Response to RC1

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This manuscript reports on detailed observations and model analysis of two rifts in the Brunt Ice Shelf. These rifts may threaten the structural integrity of the shelf, and at the very least have caused quite some concern for the fate of the Halley Research Station on the shelf. An impressive array of observations have been collected on the behaviour of these rifts, and the observations alone reveal quite a lot about the nature of rift propagation. A numerical model is applied to determine the orientation of principal stresses in the shelf, and a clever heuristic algorithm for manually modeling the trajectories of the cracks is applied. This heuristic proves successful for replicating the observed trajectories of the rifts to date, and suggests at possible future crack trajectories and their influence on the ice shelf. The manuscript is generally well written and organized, and is likely to find broad interest among ice shelf glaciologists. I really only have minor comments and suggestions for the manuscript to clarify certain aspects and elaborate on others.

We thank the reviewer for these positive comments, and for a very thorough review that has allowed us to improve the manuscript in many places. Individual replies are formulated below, and all updated figures are listed at the end of this document.

The abstract notes that a "simple fracture propagation criterion" was successfully used to hindcast the rift trajectories and suggest future trajectories. The term "fracture criterion" is commonly used to represent something like "stress intensity exceeding fracture toughness" from fracture mechanics or "stress exceeding strength" from strength of materials theory. What has actually been applied is a heuristic for iteratively and manually lengthening fractures based on (visual?) inspection of the orientation of the first principal stress ahead of the current crack tip location. I actually think this is quite a clever method, so I am not criticizing it here. Rather, I think it is somewhat misleading to call it a "fracture criterion" or "fracture model" in the usual sense of these terms. Perhaps I am being overly picky about nomenclature here, but after reading the abstract I was expecting to see more of a "hands off" fracture propagation model based on my understanding of the usual use of the term "fracture criterion."

We acknowledge the reviewer's comment and have reformulated this part of the abstract. As there are abundant potential pitfalls in fracture mechanics nomenclature, we have reverted to a more descriptive approach. Further to the reviewer's remark we should point out that, albeit heuristic, our algorithm for predicting rift trajectories is not based on a 'manual' or 'visual' approach, but is a fully automatic/programmed procedure that uses a stress field on a discretized grid, an initial fracture location, and a propagation step size as its only inputs.

The relevant part of the abstract has been reformulated as follows:
"A numerical ice-flow model and a simple propagation algorithm based on the stress distribution in the ice shelf were successfully used to hindcast the observed trajectories"

In general I think a bit more detail is needed on the modeling aspects of this study. In particular, more information is needed on the inverse modeling and fracture propagation algorithm. Specifically:

- Is regularization used in the inversion? If so, how much? And how is the level of regularization determined? The pattern of stresses will vary depending on level of regularization applied (which is often at least partially a subjective decision). Since you are relying on the stress orientations for predicting fracture trajectory, some details here are needed.

  The inversion procedure uses a Tikhonov regularization for the rate factor in Glen's flow law. The optimal regularization multiplier, λ, was determined through an L-curve approach, as shown in Figure R1 below. A value of $\lambda = 10^3$ was chosen to optimize the misfit and to avoid overfitting. In areas away from the grounding line and the immediate vicinity of the MIR, the solution converged quickly (within 100 iterations) towards observed values of the surface velocities, and the inversion was ended after 200 iterations.

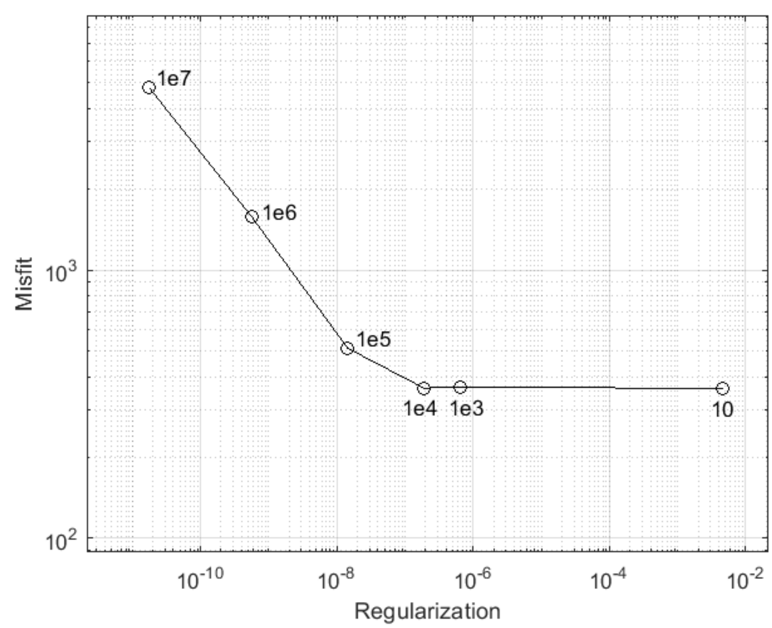

Figure R1. L-curve approach to determine the optimal regularization multiplier, shown as labels next to each point on the curve. The value 10^3 was chosen as the optimal value.

  Figure R2 shows the modeled trajectories of the HC for different amounts of regularization. The trajectory for $\lambda = 10^7$ can be rejected based on the L-curve. For $\lambda < 10^5$ the curves are robust and approach the observed trajectory. For our choice of $\lambda = 10^3$, results are independent of the exact value of λ.

