Dear Sir,

We are grateful to our reviewers for their comprehensive review of our paper “Halley Research Station, Antarctica: Calving Risks and Monitoring Strategies”.

Enclosed is our response to their reviews, we agree with most of the recommendations and propose to update our paper accordingly.

Best regards, David

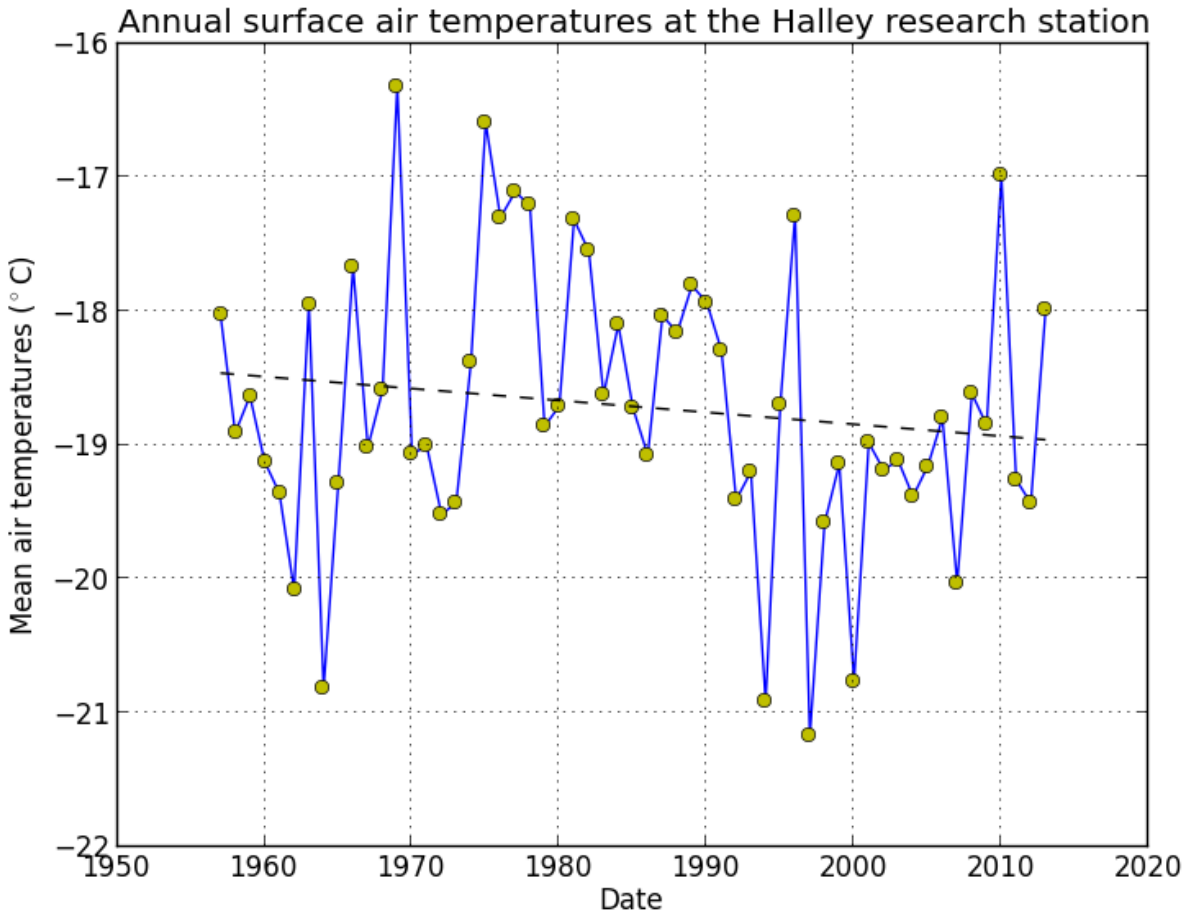
Reviewer: Ala Khazendar

Main issues:

