Responses to reviewer comments for the article "The impact of landfast sea ice buttressing in the Larsen-B Embayment, Antarctica"

We would like to thank the editor and reviewers very much for the taking the time to read the article and for providing us with valuable and insightful feedback. All reviewer comments and my responses to each are collated in this document, so that each reviewer may see the others. Each review is reproduced here in full. Responses to any general comments of the reviewers are coloured in teal, while responses to specific comments are tabulated afterwards. A difftex file showing changes made to the manuscript is attached at the end of this document.

Following general comments by the reviewers I have made some changes to the structure of the article. Firstly, to help the flow of the article and reduce confusion around methods, there are some changes relating to the presentation of methods and results. There is a new "Observational methods" section listing the methods used in observations of sea ice extent and flow speed. The "Model set up" section has been renamed "Modelling methods" and contains a more complete description of the processes that went into making figures 2, 3, 4 and 6. I have also made changes to the structure of the discussion including adding the section "The use of a viscous flow model". This compares the stresses within the modelled viscous landfast sea ice, to the yield stress in a widely-used visco-plastic model, providing evidence that our experiments constitute a 'maximum buttressing example'. Various references to the choice of rheology scattered about elsewhere in the discussion have been removed. Additionally, I have taken the 'Environmental drivers' section out of the discussion. Finally, some of the discussion sections have been re-ordered. In line with some suggestions made in community comments, I have written more explicitly about mélange in the discussion and how it might relate to the buttressing effect of sea ice.

There was general agreement between the reviewers that it needed to be clearer what novelty there was in presenting our observations, given recent publications by others looking at this region. The revised manuscript makes it more explicit that the observations we present are complementary to concurrent studies, and exist in large part to provide specific background to the modelling study.

To reflect specific comments made by reviewers and community comments, I have made alterations to the majority of figures, though many alterations have been minor. Figure 2 no longer shows percentage speed change, and includes transects of speed observations for comparison with changes in modelled speed with the introduction of sea ice. Figure 4 has changed so that it no longer show percentage difference in principal strain rate but the original principal strain rate and the difference. I have added a new figure in the section "The use of a viscous flow model". I have added an additional supplementary figure showing the model thickness, speed, misfit and control fields following the model initialisation.

Finally, following a community comment which pointed out that the ice shelves were larger in reality than in our initial simulations, I have set up a new model geometry and performed the initialisation and simulations again. Each figure has been updated to reflect the results with the new geometry, though the changes have not affected the results of the article in any meaningful way.

Responses to comments from Reviewer #2 (Camilla Schelpe)

Reviewer 2: This study focusses on the disappearance of the landfast sea ice from the Larsen B embayment in Jan 2022, and the impact this had on the glaciers that terminated in the region. The paper starts with an extensive summary of observations extracted from satellite data for the region, homing in on the Hektoria, Green and Crane glaciers that experienced the biggest speed up following the disappearance of the landfast sea ice.

Give the timing, it is most likely that the disappearance of the landfast sea ice caused the speed up of the glaciers in the region. However, the exact mechanism by which this occurred is uncertain. In this study, the authors are answering the valuable question of whether the sea ice conferred stability on the glaciers directly through a buttressing mechanism akin to the buttressing effect of confined ice shelves on upstream grounded ice.

They investigate both the direct buttressing of the grounded portion of the glaciers, and the buttressing of the floating ice tongues. The study uses a diagnostic numerical model to look at the flow speeds and stresses within the glacier, with and without an "ice shelf" of fixed thickness ranging from 1m to 50m, that represents the sea ice.

The conclusion of the paper is that the direct buttressing effect is too small to explain the observed disintegration of the ice tongues and so other mechanisms must be at play through which the sea ice conferred stability on the glaciers in the region. The authors provide many caveats on the limitation of the study such as the unknowns in the geometry.

I enjoyed reading the paper. The manuscript was well written, with a clear narrative that leads you through the paper, but I felt there were a few places where some more explanation is needed. Details below. I would fully recommend publication with these changes.

