Final author comments – TC-2018-107

We would like to thank both referees for their constructive reviews of our manuscript.

Below, we have responded to each of the reviewers' comments in blue italics. At the end of our response we included a version of the manuscript with all changes tracked.

Review 1 – Ted Scambos

Review, Miles-Stokes-Jamieson TCryo Cook Glacier

This is a good observational paper on the detailed recent history and unique events occurring on the Cook Glacier / Ice Shelf system. The system provides a number of insights into Antarctic glacier systems as additional examples of processes seen elsewhere.

I recommend publishing the paper with minor revisions. Mostly I would like to see some additional information and a few adjustments to the figures. The paper could almost go in as is, but a few extra steps would present the work better and satisfy the curiosity of the reader a bit more.

We are pleased that Dr. Scambos found our work interesting and thank him for providing helpful and constructive comments on our manuscript.

L22 'subglacial' should be capitalized.

Amended.

L92 Kääb will need its umlauts.

Amended.

L140-147 – Note the implications for the current calving of Larsen C. Some have jumped on this retreat into the embayment as an indication of the beginning of an irreversible retreat, and yet Cook East appears to be cycling back. The Larsen C stability question is an important debate these days, and may intensify with an upcoming Rignot paper.

This is a good suggestion. We now include the following sentence in relation to large ice shelf retreats and ice shelf stability: 'However, since this retreat between 1963 and 1973, the Cook East Ice Shelf has re-advanced and has remained stable, showing that a retreat deep into an ice shelf's embayment does not necessarily result in an irreversible retreat. This observation could be an important consideration in improving our understanding on how recent and future large calving events influence ice shelf stability in Antarctica e.g. Larsen C (Jansen et al., 2015).'

L148 – with your error bars, just say 'approximately 20%'. Your 1989 estimate has an error bar of ±12%.

Amended.

L178 change to '. . .measurement is high (don't need to repeat error here), the pair of measurements still demonstrates a major increase in velocity, which . . ..'

Amended.

L187-188 you already said part of this. How about: "The calving of the Cook East Ice Shelf between 1963 and 1973 was unusual in the context of large Antarctic ice shelves where calving events. . .."

Amended. The section has been re-written with some additional sentences relating to Larsen C (see comment above).

L199-200 Similar note - - just move on: "The increase in velocity between 1989 and 2000-2001 (416 to 496 if you want) coincides with an increase in the ice front advance rate. Notably, most of this increase is concentrated between. . ."

Amended.

L253 – '. . .which use(d) to flow into. . .' this is colloquial, not for written text. '..which formerly flowed into..'

Amended.

L281-285 as you know, Landsat 8 acquisitions since 2013-2014 are far better than annual now; the next fast ice break-out will be an interesting study for you (note that GoLIVE data may help as this future event unfolds, https://nsidc.org/data/golive).

Yes GoLIVE and Sentinel-1a/b will enable an interesting study of the next break-out event.

L350-353 this section is a good walk through the available climate information and related studies. One thing that would support a sub-ice-shelf melting explanation for the 1970s retreat of Cook West I.S. would be channeling or a change in the character of the bottom crevasses and rifts. This could be discussed in a bit more detail (is there evidence or no evidence) with the early images in a figure related to Figure 7 (see below).

There does not appear to be any obvious changes in the structure of Cook West between 1947, 1963 and 1973 (revised figure 5). However, the ice shelf does look, at least visually, structurally weak with extensive crevassing. This possibly explains the difference in behaviour between the neighbouring East and West Ice Shelves. We have now added this into the discussion in section 4.3.

Figures

Figure 1 - I'm feeling a bit too 'zoomed in' here, although it covers the study area well, I think for Figure 1 a slightly larger view would be good, or perhaps a third panel – Antarctica outline, then coast and near-coastal Wilkes Land from Adare to Dumont D'Urville with Bedmap data (in more detail than the current inset) and then the flow speed figure as you have it.

We have modified Figure 1 to include two panels. A) is Bedmap zoomed in over the Wilkes Subglacial Basin, with an inset of its location in Antarctica. B) is the original Figure 1 with the grounding line updated at the request of reviewer 2.

Figure 4 and 5 – consider combining these into one 3-panel figure.

Figure 4 and 5 are now combined into a 3-panel figure.

Figure 6 – difficult to tell the difference between 2006/07 and 2015/16 in the graphic, although the text makes it clear that the jump in speed is in 2006/07. A different color scheme would solve this.

We have amended the colour scheme so that it is easier to distinguish 2006/07 and 2015/16.

Figure 7 – I think you might want to include an extra figure, with the best-contrast versions of the 1947, 1963, 1973 or 1974, and 1989 images – I think the structural details in the ice shelf and the grounded portion of the lower Cook West glacier might provide some insight into the break-up causes – or at least eliminate some.

We now include an extra panel with the images of Cook West in 1947, 1963, 1973 and 1989. This shows that there is no clear evidence of any significant changes in the structure of Cook West between 1947 and 1973.

Figure 8 —lower panel, I would adjust the y-scales to separate these two data sets slightly. The graphic is confusing with such close overlap. It's nice to see the correlation, and the point of the graphic is well taken, but the graph appears at first to be showing some kind of fit or second data set for velocity. The ice front retreat curve is a repeat of the upper panel data for 1973 – present?

Taking into account the comments from reviewer 2, we have removed the second axis on the lower panel 'relative ice-front position change since 1973' to avoid any confusion.

Figure 9 – please show the proposed drainage path as determined by Flament et al. 2014 m (their figure 7) – this can be as a grey shaded strip on the bedrock mapping.

We have now added the region of most likely flow from Flament et al (2014).

Figure 10 please provide the source of the image data (Landsat 7 and Landsat 8?)

Amended.

Figure 12 interesting plot. An image or line map of Dumont D'Urville as an inset or additional panel would be good to see, with directions (0, 90, 180, 270) marked un-obtrusively. The image or line map should include the coast of Cook Glacier as well. Checking the available AWS in the area – it appears that there may be some data from the Russian base Leningradskaya that is closer (a little) than Durmont D'Urville.

We now include an inset of the coast (Cook – Dumont D'Urville) with wind directions marked. As far as we can tell from AWS project (https://amrc.ssec.wisc.edu/), the AWS at Leningradskaya was only installed January 2008. Hence. Dumont D'Urville is preferred because of the longer time-series.

Reviewer 2

Summary: This is an interesting paper, which relies on remote sensing to investigate velocity and ice front position of Cook ice shelves. The text is generally well written and structured and the images are relatively clear. However, I recommend that a few things are addressed/clarified before the manuscript can be recommended for publishing.

We are pleased that the reviewer found our work interesting and thank the reviewer for the helpful and constructive comments on our manuscript.

-I am surprised to find no mention of grounding line migration. Much emphasis is put on calving front location and velocities, which both play an essential role in ice-shelf stability. However, grounding line position is equally –if not more – important, when it comes to ice-shelf stability and loss of buttressing. All the more so, given that Cook is a marine basin with a retrograde slope.

We agree with the reviewer that grounding line migration is another very important aspect of ice-shelf stability and that this could particularly be true for Cook. One method to quantify grounding line migration would be to map changes in the break in slope as a proxy for the grounding line (e.g. Christie et al., 2016). However, because there are multiple breaks in slope visible as Cook East approaches floatation, this method could be problematic and would result in high uncertainties. Indeed, the difficulties in estimating the break in slope from optical imagery at Cook East are illustrated in the MODIS 2004 and 2009 grounding line products. Here, there is large difference in the grounding line position of Cook East in the order of several kilometres. This difference is too large to be geophysical and more likely represents difficulties in estimating the grounding line of Cook East from optical imagery. An alternative method would be to quantify grounding line migration through differential radar interferometry, but we note that this type of analysis is a large undertaking and can often form the basis of papers alone without additional ice-front/velocity analysis (e.g. Totten – Li et al., 2015). We also note additional differential radar interferometry based grounding line estimates would only be available for recent years and we note that a recent paper has already quantified grounding line migration over this period (Konrad et al., 2018). Thus, we have added some sentences which describe the results of that paper.

Is there a particular reason why only optical data are used to derive velocities and not SAR images? The latter could have helped you to overcome the lack of suitable data.

We used optical data simply because it provides the longest time series. We considered using SAR data to overcome data gaps, but on searching for imagery there was very little data for the key gaps in our time series e.g. 2006-07 subglacial flood event, early 2000s and 2011/12. We note that these same image gaps can be seen in the available annual velocity mosaics of Antarctica (see https://nsidc.org/data/NSIDC-0720/versions/1).

Have you considered the role of pinning points? You mention ice rises when it comes to co-registering the images but would it be possible that the observed acceleration is somehow linked to a loss of contact with a pinning point (ice rise or ice rumple)?

This is a good suggestion. One of the issues with Cook is the lack of bathymetric observations and we do not observe any obviously grounded icebergs. However, it is a possibility that the retreat of Cook West could be connected to a loss of contact with a pinning point and we now state this in the discussion in section 4.3.

Have looked at strain rates and their evolution? I think it could provide valuable information about dynamic changes over the period you cover.

We have not looked at strain rates and feel that this would be beyond the scope of the current manuscript. Moreover, the large error associated with the 1973/74 velocity field would make any strain rate comparison difficult.

I am surprised to see that the paper from (Liu et al., 2015) is not cited and the type of caving occurring at Cook ice shelves (tabular vs disintegrating) not discussed.

We now discuss the difference in calving types at the Cook ice shelves with reference to Liu et al. (2015) in section 4.3. Liu et al. (2015) link disintegration-type calving (e.g. Cook West) to enhanced basal melt and tabular calving events (e.g. Cook East) to neutral or positive mass balance regimes. However, given that the Cook East and west ice shelves are in such close proximity and therefore are likely to receive similar climate forcing; we suggest the difference calving type could be related to the structure of the ice shelves which might be related to bed topography as the ice shelves approach floatation.

How do your velocity fields compare to (Rignot, Mouginot, Scheuchl, 2011)? You only mention this field when you remove outliers but not when you assess your velocity fields.

We now include a comparison cross-profile to the MEASURES dataset in the revised Figure 4. This shows that our data compares well.

You talk about an increase in velocity but does this acceleration appear everywhere? Does it vary spatially? You only show changes over one velocity profile in Fig 6.

In addition to the velocity profile we already show changes in velocity over a section of the grounding line and across the ice-front. All three of these time-series over different parts of the ice shelf show a consistent acceleration.

I feel that that the overall number of figures in the main paper could be reduced, as not all of them are highlighting essential information. For instance, Fig 3 and Fig 7 could be 2 subplots of a same figure. Or Fig 2 and 12 are not really exploited in the main paper so could go in the supplementary.

We reduce the number of figures by moving Figure 2 to the supplement and combining Figures 4 & 5 to a single three panel figure. We feel all the other remaining figures are highlighting essential information.

Generally, I think it would be good to link a bit more the processes occurring in both ice shelves in the discussion. Given their proximity and the similarity in their configuration, it is surprising to find different behaviours. For instance, in section 4.2.3 you conclude that the significant retreat of Cook West's front is probably due to intrusion of mCDW but then how do you explain that Cook East didn't experience the same retreat? (you state yourselves that the ocean source is probably the same for both ice shelves).