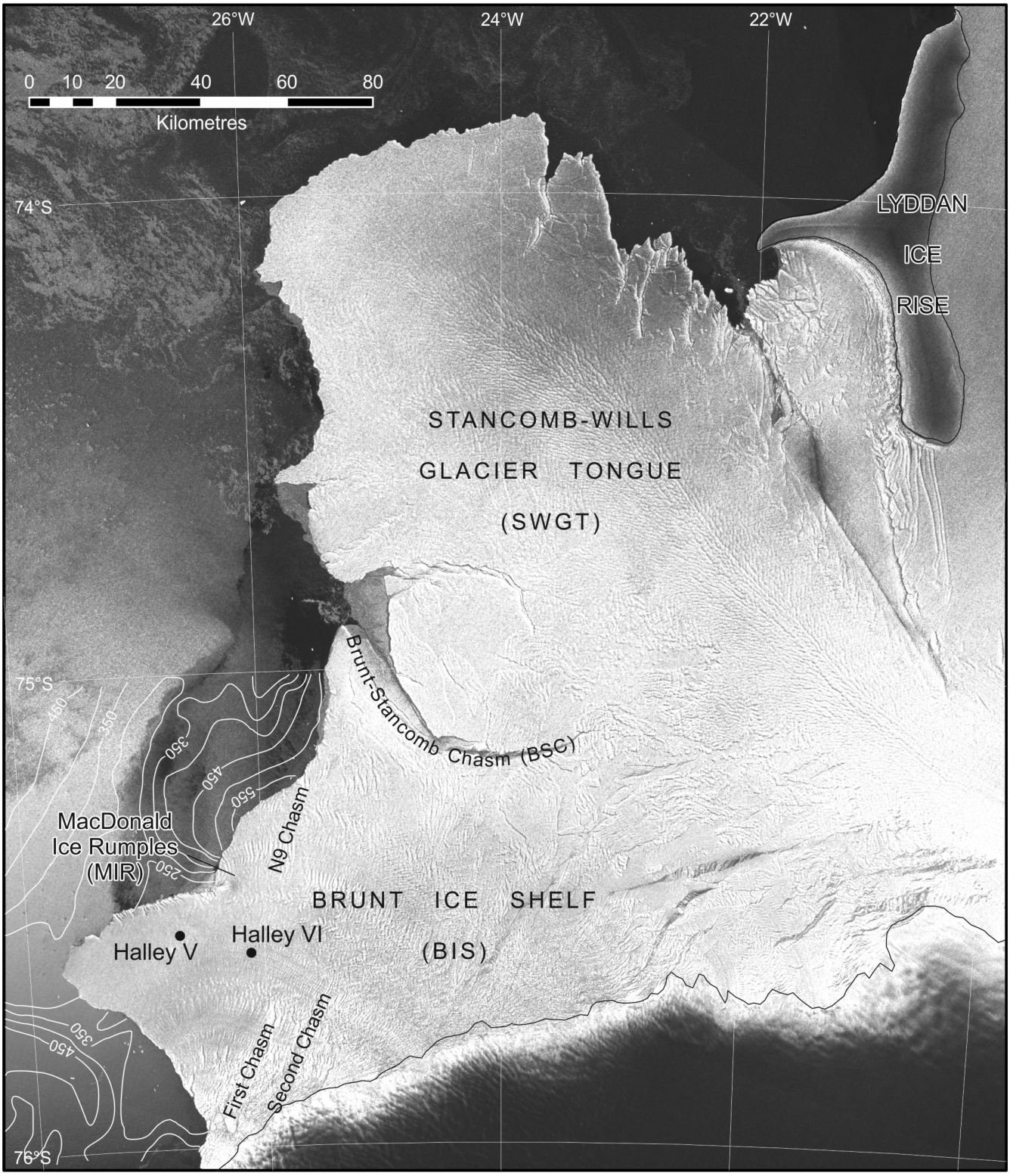
P. 6232 L. 26-27: “On Brunt Ice Shelf surface temperatures are well below the freezing point throughout the year, and surface melting does not occur.”

Given that the main concern of this work is hazard assessment, noting that currently Brunt’s surface temperatures are below freezing is insufficient to conclude that it will not be susceptible to a Larsen-B type disintegration. Has the surface temperature been showing any rising trend over the past years that could, if continued, increase the likelihood of this type of event? For this purpose, the authors could analyze the available Halley temperature time series, and/or examine the findings of published work (e.g., Screen and Simmonds, 2012).

The surface temperature has shown a slight decrease annually since records began in 1956 (see figure below). Reference: Turner, J., S. R. Colwell, et al. (2004). "The SCAR READER project: Towards a high-quality database of mean Antarctic meteorological observations." Journal of Climate 17: 2890-2898.



P. 6236 L. 9-10: “The BIS has two natural protections against iceberg collisions: a shallow 250m plateau in the sea bed that extends approximately 50 km out from the ice front,” Could the authors please cite a reference of the presence of this plateau, and perhaps show its location on the map in one of the figures.



Contours on sea bed from unpublished 2004 Swath Bathymetry survey. 250 m deep plateau visible

above Halley V.

More substantively, I would think that many, if not most, Antarctic icebergs are less than 300 m in draft, so I do not see how the presence of this plateau can afford protection. Could the authors please elaborate?

We agree

BIS is naturally protected against iceberg collisions by the SWGT, which acts as a barrier to incoming icebergs arriving from the east with the Antarctic Coastal Current.

P. 6237 L. 20-27 and Fig. 7, 8: "The long term progress of this rift can be seen in Figs. 7 and 8 ..."

- In this paragraph and the figure captions there is no description at all of the data used, and analysis methods applied, to obtain these figures and the conclusions drawn from them about the Brunt-Stancomb Chasm. Could the authors please provide those details?