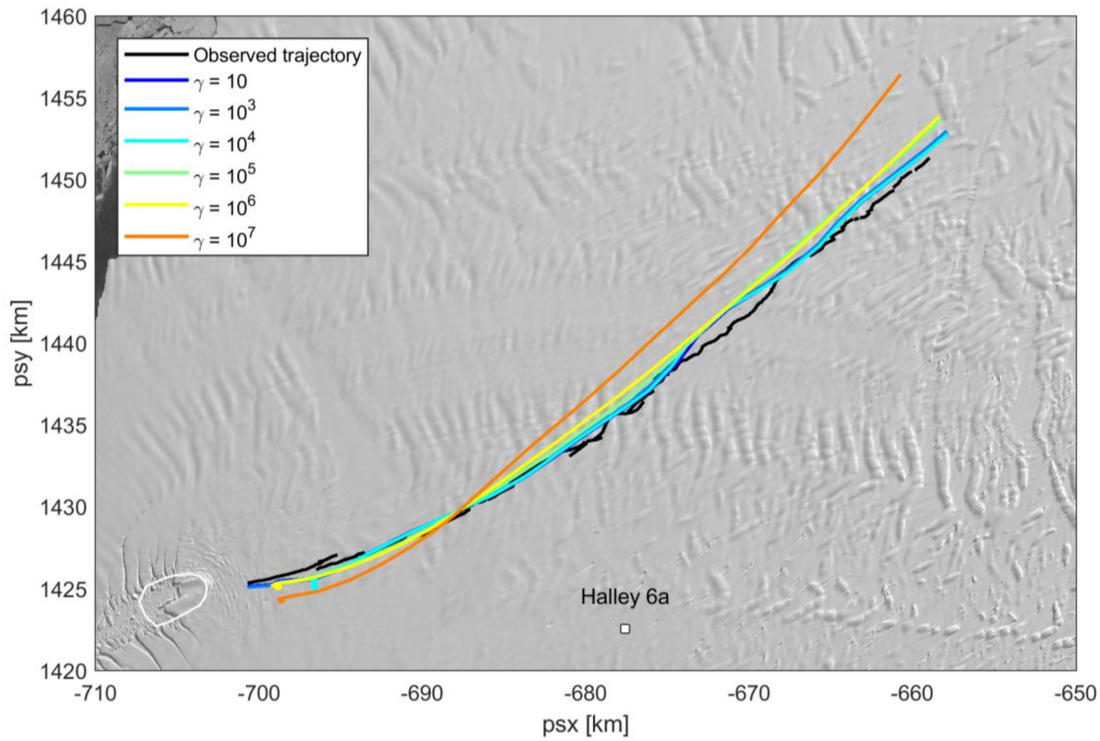

Figure R2. Modeled trajectory of the Halloween Crack for different values of the regularization multiplier. The curve approaches the observed trajectory for $\lambda < 10^5$.

In Figure R3, the impact of mesh resolution on the modeled trajectory of the HC is tested, with the average distance between nodes ranging from 250m to 2000m. The resulting trajectories for the HC are closely spaced, with the largest deviations corresponding to the lowest mesh resolution. Trajectories presented in the manuscript are obtained for 250m resolution, which is sufficiently small to guarantee robust results.

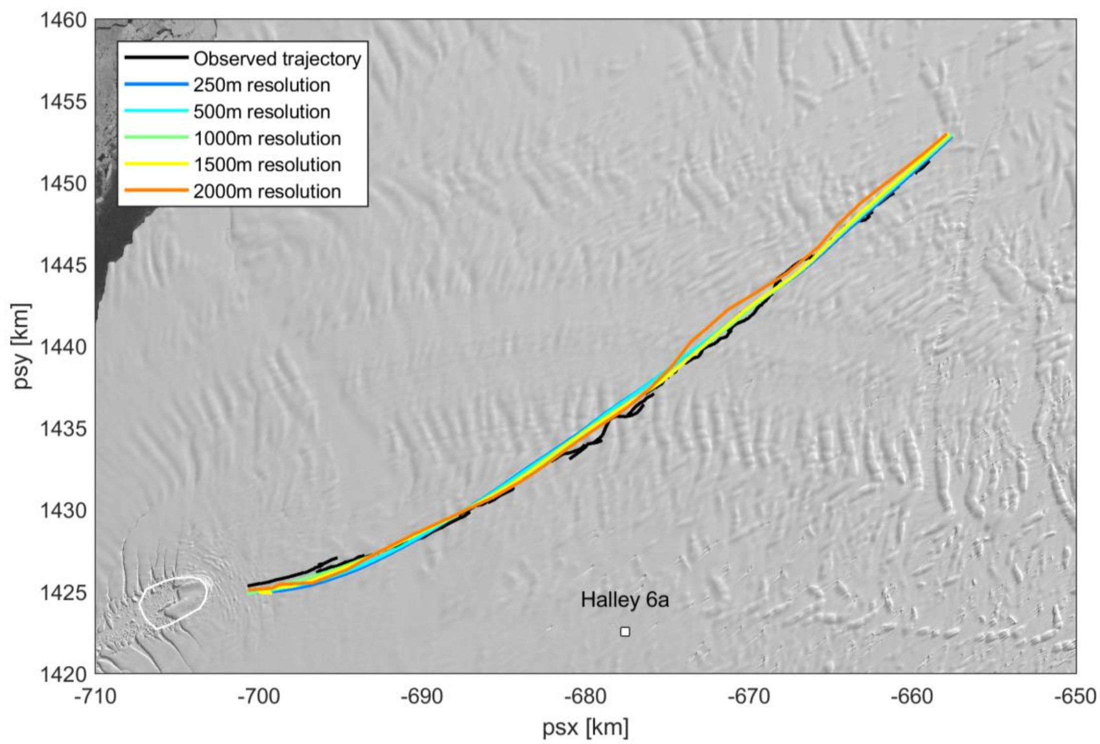

Figure R3. Modeled fracture trajectories for different choices of mesh resolution.

It should be noted that these results are case specific and robustness of each fracture trajectory can/should be tested for every application.

The manuscript has been amended to include the following paragraph:

"A priori, the calculated fracture trajectories depend on the amount of regularization (λ) and the model resolution. Sensitivity tests were carried out for both variables and the final trajectories of the HC were found to be independent of the exact value of λ and mesh resolution. A further reduction of the regularization and additional mesh refinement did not significantly change the results, and only for a much coarser mesh (2 km nodal separation) or a much larger amount of regularization ($\lambda > 10^5$) did the modeled trajectories start to deviate from the observed trajectory. It should be noted that this result is case specific, and robustness of the fracture trajectories should be considered on a case-by-case basis, in particular for applications with a more complex stress distribution."

- It might be helpful to see an example of a single step of the crack propagation algorithm to better outline this heuristic procedure. For example, show the current extent of the crack, and the stress rosettes ahead of the crack, at a scale that resolves the step size (chosen as the mesh resolution here). Ahead of an existing crack there will be multiple rosettes, in principle one rosette for every triangular finite element (since you are using linear elements). Unless there is a rosette in an exact straight-line distance ahead of the current rift tip, I presume some choice must be made about some kind of averaging of the principal stress directions from rosettes in the vicinity of the tip. Is this simply a choice based on visual inspection? The directions may not vary much in this particular case study, but if the rift encounters a region of strongly varying flow then the decision about what direction to manually project the rift may not be so straightforward.