This is an interesting point which we now address in the main text through an additional paragraph in section 4.3. Essentially, we argue that because both ice shelves are so close to each other, they must receive a similar ocean forcing. Thus, we suggest that their difference in behaviour could be driven by different conditions at the bed as the ice shelves approach floatation, leading to different ice shelf structures and calving behaviour. We note that it is difficult to interpret the tabular calving behaviour of Cook East because it is not known what constitutes its typical or natural calving cycle because the length of its calving cycle is longer than our observational record. In some cases large tabular calving events have been attributed natural advance and retreat cycles connected to internal stresses e.g. Amery Ice Shelf (Fricker et al., 2002). However, it is not fully understood how tabular *calving events respond to climate variability. We argue that there are hints that Cook East's current calving cycle is different to its last e.g. its current ice-front positon is ~6 km further advanced than its last calving event and its present day morphology indicates that a calving event is at least a few years away.*

Specific and technical comments

L27 : "Ice which is grounded well below sea level in the marine basins of Antarctica is potentially vulnerable to marine ice sheet instability." To trigger a marine ice sheet instability, you need two conditions: 1) a bed grounded below sea-level and 2) and retrograde slope (i.e. an inland-sloping bed. It would be good to state this fact more clearly in the text. A bedrock below sea level is not sufficient alone to trigger a marine ice sheet instability. I find that your phrasing here is somehow ambiguous.

We have amended the text to clarify that marine ice sheet instability requires a bed grounded below sea level and a retrograde slope.

L39: "WAIS" is it really useful to introduce this acronym that is used only once?

We have removed the acronym.

L44: "substantial" can you give an order of magnitude?

On the order of ~3 m. This has been added to the text.

L49: "SLE" acronym not defined

Acronym defined.

L76, L83 : position not "positon"

Amended.

L78: "Errors using this method" how is it quantified?

Error from co-registration was quantified by digitizing the difference between stable features in image pairs (1 pixel). The error associated with mapping ice-front has been widely attributed to be 0.5 pixels (e.g. Miles et al., 2013; 2016). This gives a total estimated error of 1.5 pixels. We now detail this in the text.

L102: coregistration: aren't the orbital data precise enough to co-register the images? (at least for landsat 8)

Yes, for Landsat 8 the orbital data is precise enough to co-register the images without manual co-registration. For all other image pairs ASTER, Landsat 1,4 and 7 manual co-registration was required. We have now clarified this in the text.

L105: "Because these features were relatively common" the features 'are' (it's still the case).

Amended.

L107: "a grid size of 20 x 20 pixels" what do you mean? Is the spacing 20 pixels or the final grid made of 400 pixels in total? Also, what is the final resolution of your velocity fields?

The spacing is 20 x 20 pixels. This means that the final resolution of the velocity fields is 20 x the image resolution e.g. Landsat 8 300 m, Landsat 4 600 m etc. We have clarified this in the text.

L108: “Error in surface displacement was estimated at 0.5 pixels” how is it estimated? With stable surfaces?

It was estimated from manually tracking large surface features e.g. crevasses, we have amended to text accordingly.

L117: why this value of 450 m/a?

This value is chosen because it the estimated error of the Landsat – 1 image pair velocity field.

L116: Fig 2.). Bracket is missing

Amended.

L144-147. I am a bit lost here. What makes you say that? Why 2015? It’s not very clear from Fig. 4.

We know that Cook East calved at some point between 1963 and 1973, but do not know the exact date. From extrapolating the rate of advance, its maximum possible extent would have been similar to its 2015 position, meaning its current extent must be further advanced than the last point it calved. To simply this we have amended the text to simply say ‘Through extrapolating the rate of advance between 1947 and 1963 to establish Cook East’s maximum possible extent, it is clear that its present-day ice-front is further advanced than the point at which it last underwent a major calving event/retreat.’

L170-172: “This resulted in an estimated total loss of 1,200 km2 of ice shelf between 1947 and 1989. The large retreat of 5 km between November 1973 and January 1974 (Fig. 7 8)” It is visible in Fig 7 but I cannot see the 5km retreat between 1973-1974 on Fig 8. Why?

The 5 km retreat is visible on Figure 8 (top), but we did not include the 1974 measurement on Figure 8b (bottom). The amended Figure 6 does not included the second y axis ‘relative ice-front retreat since 1973), so this is no longer an issue.

L188: How can you be sure that the ice shelf has retreated in the constrained section of the embayment? Have you checked on passive shelf map from Fürst et al (2016)? Have you looked at the strain rates? I think that this claim needs to be substantiated.

On the revised Figure 2 we now include the passive ice boundary calculated in Fürst et al (2016). This shows that the ice-front positon of Cook East in 1973 was several kilometres into the constrained section of the embayment.

L202-203: I don’t agree with you when you say that “The rate of ice-front advance is not a direct estimate of velocity because there are processes such as longitudinal stretching which can result in changes in the ice-front advance rate, without altering velocity over the grounding line” While it is true that it is not a direct estimate of velocity because icebergs calve off (as you explain in the methodology). It is not correct to suggest that longitudinal stretching shouldn’t be included in velocities. This stretching is the main deformation process that occur on an ice shelf and is also what causes such fast ice flow on ice shelves (and some ice streams). It is however true that, because of longitudinal stretching, velocity of the ice shelf front is different from that of the grounding line. Moreover, how does your feature algorithm work? Does it exclude the ice-shelf front? If not, I would assume that contrasts between the ocean and the ice is a good feature to track and therefore that you would get a very reliable velocity data point at the front (in the absence of calving).

To avoid any unnecessary confusion we now remove the section 'The rate of ice-front advance is not a direct estimate of velocity because there are processes such as longitudinal stretching which can result in changes in the ice-front advance rate, without altering velocity over the grounding line'

The feature tracking algorithm does exclude the ice-shelf front. The ice-front advance rate was calculated by manually digitizing the ice-front and is described in section 2.3. We agree that in the absence of calving it does provide a very reliable estimate of velocity.

L208: "change in ice shelf thickness". Have you checked if they present Cook ice shelf in the supplementary of (Paolo, Fricker, Padman, 2015)?

We have obtained the data from Paolo et al (2015), it does show a potential ice shelf thinning episode in the late 1990s (coinciding the increase in velocity of Cook East) and considered using it in the manuscript. However because the associated error is high and it is not clear which part of the ice shelf is actually measured, we decided not to include it.

L213: "ice shelf was flowing 12In find this phrasing confusing as I understand the sentence as " the velocity at the grounding line was faster than the average of the whole ice shelf", which is not what you mean (I think). It could be a good idea to rephrase this sentence.

We have now simplified this to 'the ice shelf was flowing 12% faster than its 2001-2016 average speed' to avoid confusion.

L221: 5.2 . . . units are missing here

Amended

L223: "the calculated flow path" I get what you mean as flow paths are related to drainage basins but this is not what Fig 9 shows.

We have now added the region of most likely flow path from Flament et al (2014) to the revised Figure 7.

L250: "thinning signal is modest" which order of magnitude?

The thinning signal is in the region of 50 cm/yr. we have clarified this in the main text.

L280-285: Nice to see that!

Thanks!

L314: do you mean "discharge SINCE 1980"?

Amended

Figures

Figure 1: -I find it confusing to have Cook East and West on the left and right, respectively, as maps are generally oriented towards the north. Have you considered rotating the map to make the North appear at the top? Or adding an arrow pointing towards the north or something?

-It would be nice to have the grounding line also on the left part of the image. Have you considered another grounding line dataset like (Depoorter et al., 2013) or the updated version of the MEASURE dataset (Rignot, Jacobs, Mouginot, Scheuchl, 2013)?

-I don't find the color scale of the overview very helpful: I am not sure it is colorblindfriendly and, given the boundary of the color scale, it is hard to distinguish which part of the basin is below sea level.

-Have you considered delineating Wilkes Basin? (The overview map might be too small to discern anything though).

These are all helpful suggestions and based on these and the comments from reviewer 1 we have made amendments on Figure 1. The Figure now has two panels a) is bedmap zoomed into the Wilkes Subglacial Basin with a nicer colour scheme. b) is the original figure with the Depoorter et al. (2013) grounding line and we have also inserted a north arrow to avoid confusion.

Figure 2: -As the limit of the color scale varies for every map, it is hard to compare them. -What is shown in background? Landsat images?

We have now amended the colour scale so it is consistent for each set of images and clarify that the background images are the corresponding Landsat images. We have now moved this figure to the supplement.

Figure 4 -It might be good to specify here as well that the ice-front position is taken in the box delineated in Fig 3

-I am confused here: you claim that ice-front advance accelerates (cf Fig 3) but in Fig 4 all what we see is a straight line, which suggests a constant advance.

The purpose of Figure 4 is to show the long term calving cycle of Cook East which is an important observation, this requires a y-axis scale range in the order of 35 km. The magnitude of the increase in ice-front advance shown in Figure 5 (Now Figure 3) is in the order 50m/yr. This equates to a ~12% increase in ice-front advance, which is significant, but also would not be clear on a y-axis scale of 35 km. For example, if the ice-front is advancing an additional 50m/yr, over 20 years it would mean an additional 1 km advance than it otherwise would have if its advance rate had remained constant. On a y-axis scale of 35 km an additional advance of ~1 km is relatively small, hence why the increase in ice-front advance is not clear. Essentially, it is a question of scale. We now specify that the ice-front position is taken from the box delimited in Figure 3 (now Figure 2).

Figure 5: -Using the same color as the lines in Fig 3 (or Fig 6), could help identifying the data points you are referring to.

-Have you thought about marking the different periods you're referring to in the text?

We do not use the same colour as the lines in Fig. 3. We feel these figures have different purposes and not want to confuse them. Fig 3 (Now Fig.2) shows the longer term evolution of Cook East and because of the scale of the figure it is very difficult to see the acceleration in its ice-front advance rate shown in Figure 5 (Now 3c). We do however note the accelerations referred to in the text in the figure caption.

Figure 7 -To improve the readability of the figure I would suggest to delineate the grounding line with a dashed line.

The grounding line is now a dashed line.

Figure 8 -I find this figure a bit hard to read -I am not sure than the right part (relative ice-front change) of the bottom panel is adding much information. However, if you decide to keep it, you

could consider changing the color of labelling, to match the color of the markers. -It is confusing to have different x-axis boundaries for the top and bottom panels

To simplify this we have now removed the 'relative ice-front change' additional axis from the bottom panel.

Figure 9 -Same comment as for the overview in Fig 1 -The star that locates Lake cook is relatively hard to spot, could you make it appear more clearly? -I also think it would be interesting to delineate the ice shelves

We have changed the colour scheme and made the location of Lake Cook clearer. We have also added the most likely flow route of Lake Cook from fig. 7 (Flament et al., 2014) and delineated the ice shelves.

Figure 10 The lightest lines (2009 on the left and 2014 on the right) are not very visible.

The colour scheme has been amended to a bright and more visible yellow.

Figure 11 It could be a nice addition to delineate the grounding line here.

The grounding line has been added.

Figure 12 I think units are missing on the y-axis

Amended

Velocity increases at Cook Glacier, East Antarctica linked to ice shelf loss and a subglacial flood event

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Abstract: Cook Glacier drains a large proportion of the Wilkes Subglacial Basin in East Antarctica, a region thought to be vulnerable to marine ice sheet instability and with potential to make a significant contribution to sea-level. Despite its importance, there have been very few observations of its longer-term behaviour (e.g. of velocity or changes at its ice front). Here we use a variety of satellite imagery to produce a time-series of ice-front position change from 1947-2017 and ice velocity from 1973-2017. Cook Glacier has two distinct outlets (termed East and West) and we observe the near-complete loss of the Cook West Ice Shelf at some time between 1973 and 1989. This was associated with a doubling of the velocity of Cook West glacier, which may also be linked to previously published reports of inland thinning. The loss of the Cook West Ice Shelf is surprising given that the present-day ocean-climate conditions in the region are not typically associated with catastrophic ice shelf loss. However, we speculate that a more intense ocean-climate forcing in the mid-20th century may have been important in forcing its collapse. Since the loss of the Cook West Ice Shelf, the presence of landfast sea-ice and mélange in the newly formed embayment appears to be important in stabilising the glacier front and enabling periodic advances. We also show that the last calving event at the larger Cook East Ice Shelf resulted in the retreat of its ice-front into dynamically important ice and observe a short-lived increase in velocity of Cook East between 2006 and 2007 which we link to the drainage of Subglacial Lake Cook. Taken together, these observations suggest that the velocity, and hence discharge, of Cook Glacier is highly sensitive to changes at its terminus but a more detailed process-based analysis of this potentially vulnerable region requires further oceanic and bathymetric data.