- Why is the method used here (Fig. 7) not considered part of the monitoring program, given that it allows tracking the evolution of potentially threating fractures?

- In our work (Khazendar et al., 2009; section 4.3) we explicitly proposed, and explored in detail, the possibility that this rift will widen and lengthen, and that the rift in the south will also widen. The results there largely support the findings here, so the authors could consider citing that work in this context.

The main concern is the Brunt-Stancomb chasm. Ice flow modelling of the region predicts that this rift could widen and extend further inland (Khazendar 2009). By comparing Landsat photos of this rift from 1986, 1998 and 2002, and Envisat SAR photos from 2009 and 2012 it can be seen that the rift is widening and extending (see figures 7 and 8).

When the sentinal constellation of satellites is operational we will recommence this analysis as part of the risk monitoring programme.

P. 6238 Section 4.1.1: "Velocity calculation"

Could the authors please address the following questions:
- What is the spatial resolution of the inferred velocity fields? What is the uncertainty?

The spatial resolution is that of Wide Swath SAR (25m). The uncertainty from NCC matching depends on the availability of stable tracking features.

- Why are the speed values shown in Fig. 10 much smaller than published speeds in, for example, Wuite and Jezek (2009; Fig. 2) and Khazendar et al. (2009; Fig.2)?

In (Khazendar et al, 2009) speeds are calculated from RADARSAT-1 observations made in 1997 and 2000. Since this period, the Brunt Ice shelf has significantly slowed down (based on data from the GPS

network on BIS), so the smaller speeds calculated from our NCC analysis are to be expected.

- Are there particular advantages for using the NCC method over other techniques (e.g., InSAR) for the purposes of hazard detection?

Normalized cross-corellation is a widely used technique, in part due to it being insensitive to differences in brightness and contrast. (Measurement of Surface Displacement and Deformation of Mass Movements Using Least Squares Matching of Repeat High Resolution Satellite and Aerial Images , Misganu Debella-Gilo, Andreas Kaab, Remote sensing journal).

InSAR uses phase comparison of the radar signal obtained for a pair of SAR images, in order to generate an interferogram which directly displays relative ground motions. The interference cannot be obtained from a pair of complex images taken more than a few days apart in time, becuse ongoing changes in the ice/snow surface at the radar wavelength scale ultimately destroy the detailed phase coherence between the two images upon which the interference depends. (Satellite Radar Inteferometry for Monitoring Ice-sheet motion: Application to an Antarctic Ice Stream, Richard M. Goldstein, Hermann Engelhardt, Barclay Kamb, Richard M. Frolich, Science, 3 December 1993). The low frequency of available SAR image coverage in the region prevent us from using InSAR.

- If the purpose of finding the velocity fields is to derive strains rates and determine which rifts are active, why have the method not been tested on, for example, the case of the Brunt-Stancomb Chasm (Fig. 7), to demonstrate its effectiveness?

The first-order control on calving is the strain rate arising from spatial variations in velocity, which determines the location and depth of surface crevasses (Calving processes and the dynamics of calving glaciers, Douglass I. Benn, Charles R. Warren, Ruth H. Mottram, Earth-Science Reviews, Volume 82, 2007). Figure 10 shows the change in flow speed across the Brunt-Stancomb Chasm as 300m/a. This is greater than at any other point in figure 10. This explains why the Brunt-Stancomb Chasm is more active than other regions.

P. 6241 L. 18-20: “Before 2020, there is a high probability that the SWGT ice shelf will have a large calving event, as evidenced by the steady advancement of a rift in the west, and a widening rift in the south.”
This is the first time in the manuscript that the widening of the rift in the south is mentioned. Could the authors please explain how the widening was detected?

Manually georeferenced features in ArcGIS from two separate greyscale SAR images, separated by one year.

P. 6242 L. 2-17: “The Brunt itself may yet calve between the Halley station and the mainland, due to its own natural tidal flexing cycle.”

Brunt might also calve between Halley station and the grounding line (or mainland) along First or Second chasms, or another rift there resulting from changes in the flow regime after a calving at the front (e.g., N9) or an iceberg collision, as the authors describe on P. 6231 L.19-23 and elsewhere in the manuscript. Given the possible consequences of such an event, are there plans to extend the GPS

network to cover that area? Are the other components of the monitoring program sufficient to provide enough warning of such an event?

During the 2011/2012 austral summer we moved the network to surround the Halley VI base. This also moved the network further inland, better placing us to detect changing strain rates between the base and the Brunt grounding line.

Other issues:

P. 6229 L. 11: "The surface mass balance of BIS is positive"
Please provide a reference to support this statement.

(The surface energy and mass balance at Halley, Antarctica during winter. J. C. King, P.S. Anderson, M. C. Smith, S.d. Mobbs, Journal of Geophysical Research).

