift position delineates the new calving front. We did not run a simulation with the propagated rift, but did simulations with soft fillings in the rift prior to its propagation through the suture zone to investigate the influence on the stress field; you can find these results in Kulessa et al. (2014) in the supplementary material.

It was not our aim to model rift propagation, we wanted to focus on the calving front stability after the calving scenarios.

P. 866, L. 22-24: Here it would be relevant to have a table or list of the rate per year. This would highlight the observed change in rate nicely, in addition to exhibit what is meant by “grown intermittently”. I think a table of values for both rift length and rift width would be a great addition.

We agree that a table of the imagery used and data points would be useful and upload it as supplementary material. We do not agree that presenting rift propagation rates would be appropriate for reasons stated above.

P. 866-867: Perhaps it is outside the scope of this manuscript (likely so), but the subject has me wondering, do the authors have a feeling for why this sudden increase in rift propagation rate occurred or why the rift suddenly jumped across a suture zone? This isn’t covered much in the paper as it stands now, and it would be interesting to possibly understand a little bit more about possible reasons for this sudden change, if any.

Here we can only speculate, and this is why we did not include this in the paper, which is focused on the consequences of a possible calving. It might be that the influence of the marine ice layer is weakening due to basal melting (Kulessa et al., 2014; Holland et al., 2015).

Figure 2: Though it might make the figure unwieldy, it would be neat to see the appearance of this region in Nov. 2010 in contrast to this image, so the reader could observe changes not only in the length/shape of the rift in question but also its neighbors. Also,would it be possible to label propagation rates on the plot? Additionally, I think the Dec 2012 label should be Dec 2013?

We considered all of these suggestions carefully. A comparison with the Nov. 2010 image reveals nothing more than that the rift propagated through the suture zone. Changes in neighbouring rifts are not significant over the same time period. We therefore do not think that this would be a useful addition to Fig. 2. For reasons already given, we do not think it appropriate to present propagation rates because these are only mean values between the available observations, and are not necessarily indicative of true propagation rates, especially where images are infrequent. Yes, the label is correct. We labelled only those points that showed significant advance of the rift tip.

Short Comment: Maurice Pelto

Jansen et al (2015) provide a compelling observation of rift extension on Larsen CIce Shelf that could have important implications. This is an important finding and will prompt further investigation of this feature. Most of the comments below are simply a request for more detail that would help us learn more from this interesting dynamic change in the ice shelf that could have large consequences. This includes possibly referencing other ice shelves that experienced ice losses that could have had similar changes in flow stress fields (flow angles) besides Larsen B. Providing a brief example of model validation is essential. It would be worth noting briefly whether or not thereare there any velocity output differences between models or with present observations.The model does not have to be reviewed in detail as that is in previous papers.

We include here (figure R1) a comparison of the modeled flow velocities of the reference run and the velocity data of Rignot et al. (2011), which are easier to compare than the point results in Haug et al., (2010) you suggested. The model does not quite capture the strong gradients at Gipps ice rise, as we only have a soft ice filling in the rift and not an open rift. In the central part it agrees better. As we are restricted to three figures in the manuscript we did not include this figure in the paper.

862-21: A different specific example of a rift tip ending at a confluence flow unit would be useful.

The tips of basal crevasses are aligning at the suture zones across the entire Larsen C. The open rifts in this southern area of Larsen C all stopped opening before they reached the margin of the suture zone but there are some examples in the north of the ice shelf of open Rifts stalled by suture zones which are containing marine ice (McGrath et al., 2012).

863-3: Given previous satellite imagery, has a rift not propagated across the suture zone before? This needs to be stipulated along with the interval that imagery was observed. Does not need to be detailed, and can be done at 865-11.

We refer to Glasser et al. (2009), who show a nice overview of structures on the Larsen C. A calving event did occur in 1986, where the suture zone was cut through, but this was 50 km downstream, 25 km downstream of today's calving front.