1. Introduction

Ice which is grounded well below sea level in the marine basins of Antarctica with an inland-sloping bed is potentially vulnerable to marine ice sheet instability. This is because an initial grounding line retreat into deeper water can create an unstable and self-sustaining feedback leading to increased ice discharge, inland thinning, and a rapid sea level contribution (Hughes, 1981; Schoof, 2007). Floating ice shelves are crucial to the stability of ice streams and outlet glaciers that drain marine basins because they can exert an important buttressing effect (Furst et al., 2016). Thinning or retreat of these ice shelves reduces their ability to restrain flow from the ice sheet (Pritchard et al., 2012). This is evident in parts of the West Antarctic Ice Sheet where the feedbacks resulting from the rapid thinning of ice shelves (Paolo et al., 2015) has resulted in an increased discharge of ice into the ocean (Mouginot et al., 2014). This oceanic-driven thinning of ice shelves may have destabilized the Thwaites Glacier basin, where marine ice sheet instability may already be underway, and which might undermine much of the WAIS over the coming decades to centuries (Joughin et al., 2014).

The Wilkes Subglacial Basin (WSB) in East Antarctica contains 3-4 m of sea level equivalent of ice grounded below sea level (Mengel and Levermann, 2014). Geological evidence suggests the WSB may have made substantial (~3 m) sea level contributions during the warm interglacials of the Pliocene (Williams et al., 2010; Cook et al., 2013; Bertram et al., 2018), which are thought to represent the best analogue for near-future climates under continued global warming. Indeed, numerical ice sheet models predict future sea-level contributions from the WSB, but the magnitude and timing of the contributions varies (Golledge et al., 2015; Ritz et al., 2015; DeConto and Pollard, 2016). Furthermore, dynamical modelling of the present day ice-sheet margin of the WSB shows that its stability might be controlled by a relatively small band of coastal ice (~80 mm Sea Level Equivalent), which is preventing a self-sustained discharge of the entire basin (Mengel & Levermann, 2014). The majority of this coastal band of ice is drained by Cook Glacier (Mengel & Levermann, 2014), which is one of the largest in Antarctica. Its current configuration consists of two distinct distributaries: Cook East and Cook West (Fig. 1). Cook East flows into a large 80 km long ice shelf, whereas Cook West terminates close to, or at, its grounding line (Fig. 1). Despite having one of the largest annual discharges of any Antarctic outlet glacier (Rignot et al., 2013) (~36 Gt a^{-1}), and given its potential significance to the stability of the WSB, there have been very few observations of its recent behaviour. Along with Totten Glacier, it was specifically highlighted in the most recent IPCC report (2013) as being potentially vulnerable to marine ice sheet instability but, unlike Totten, there has been no obvious changes in ice shelf thickness, ice surface elevation or grounding line position over the past decade (Pritchard et al., 2009; McMillan et al., 2014; Paolo et al., 2015; Konrad et al., 2018). However, some studies have previously highlighted Cook as a region of modest inland thinning (e.g. Shepherd and Wingham, 2007) and Frezzotti et al. (1998) reported a major retreat of the Cook West Glacier, which others have suggested might be flowing too fast to be in balance (Rignot, 2006). In this paper, we report on the long-term changes in Cook Glacier by combining measurements of ice-front position from 1947-2017, together with glacier velocity estimates from 1973-2017 from optical based feature-tracking. Our results indicate that despite little change over the past decade, there has been a long-term increase in the velocity of both Cook East and Cook West Glaciers that can be linked to changes at its ice-front.

2. Methods

2.1 Ice-front position change

We revisit and extend the results of Frezzotti et al. (1998) by using a combination of oblique aerial photography from 'Operation Highjump' in 1947, ARGON, RADARSAT, ASTER, Landsat and WorldView-2 satellite imagery to create a 70 year time-series of ice-front position change from 1947-2017 for both Cook West and Cook East glaciers (Table S1). Changes in ice-front position were quantified by the well-established box method which takes into account uneven changes along the ice-front (e.g. Moon and Joughin, 2008). Errors using this method arise from the co-registration of satellite images, quantified by digitizing the distance between stable features on image pairs (1 pixel) and the manual digitization of the ice-front, which has been calculated at 0.5 pixels in other studies (e.g. Miles et al., 2013; 2016), giving an estimated total error of 1.5 pixels (22.5 – 90 m). These errors are in the range of similar studies and are insignificant when quantifying ice-front position change of large Antarctic outlet glaciers (Miles et al., 2013; 2016). Because the 1947 aerial photographs were taken at an oblique angle we estimate the ice-front position relative to stable features which have not moved over time (e.g. ice rises). This creates larger uncertainties compared with measurements from orthorectified satellite imagery. We estimate these uncertainties at ~±2 km.

2.2 Glacier velocity from feature tracking

Estimates of glacier velocity were derived using COSI-Corr (Co-registration of Optically Sensed Images and Correlation) feature-tracking software (Leprince et al., 2007; Scherler et al., 2008). This software tracks spectral signatures which relate to features on the glacier surface that can be identified in multiple images through time, and it has been shown to be one of the most robust methods of glacier velocity mapping (Heid and Kääb, 2012). It requires pairs of co-registered optical cloud-free images which are spaced close enough in time for surface features to be identified in both images. In this study, the temporal resolution of image pairs was largely determined by the availability of appropriate satellite imagery, which was generally sparse due to a combination of poor coverage and persistent cloud cover. However, by using a combination of Landsat-1, Landsat-4, Landsat-7, ASTER and Landsat-8 we were able to create a velocity time series from 1989-2016 for Cook East (Table S2) and 1973-2017 for Cook West (Table S3). Image pairs were typically spaced 1 year ± 100 days apart, which is a suitable gap for the preservation of surface features. The exception to this was in 1973-74 where image availability only allowed temporal gap of 73 days (Table S3).

The COSI-Corr procedure first requires the accurate co-registration of image pairs. For Landsat 8 image pairs the orbital data was of sufficient quality that no further manual co-registration was required. However, for all other image pairs, manual co-registration was required and was achieved by using a combination of nunataks and the boundaries of ice rises, which are known to be stable features over time. Because these features are relatively common in the vicinity of Cook Glacier, images pairs could be co-registered to an estimated accuracy of 1 pixel. We used a window size of 256 x 256 pixels and a grid size of 20 x 20 pixels to detect surface displacement, which results in the production of velocity fields at a resolution of 20 times coarser of the pixel resolution of the image pair (Table S2 and S3). Error in surface displacement was estimated at 0.5 pixels by manually tracking large surface features, which is consistent with other studies using this method (Scherler et al., 2008; Heid and Kääb, 2012). Total error ranged from ±51 m yr^{-1} in 1989 to between ±19 and ±24 m yr^{-1} from 2000-2017 (Table S2 and S3). The coarser resolution and closer temporal resolution of the 1973/4 Landsat-1 image pairs resulted in a considerably higher error of ±450 m yr^{-1} (Table S3).

Post-processing of ice velocity grids can reduce noise and remove erroneous pixels (e.g. Mouginot et al., 2017). We removed pixels which were greater than ±25% of the MEASURES ice velocity product (Rignot et al., 2011) in velocity grids from 2000-2017 and ±40% in the velocity grid from 1989 to account for any larger changes in glacier velocity. For the 1973/4 velocity grid, we filtered out all pixel values below 450 m yr^{-1} to account for the larger error of the Landsat-1 image pair. We then applied a low pass filter to all velocity grids to create the final products (Fig. S1). To create the velocity time series we extracted the mean value of pixels within a defined box across all epochs, in each epoch all pixels were sampled within the defined box i.e. there were no rejected pixels. For Cook East the defined box was on a section across the grounding line (Fig. S1), because Cook West terminates close to its grounding line we extracted velocities 2 km upstream (Fig. S1).

2.3 Ice-front advance rate

Preliminary inspection of the imagery clearly indicated that there have been no major calving events on the Cook East Glacier since 1973 because the shape of the ice margin is unchanged. Thus, we were able to create a time series of the rate of ice-front advance between 1973 and 2016. Although it is not a direct measurement of glacier velocity, the rate of ice-front advance is helpful in enabling additional independent estimates of ice advance (a proxy for ice velocity at the terminus if no major calving events have taken place) further back in time (i.e. between 1973 and 1989) and allows additional measurements to be made in the 1990s (Table S4). Ice-front advance rate was quantified by dividing ice-front position change by the number of days between image pairs. Taking into account the error of 1.5 pixels associated with co-registration and manual mapping, errors were estimated between ±1 to ±86 m yr^{-1} with range in error accounting for the varying spatial resolution of images and the temporal gap between image pairs (Table S4).

3. Results

3.1 Cook East

The Cook East Ice Shelf last underwent a major calving event at some point between 1963 and 1973 (Fig 2 & 3). This calving event resulted in the retreat of its ice-front deep into the constrained section of its embayment, resulting in the loss of all passive ice and retreat into the dynamically constrained section of the ice shelf. (Fig. 2). Since 1973 it has advanced ~31 km and there have been no major calving events. By extrapolating the rate of advance between 1947 and 1963 to establish Cook East's maximum possible extent, it is clear that its present-day ice-front is further advanced (by ~6 km) than the point at which it last underwent a major calving event/retreat.

The velocity of Cook East increased approximately 20% from 416 ±51 m yr^{-1} in 1989 to 496 ±19 m yr^{-1} in 2000/01 (Fig 3b). Throughout 2001 to 2016 velocity remained consistent with an average speed of 489 m yr^{-1}, with little year to year deviation. The only exception to this was between 2006 and 2007 where Cook East was flowing 12% (545 ±22 m yr^{-1}) faster than its 2001-2016 average. Velocity profiles across the Cook East Ice Shelf show similar patterns (Fig. 4), with the exception of 1989 and 2006-07, all profiles are clustered in a narrow band. In 1989 velocity was anomalously slow across the entire ice shelf and between 2006 and 2007 velocity was anomalously fast. Notably, these patterns also persist several kilometres upstream of the grounding line (Fig. 4).

There was little change in the rate of mean ice-front advance between 1973 and 1997. However, from 1997-2000 (720 ±20 m yr^{-1}) and 2002-2006 (749 ±8 m yr^{-1}) there was a consistent increase in the rate of ice-front advance (Fig. 3c). This is consistent with velocity estimates from the grounding line which show an increase in velocity between 1989 and 2001. Throughout 2002-2016 there were small internannual variations in ice-front advance rate, with no obvious trend. In a similar manner to velocity estimates from the grounding line, the only exception to this was between 2006 and 2007 where the ice front advanced at 792 ±30 m yr^{-1}, higher than the 2002-2016 average (752 m yr^{-1}) (Fig. 3c).