P. 6229 L. 11-12: "The surface mass balance of BIS is positive, and the mass loss of BIS therefore happens exclusively through calving"

This statement ignores the possibility of basal melting at the ice-ocean interface. The authors are probably right in assuming that most mass loss of BIS happens through calving. Examining the results of recent papers by Depoorter et al. (2013) and Rignot et al. (2013) should resolve this issue.

The mass loss of BIS is predominantely caused by calving fluxes (Calving fluxses and basal melt rates of Antarctic ice shelves, Nature letter, M. A. Depoorter et al.)

P. 6231 L. 9-11: "All three Brunt rifts are located between the Halley locations (both V and VI) and the mainland."

- That is not case of the N9 Chasm.
- The term "grounding line" would be clearer than "mainland" here and elsewhere in the manuscript.

The First and Second Chasms are located between Halley VI and the grounding line.

P. 6234 L. 1-8: "Ice front positions …"

- Could the authors please explain why do they consider the 1956 front position less reliable?
- Could they also please give the references reporting the findings of the Argentinean ship, and those of the 1958 survey?

The 1956 coastline is incongruous with the 1958 position which was compatible with all of the regular coastline surveys from Halley thereafter.

Argentine Antarctic Expedition, 1954-55. Two unpublished Argentinian maps entitled "Mar de Weddell. Leviartamiento expeditivo efectuado pol el rompehiclos A.R.A Gral San Martin, Enero 1955" 1:500,000, Scott Polar Research Institute, MS 291/3-4

International Geophysical Year survey map, BAS internal archives, ES2/EW 1000/145A

P. 6235 L. 14-16: “BIS is grounded on the MacDonald Ice Rumples and the GPS measurements of ice velocity conducted in 2009 showed the ice at the top of the MIR to be stagnant.”

Could the authors please clarify whether they conducted these 2009 GPS measurements, or otherwise give a relevant reference.

BIS is grounded on the MacDonald Ice Rumples and the GPS measurements of ice velocity, conducted by the authors as part of this BIS risk assessment in 2009, showed the ice at the top of the MIR to be stagnant.

P. 6237 L. 17-18: “On the south side, another 100 km rift runs parallel to the Brunt–Stancomb chasm.”

It runs parallel to the grounding line, rather than to the chasm.

On the south side, another 100 km rift runs parallel to the BIS grounding line

P. 6242 L. 10-11: “The GPS network continues to provide short-term data on the movements and internal strains of both ice shelves.”

Yet, as the authors explain earlier in the text, only Brunt has a GPS network, not “both” ice shelves.

The GPS network continues to provide short-term data on the movements and internal strains of the Brunt ice shelf.

Fig. 3: It would be useful here to show the 2009 location of Halley V and the flow line going through it, both of which are mentioned in the caption of Fig. 4.