864-2: Has the width changed near the actual width tip as it has propagated, for example500 m from the tip how wide is it now compared to at the initiation of the expansion,can be reported later.

As the rift is very thin close to its tip it is not possible to resolve these changes on satellite imagery, so we decided to measure rift width changes at a position further down the rift. The rift tip is detected where its width is just visible, which is inevitably less than one pixel in size.

864-9: What are the existing weaknesses?

The existing weaknesses are most likely basal crevasses in the central front of the ice shelf. We refer to Luckman et al. (2012) to explain our assumption that such features are most likely basal crevasses. Please see also the answers to the reviewer comments above.

864-25: This model has in other studies been validated with comparison of simulated and observed velocities. Details of the model do not have to be reviewed here; however,some means of validation needs to be offered. Haug et al (2010) Figure 3 provides a velocity field for validation.

Please see comment above and figure R1.

865-11: If not addressed earlier refer to the period of observations in satellite images that the rift had not crossed the suture zone.

Since the calving in 1986 the suture zone has not been crossed, we added this to the text.

865-19: Is this November 2010? What is the current rift width at this point and what does that imply? Over what length has the rift width reached a value of twice the ice surface elevation or some critical width versus thickness?

Yes, November 2010, we added this to the manuscript. The current rift tip is given in the supplementary table. As stated earlier, the rift width at the detected tip is necessarily on the order of a pixel in size, so this kind of criteria cannot be investigated.

865-21: How does the actual velocity change as it crosses into the new flow unit? Haug et al (2010) Figure 3 provides a velocity for this region to address this.

We do not see how this is relevant to the paper.

866-7: What were and are the angles? The difference needs to be better illustratedand quantified in Figure 3 it is hard to accurately identify the difference field.

The stress-flow angles may be read approximately from the figure using the colour scale. The important observation is that ‘stable’ values are a deeper shade of red than ‘un-stable’ values. We believe that this is sufficiently explained and illustrated and that the implication in the figure is clear. But to make things a little clearer, we added indicators for the direction of the first principal stress to the figure.

866-17: What angles area very low? Is there any thickness or velocity output from the models that would provide further insight to future changes?

There are certainly no thickness changes, as the model is diagnostic, so there is no evolution of geometry. The velocity changes are summarized in the figure 1R below, but in our view they are not essential for the stability of the calving front.

867-11: Is Larsen B the best analog since surface melt played such a key role there? Do either George VI (Figure 2 and 5; Holt et al (2013), Wordie (Figure 4.3; Cook andVaughan, 2010) or Wilkins (Figure 5, Braun et al (2009)) provide a good example interms of rift development, ice rise impact or changing flow angle versus calving front? If not no need to cite.

We think that surface melt alone cannot explain the retreat of the calving front of Larsen B. The region between former Larsen A and B is subject to strong surface melt as well and is still there. Thus the geometrical setting and the ice dynamics have to play a role as well.

It would certainly interesting to extend the analysis to other ice shelves, but we haven't done so at the moment and it would be beyond the scope of this Brief Communication manuscript.