We thank the reviewer for their praise of the article and their thorough and thoughtful review. Each suggestion has been taken into consideration and the vast majority have been implemented. My responses are tabulated below

Responses to specific comments from Reviewer #2

	Reviewer 2	
ID	Reviewer Comment	Response
1	L4: "satellite measurements show that Hektoria, Green and Crane Glaciers have sped up by... more than 100 ma^{-1}." As it stands, it is not clear that these observations constitute part of the novel contribution of this paper, and yet Section 2 is devoted to the processing of the satellite data to arrive at these values. Perhaps add something like "we show from satellite measurements that Hektoria, ..."	This is a good point. We show this to be true using ice speed measurements generated from satellite data, though the speed-up of these glaciers has been documented before in the preprint by Ochwat et al. (2023). We thought it best to include our independent measurements, made in parallel with Ochwat et al. (2023), though given the appearance of this other paper before our own, these observations do not constitute the major novelty of this work. Still, it is useful to remove the ambiguity, so I have added lines to the introduction making it clear that our observations are complementary to these other studies. I have also reworded this particular sentence as suggested to read: "We show using satellite measurements that, following a decade of gradual slow-down, Hektoria, Green and Crane Glaciers have sped up..."
2	L79: "Speed changes extend up to 10 km upstream of the 2021 grounding line on Hektoria, Green and Crane Glaciers, where the speed up is most pronounced." Does this refer to the speed up being most pronounced on Crane glacier, or the 10km upstream, or indeed on all three glaciers relative to the rest of the region? Consider rewording.	Thank you for pointing out this ambiguity. I meant the former, and have restructured the sentence to read: "On Hektoria, Green and Crane Glaciers, where the speed-up is most pronounced, speed changes extend up to 10 km upstream of the 2021 grounding line."
3	There are two places where the paper refers to "mean" ice speed, but it isn't clear whether that is data averaged over time, or a spatial average. It would be helpful for that to be made explicit. a. The first is the grey-scale plot in Fig 1.a "Inverse-error-weighted mean ice speed of glaciers... between October 2014 and April 2023". Is this the average over that entire time period? I found it surprising to have the average over such a long time, spanning the entire period that changes are being investigated in the study, if that is indeed what is plotted. b. The second is on L123: "mean observed ice speed across... in 2021". Is this what was plotted in greyscale in Fig 1a? Or is this an average over data gathered in 2021? Or in this case is it a spatial average?	Thank you for pointing out these points of confusion. In both instances, we are referring to averages taken over time. a. This is indeed the average over the entire time period. It's only really meant to highlight the locations of the main glaciers to give the reader some understanding of how the area looks. The caption has been slightly reworded to make this seem less like the focus of panel a. b. I have reworded this sentence to read: "We performed an inversion for basal traction (C) and stiffness (ϕ) fields using observations of ice speed across the HGE and Crane basins averaged over 2021." For reference, I have also replaced instances of 'enhancement factor' with 'stiffness' throughout the manuscript.

4	L123. Add an explanation of what the enhancement factor ϕ is in Biscicles. I don't think the authors define $\bar{\mu}$ at any point in the paper (introduced on L502); presumably the viscosity? But the relationship to the enhancement factor is unclear. It would be helpful to explain how the rheology is set in the simulation.	Thank you for pointing this out. I have added some general background to BISICLES ahead of the start of the new 'Modelling methods' section. This introduces the model, $\bar{\mu}$ and ϕ more completely.
5	L151-153. It wasn't immediately clear to me why this choice of Coulomb sliding law would ensure that "basal stresses on much of the grounded ice remain relatively unchanged". Could the authors elaborate?	The choice of sliding law is an important determinant of whether there will be any perceptible change in speed on grounded ice when the sea ice is added/taken away. The regularised Coulomb law is plastic above the threshold sliding speed. This speed, which we set to 300 m a^{-1}, is significantly less than the flow speed on most of the grounded ice we are interested in. This means that when the stress boundary condition at the edge of the ice shelf changes (because the sea ice is added or taken away), the new stress distribution has to be accounted for by changes in viscous stresses, i.e. changes in speed gradients, as basal stresses will remain the same. Using, for example, a linear sliding law, could suppress changes in speed. I have changed the sentences here slightly to read: "For these simulations, we use a regularised-Coulomb sliding law (Schoof, 2005; Joughin et al., 2019) with a threshold ice speed of $u_o = 300$ m a^{-1} so that sliding is plastic on much of the grounded ice. This ensures that basal stresses remain relatively unchanged as landfast sea ice is introduced. This results in enhanced changes to the viscous stress and, consequently, greater ice speed change."