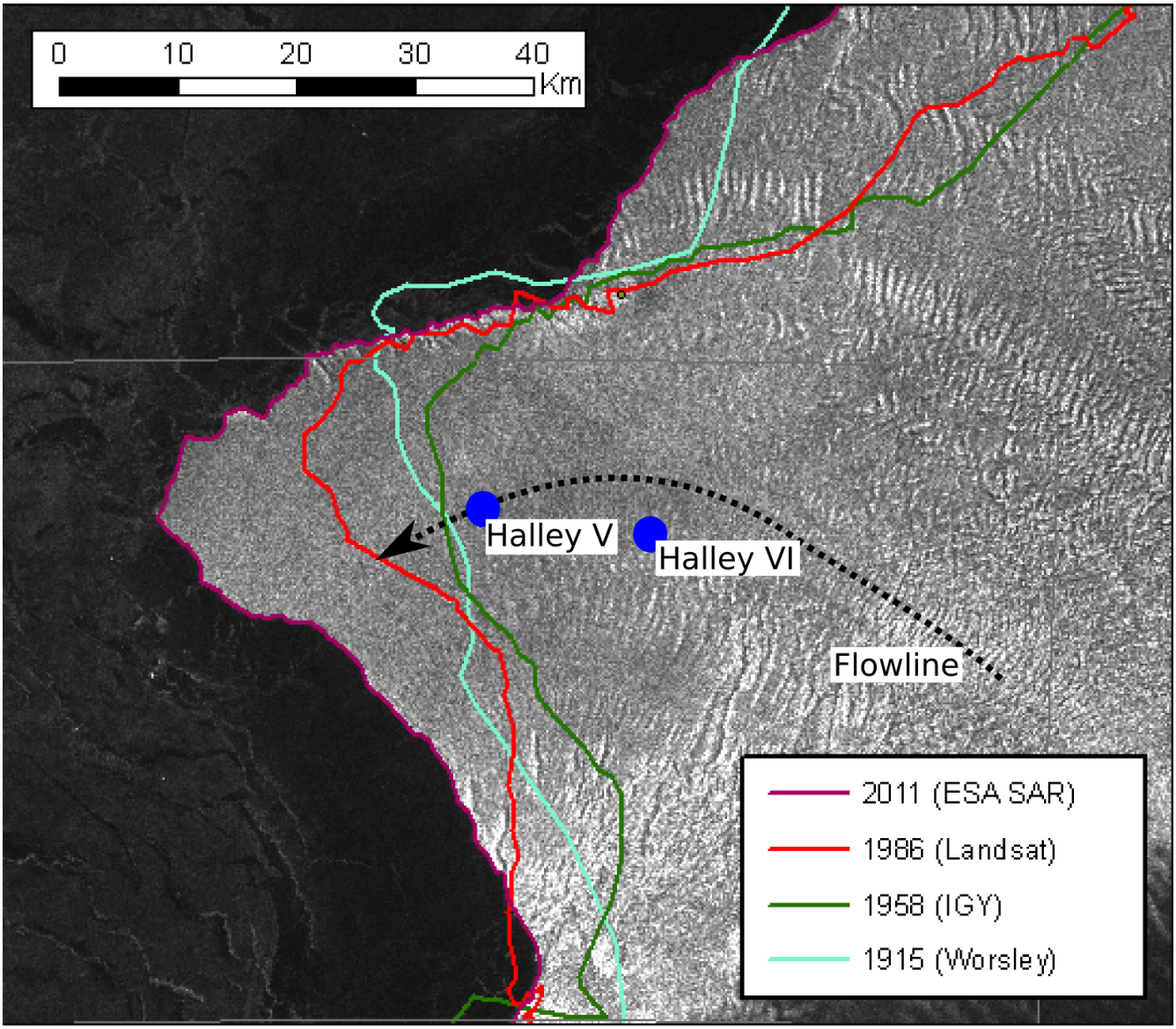
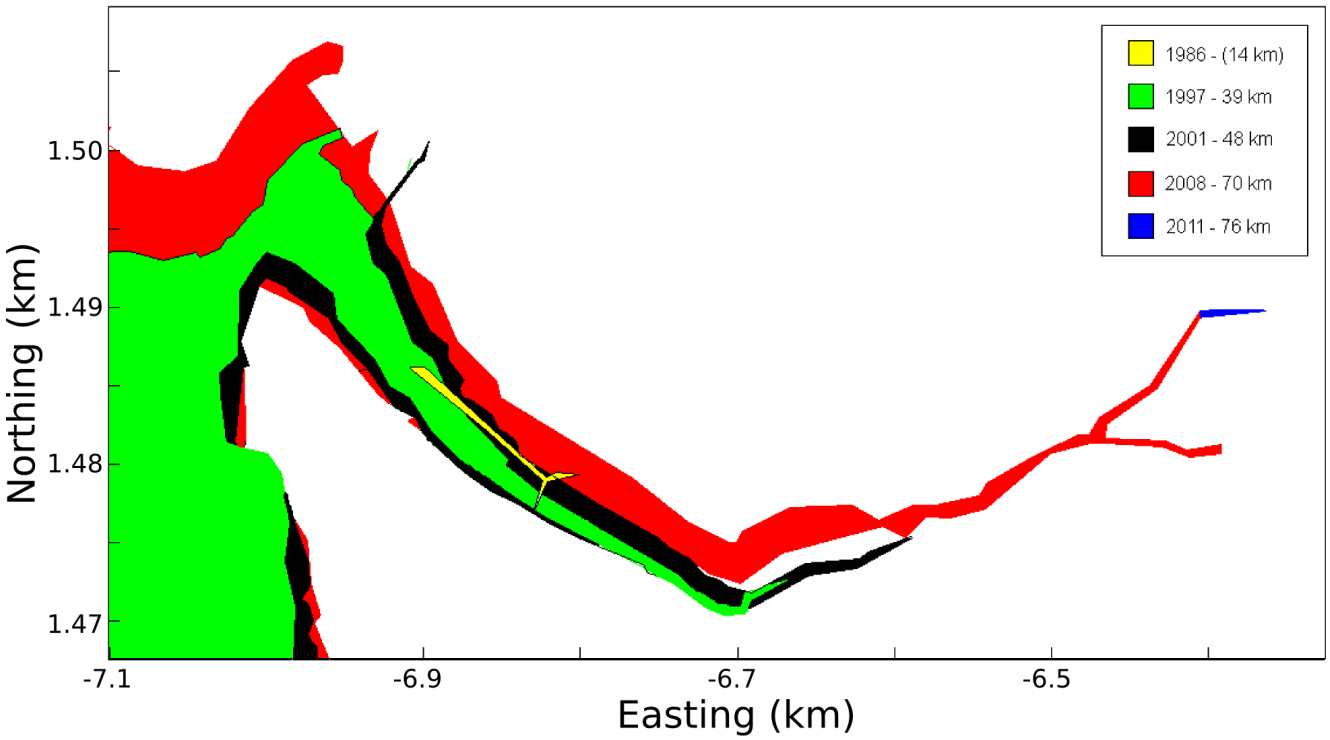


Fig. 6: The legend mentions a "1955" front, this probably should be 1956 according to the main text. Furthermore, could the authors please explain why are they showing here the 1956 front, which they consider unreliable, and not the 1958 front?