The algorithm is fully automated and no manual selection of propagation direction is required. The fracture is propagated step-wise along line segments with a fixed length, and the orientation of each segment is always perpendicular to the local maximum tensile stress at its origin. The local values of the stress tensor are obtained from the modeled stress field through a linear interpolation. We agree that for a more complex stress field, one will need to optimize the mesh resolution of the model and/or the length of the line segments that build the fracture trajectory. We have made the following changes to the manuscript to address these points:

- Figure 8a (all updated figures are listed at the end of this document) has been zoomed in and individual strain rosettes (subsampled on a regular 2.5 x 2.5km grid) should now be better visible, allowing one to better visualize the propagation algorithm.

- More details about the algorithm have been given in the main text:

  "Each rift was seeded at a predefined location in the model, informed by the observed location of an initial fracture or the tip of an existing rift in the ice shelf. Subsequently, the local direction of maximum tensile stress was identified from a linear interpolation of the modelled stresses, and the crack was propagated perpendicular to this direction along a line segment with fixed length. The end point of this segment was marked as the new location of the rift tip, and the process was repeated for updated values of the local stress tensor. Through this algorithm, a fracture trajectory was constructed consisting of line segments with fixed length, and each segment was oriented perpendicular to the local direction of maximum tensile stress. The length of the segments was chosen to be on the order of the minimum mesh resolution, i.e. 250 m, although the algorithm could easily be adapted to allow for a variable step size, based on the local gradients in the stress field or other suitable criteria. It was shown that a step size of 250 m was sufficiently small for the results to be independent of its exact value. The automated process was iterated for a fixed number of steps, or until a certain rift length was reached."

- A note of caution has been given about the use of this algorithm in application with a more complex flow distribution – see our reply to the previous comment about regularization.

- P15 L30 (and subsequent residual reporting): I don't think the "mean residual" is the best measure of model performance here, since you are looking at a misfit that can have positive and negative values. You could have areas of very large negative and positive misfit (indicating a potentially poor fit to the observed data) and yet still have a mean/median residual close to zero. In this case it would be better to report something like the root mean square or mean absolute deviation.

In addition to the mean residuals, we have included the standard deviation of the residuals. The conclusions in the text remain the same.

- Figure 8: The stress rosettes are too small to see! The areas around the rifts could be zoomed in on much more, as it is not necessary here to see the full extent of previous figures. As the figure stands currently, I cannot really judge the performance of your manual rift trajectories. It is clear that they are quite close to the actual trajectories, but I think most readers would like to better see the detail around the individual cracks than the whole ice shelf domain.

  We have changed the limits of the axes in Figure 8a to show the strain rosettes and rift trajectories in more detail, and included an extra sentence to explain the likely cause of discrepancy between both:

  “Deviations between the observed rift trajectory and model results are likely caused by the interaction of the rift with spatial variations in ice properties, such as fracture toughness, that cannot be captured by a propagation algorithm based on stress directions alone.”

Additional specific and line-by-line comments:

- The use of the term “chasm” sounds particularly ominous, but is a rather vague and unspecific term for a rift. This term is not defined at first use in the manuscript either, which could leave some readers in question as to what specifically a chasm is (especially as “chasm” and “rift” are used interchangeably in the text). Moreover, in the literature I don’t see the term “chasm” being used to describe rifts, which in the context of an ice shelf refers specifically to a through- thickness fracture (and not other features that might also be considered “chasms” such as partial-thickness crevasses or moulins). Since the manuscript is dealing specifically with through-thickness fractures, I would recommend using the more common and specific term “rift”. I have no problem with using “chasm” in a naming convention (e.g. “Chasm 1”).

  We have replaced ‘chasm’ by ‘rift’ throughout the manuscript.

- Throughout the text you interchange Halley “VI” and Halley “6” for naming the research station. For example, Figure 1 shows “Halley 6” and “Halley 6a” but the caption notes “Halley VI” and “Halley VIa". Probably best to choose one style of naming and stick to it throughout.

We have replaced all Roman numbers VI by 6.

- P2 L8: calving induced -> “calving-induced”

  done

- P3 L8: ice-shelf wide -> “ice-shelf-wide”

  done

- P4 L6: it could be helpful to indicate on an earlier figure the outline of this previous calving event. It is eventually shown in Figure 8, but when discussed in the early part of the manuscript here it might be helpful on e.g. Figure 1 or 4 as well.

  In order not to overburden Figure 1 with too much information, we have referred the reader to Figure 8b in the introduction, when the 1970s calving event is discussed:

  For illustrative purposes, the location of the ice front shortly after the calving event in the 1970s is shown in Figure 8b.

- Figure 2 caption:

  - In describing panel (b), you mention “blue-to-purple” dots for GPR data, but I only see pink dots which seem to indicate the crack tip. Can you clarify?

    We agree that the blue-to-purple dots were not clearly visible. We have changed their color to black, and made changes to the caption and main text accordingly.

  - The radius of circles in panel (b) are said to represent the “local strain rate” which presumably is measured along baselines between pairs of GPS stations across the rift (this is later described on P7). It would be worth being more specific about this in the caption here, as strain rate is formally a tensor.

    Circles have been replaced by strain rosettes, which have been calculated from the relative movement of the strain stakes. Now both the direction and magnitude of the principal strain rates are shown.

  - In describing panel (c), you mention the “Gatekeeper” but I didn’t see this defined.

    Apologies, we have removed this reference from the text.

- Describing “average propagation speed” of a rift (Figure 2 caption and elsewhere) may not be appropriate if the lengthening of the rift comes in episodic bursts (which seems to often be the case). The distribution of actual propagation speeds would be strongly bi-modal, with long periods of no propagation and short periods of very fast propagation. For such a distribution, the mean is probably not a meaningful measure of central tendency. It might be more appropriate to describe this as something like a "lengthening rate," which would of course have the same units but not the same meaning as "propagation speed."

Although there is no evidence that the rifts on the BIS lengthen episodically rather than through a continuous fracturing process, we have no objection against using "lengthening rate" instead of "propagation speed". We have made changes in 5 places.

- Figure 3: It's not clear how/why the blue dots have been connected in panel (a)

  Connecting lines between the dots in Figure 3 have been removed.