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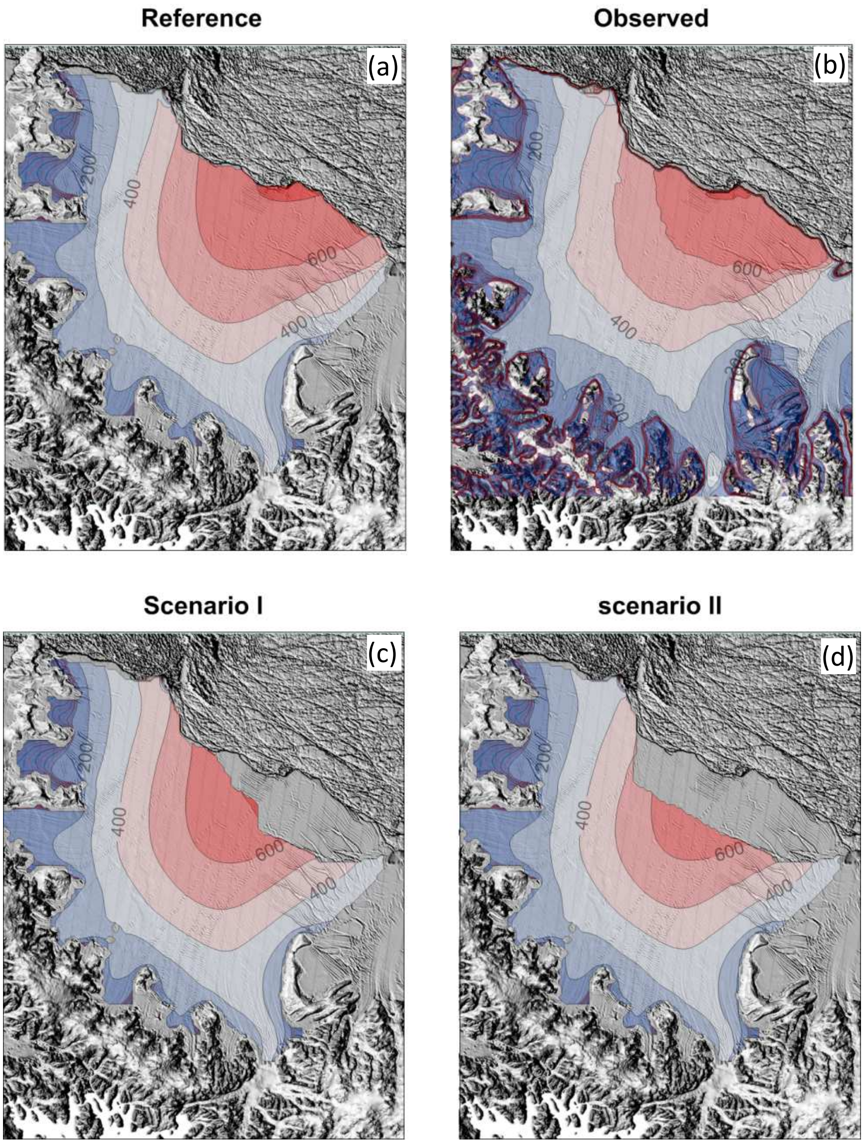

Figure R1: Comparison of the velocity fields. (a) Simulated velocity field for the reference simulation with the 2015 calving front. (b) Observed velocities (Rignot et al., 2011). (c) simulated velocities for Scenario I. (d) Simulated velocities for Scenario II. Background image is MODIS Aqua, Dec. 3rd 2014. The DEM of the Antarctic Peninsula: Cook et al. (2012).

Brief Communication: Newly developing rift in Larsen C Ice Shelf presents significant risk to stability

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Abstract

An established rift in the Larsen C Ice Shelf, formerly constrained by a suture zone containing marine ice, grew rapidly during 2014 and is likely in the near future to generate the largest calving event since the 1980s and result in a new minimum area for the ice shelf. Here we investigate the recent development of the rift, quantify the projected calving event and, using a numerical model, assess its likely impact on ice shelf stability. We find that the ice front is at risk of becoming unstable when the anticipated calving event occurs.