The 1958 ice front was only of Halley, but the 1956 included Stancomb-Wills.

Fig. 7: Please show the labels on the axes.

Eastings and Northings in km on a UTC Zone 26 projection.



In the legend, what do the figures in km signify?

The length of the chasm from the south promontory to the furthest visible end of the chasm in the interior.

Fig. 9: In the top panel, please explain in the caption the red, dotted line?

It is the region across the main flow line of Stancomb-Wills, where the ice is in strong compression and will be the last to rift. When it does, that will be the calving event.

P.6228, line 20: "existence"

The research station has a primary focus on atmospheric sciences, and is the site for many long-term monitoring datasets including the records that first indicated the existence of the Antarctic ozone hole (Farmen et al., 1985)

Line 21: it would be helpful to mention why it has been necessary to build Halley on the ice shelf, unlike bases that are more easily accessible .

The first Halley station was built at the conclusion of the IGY Trans-Antarctic Expedition, its location was determined by the end point of the expedition. This expedition followed the routes originally laid out by Shackleton as part of the Imperial Trans-Antarctic Expedition.

P.6229, lines 2-3: rephrase "Halley 1 through to Halley IV were each occupied for a maximum of ten years"

Halley has been rebuilt six times since the start of operations in 1956. Although calving has always been a threat to the Halley Research Station, this has not been the primary reason for rebuilding it. With one metre of snow accumulating annually, buildings are eventually buried and must be abandoned. The longest occupied Halley station was Halley IV. It was occupied for 12 years (1972-1984) because its steel tubing construction was designed to withstand being buried.

Line 7: underground? Perhaps misleading. Reword, e.g. "sub-surface"?

However, its sub-surface infrastructure had become unsafe,....

P.6230, line 9: "considerably"

...a considerably larger ice shelf than BIS....

Line 17: "Thomas (1973)" -

The paper uses the correct reference formatting for this journal.

P.6231, para 2: What I might suggest is that you mark the chasms on the map (Fig 2) with lines. They are not clear on the image at that scale and although the place-names show the general location they could be shown as lines to show their extent.

Figure 9 better shows the extent of each chasm. Figure 2 shows their location relative to significant features of BIS. Adding artificial lines which aren't contours or boundaries, to this diagram could confuse it.

Lines 10-11: I would say the N9 chasm is different as it's not located between Halley and the mainland and it's not upstream of the MIR.

Agreed

Line 24: The SWGT chasms could also be shown on Fig 2.

P.6232, line 20: "disappearance" is not strictly true – "retreat" or "collapse" would be more accurate

The disintegration of Larsen B was part of a string of large calving events that have seen the collapse or retreat of a number of large ice shelves along the Antarctic Peninsula over the last 100yr (Cook and Vaughan, 2010).

Line 25: Banwell et al (2013) could also be cited here: Banwell, A. F., D. R. MacAyeal, and O. V. Sergienko
(2013), Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes, Geophys. Res. Lett., 40, 5872–5876, doi:10.1002/2013GL057694.

It is generally accepted that surface melting enabled the large-scale disintegration of Larsen B by allowing progressive downwards propagation of pre-existing surface cracks (Holland et al., 2011), (Banwell et al., 2013).

P.6233, line3: "collapse"

For both reasons we can discount the possibility of a “Larsen-B” type collapse happening on either BIS or SWGT.

Line 10: no commas needed: “Each ice shelf can hence be expected to produce...”

Each ice shelf can be expected to produce large or small, frequent or less frequent calving events, depending on local conditions and its rate of growth.

Line 18: should be capitalised as follows - “Synthetic Aperture Radar images”

Since 1990, ice fronts have been tracked using Synthetic Aperture Radar (SAR) satellites.

Line 19: “early 1970s”. It might be best to specify that Landsat are visible-band images rather than radar.

From the early 1970s, Landsat images provided visible-band images of ice front positions,