- P6 L 6-7: It is rather hard to see this in Figure 3, as the horizontal scale has presumably been adjusted to view the meteoric inclusion rather than to highlight the fracture identification. As both points are interesting in this context, perhaps it would be appropriate to show additional panels that zoom in on the fractures in the radar sections.

  We have added two additional panels (d and e) to Figure 3, showing a zoom of the radar sections around the fractures.

- P6 L9: extend -> extent

  done

- P7 L24-25: I'm not sure I would call the rate of opening across an existing fracture a "strain rate." You can use the same units, but this isn't really a material rate of strain in the usual sense of the term "strain rate." Ahead of the crack tip this term would be appropriate.

  We agree with the reviewer, and have elaborated on this point in the text:

  "Further details about the propagation behavior of Chasm 1 can be obtained from a full strain rate analysis of the stake network. Strain rosettes in Figure 2b show the principal strain rate directions and magnitudes, as computed for five different squares within the network. Note that to the south of the A500-B500 line, these results also incorporate widening (Mode I) and shear (Mode II) of the rift, and they are therefore not material strain rates in the strictest sense."

- Figure 4: upon reading the text describing the Halloween Crack and studying Figure 4, I was missing the context of the general flow structure of the ice shelf. Although this later comes in Figure 7, it would have been helpful at this stage to determine whether the GPS baselines are representative of the crack's influence or just the divergent flow dynamics due to the geometry of the shelf and the presence of the McDonald Ice Rumples.

To illustrate the general flow of the ice shelf, we have added velocity arrows to Figure 1, as well as detailed streamlines (based on a 2015 velocity field) in the vicinity of the MIR in Figure 4. The latter illustrate the local divergence of flow around the MIR, but do not show any abrupt changes in direction (or speed) along any of the paths followed by the GPS stations prior to the formation of the HC.

- P9 L30-31: this may in fact always be the case if rifts propagate in episodic bursts, which relates to my comment above about characterizing an "average" propagation speed.

  As noted in the discussion section (page 18) we have no evidence for a stick-slip mechanism of fracture propagation for the rifts on the BIS, nor can we exclude this mechanism. More data from other sources, e.g passive seismics, are needed to conclusively answer this question. This has been elaborated on in the discussions:

  "In particular, the propagation of the rift tip, which happens in alternating phases of slow and fast movement in response to spatially variable properties of the ice shelf, has no important influence on the widening rates, and we find no evidence for a stick-slip mechanism of tip propagation as proposed by Larour et al. (2004a). However, we can also not exclude this mechanism based on current data, and alternative methods such as passive seismic measurements might be able to shed more light on this question."

- I struggled with Figure 5, as I didn't yet have the context of the flow vectors shown in Figure 7. At this point I wasn't sure whether the Halloween Crack was an opening-mode crack or a shear crack (the situation is more obvious for Chasm 1). The distinction is important for interpreting this figure. If it has any component of shear, then the change in baseline is in part due to shear translation across the crack. Clearly from panel (b) the appearance and influence of the crack is obvious. However, I think it would be helpful to resolve the GPS signals into components transverse to and parallel to the crack, after which the specific components of shear translation and crack opening can be resolved. Using a simple baseline connecting stations across this crack does not resolve this.

  We have added streamlines to Figure 5 that help illustrate the general flow dynamics in this area, prior to the formation of the HC. The flow in this part of the ice shelf has no significant shear, which would be characterized by convergence or a change in curvature of the streamlines. In addition, we have computed the full strain rate tensor from the gps data, providing both principle strain rate directions. The results have been summarized in the text as follows:

"A full strain rate analysis of the differential movement between stations L2, K0 and H0 between 3 October 2017 and 1 February 2017, i.e., after the formation of the HC, shows that the principle strain rate directions are both extensive, and oriented perpendicular and parallel to the HC. The corresponding strain rosette is shown in Figure 4 and provides evidence for a pure mode I loading of the rift."

- Figure 5 panel (c) (and in text on P 11): This baseline is across the McDonald Ice Rumples and thus beyond the extent of the Halloween Crack, so I don't see why they would have anything to do with the crack. The change in baseline looks to me like it is due to the flow diverging around the ice rumples, which would happen with or without the crack. Thus I'm not convinced that this panel is useful here. I suspect that it is simply coincidence that the change from linear to nonlinear baseline rate-of-change (blue to red in the panel) happens around the same time the crack forms.

  We disagree. There is a clear change in the separation between the eastern and western sides of the McDonald Ice Rumples (MIR) after the formation of the HC, even downstream of the MIR. This is reflected in the strain rates in Figure 7b, which show higher-than-average values on the seaward side of the MIR. Where the Halloween Crack meets the MIR, it transitions from a single rift into a band of many parallel fractures with a regular spacing of about 250 meters (see Figure R4 below). Some or all of these fractures widen by a small amount to account for the total increase in separation between gps stations I0 and K0.