1 Introduction

The Larsen C Ice Shelf is the most northerly of the remaining major Antarctic Peninsula ice shelves and is vulnerable to changes in both to ocean and atmospheric forcing (Holland et al., 2015). It is the largest ice shelf in the region and its loss would lead to a significant drawdown of ice from the Antarctic Peninsula Ice Sheet (APIS). There have been observations of widespread thinning (Shepherd et al., 2003; Pritchard et al., 2012; Holland et al., 2015), melt ponding in the northern inlets (Holland et al., 2011; Luckman et al., 2014), and a speed-up in ice flow (Khazendar et al., 2011), all processes which have been linked to former ice shelf collapses (e.g. van den Broeke, 2005). Previous studies have highlighted the vulnerability of Larsen C Ice Shelf to specific potential changes in its geometry including a retreat from the Bawden Ice Rise (Kulessa et al., 2014; McGrath et al, 2014; Holland et al., 2015) and Gipps Ice Rise (Borstad et al., 2013). Rift tips in the latter area have been observed to align as they terminate at a confluence of flow units within the shelf. Several studies have provided evidence for marine ice in these *suture zones* (Holland et al, 2009; Jansen et al., 2013; Kulessa et al., 2014; McGrath et al., 2014). The relatively warm, and thus soft, marine ice has been found to act as a weak coupling between flow units with different flow velocities. It has been concluded that this ice inhibits the propagation of rifts because it can accommodate strain in the ice without fracturing further (Holland et al., 2009; Jansen et al., 2013; Kulessa et al., 2014).

In a change from the usual pattern, a northwards-propagating rift from Gipps Ice Rise has recently penetrated through the suture zone and is now more than halfway towards calving off a large section of the ice shelf (Figs. 1 and 2). The rate of propagation of this rift accelerated during 2014. When the next major calving event occurs, the Larsen C Ice Shelf is likely to lose around 10% of its area to reach a new minimum both in terms of direct observations, and possibly since the last interglacial period (Hodgson et al., 2006).

Here, using satellite imagery and numerical modelling, we document the development of the rift over recent years, predict the area of ice that will be lost, and test the likely impact of this future calving event on ice shelf stability.

2 Methods

2.1 Satellite Observations

We use data from NASA MODIS at a pixel size of 250 m (red band) from the near-real-time archive (http://lance-modis.eosdis.nasa.gov/cgi-bin/imagery/realtime.cgi) to monitor the general propagation of the rift and to explore its likely future path (Fig. 1). These data, however, did not provide sufficiently high spatial resolution to measure the rift tip position with satisfactory precision. Using Landsat data at high spatial resolution (15m, panchromatic) from the NASA archive (http://earthexplorer.usgs.gov/), we measure in detail the rift's recent propagation (Fig. 2). Growth of the rift is assessed by digitizing the position of the rift tip in all Landsat images unobscured by cloud between Nov. 2010 and Jan. 2015 working within the Polar Stereographic map projection in which the data were provided. The start of this sequence is chosen to show normal behaviour of the rift over three years before its more rapid propagation in 2014. Between January 2015 and the final paper submission, no additional images showed notable further propagation. Rift length is presented relative to the position in Nov. 2010 prior to the breach of the Joerg Peninsula suture zone. Rift width is measured at the Nov. 2010 rift tip position. These satellite data are subject to variable cloud conditions and solar illumination, the impact of which we minimize by optimizing brightness and contrast in each image separately. Nevertheless, measurements of rift tip position and width are potentially subject to error of up to a few tens of meters. A table listing all Landsat images used for this study as well as the measured rift lengths and widths can be found in the supplementary material.

To investigate a range of possible outcomes from the proposed calving event, we present two scenarios for the rift trajectory based on its current orientation and direction of propagation, and on visual inspection of MODIS data (Fig. 1). Surface features in these data indicate the scale and orientation of existing weaknesses (e.g. basal crevasses) along which the rift might be expected to preferentially propagate (Luckman et al., 2012). In Scenario I the rift approaches the calving front by the shortest route via existing weaknesses, and so would result in a reasonable minimum estimate for the calved area. In Scenario II the rift continues along its current trajectory for a further 80km before approaching the ice front. The hypothetical turning point in this scenario is chosen to smoothly continue the orientation of the ice front where the rift will meet it (Fig. 1), and imitates the pattern of calving of a large iceberg in 2008. We present these scenarios as reasonable possibilities for which to test the impact of a calving event, rather than a range for the projected calved area. The eventual calving may be within the range we test, or may be more extreme still.