6	L175-183, Fig 3 and Appendix A2. This section about the sensitivity to the ice thickness is quite difficult to make sense of and I think generally needs more explanation. It can feel a bit vague and confusing at points as it stands. I've added some specific points below: a. The label on Fig 3.a is "$\ln(Du/D\phi)$". The caption says that (a) is log and (b) is linear. Does that mean the y-axis in Fig 3.b is $Du/D\phi$? It would be clearer to label the y-axis that way rather than simply "sensitivity", or define "sensitivity" in the caption. b. Could the authors expand on the derivation of Eqs (A3) and (A4) in the appendix? The reference to Goldberg & Sergienko 2011 is sufficiently different to the problem set up that it would be helpful to provide the full derivation here, and lay out the assumptions more clearly. c. Is the exact location of the coloured circles in Fig 3.a significant? My understanding from the text in the Appendix is that they mark the model domain Ω_{HC} and represent the catchment area of the two glaciers, but reading the caption for Fig 3a it was quite confusing. "Magnitudes of different sensitivities of ice speed in the locations marked by the coloured circles..." It sounds as if those are two singular points. I would suggest either representing the domain Ω_{HC} by an outline in the figure, or at least refer to "regions marked" not "locations marked" in the caption.	Thank you for pointing out the confusing nature of the sensitivity plot and the discussion of how it was made. I have attempted to re-write the part of the "Modelling methods" section that deals with this to better explain what's going on. I hope that the reviewer finds the new manuscript less opaque. To deal with the specific points raised by the reviewer: a. I have changed the y-axes labels to read $\mathcal{D}u/\mathcal{D}\phi$ as suggested. b. Though it might be a bit unsatisfactory, I have not expanded on this derivation within the article, simply because it could become quite long. However, I have added perhaps a more appropriate reference that the reader can use to see how the calculation works (Morlighem et al., 2013). c. This was not very well explained in the original article. The sensitivity is the gradient of the *mean ice speed over the areas shown by the coloured circles* with respect to ϕ. I have tried to make this clearer in the modelling methods section, and by highlighting the areas in the revised figure.
7	L192 – 199 and Fig 4. Could the authors elaborate on how they extracted the principal strain and stress components across the region? Is the direction for ϵ_1 and σ_1 determined for each parcel of ice, or is it taken as the average for the domain?	Good question, it is the former. The strain rate tensor was calculated local to each parcel of ice, in coordinate system aligned with the figure 4 a (x left to right along the bottom, y bottom to top). The principal strain rates were then calculated as local eigenvalues of the strain rate tensor with $\varepsilon_1 > \varepsilon_2$. Similarly for the principal stresses. The last sentence of the "Modelling methods" section now reads: "Principal strain rates ε_1 and stresses σ_1 (the largest eigenvalues of the strain rate and stress tensors local to each parcel of ice) were calculated for the HGE and Crane ice shelves for 10 m of lanfast sea ice vs 0 m.".