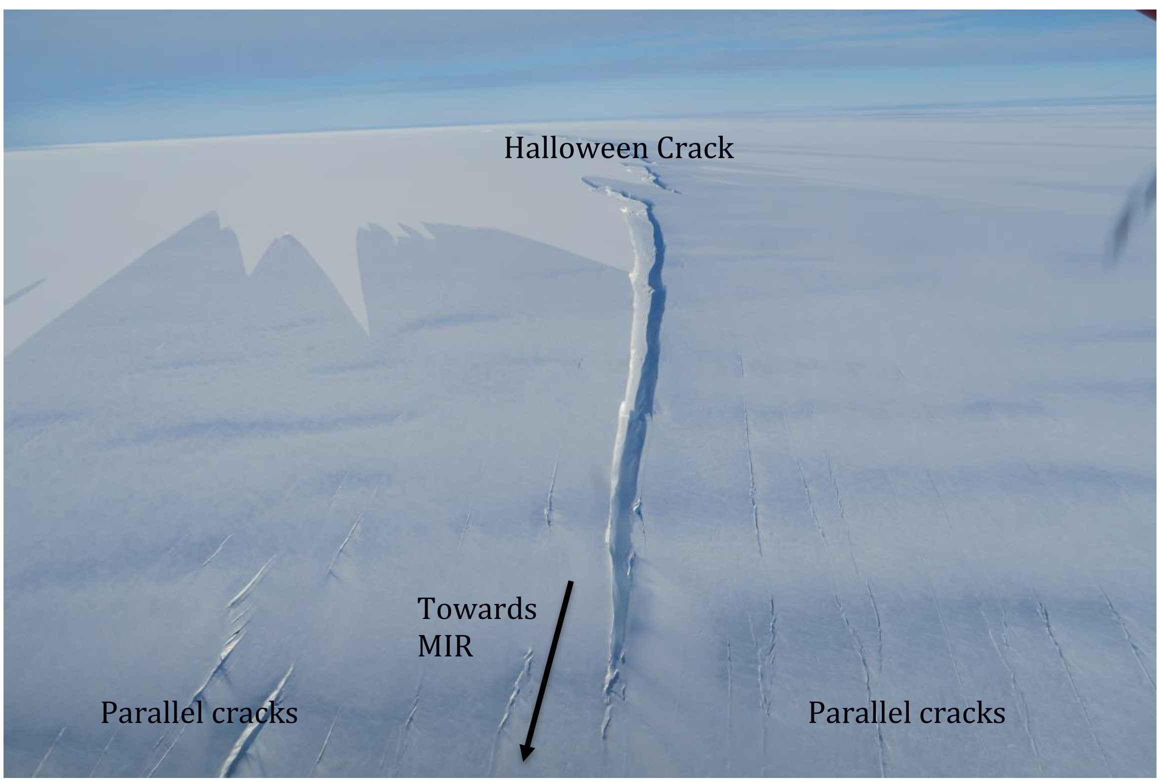

Figure R4. Halloween Crack looking towards the east.

The streamlines in Figure 4 illustrate the ice dynamics in this area before the formation of the HC, and there is no indication for any changes in flow direction or speed large enough that could explain the change from linear to nonlinear baseline extension between stations I0 and K0. Moreover, this transition happens sometime within a period of 3.5 months (data gap) during which the gps stations would only have moved by about 400m. Given the historical flow field around the MIR, it is unlikely that such large changes happen over such a short distance.

- P10 L2: as per comment above about resolving shear vs. opening displacement, I'm not convinced that the baseline change is due solely to "opening of the crack"

The strain rosette in Figure 4 now decomposes the relative movement of L2, K0 and H0 after the formation of the HC into its principle components. Components are oriented perpendicular and tangential to the trajectory of the HC, indicating that the dominant behavior is 'opening' rather than 'shear'.

- P11 L12: as above, "spreading rate" may have both opening and shear components

We have modified this part of the text as follows:

"From the 2015 streamlines in Figure 4 (prior to the formation of the HC) it is clear that the divergence of flow is localized around the MIR, and all GPS stations are located on continuously diverging paths without abrupt changes to their direction and speed that could explain the sudden acceleration in baseline distance. We therefore conclude that the sharp increase in extension rate between L2 and H0 on 3 October 2016 can be fully attributed to the formation, opening and shear displacement of the HC."

- P11 L14: but you don't have GPS data for the K0-I0 baseline on the date that the crack formed, so I don't see how you can substantiate this claim. The extension rate may have sharply increased, but can this not be (at least in part) due to changing flow dynamics from these units diverging around the ice rumples?

The results for both baselines (L2-H0 and K0-I0) are now discussed separately. For the K0-I0 baseline, which has missing data around the transition from linear to nonlinear baseline rate of change, the conclusions have been drawn more carefully:

"Both baselines show a qualitatively similar behavior over the measurement period, with a close-to-linear extension rate (dashed blue line in Figures 5b and c) followed by a rapid deviation from the historical trend line and a significant acceleration. For the L2-H0 baseline, the transition happened abruptly on 3 October 2016, as indicated by the kink in the deviation from the historical trend, which is plotted on the right axis in Figure 5b (black line). On that date, spreading rates along L2-H0 increased near-instantaneously from 22.2 cm/day to 34.7 cm/day with an acceleration of 0.142 cm/day2.

For the K0-I0 baseline, a gap in the data prevents precise dating of the transition, but extrapolation of the trend lines indicates early October as the most likely time of change. Although the stations are positioned on opposite sides of the MIR, an area of naturally diverging flow, it is unlikely that the large change in separation between K0 and I0 can be attributed to background flow dynamics during the 3-month period of missing data. From the 2015 streamlines in Figure 4 (prior to the formation of the HC) it is clear that the divergence of flow is localized around the MIR, and all GPS stations are located on continuously diverging paths without abrupt changes to their direction and speed that could explain the sudden acceleration in baseline distance.

Based on these observations we conclude that the sharp increase in extension rate between L2 and H0 on 3 October 2016 can be fully attributed to the formation, opening and shear displacement of the HC. Equally, the increased divergence between K0 and I0 in early October 2016 is attributed to the formation of the HC, and indicates an increased separation between the north and south sides of the MIR.

- P11 L20: I'm convinced on the influence of the crack for H0, and probably at least partially for I0. However, does the speed normally increase in the region of I0 as the ice shelf moves past the ice rumples and begins to flow more or less unobstructed? A version of e.g. Figure 7a from before the Halloween Crack formed would be helpful for addressing this question.

  The change in velocity at I0 after the formation of the HC was directed towards the northeast. Before the formation of the HC, ice that moved past the Rumples would increase its velocity by only a very small amount, and changes would be directed towards the northwest.

- P13 L10: high strain -> high strain rate

  done

- P14 L20 (and elsewhere): principle stress -> principal stress

  done

- P14 L25: do you mean Sentinel-1 here?

  well spotted, this should be Sentinel-1 indeed.