2.2 Numerical modelling

To determine the influence of the potential calving event on the future stability of the Larsen C Ice Shelf we use a numerical ice shelf model, previously applied to the Larsen B (Sandhäger et al., 2005) and the Larsen C ice shelves (Jansen et al., 2010; Jansen et al., 2013; Kulessa et al., 2014). This finite difference model is based on the continuum mechanical equations of ice shelf flow. Friction at the ice shelf base as well as vertical shear strain due to bending is neglected. Thus horizontal flow velocities are vertically invariant and the flow field is two-dimensional. In the vertical dimension the model domain is divided into 13 levels, scaled by ice thickness, to allow for a realistic vertical temperature profile, influencing the vertically integrated flow parameter.

Simulations are carried out on a 2.5 km grid varying only the position of the ice shelf calving margin between the present ice front position and rift Scenarios I and II. The model we apply is a steady-state mode which assumes that the ice shelf is not in transition from one geometry to another. It is important, therefore, to investigate the present stress field at the predicted calving margin as well as the new stress field at the predicted calving margin under the new geometries. These two states represent the stress field immediately after calving, and the stress field towards which the shelf will develop in time through the process of the velocity field adapting to the new geometry (assuming no immediate further calving). The two stress fields may be different, and may indicate increasing or decreasing stability under the new geometries.

3 Results

3.1 Rift evolution and possible calving scenarios

The rift first propagated into the Joerg Peninsula suture zone in 2012 and progressed during 2013 into a region which previously appeared to resist transverse fractures (Fig. 2). The rate of rift propagation increased sometime between January and August 2014, crossing the entire Trail Inlet flow unit (~ 20 km) in just 8 months. We do not have observations within this time period so we cannot say whether the rift propagation during this time period was uniform or was very rapid for only a short part of it. Between Aug. 2014 and late Jan. 2015, the rift length increased further about 1.25 km, propagating into the next suture zone. From the start of our measurements the width of the rift at the 2010 rift tip position has increased at a more uniform rate than the length, and is still growing at a rate of ~40 m/year (Fig. 2).

The area of Larsen C Ice Shelf after the proposed calving event will be 4,600 km^2 less than at present for Scenario I, and 6,400 km^2 less for Scenario II (Fig. 1). This amounts to potential area losses of 9% and 12% respectively.

3.2 Stress field development

To investigate the impact of the two calving scenarios on ice shelf stability, we present fields of the difference between the predicted directions of ice flow and of first principal stress (the *stress-flow angle;* Fig. 3). This diagnostic has previously been used to investigate ice shelf stability on the basis that existing weaknesses (rifts and crevasses) are typically oriented across-flow (Kulessa et al., 2014). Regions of the shelf exhibiting low stress-flow angles are likely to be more affected by small-scale calving because stresses act to open existing weaknesses; conversely, regions with a stress-flow angle approaching 90° are likely to be stable.

The stress-flow angles at the present (early 2015) ice front are generally high (Fig. 3a) and, as a result, calving events are rare and the ice front is stable (Kulessa et al., 2014). If the ice shelf calves under Scenario I, the new ice front will, in the immediate term, still mostly be fringed by ice with a high stress-flow angle (Fig. 3a). However, this safety margin is narrowed by the calving, and the centre of the new ice front will exhibit very low stress-flow angles. Under this modest calving scenario, if the ice shelf is able to adapt to the new geometry (Fig. 3b),a new region of high stress-flow angles develops, but this region remains significantly narrower than at present. Under calving Scenario II, much more of the ice front is immediately left without a buffer of high stress-flow angle ice (Fig. 3a). Even if it were possible to adapt to this new geometry (Fig. 3c), a significant section of the new ice front would retain very low values of stress-flow angle.