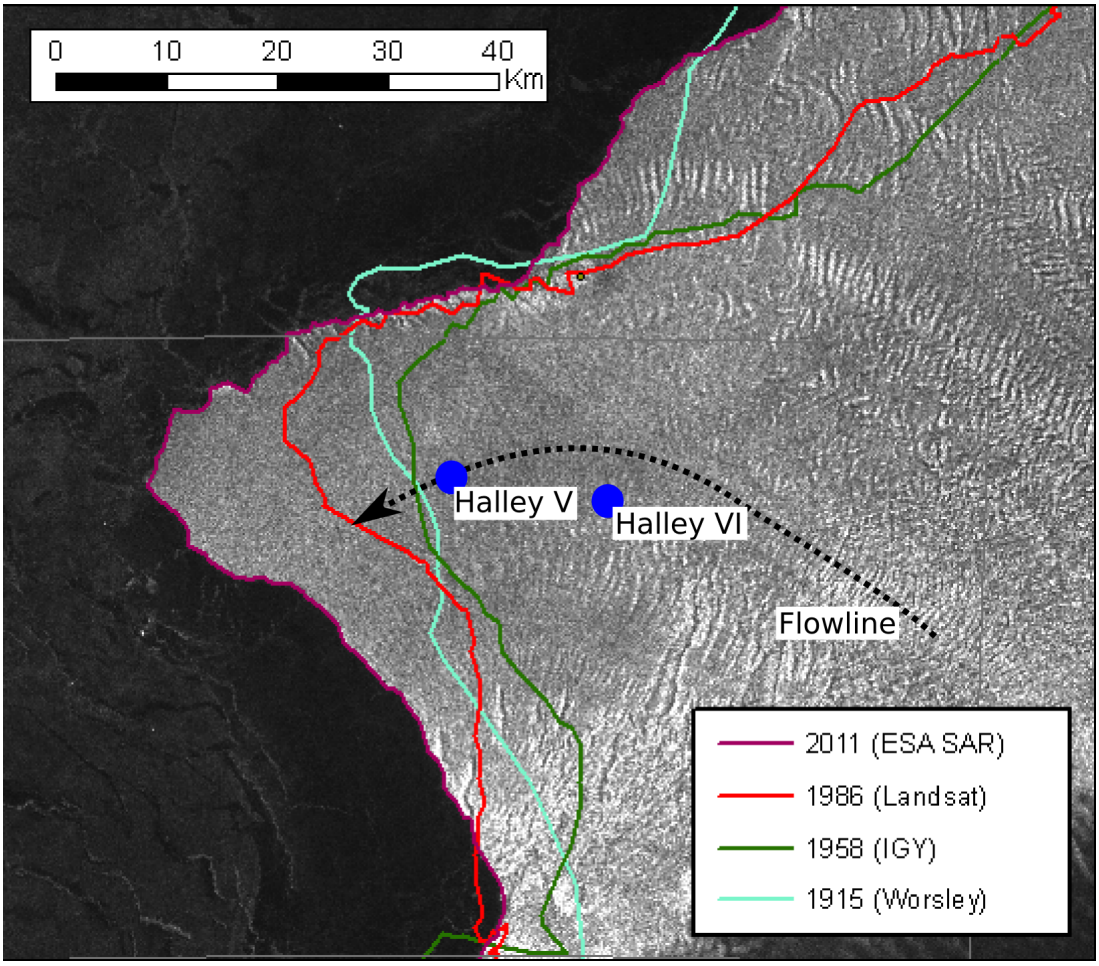
Line 23: “3.2” is unnecessary .

Agreed

P. 6233, last para and P.6234, para 1: the reliability of different sources must be stated and quantified in some way. Since you use the 1915 position as a benchmark, how might the error margin affect the projected ice front position? How did you assess the 1956 and 1958 maps to conclude that the 1958 position is more accurate? This position is less reliable than recent positions acquired from accurately georeferenced satellite images but this must be stated with a comparison of errors.

The 1956 coastline is incongruous with the 1958 position which was compatible with all of the regular coastline surveys from Halley thereafter.
It is impossible to repeat the historical ice-front measurements in order to derive an error margin. In this paper we only use it to show that, in conjunction with the current observed rate of growth of BIS, the only way to rationalise the 1915 and 1958 coastlines is with a calving event.

P.6234, Line 13-14: it would be good to see the flow line you have used, perhaps best on Figure 3
Line24-25: this sentence is repetitive



P.6235, line 4: “then” instead of “than”

Indeed, if the calving event occured anytime in the first thirty-five years of this forty-three year gap of data, then the Halley V location would already be in formerly open water.

Line 10: I’m not sure the reason for having the SWGT map as Fig 6 rather than Fig 5. It would be more logical to have them the other way round.

Section 3.3 discusses the iceberg collision scenario. Section 3.4 discusses the SWGT calving scenario. Hence the order of the figures.

P.6236, line 5: reference?

The Antarctic Coastal Current in the southeastern Weddell Sea, E. Fahrbach, G. Rohardt, G. Krause, 1993

P.6237, line 6: “A large iceberg...”

A large iceberg resulting from SWGT itself may collide with the Brunt.

Line 11: It would be more suitable to call this Fig 7 rather than 10.

Agreed

This is a velocity map rather than a velocity profile. The map shows a strong difference in the velocities of the SWGT and the Brunt – this should this be pointed out here since the Brunt doesn't have the same relationship between speed and distance from grounding line (which is very striking on the map).