3.2 Cook West

From 1947 to 2018 the Cook West ice-front retreated approximately 34 km (Fig. 5 & 6). This retreat largely occurred in two stages, with retreat initiating between 1947 and 1963 when Cook West retreated 20 km, before stabilizing between 1963 and 1973 when the ice-front retreated 2.8 km and there was no obvious change in the surface structure of the ice shelf (Fig. 5). From 1973 to 1989 the remaining section of Cook West's Ice Shelf retreated 13 km close to, or onto, its present grounding line (Fig. 5 & 6). This resulted in the estimated total loss of 1,200 km^2 of ice shelf between 1947 and 1989. The large retreat of 5 km between November 1973 and January 1974 (Fig. 5 & 6) suggests that this retreat was more likely to have occurred in the mid-1970s. Since 1989, observations show relatively little change, with only minor fluctuations (~3 km) in ice-front position. Perhaps surprisingly, we observe no signs of a re-advance of Cook West Glacier comparable to its pre-1989 ice-front position.

The velocity of Cook West Glacier increased from 692 ±450 m yr^{-1} in 1973/4 to 1438 ±51 m yr^{-1} in 1989 (Fig. 6b). Although the error associated with the 1973/74 measurement is high, the pair of measurements still demonstrate a major increase in velocity, which coincides with the retreat of the Cook West ice-front (Fig. 6b). There were small variations in the velocity of Cook West between 2001 and 2017, with no velocity estimates deviating from ±5% of the 2001-2017 mean (1368 m yr^{-1}). Between 2001 and 2017, Cook West was flowing fastest from 2001-2002 at 1463 ±24 m yr^{-1} and slowest from 2016-2017 at 1306 ±22 m yr^{-1} (Fig. 6b).

4. Discussion

4.1 Cook East

4.1.1 Long-term behaviour the Cook East Ice Shelf

The calving of the Cook East Ice Shelf between 1963 and 1973 resulted in the loss of dynamically important ice (Furst et al., 2016) (Fig. 2). The retreat of large Antarctic ice shelves into the dynamically important sections of their embayment is unusual (Fig. 2), where calving events typically occur within the bounds of the unconstrained section of ice shelves (Miles et al., 2013). However, since the retreat between 1963 and 1973, the Cook East Ice Shelf has re-advanced and has remained stable, which is reinforced by data suggesting that there has been little change in the grounding line position of Cook east in recent years (Konrad et al., 2018). This indicates that a terminus retreat deep into an ice shelf embayment does not necessarily result in an irreversible retreat. This observation could be an important consideration in improving our understanding on how recent and future large calving events influence ice shelf stability in Antarctica e.g. Larsen C (Jansen et al., 2015). The return period of any potential calving cycle at Cook East may be too long to determine if this relatively deep retreat into the embayment is typical of its normal behaviour (Fig. 2 & 3). Based on the morphology and size of an iceberg located near the Mertz Ice Tongue in satellite imagery in 1984, Frezzotti et al. (1998) estimated that the calving of Cook East between 1963 and 1973 occurred in the early 1970s. This means that its current ice-front position is further advanced than its last calving event (Fig. 3a). However, an inspection of the current morphology of the Cook East Ice Shelf reveals no obvious signs of an imminent calving event and we suggest another calving event is at least several years away.

The increase in velocity between 1989 and 2000-2001 (416 ±51 m yr^{-1} to 496 ±19 m yr^{-1}) coincided with an increase in the ice front advance rate and notably, most of this acceleration is concentrated between 1997 and 2002 (Fig. 3c). On the basis of this, we suggest that the increase in velocity between observations in 1989 and 2000-01 is likely to have occurred in the late 1990s. There are limited oceanic data available to investigate possible changes in oceanic conditions, but a potential mechanism could be changes in ice shelf thickness driven by enhanced basal melting. Indeed this increase coincides with the intense 1997/98 El Nino event which has been linked to abrupt changes in environmental conditions in the Pacific sector of Antarctica and ice shelf mass loss (Paolo et al., 2018).

4.1.2 Drainage of subglacial Lake Cook and short-lived velocity increase

Between the 1st December 2006 and 4th December 2007, the Cook East Ice Shelf was flowing 12% faster than its 2001-2016 average speed (Fig. 3b). A similar speed-up is also evident on the grounded ice upstream and across the entire ice shelf (Fig. 4). This is a greater magnitude of change than expected by interannual variability. In Antarctica, a small number of short-lived accelerations in glacier flow have been observed and linked to subglacial flood events perturbing basal conditions and leading to enhanced lubrication (e.g. Stearns et al., 2008; Scambos et al., 2011; Siegfried et al., 2016). Between November 2006 and March 2008, we note that a subglacial lake drained ~450 km upstream of Cook East Glacier (Smith et al., 2009; McMillan et al., 2013; Flament et al., 2014), resulting in the discharge of 5.2 ± 1.5 km^3 (Flament et al., 2014) or between 4.9 and 6.4 km^3 (McMillan et al., 2013) of water, the largest single subglacial drainage event ever recorded. The calculated flow path suggests that the flood could have reached Cook East, but not Cook West (Flament et al., 2014; Willis et al., 2016) (Fig. 7). Because the timing of these two events coincide, we suggest that the acceleration of Cook East Glacier could have been triggered by the drainage of the Cook subglacial lake. The quick response time between the onset of the drainage event and the increase in velocity suggests that at least some of the flood water flowed rapidly through existing channels, even if some of the floodwater was stored in connecting subglacial lakes (Flament et al., 2014). This adds to the few observations which link changes in subglacial hydrology to glacier flow dynamics in Antarctica (e.g. Stearns et al., 2008; Scambos et al., 2011; Siegfried et al., 2016). This is important because there are a number of other subglacial lakes which could be routed through Cook East Glacier (Wright et al., 2008). If any changes in subglacial hydraulic conditions occur in the future, the sensitivity of Cook East to perturbations in its basal conditions could be an important consideration.

4.2 Cook West

4.2.1 Link between ice shelf retreat and increased velocity

The near-complete loss of the Cook West Ice Shelf (Fig. 5 & 6) is highly unusual in the context of East Antarctic outlet glaciers in the past 50 years. Broad trends in their ice-front position have been linked to climate at decadal timescales, but no other East Antarctic ice shelves have been observed to retreat to their grounding lines and then not re-advanced (Miles et al., 2013; 2016). Our results show that the near-complete loss of the Cook West Ice Shelf between 1973 and 1989 coincided with a likely doubling of Cook West's velocity (Fig. 6). This suggests that the increase in velocity was linked to a reduction in buttressing caused by the loss of the Cook West Ice Shelf. It would be expected that an increase in velocity of such magnitude would be accompanied by dynamic inland thinning. Consistent with this notion are satellite altimetry records that, despite covering different time periods between 1992 and 2010, all report an inland thinning signal upstream of Cook West (Davis et al., 2005; Zwally et al., 2005; Shepherd and Wingham, 2007; Pritchard et al., 2009; Flament and Remy, 2012; Schröder et al., 2018). The thinning signals are modest (~50 cm yr^{-1}) in comparison to observations in the Amundsen Sea Sector, but we note that these observations were made, in some cases, decades after the loss of the Cook West Ice Shelf. Thinning rates could have been higher in the immediate years following ice shelf retreat, as observed in the Crane Glacier which formerly flowed into the Larsen B Ice Shelf (e.g. Rott et al., 2018). However, from 2010 onwards inland thinning upstream of Cook West appears to have slowed down or ceased (McMillan et al., 2014), suggesting that the system might be approaching equilibrium following the loss of the Cook West Ice Shelf.

4.2.2 Behaviour of Cook West post ice shelf loss

Since the near-complete loss of the Cook West Ice Shelf, the ice-front has fluctuated by ~3 km, but there have been no signs of a substantial re-advance (Fig. 5 & 6). As a consequence of the increase in Cook West's velocity following the retreat of its ice shelf, its strain rate near the ice-front will have increased (Benn et al., 2007). This may explain the absence of a re-advance because the increase in strain rate has resulted in an increase in the calving rate. However, because the ice-front position fluctuates by ~3 km it suggests that other external factors may also be important in stabilising the ice front position.

The retreat of the Cook West Ice Shelf resulted in the formation of an embayment, which has been growing in size as the neighbouring Cook East Ice Shelf advanced (Fig. 1). This embayment is typically filled with landfast sea-ice, which may act to stabilize ice tongues (Massom et al., 2010). Conversely, sea-ice break-out events have been linked to major instability and calving events elsewhere in East Antarctica (Miles et al., 2017). Whilst we observe calving events with sea-ice present, and leading to the build-up of ice mélange at the ice-front, the continuous presence of landfsat sea-ice and mélange appears to be important in enabling ice-front advance (Fig. 8). Between 2009 and 2013 the Cook West ice-front maintained approximately the same position (Fig. 8a), suggesting that repeated calving events prevented ice-front advance. Using the MODIS Worldview viewer, we observe multiple sea-ice break-out events during this time period. In contrast, between 2014 and 2016 the ice-front advanced ~3 km, during which we observe no break-out events and see that landfast sea-ice and mélange were continuously present at the ice-front (Fig. 8b). This suggests that the backpressure applied by the landfast sea-ice and mélange was enough to limit calving and enable ice-front advance. This behaviour is similar to seasonal ice-front fluctuations of some outlet glaciers in Greenland, where the seasonal formation of mélange inhibits calving resulting in ice-front advance (e.g. Amundsen et al., 2008; Todd and Christoffersen, 2014). The annual resolution of our data makes it difficult to determine if these fluctuations in ice-front position have a direct effect on the velocity of Cook West because calving events occur on a sub-annual scale. Future investigation into this process is important because the interaction between ice-front position, landfast sea-ice, mélange and ice dynamics, following the loss of ice shelves is poorly understood in Antarctica, and might be an important process missing in current numerical models simulating future sea level contributions from the ice sheet (e.g. Golledge et al., 2015; DeConto and Pollard, 2016). The recent behaviour of Cook West could be one of the clearest modern-day observations for this process.

4.3 What caused the calving behaviour of the Cook Ice Shelves?

Despite their close proximity, the behaviour of the Cook East and Cook West Ice shelves differ over the observational period. This can potentially be explained by the contrasting structures of the ice shelves. Inspection of the Cook East Ice Shelf (Fig. 2) shows little evidence of crevassing or fracturing throughout the observational period, whereas the Cook West Ice Shelf (Fig 5b, c, d) was heavily crevassed and comparatively structurally weaker. This resulted in a different type of calving behaviour whereby Cook East underwent infrequent tabular calving events, whilst Cook West underwent more frequent disintegration-type calving events (e.g. Liu et al., 2015). The contrasting calving style, is unlikely to have been driven by environmental forcing, as inferred by Liu et al. (2015) for some other Antarctic ice shelves, because the proximity of both ice shelves means they are likely to receive similar forcing. Instead, it is more likely that the underlying bed topography where the ice shelves approach floatation is more important (e.g. Bassis and Ya, 2015). However, even taking into consideration the structurally weak nature of the Cook West Ice Shelf, there still must have been significant ocean-climate forcing in order to force the complete loss of its floating ice shelf.