An alternative measure of stability was presented by Doake et al., (1998), whereby ice downstream of a “compressive arch” represented by a contour of zero second principle stress is subject to purely tensile stresses and regarded as a passive part of the ice shelf, its presence indicating a stable front. This is a more conservative measure of stability than the stress-flow angle and we include it for completeness. The dotted line in all panels of figure 3 represents the zero second principal stress contour line for the reference simulation and the two new calving fronts. For Scenario I this line is breached by the new calving front in the south at the Gipps Ice Rise,for Scenario II it is breached on both sides.

4 Discussion

The rift highlighted here has been present since the earliest satellite imagery (Glasser et al., 2009) but has recently propagated beyond its neighbouring structures to the point at which a large calving event is anticipated. Over the past 4 years the rate of development of the rift width has been steady, but the length has grown intermittently with a particular acceleration during 2014 (Fig. 2). We hypothesize that the strain which opens the rift may be relatively constant, but that the fracture response varies with tip position. This may be a result of variations in fracture toughness of the ice which are likely to be related the presence of marine ice in suture zones (Holland et al, 2009; Jansen et al., 2013) and the locations of pre-existing weaknesses. The mean rate of rift propagation appears to be smaller when the rift tip is within a suture zone (Fig. 2).

The reduction in area of Larsen C Ice Shelf under Scenarios I and II of 9% and 12% respectively will be significant, but will of course not contribute to immediate sea level rise since the floating ice already displaces its own weight of sea water. The predicted ice loss is also not unprecedented: in the late 1980s a calving event removed 14% of Larsen C Ice Shelf (Cook and Vaughan, 2010). The real significance of this new rift to this ice shelf is two-fold. First, the predicted calving will reduce its area to a new minimum both in terms of direct observations, and probably since the last interglacial period (Hodgson et al., 2006). Second, unlike during the 1980s, but highly comparable to the development of Larsen B Ice Shelf between 1995 and 2002, the resulting geometry may be unstable. According to the stress-flow angle criterion, our calving scenarios lead to a range of unstable outcomes from partial to significant. Under our modest rift propagation Scenario I, immediately following the predicted calving event, the central part of the ice front will be unstable and prone to persistent calving of small ice blocks as the principal strain works to open existing fractures. It is not clear how quickly the velocity of a real ice shelf will be able to adapt to the new boundary conditions, but even if this is rapid, the margin of stabilizing ice becomes very narrow. Under Scenario II, the unstable part of the new ice front is considerably larger and, even if the flow field adapts quickly to the new geometry, parts of the calving margin remain unstable and prone to run-away calving of a similar nature to Larsen B Ice Shelf between 1995 and 2002. Assessing the stress field according to Doake et al. (1998), Scenario II would also be considered as an unstable calving front.

Our model demonstrates that the newly developing rift presents a considerable risk to the stability of the Larsen C Ice Shelf.

5 Conclusions

We have investigated a newly developing rift in the south of Larsen C Ice Shelf which has propagated beyond its neighbours in 2013, and grew very rapidly in 2014. It seems inevitable that this rift will lead to a major calving event which will remove between 9% and 12% of the ice shelf area and leave the ice front at its most retreated observed position. More significantly, our model shows that the remaining ice may be unstable. The Larsen C Ice Shelf may be following the example of its previous neighbour, Larsen B, which collapsed in 2002 following similar events.