8a.	The paper is well written overall, but Section 4 (Discussion) was generally a bit weaker than the rest of the paper, and lets it down. A few specific notes: Section 4.2 presents new data and comes as a bit of a surprise when reading the discussion section. Perhaps a more natural home for this section is under "Section 2. Observations"?	It is right to say that the discussion is a bit less focused than the rest of the article. I have made substantial modifications to the discussion in the revised manuscript and I hope that the reviewer finds these have improved it. On this specific point, I have left the "Environmental drivers" section out of the observations section for the time being, but have given it its own section before the discussion. Moving it to "Observations" disrupts the flow of the main article slightly and makes these observations seem like too much of a focus of the article (whereas in reality they are not key to the narrative or conclusions of the article). We felt it was worth including these observations to highlight the many different processes going on at the time of the sea-ice evacuation and dynamic change in the glaciers. I have modified the section slightly - making it shorter and explaining the reasoning for its inclusion.
8b.	L300: "Several studies have indicated the importance of sea ice...and the results of this study do little to suggest otherwise." The modelling results of this paper generally show that the buttressing action of the sea ice is not significant, so shouldn't this be "despite the results of this paper"?	This is a good point and I have added the caveat "- merely highlighting that this importance is unlikely to stem from its ability to buttress glaciers in the way an ice shelf can buttress a grounded ice stream." at the end of the sentence.
8c.	L302: "However, to more accurately judge the extent to which sea ice stabilises ice shelves... measurements at the critical zone near glacier calving fronts." This statement would be more meaningful if the authors gave specific detail about how access to these measurements would have helped their modelling study. What would different measurements enable you to do differently/more accurately in the study?	I have added the example: "For example, knowledge of sea ice thickness at the point of contact with the calving front, along with calving front morphology would help better our understanding of processes in which sea ice might inhibit iceberg calving via its influence on torques at the glacier front."
8d.	L308: "We argue that the results represent an upper bound.... assuming viscous rheology, however, this may not be the case". I think given what follows, the authors mean that the results may not be restricted to viscous rheology, but it reads as if it may not be any kind of upper bound. Consider rewording that sentence.	This is a good point! Though this part of the discussion has been rewritten to no longer focus on the question of rheology in light of the new section "The use of a viscous flow model" that deals more completely with this issue.

8e.	L310: "the specification of a particular constitutive relation has no impact on the stress distribution". I'm not sure what the authors are saying here; a different value for viscosity would certainly change the equilibrium profile of an ice shelf. Could this point be explained more?	It was a mistake to include this line in the manuscript as it did not add much, while making things a bit confusing. What I was trying to get at is that there are 1D models of ice shelves where the stress distribution is uniquely determined by the geometry, regardless of the constitutive relation used. These don't extend to the situation under consideration but at the time of writing I wondered whether they did to some extent. This part of the discussion has been removed anyway in favour of the new section: "The use of a viscous flow model".
8f.	L311: "Fig. 3 a suggests that the sea ice in front of the centre of the ice shelf... has greatest impact on upstream flow." I assume this is referring to the magnitude of "$\ln(Du/D\phi)$" in the plot, and yet by eye the values seem rather similar for all the sea ice in front of the ice shelf not just along the centre line. Could this be clarified?	As I have removed all the discussion of one-dimensional ice shelves, I have removed this line as well.
9.	**Technical Corrections:** 1. Fig 1(f). There is a mismatch between the figure legend and the caption, one has "HGE" and the other "Hektoria Glacier". I think in this case the time series does relate to Hektoria Glacier specifically so the legend on the plot should be updated? 2. Fig 3.b.1. The y-axis ticks are obscured by the label. 3. L136. "thin-ice-covered leads". I'd never heard this term before, is it a typo? 4. Fig 4a. The grey dashed line for the floating ice region of HGE does not line up with the edge of the reddish coloured domain. Is this just a plotting problem or is there something else going on here? 5. L216. "geomeotry" typo 6. L225. "to" missing 7. L316 "chocking" I'm not sure what that means in this context. Could it be a typo? 8. L538. "between" repeated.	Thank you for pointing these out! 1. I have changed the legend to read "Hektoria". (The confusion occurred because the distance is drawn from a point on Hektoria, while the calving front is common the the whole HGE system.) 2. This has been fixed. 3. This is not a typo, I just mean leads in the sea ice (gaps of open water), covered perhaps with a layer of ice much thinner than the surrounding ice. 4. This is not a plotting problem, the domain was drawn this way to avoid values very near the front that may be wrong due to edge effects when we differentiate the velocity components. 5. This has been corrected. 6. This has been corrected. 7. Perhaps a better term would have been 'wedging'? Regardless, this line has been removed anyway. 8. This has been corrected.