UPDATED FIGURES

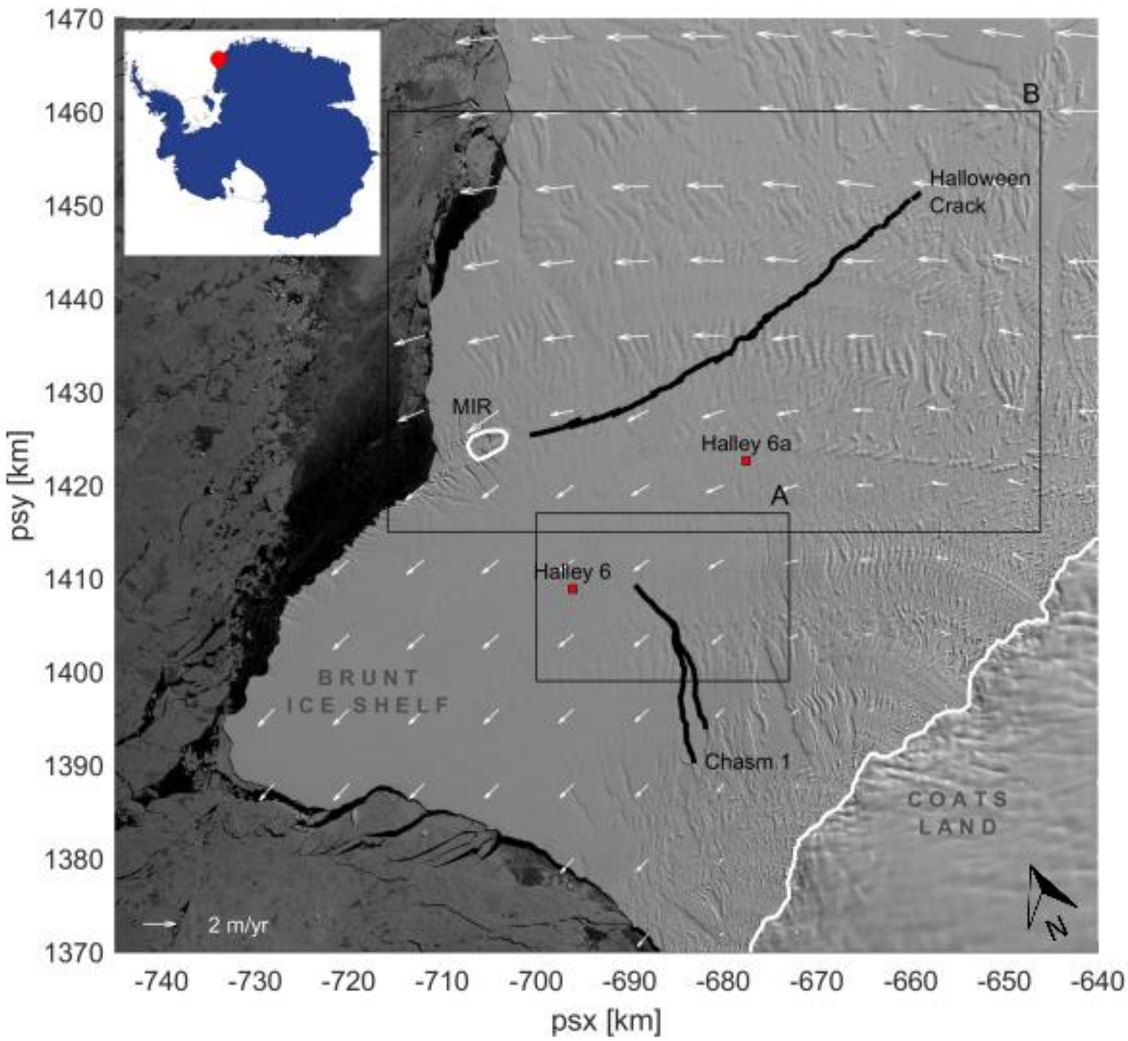

Figure 1. The Brunt Ice Shelf covers a 6500 km^2 area along the Coats Land coastline in East Antarctica (see inset). The grounding line from the SCAR Antarctic Digital Database 6.0 (www.add.scar.org) is delineated in white, and marks the boundary between the ice shelf and the adjacent continent, as well as a small pinning point at the McDonald Ice Rumples (MIR), which is absent in the ADD. The background image is a subset of a Landsat-8 scene (panchromatic band) from 15 March 2017, which was used to outline the present-day active rifts, Chasm 1 and Halloween Crack, which are highlighted in black. The flow of the ice shelf is illustrated by white arrows, sampled on a regular 8 km by 8 km grid.} Red dots indicate the location of the Halley 6 Research Station (operational since 2012) and its new location at Halley 6a (since February 2017). The black boxes indicate the geographical extent of Figures 2a (A) and 3 (B).