The widespread retreat of outlet glaciers in the Antarctic Peninsula (Cook et al., 2016) and the collapse of the Larsen B Ice Shelf (e.g. Scambos et al., 2003) have been linked to an increase in surface air temperatures and warm ocean forcing; while the rapid thinning of ice shelves in the Amundsen Sea Sector and at Totten Glacier have been linked to intrusions of modified Circumpolar Deep Water (mCDW) (e.g. Jenkins et al., 2010; Rintoul et al., 2017). Satellite and modelled estimates of the present day basal melt rate of the remaining Cook East Ice Shelf are low suggesting that, on average, it receives a relatively weak ocean heat source (Depoorter et al., 2013; Rignot et al., 2013; Kusahara et al., 2017). Given the proximity of Cook East to Cook West, it is also likely that Cook West also receives a relatively weak oceanic heat source. We also do not observe any surface melt features in the form of supraglacial lakes or channels during our observations and regional ice core records show no long-term trend in accumulation (Goursaud et al., 2017). Thus, these are not the ocean-climate conditions which would typically be associated with the retreat, thinning or catastrophic loss of ice shelves. Therefore, it is likely that the rapid and near-complete loss of the Cook West Ice Shelf was driven by ocean-climate conditions that were likely quite different from present-day.

Multiple studies point towards a shift in climate towards greater decadal extremes since the mid-20th century in the wider Cook-Ninnis-Mertz region (Fig. 9). Reconstructions of sea surface conditions over the past 250 year show that since 1960 there has been an increase in glacial meltwater as more intense winds enhance mCDW intrusions onto the continental shelf (Campagne et al., 2015). This deviates from the cyclic behaviour of sea surface conditions driven by the periodic formation of the Mertz polynya in association with the ~70 year calving cycle of the Mertz Tongue (Campagne et al., 2015; Giles, 2017). Reconstructions of ice discharge of the region from marine sediment cores west of Mertz show an increase in ice discharge since ~1980, the magnitude of which might be unprecedented throughout the Holocene (Crespin et al., 2014). This was linked to an out of phase calving event of the Ninnis Glacier (Crespin et al., 2014), but we suggest the increase in discharge of Cook West following the loss of its ice shelf may have also contributed to this recorded increase in ice discharge.

In addition, a climate coupling exists between the Cook-Ninnis-Mertz region and New Zealand's glaciers, whereby large-scale atmospheric waves connect the two regions (Crespin et al., 2014; Mackintosh et al., 2017). The onset of the rapid retreat of mountain glaciers in New Zealand occurred around the 1940s; this retreat continued at varying rates until the 1990s, when glaciers advanced in response to regional cooling (Mackintosh et al., 2017). A similar trend is seen in the Cook-Ninnis-Mertz region; along with Cook West (Fig. 5), Ninnis Glacier underwent a major retreat in the 1940s (Frezzotti et al., 1998) and there was a switch from dominant outlet glacier retreat across the wider region in the 1970s and 80s to cooler conditions and glacier advance from 1990 to 2010 (Miles et al., 2013). A similar change in wind pattern may also be reflected in temperature reconstructions from 1870 to 2010 in the New Zealand subantarctic islands, which lie directly between the Cook-Ninnis-Mertz region and New Zealand, where there is an abrupt switch towards a more variable climate from the 1940s onwards (Turney et al., 2017). Evidence of such variability is also recorded in wind direction at the nearest research station, Dumont d'Urville, where there was an abrupt shift in the 1990s towards more easterly winds (Fig. 10). Taken together, analysis of these studies hints at warmer regional climate during periods of the mid-20th century and a cooler climate from the 1990s onwards. This is consistent with our interpretation that warmer than present ocean-climate forcing is likely to have driven the rapid retreat of the Cook West Ice Shelf.

At present there have been no subsurface ocean measurements in the immediate vicinity of Cook West Glacier. However, the local oceanography west of Cook near the Mertz and Ninnis Glaciers is one of the most extensively studied in Antarctica (Beaman et al., 2011; Kusahara et al., 2011; Williams et al., 2011; Tamura et al., 2012; Campagne et al., 2015; Aoki et al., 2017). Numerical modelling has suggested that a key component of the local oceanography in the Mertz-Ninnis region is the westward advection of warm mCDW from a depression on the continental shelf in front of Cook glacier (Kusahara et al., 2017) (Fig. 9). The amount of warm mCDW advected onto the continental shelf from the bathymetric depression is sensitive to both interannual variability in atmospheric forcing and large changes in the regional 'icescape' (e.g. calving of the Mertz Glacier Tongue) (Cougnon et al., 2017; Kusahara et al., 2017). Therefore, the more variable climate in the mid-20th century may have resulted in greater mCDW intrusions. There have been no observations of the bathymetry in front of Cook Glacier so it is not known if there are any connecting troughs to this depression which could facilitate the delivery of warm mCDW intrusions towards the Cook outlets. However, given the proximity of a potential ocean heat source to the Cook West Glacier and the absence of any other obvious drivers, we suggest that periodic mCDW intrusions forced by a more variable climate could have been important in driving the rapid retreat of the Cook West Ice Shelf. It is possible that any climatically-forced initial retreat of the Cook West Ice Shelf could have been enhanced if contact with a bathymetric pinning point was lost, but we do not see any evidence of icebergs grounding on any former pinning point since its retreat. However, we do note that the loss of the Cook West Ice Shelf must have occurred shortly after the calving of the neighbouring Cook East Ice Shelf between 1963 and 1973. Therefore, any loss of contact with the neighbouring Cook East Ice Shelf may have had a destabilizing effect on Cook West increasing its vulnerability to retreat (e.g. Albrecht and Levermann, 2014).

The tabular calving regime of the Cook East Ice Shelf means its observed behaviour is more challenging to interpret than the neighbouring Cook West. Cyclic tabular calving events are typically considered to be part of a natural cycle of advance and retreat linked to the internal stress regimes of ice shelves e.g. from the Ross Ice Shelf (Joughin and MacAyeal, 2005) and Amery Ice Shelf (Fricker et al., 2002); and/or bathymetric constraints e.g. at Mertz ice tongue (Giles et al., 2017). However, the potential impact of multi-decadal climate variability on have on the periodicity and magnitude of major calving events has only rarely been considered. Whilst it is difficult to interpret any changes in the calving cycle of Cook East Ice Shelf owing to the lack of calving observations, there are notable differences between its current cycle and its previous calving cycle. Its present day ice-front position is around 6 km further advanced than its estimated maximum in the previous calving cycle. Given that there are no obvious rifts and that these can take years to fully develop, it likely that its next calving event will be from a significantly more advanced position than the last event between 1963 and 1973. Furthermore, the unusually deep retreat of the Cook East ice-front into the dynamic section of the ice shelf in the 1970s (Fig. 2) possibly indicates that it calved earlier and deeper than it perhaps would have under a natural cycle of advance and retreat. Therefore, the behaviour of the Cook East Ice Shelf may also be consistent with a more variable climate in the mid-20th century (e.g. Crespin et al., 2014; Campagne et al., 2015; Turney et al., 2017) driving its deep retreat into its embayment, whilst the cooler conditions of the more recent decades are associated with the advance and stability of the ice shelf. Future investigation is needed on the potential influence of climate variability into the long-term calving cycles of medium to large ice shelves in Antarctica.

5. Conclusion

We have shown that despite little change over the most recent decade, there have been dynamic changes in the velocity of both the Cook East and West glaciers during periods over the past ~45 years. For Cook East we provide one of the few observations linking a short-lived increase in velocity to a subglacial flood event, in addition to a longer-term velocity increase of approximately 20% between 1989 and 2001. For Cook West we link a doubling of its velocity to the near-complete loss of its floating ice shelf between 1973 and 1989, which may have been forced by a more variable climate in the mid-20th century. Since the loss of the Cook West Ice Shelf, there have been no signs of a comparable re-advance, but small cycles in ice-front position appear to be linked to sea-ice conditions.

The changes we observe highlight the importance of extending observational records of glacier change in Antarctica, which are typically confined to satellite altimetry and velocity measurements from the mid-1990s onwards. It is possible that in regions where there is multi-decadal climate variability, this may not be a long enough time-period to assess the sensitivity of outlet glaciers to changes in climate. In the case of Cook West, the changes in velocity we observe in response to the loss of its floating ice shelf are some of the largest recorded in the satellite era in Antarctica. However, in terms of observations of subsurface ocean temperatures, bathymetry and bed topography, it is one of the least studied. This needs to be addressed in order to fully understand the processes driving changes in the recent past and improve our understanding on how it will respond to future changes in climate. This is important because Cook Glacier drains a large proportion of the Wilkes Subglacial Basin and may have the potential to make future rapid sea level contributions.

Data Availability: Landsat and ARGON imagery along with the aerial photography used in this study are freely available from Earth Explorer. Cosi-Corr is an ENVI plug-in and can be freely downloaded via its webpage. GEBCO bathymetric data is available to download from https://www.gebco.net/. Meteorological data from Dumont d'Urville is available from the SCAR MET READER. Ice-front position shapefiles and velocity grids are available from the corresponding author.

Author Contributions: BM conceived the study, designed and executed the method presented in the research, conducted the analysis, and drafted the original manuscript. All authors discussed the results and contributed towards editing the manuscript.

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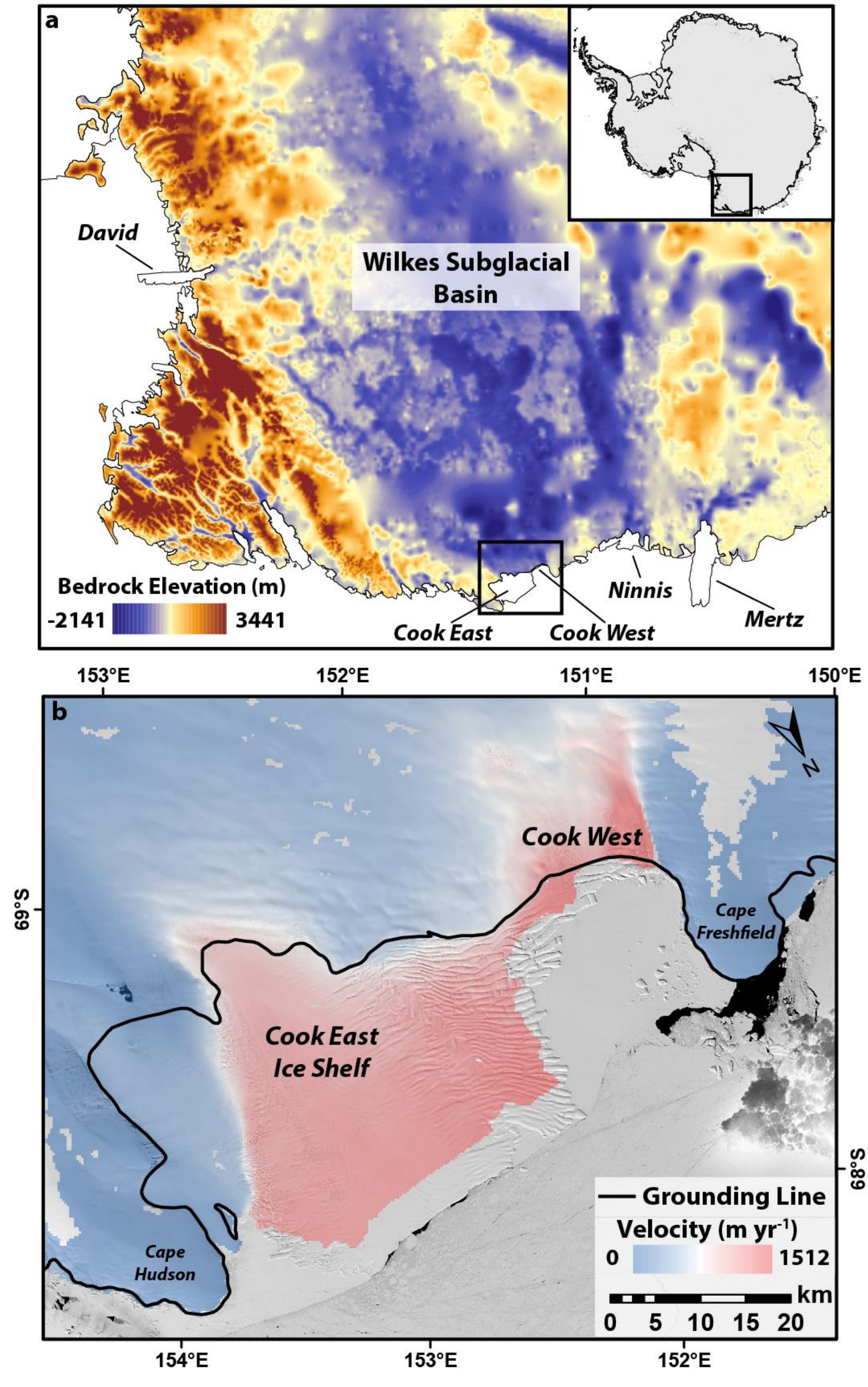
Figures



690 **Figure 1:** **a)** Bedmap-2 bed elevation of the Wilkes Subglacial Basin (Fretwell et al., 2013), note that Cook East and West drain a large proportion of the Wilkes Subglacial Basin. **b)** Landsat-8 image of Cook East and West Glaciers from February 2017, overlain with velocities (Rignot et al., 2011b) and grounding line (Depoorter et al., 2013).