Responses to comments from Reviewer #3 (Jason Amundson)

Reviewer 3: In this study the authors combine remote sensing observations and numerical modeling experiments to assess the potential impact of the loss of sea ice buttressing on the flow and stability of glaciers in the Larsen B Embayment. Essentially, they find that sea ice is unlikely to provide a direct control on glacier flow and stability, though they suggest that it can have indirect effects. Overall I think the paper is pretty easy to read and the results seem robust and interesting. That said, I do think the paper would benefit from moderate revisions. [Below] are a few general comments.

We thank the reviewer for their praise of the study and insightful comments. Their feedback has been very valuable and, I hope they agree that the resulting changes have resulted in a clearer and more robust article.

Structure The paper is written in the way that one might tell a story, which isn't necessarily bad, except that I find it a little jarring to go back and forth between methods and results (particularly in Section 2). I understand that the methods in this section are relatively basic, but I still think a different structure here is warranted. Perhaps start with a paragraph or two that that describes all of the data sets and how you analyzed them before getting into a description of the observations. It also seems that there are a couple of other papers out there discussing similar observations. Make it clear how this study is different or complementary.

Considering the reviews together, it is clear that the article would benefit from a restructure in the way the reviewer suggests. I have fit section 2 into a more traditional structure with separate 'Observational methods' subsection before going into the two 'Sea ice area change' and 'Ice dynamic and calving response' results sections. The modelling sections have been adjusted with an extended "Modelling methods" section followed by results. I hope the reviewer finds the new structure easier to read.

Regarding how the observations presented in this article differ from those in concurrent studies, I have not made substantial changes detailing where results are complementary or conflicting. As a bit of a catch-all, I have added the following sentence to the introduction:

"These results complement recent work by Sun et al. (2023) and Ochwat et al. (2023), which document many similar observations to those presented here."

I think it is useful to present our observations as they differ to some extent and form a more specific background to the modelling study. (This also allows us to do things like compare the modelled and observed speed changes at the same locations.)

Terminology: The authors use the expression "floating ice/melange tongues". I don't know what this is referring to. "/" typically means "or", so is this "floating ice" or "melange tongues"? And what is meant by "melange tongues"? And later, is "ice tongue" really referring to an "ice shelf"? At least in the Antarctic context, when I hear about ice tongues I usually first think of something like the Drygalski Ice Tongue, which is not bounded by fjord walls.

I didn't commit fully to using the term 'ice shelves' because, for a while at least, there was no real boundary between the ice shelves and the mélange in front of them. However, this is not very clear and it is certainly correct to refer to the bulk of the floating extensions of the glaciers as "ice shelves". Hence, I have reverted to more standard uses of these words. I have removed all instances of "ice/mélange", changed all instances of "ice tongues" to "ice shelves". At various points in the article, it is made clear that there are regions of mélange in the transition between the pure ice shelves and the pure landfast sea ice.

Sea ice model: I have some concerns about the authors use of a viscous flow model to describe stresses in sea ice, and I'm not sure that I follow why this model should provide an upper bound on the buttressing stress. At the same time, I think the authors could use their observations and some simple arguments to support their conclusion that sea ice buttressing is not directly important unless the sea ice is tens of meters thick—which would also help to back up their model results.

Whether you invoke a viscoplastic or purely viscous rheology, the depth-averaged tectonic (or resistive stress) should scale with the depth-averaged strain rate:

$$R_{xx} \propto \dot{\epsilon}_{xx} \tag{1}$$

where I am taking x to be perpendicular to the glacier or ice shelf face and the tectonic stress is related to the Cauchy stress by

$$\sigma_{xx} = R_{xx} - P \tag{2}$$

with P the depth-averaged glaciostatic pressure. The force per unit width acting on the glacier face is then

$$F/W = -H\sigma_{xx} = -HR_{xx} + HP. \tag{3}$$

To get the buttressing stress, you need to subtract the force from the depth-averaged water pressure P_w, which would also act on the glacier if the sea ice was removed. This gives

$$F/W = -HR_{xx} + HP - HP_w = -HR_{xx} + \frac{1}{2}\rho g \left(1 - \frac{\rho}{\rho_w}\right) H^2. \tag{4}$$

The reason that it's not clear to me that a viscous model will provide a maximum bound on the buttressing force (as stated in line 145) is that I don't know how a viscous rheology will affect R_{xx} compared to a viscoplastic rheology.