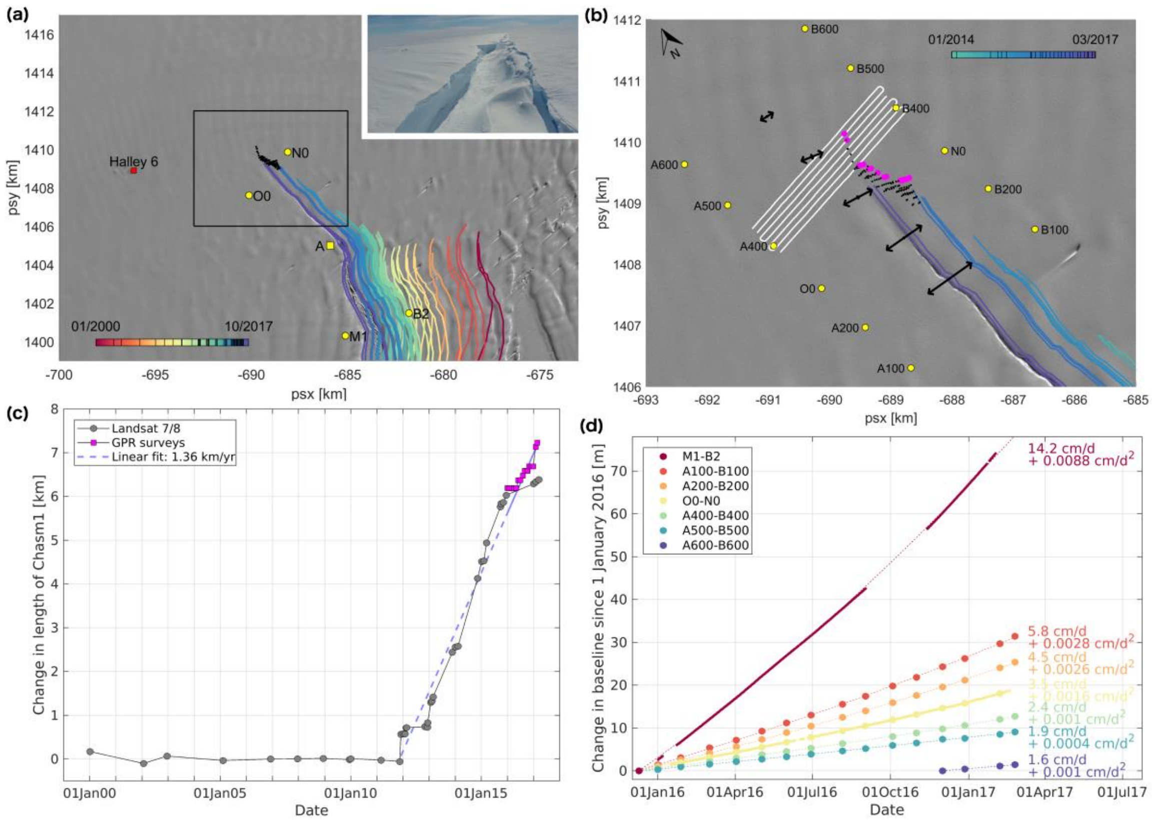

Figure 2. (a) Historical outlines of Chasm 1 from 6 January 2000 (red) to 15 March 2017 (purple), as the rift got advected by the ice flow. Outlines were obtained from a sequence of Landsat-7 and Landsat-8 panchromatic images, with acquisition dates as indicated by the black ticks in the colour bar. The background image is a subset of a Landsat-8 scene from 15 March 2017. The red dot indicates the location of Halley 6 research station, yellow dots are the locations of 4 permanent dual frequency GPS stations, and the black box outlines the extent of Figure b. The inset in the top right shows an aerial image of Chasm 1 taken in December 2015, looking from the reference point A towards the crack tip. (b) Detailed overview of the area around the tip of Chasm 1, showing the local snow stake network (yellow dots), an example of the GPR survey lines (white lines), and progression of the crack tip as obtained from satellite (blue-to-purple outlines) and GPR data (black dots). Strain rosettes were obtained from the relative movement of the snow stakes, and capture the widening of Chasm 1 as well as local strain rates in the ice shelf. (c) Propagation of the tip of Chasm 1 with respect to its historical location prior to the reactivation in December 2012, based on Landsat-7/8 images (grey markers), and monthly GPR surveys (magenta markers). A linear fit through all datapoints shows an average lengthening rate of the rift of 1.36 km/yr. (d) Baseline distance across Chasm 1 as a function of time, measured by two pairs of permanent GPS stations (O_0-N_0 and M_1-B_2 in (a)), and five pairs of snow stakes (A_{i}-B_{i}, with $i \in \{100,200,400,500,600\}$ in (b)). The least-squares quadratic fit is plotted as a dashed line.

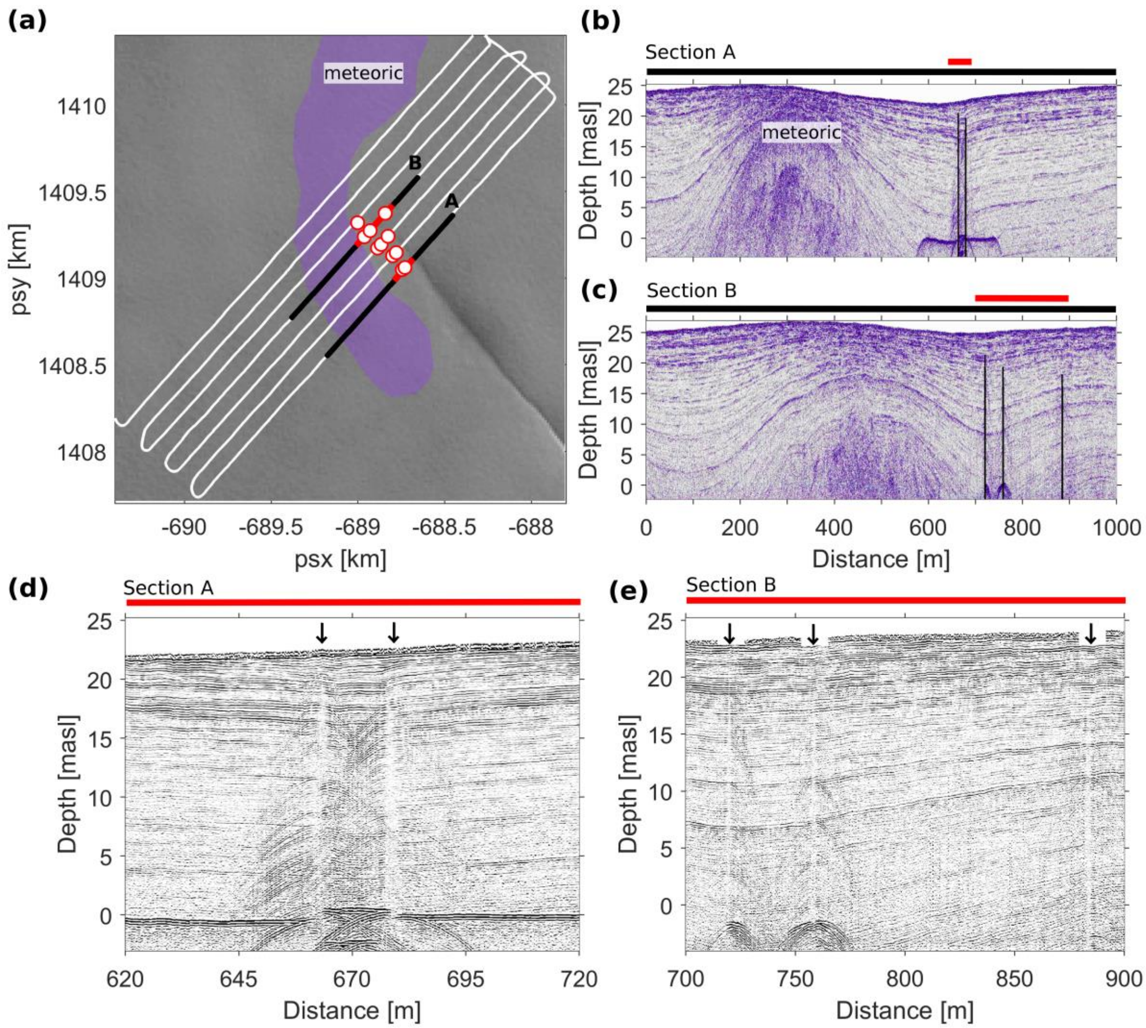

Figure 3. (a) GPS track of a GPR survey carried out on 4 May 2016 (white line), overlying a Landsat 8 image from 3 March 2016. Red dots correspond to locations where a fracture has been observed in the GPR data. Black line segments A and B correspond to the location of the radar sections displayed in Figures b and c respectively. The purple shading outlines the location of a large structure of meteoric ice embedded within the ice shelf (b) Radar section along line segment A in a. Vertical black lines indicate the location of fractures in the ice shelf. (c) Similar to b but for line segment B. (d) A detailed view of the fractures along section A. The spatial extent is indicated by the red line above panel b and vertical arrows locate the radar signature of each fracture. (e) Similar to d but for section B.