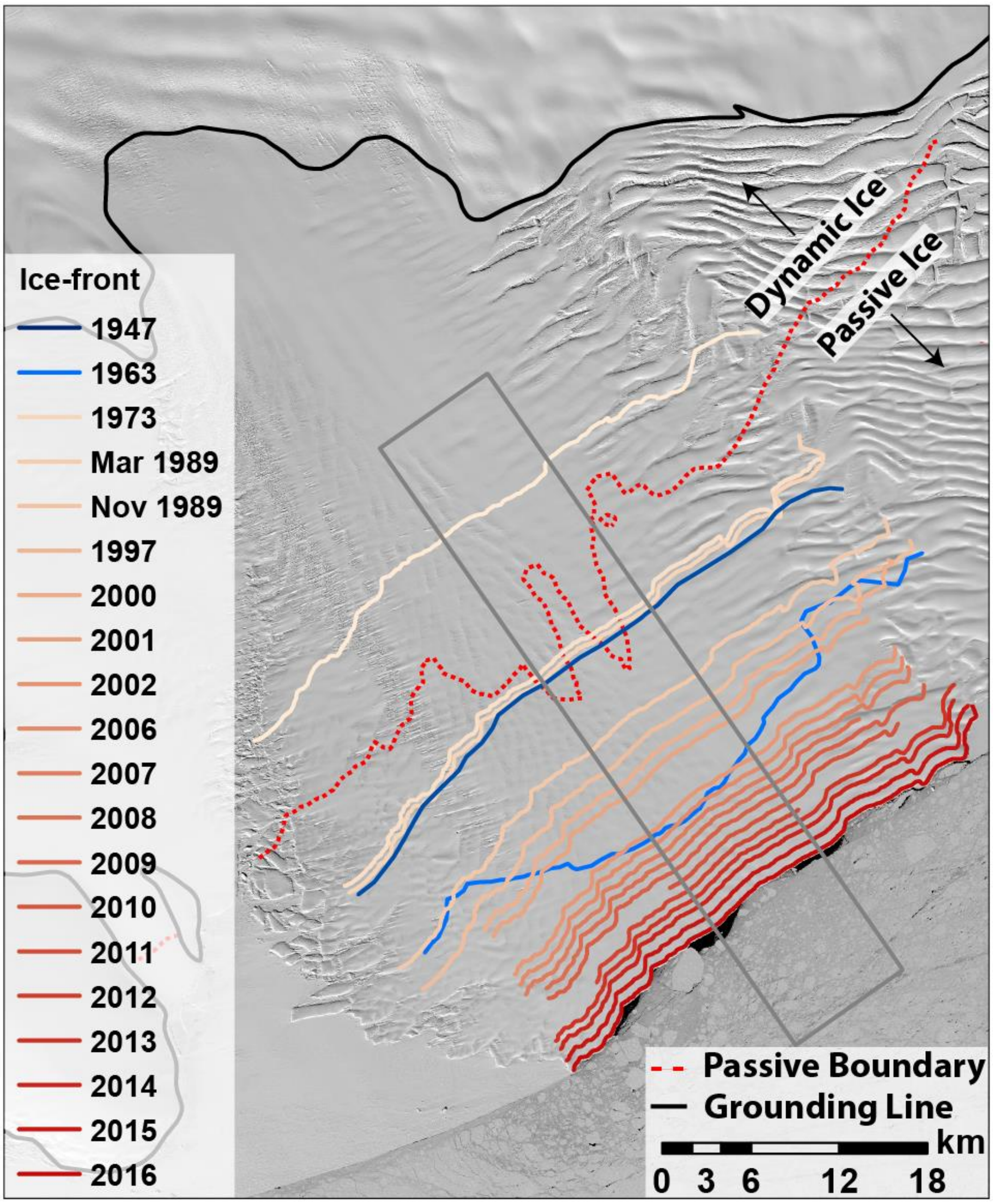


Figure 2: Mapped ice-front position of the Cook East Ice Shelf between 1947 and 2016, with the passive ice boundary overlain (Furst et al., 2016). Note that the 1973 ice-front position of Cook East lies several kilometres inland the of the passive ice boundary. The grey box delineates the region where ice-front position change was calculated.

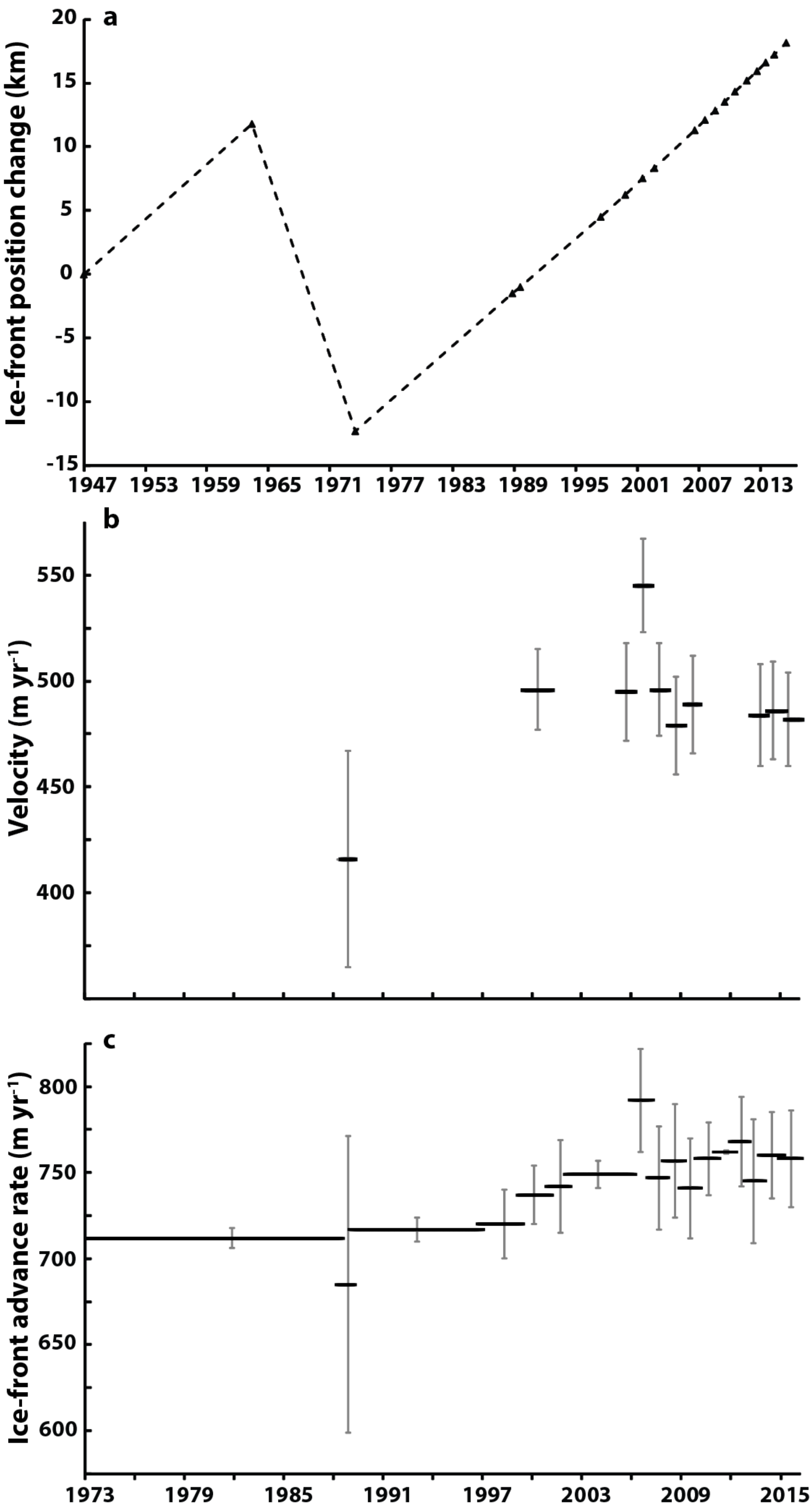

a
Ice-front position change (km)
20
15
10
5
0
-5
-10
-15
1947 1953 1959 1965 1971 1977 1983 1989 1995 2001 2007 2013
b
Velocity (m yr-1)
550
500
450
400
c
Ice-front advance rate (m yr-1)
800
750
700
650
600
1973 1979 1985 1991 1997 2003 2009 2015

Figure 3: a) Ice-front position change of the Cook East Ice Shelf 1947-2016 from the grey box delineated in Figure 2. **b)** Mean velocity extracted from the grounding line of Cook East 1989-2016. **c)** Cook East ice-front advance rate 1973-2016. Note the increase in both velocity (b) and ice-front advance rate (c) in the 1990s and between 2006 and 2007. Grey bars represent the errors in both (b) and (c).