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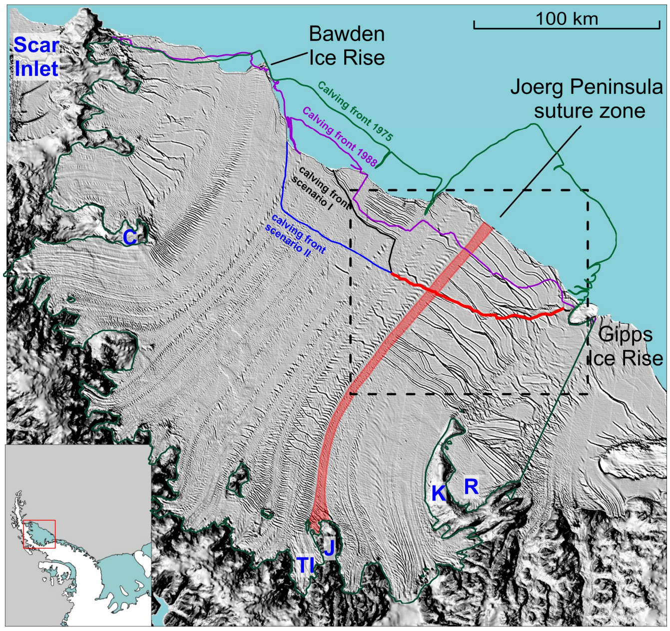

Figure 1: Overview of the Larsen C Ice Shelf in late 2014 showing the contemporary location of the developing rift (red line), and a selection of previous and predicted future calving fronts. Background image is MODIS Aqua, Dec. 3rd 2014 for the ice shelf and a shaded relief DEM of the Antarctic Peninsula mountains: Cook et al. (2012). Geographic features of interest are marked (TI = Trail Inlet, K = Kenyon Peninsula, R = Revelle Inlet, J = Joerg Peninsula, C= Churchill Peninsula) and the dashed box shows the extent of Figure 2. The highlighted flow line indicates the location of the Joerg Peninsula suture zone.