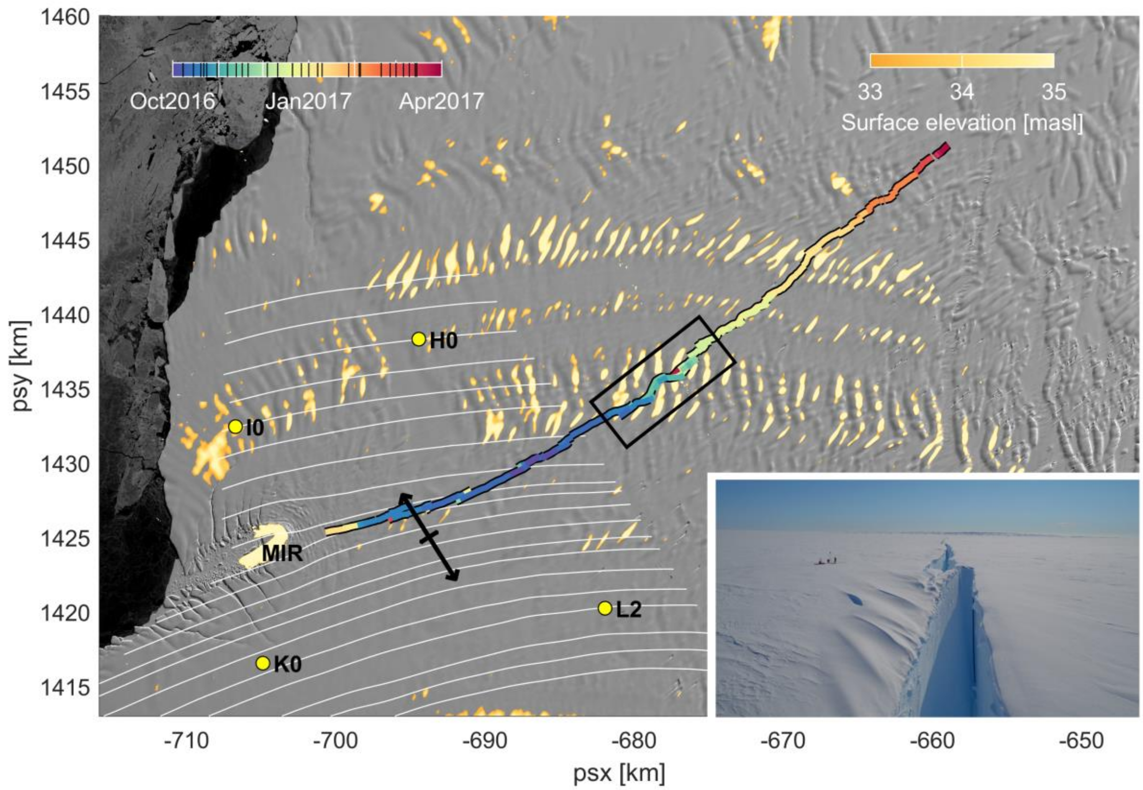

Figure 4. Extent of Halloween Crack (HC) based on a time series of manual outlines from Landsat-8 and Sentinel-2 images; the corresponding dates are indicated by black ticks in the colorbar. The background image is a Landsat-8 scene from 15 March 2017, yellow dots correspond to the location of 4 permanent GPS stations (K0, I0, H0 and L2), and the inset in the lower right shows an aerial image of the HC taken in January 2017 from a location 5 km to the east of the MIR. Orange-to-yellow colours highlight areas with a surface elevation above 33 m, and the black box outlines an area where the HC cuts through a band of thicker ice. White lines are flowlines based on a velocity field from 2015, prior to the formation of the HC, and indicate a localized divergence of flow around the MIR. The strain rosette is calculated from the differential motion of L2, K0 and H0 between 3 October 2016 and 1 February 2017.

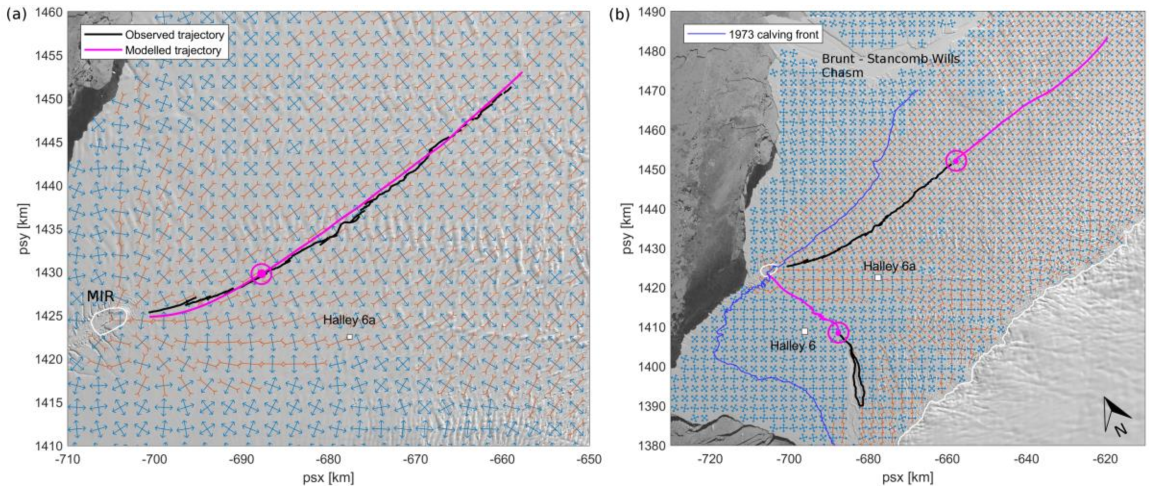

Figure 8. (a) Modelled principal stress components (red are compressive, blue are extensive) in June 2015, resampled on a regular 2.5 km by 2.5 km grid. The modelled trajectory of Halloween Crack based on the direction of maximal tensile stress is shown in magenta, the observed trajectory from 15 March 2017 is plotted in black. (b) Modelled principal stress components in March 2017 and predicted future trajectories of Chasm 1 and Halloween Crack. The purple line corresponds to the 1973 calving front.