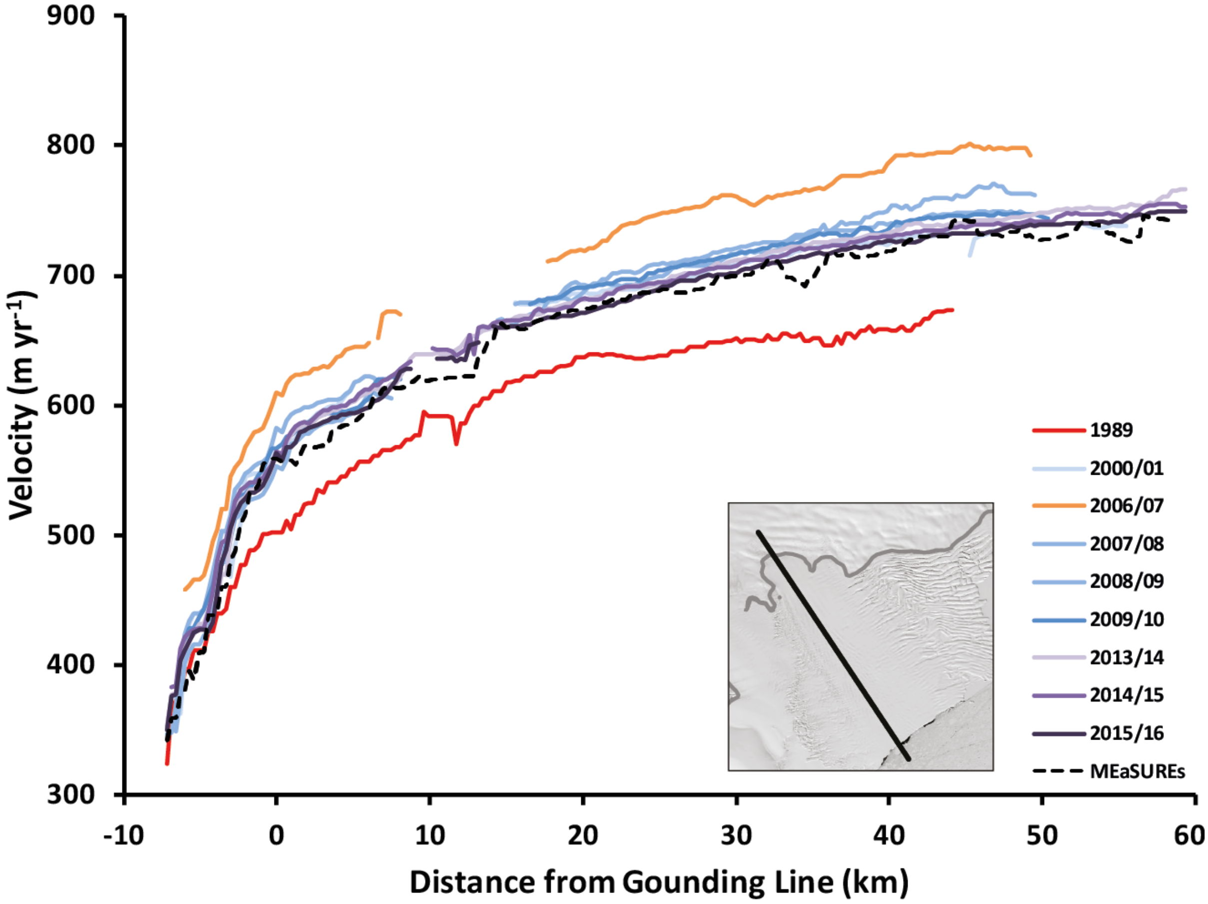


Figure 4: Cross-profile of the velocity of the Cook East Ice Shelf. Velocities were extracted along the same series of points shown on the inset. The dotted line is velocities extracted from the same cross-profile of the MEaSUREs dataset (Rignot et al., 2011a).

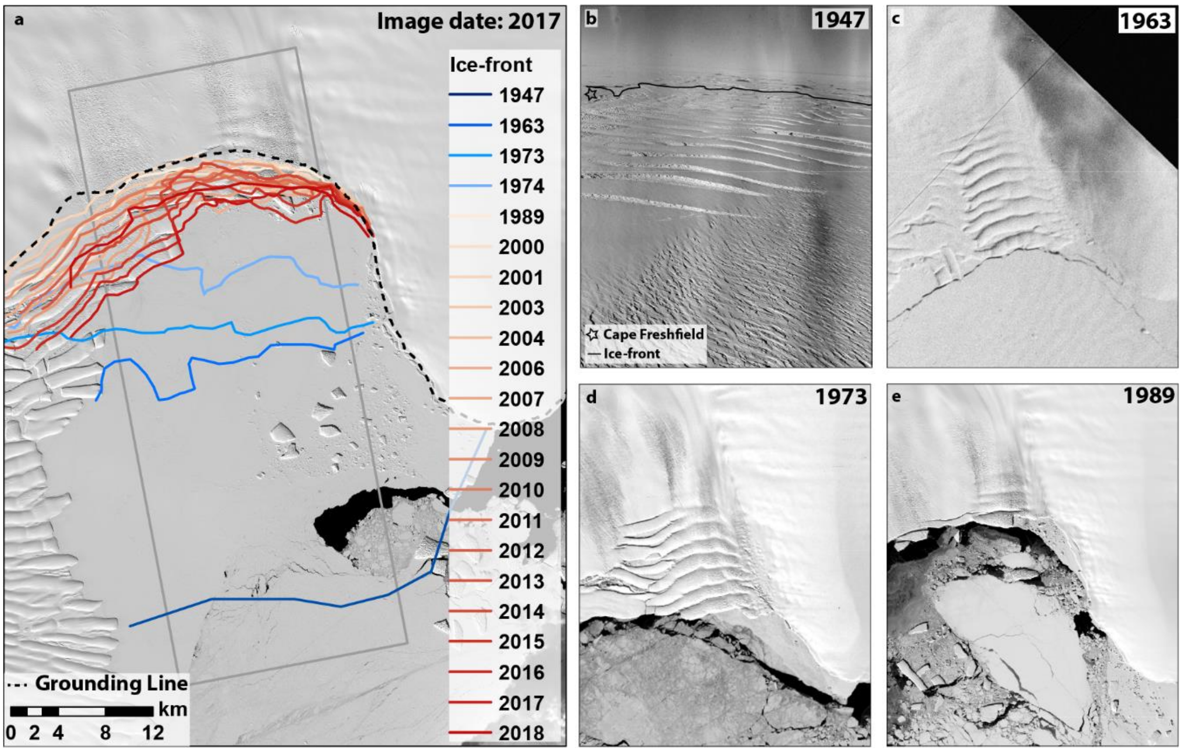


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Figure 5: a) Mapped ice-front position of the Cook West between 1947 and 2018. Note the exceptional retreat between 1947 and 1989. Grey box delineates the region where ice-front position change was calculated. Grounding line is from Depoorter et al. (2013). **b-e)** Images of Cook West Glacier in **b)** 1947, **c)** 1963, **d)** 1973 and **e)** 1989.

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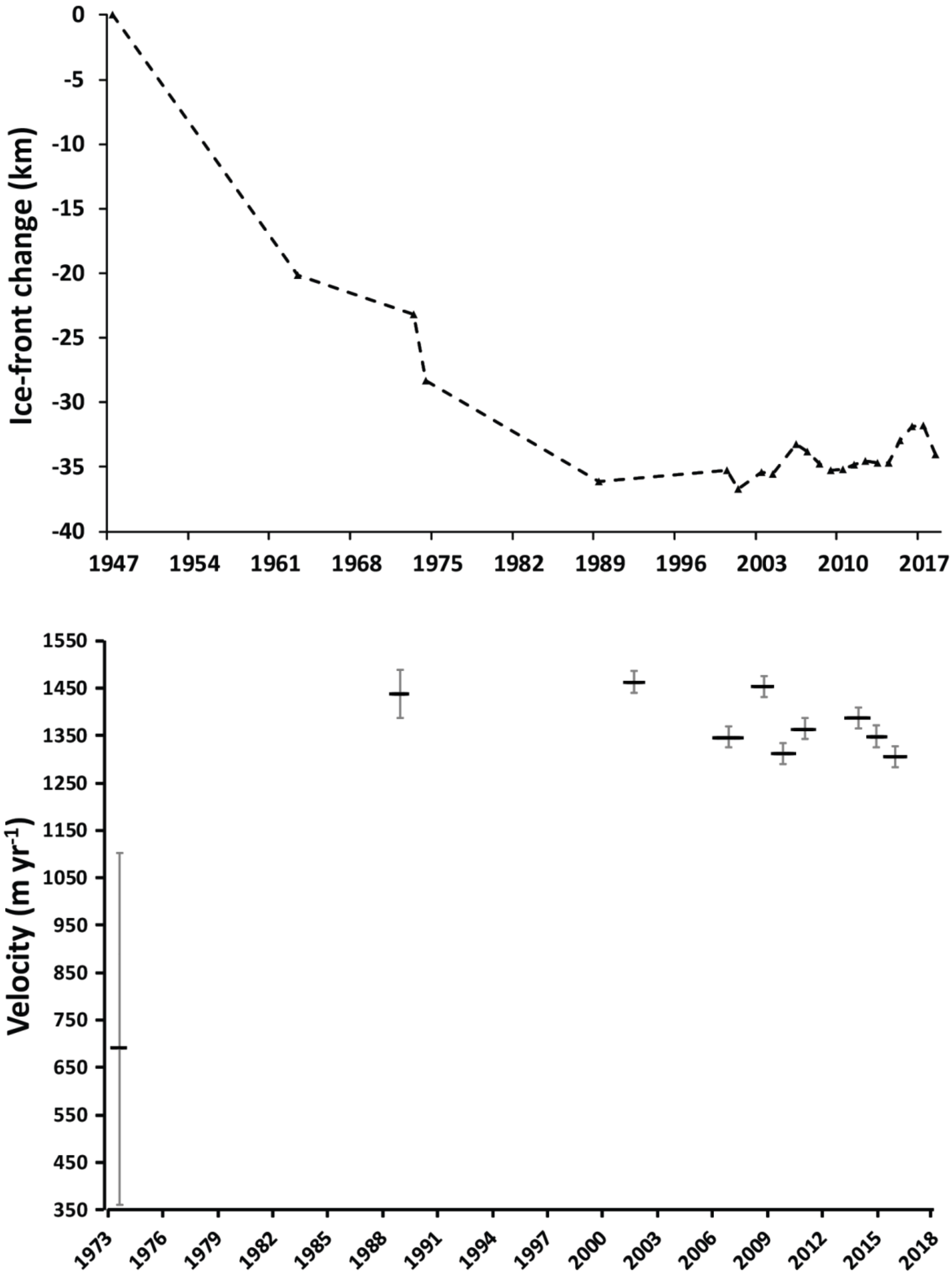

Figure 6: a) Ice-front position time series of Cook West between 1947 and 2018. **b)** Velocity estimates and ice-front retreat of Cook West Glacier between 1973 and 2017 based on feature-tracking. The grey bars represent error. Note the increase in velocity between 1973-74 and 1989 coincides with the retreat of the Cook West Ice Shelf.