Figure 10 shows the speed change across the Brunt-Stancomb Chasm as 300m/a. This is greater than at any other point in figure 10. This explains why the Brunt-Stancomb Chasm is more active than other regions.

Line 16: for consistency, the name should be "Riiser-Larsen Ice Shelf"

This rift separates the fast-moving SWGT from the much-slower Riiser-Larseninen Ice Shelf

Lines 21-24: I would say you need to show Fig 9 before Figs 7 and 8, to show the location of the three rifts in SWGT. Your description of the events would then make more sense, once the reader knows what you mean by southern rift. In line 22, it would perhaps be clearer to word as follows: "The northern end
of the crack has forked in the last 15 yr and has continued to widen in a north-easterly direction".

Without the preceding explanation and figures 7 and 8, the dotted red line on figure 9 doesn't make sense. The point of figure 9 is to show the weakening effects of the rift extension on SWGT.

Line 25-27: make it clear that you mean linear growth at the southern end of the crack.

However, if linear growth should recommence from the southern tip of the crack and in a southerly direction, the crack would join with the southern rift by 2020.

Line 27 – do you mean growth in the crack would accelerate? Maybe add an extra sentence to explain why you might expect this to happen?

As the crack approaches the southern rift, the dynamics of Stancomb Wills will be increasingly disconnected from those of the BIS, potentially resulting in increased strain rates and an acceleration of the growth of the crack, reducing the time frame accordingly.

P.6240, line4: I'm not sure you need "RTK" since you don't refer to this again. "real-time kinetic" is probably sufficient.

(Note that double-differencing for a precise real-time match is not possible...

P.6241, line 12: I'd suggest re-wording, "SWGT is currently very active". Also line 15: "which might also destabilise the BIS."

In contrast to the BIS, SWGT is currently much more dynamic, with several rifts that are growing at a linear rate. If this linear growth is maintained, these rifts could join together within ten years and form a full calving event, which might also destabilise the BIS.

Line 19: “advance” rather than advancement. It might be helpful to write “... the steady southerly advance of a rift in the west”, just to clarify that this is the end of the rift that is of concern.

Also, you mention that the rift in the south is widening, but I don’t see this described in your Section 3.4 (it should be stated perhaps on P.6237, line 27).

Agreed – will remove the reference to this rift widening.

Before 2020, there is a high probability that the SWGT ice shelf will have a large calving event, as evidenced by the steady southerly advance of a rift in the west.

P.6242, line 11: do you mean to say “both ice shelves” here? The GPS network doesn’t detect strains in the SWGT.

The GPS network continues to provide short-term data on the movements and internal strains of the Brunt ice shelf.

P.6243, line4: “described in Humbert and Pritchard (2006).”

It is currently the correct reference format for this journal.

Other comments:

As regards current risk monitoring methods or future work, have the authors considered detecting changes in pressure ridges and surface features using digital elevation models? Adrian Fox (BAS) produced a photogrammetrically derived DEM with draped aerial photographs for the MIR region. I don’t know if this was published but it would be useful for the authors to know about the result and whether it revealed anything about the activity in this region.

Adrian's DEM is available to the authors, but he has not produced a second one from later photography, so we cannot use it for velocity calculations.

Figures:
It may be best to change the order of your figures. See suggestions in specific comments above.
Fig 2 – draw lines marking the three chasms on BIS.
As discussed previously
Fig 3 – the dark green line is not very visible. It would be good to show the flow line that is used for the results in Fig 4.
Agreed
Fig 5 – in the caption, do you mean 26 April rather than 28 April (as labelled on image).
Yes, 26th April.
Fig 6 – why is the 1955 ice front position shown here instead of the position in 1958, which was stated as being more reliable?
The 1958 ice front doesn't show the Stancomb-Wills coastline, only the Brunt Ice Shelf
Fig 7 – what is the x, y reference shown here? Also, the text on the axes and the legend needs to be larger. The slivers shown for 1986 and 2011 are confusing – it implies that the gap was very small in these years. I assume the 2011 chasm outline is beneath the 2008 outline? Perhaps make one or two

layers semi-transparent, or use outlines without a fill for some. The Figure caption spelling corrections are: “coloured” (or “colored”) and “respectively”.
Agreed. Eastings and Northings in km on a UTC Zone 26 projection.
Fig 9 – explain what the red dashed line is in the top map. Also, it may be helpful to label the three rifts on SWGT, perhaps with E, W and S so the reader can easily identify which ones are being described in the text. The rifts are described in Section 3.4, rather than Section 5.
Agreed
Fig 10 – this is a velocity map rather than a speed profile.
No – it doesn't show the direction of flow, only its speed.
Fig 11 – can you add the positions of the 2011/12 GPS units near Halley VI?
Not without confusing the diagram – the 2011 sites have been moved or removed as part of the shift to Halley VI
Fig 12 – The axes are rather confusing – it may be clearer simply to have a scalebar as in Fig 11.
Agreed