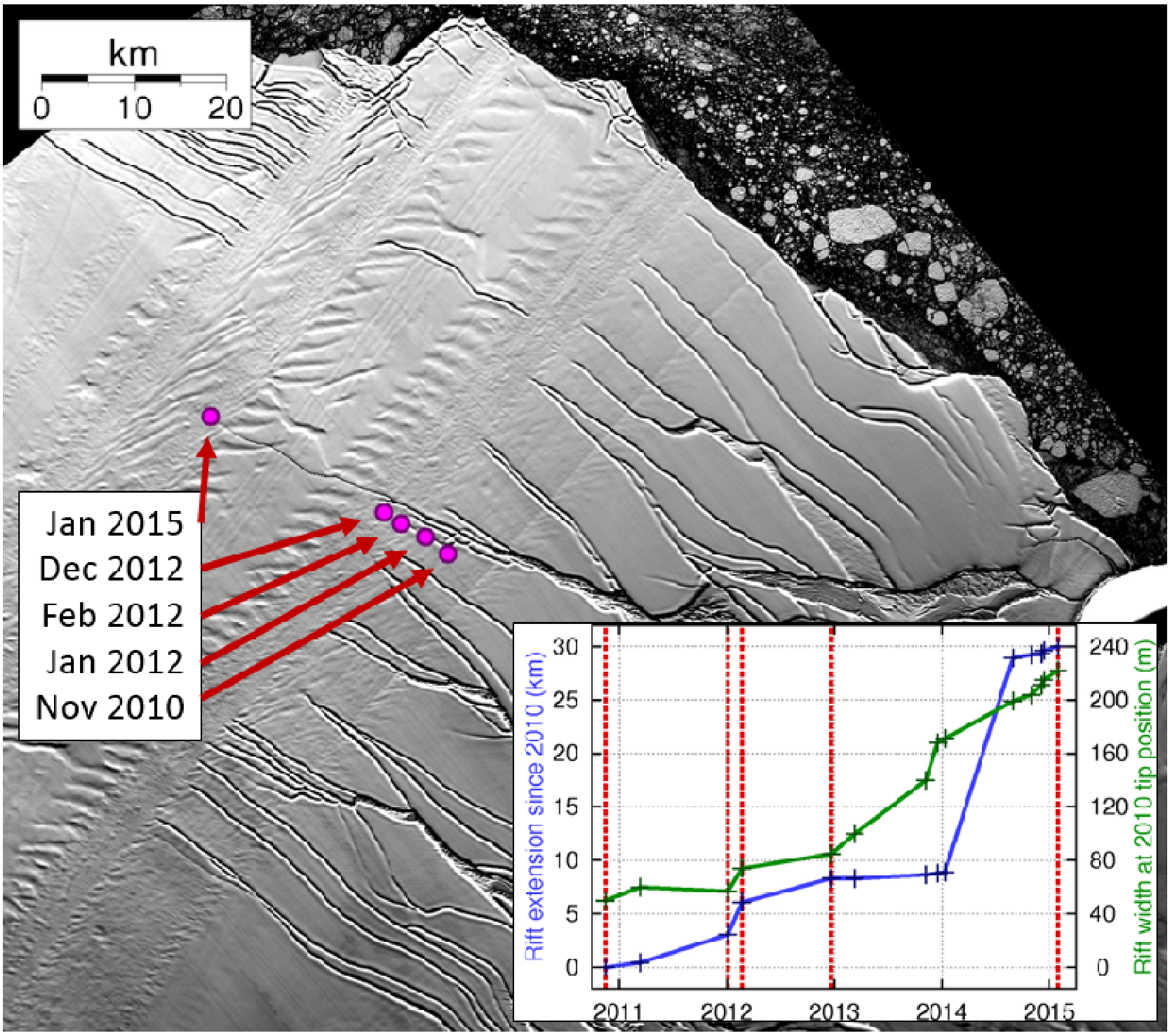

Figure 2: Analysis of rift propagation using Landsat data. Background image, in which the rift is visible, is from Dec 4th 2014. Inset graph shows the development of rift length with respect to the 2010 tip position, and rift width at the 2010 tip position, measured from all available Landsat images (crosses; 15 in total). The line joining data points illustrates only the mean propagation rate between observations. Actual propagation of the rift may be sporadic and true propagation rates cannot be known without regular frequent observations which are not available. Circles and labels on the map, and dotted red lines on the graph, show the positions of notable stages of rift development.

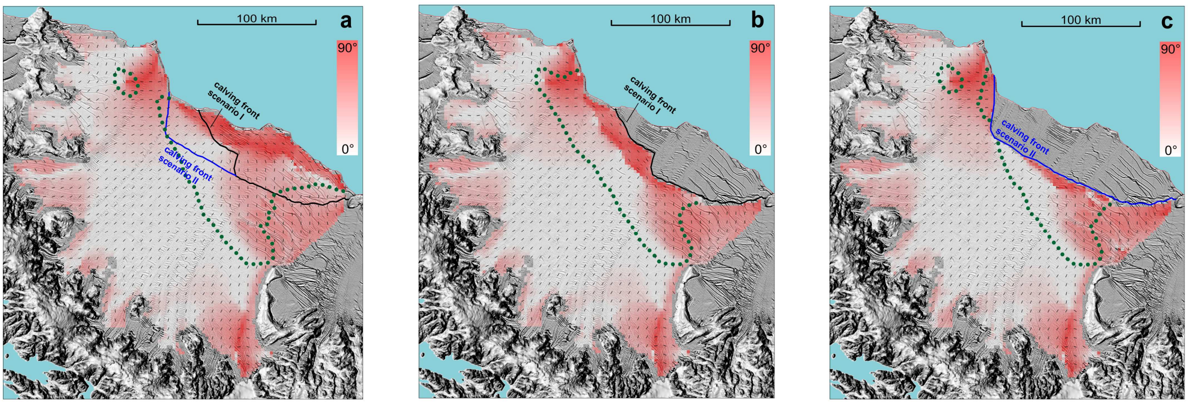

Figure 3: Results from ice shelf flow model: Stress-flow angle fields for the present day ice front geometry (a) and for the new geometries under Scenarios I (b) and II (c). The green dotted line represents the contour line of zero second principal stress.