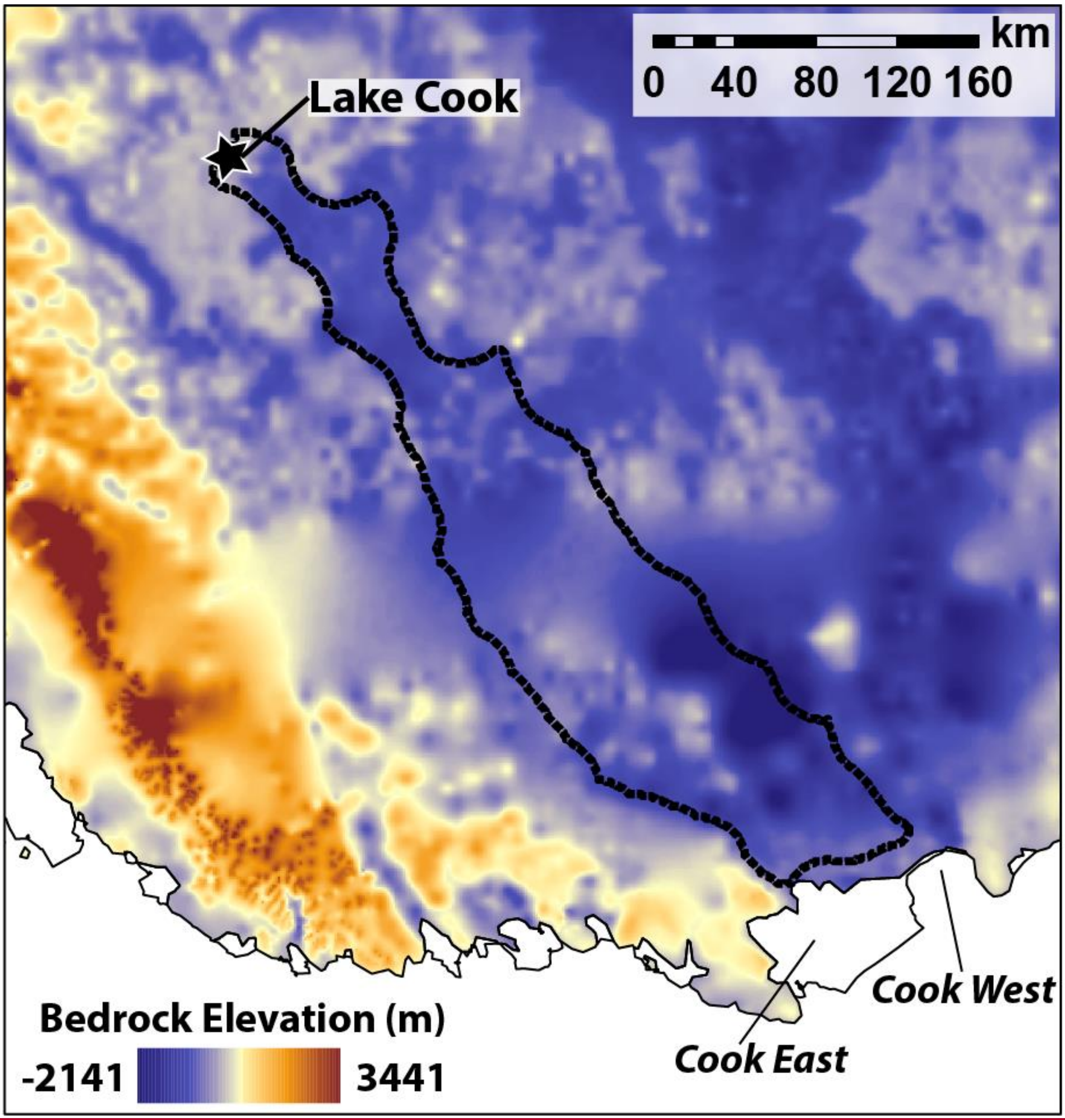

Figure 7: Region of most probable flow path (dashed line) of Subglacial Lake Cook (Flament et al., 2014) overlain on bed elevation from Bedmap-2 (Fretwell et al., 2013).

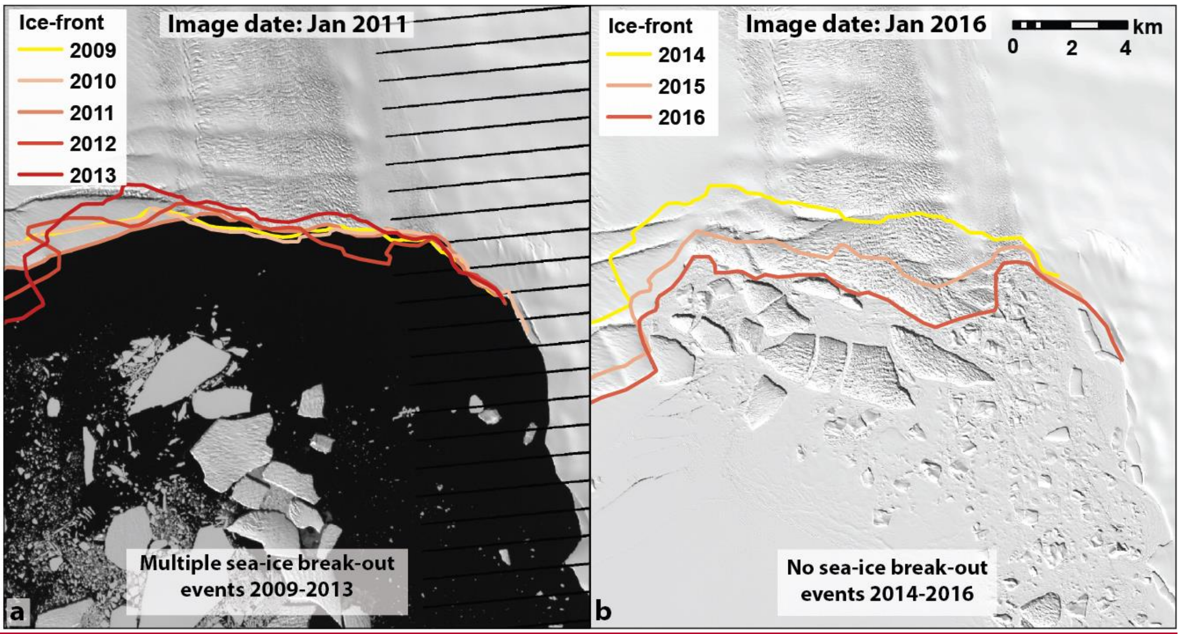

Figure 8: Relationship between ice-front position of Cook West and the presence of landfast sea-ice and mélange at its ice-front. **a)** Mapped ice-front position overlain on a Landsat 7 image between 2009 and 2013 during which multiple sea-ice break-out events were observed and there is little change in ice-front position. **b)** Mapped ice-front position overlain on a Landsat 8 image between 2014 and 2016 during which no sea-ice break-out events were observed, and the ice-front was able to advance. Note the build-up of ice mélange near the ice-front.

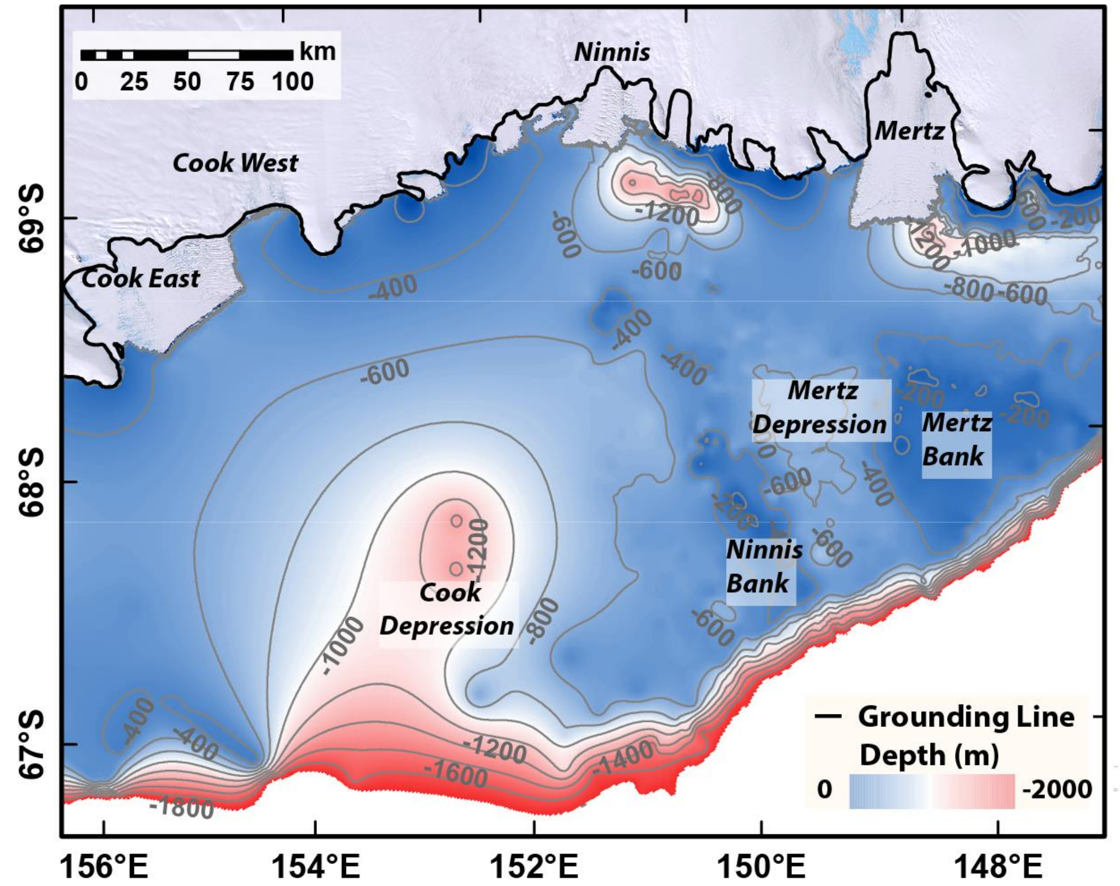

Figure 9: General Bathymetric Chart of the Oceans (GEBCO) bathymetry of the Cook-Ninnis-Mertz region overlain on the LIMA mosaic. Note location of the Cook Depression on the continental shelf.

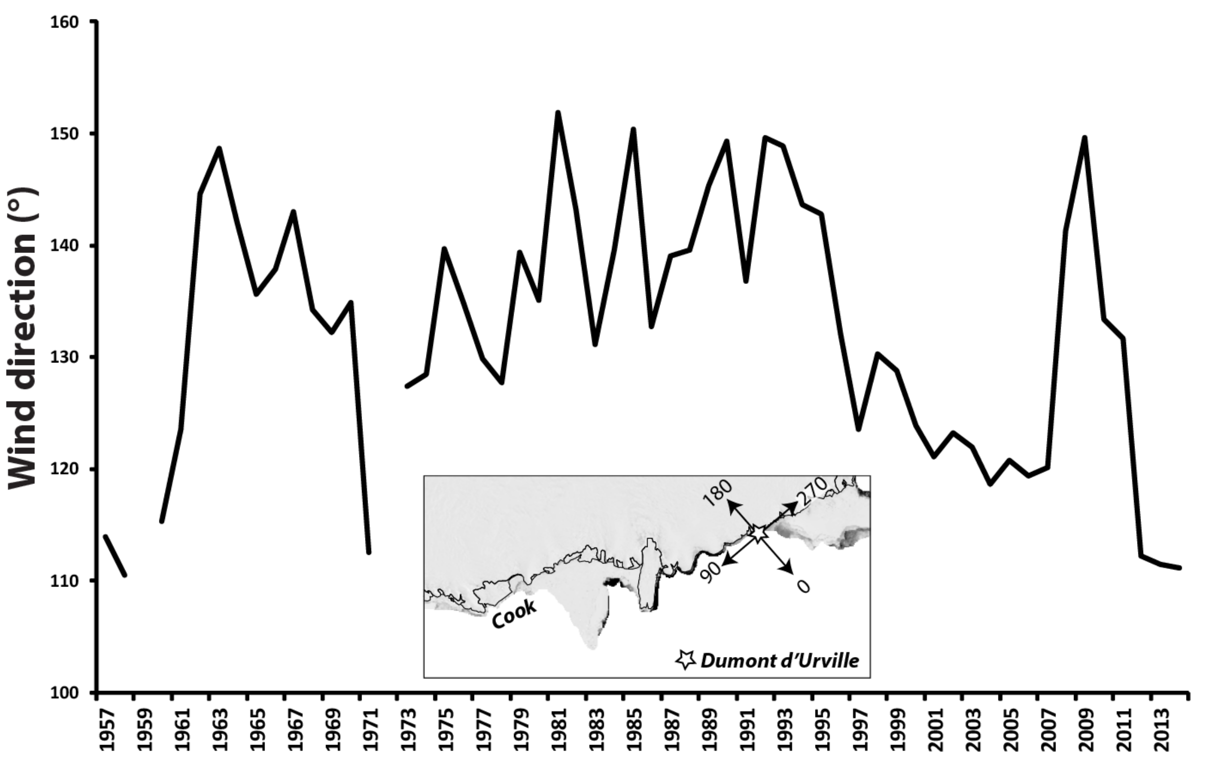

Figure 10: Mean annual wind direction from Dumont d'Urville research station 1957-2014.