Nonetheless, the sea ice flow seems to be extensional in the observations, implying that R_{xx} is positive. In other words, the last term in Equation 4 would seem to provide a good estimate of the upper bound on the sea ice buttressing force. Unless H^2 is large, this force will be pretty small.

Perhaps it would be interesting to compare the modeled buttressing force to the quasistatic force (i.e., when $R_{xx} = 0$).

One advantage of framing the discussion around something like Equation 4 is that it doesn't very strong assumptions about the rheology (e.g., which may be inconsistent with sea ice literature). You can also look at the field observations to get an idea of the forces

involved without worrying about the details of the rheology. Only if the flow is highly compressive would I expect to see large forces. Perhaps that is happening at scales that you can't resolve in the satellite data, but then I'm not sure that they would be resolved in a viscous flow model either

The reviewer is right to raise this very important point. The conclusions of the article rest heavily on the assertion that the viscous flow model provides an upper bound on the buttressing capacity of the ice (far more than, for example, the accuracy of the geometry or the order of the adding of the sea ice in the model vs in reality). We have taken on board the insightful points raised and useful suggestions in this part of the review. However, I would argue that rather than making substantial changes to the methods used in the study, all that is needed is the addition of some more explanatory text.

Firstly, I agree with the reviewer's analysis and the resulting equation 4. This, along with the suggestion of looking at extensional or compressive flow would be a good solution when considering a one-dimensional model. However, the difficulty in the system under consideration is that it is two-dimensional, where it is difficult to argue that a local measure of buttressing such as that proposed by the reviewer would accurately describe the effect of the sea ice on the glacier ice. Instead, things like shear stresses near the margins of the sea ice, and the lateral transmission of the stresses are likely to be critical. Though we could estimate shear strain rates from observations of sea ice flow speed, it would be difficult to assess the net effect of these on the glacier.

Regardless, the existence of other ways of looking at the problem does not invalidate the method we chose to apply; but our choice of rheology could - as the reviewer is right to point out. However, there are good reasons believe that the use of a viscous flow model is sufficient to answer the question posed in the article about sea-ice buttressing. I have added a variant of following argument, along with an additional figure (reproduced below - Fig. 1) to a new section of the discussion called "The use of a viscous flow model" that I hope makes this more convincing. In essence, it shows, as the reviewer asks, how a change in the rheology might affect resistive stress (though we consider viscous stress).

Firstly, it is clear that there is large-scale deformation over the landfast sea ice in the embayment, above the random wedging together of floes. A number of different rheologies have been considered for sea ice, but it is generally agreed that large-scale deformation is plastic - due to the opening of cracks, raising of pressure ridges and shearing along crack boundaries. The stress state for such deformation lies on a yield curve of critical stresses. Various commonly used models employ this kind of rheology. An assumption of isotropic ice allows this yield curve to be plotted as a function of principal stresses. However, the models disagree on subcritical rheology - where the bumping of floes together and deformation internal to individual floes is important. Intuitively, this might be first considered as elastic due to the short-timescales on which these kinds of interactions happen (Coon et al. (1974)). However, it was shown by Hibler (1977) that the jostling of floes approximates viscous behaviour at small strain rates. This led to a commonly used parametrisation of sea-ice rheology that takes the form:

$$\sigma_{ij} = 2\eta\dot{\varepsilon}_{ij} + [(\zeta - \eta)\dot{\varepsilon}_{kk} - \frac{P}{2}]\delta_{ij} \tag{5}$$

where P parametrises the strength of the ice and $\zeta \equiv \zeta(\dot{\varepsilon}_{ij}, P)$ and $\eta \equiv \eta(\dot{\varepsilon}_{ij}, P)$ are bulk

and shear viscosities respectively. The functional forms of the viscosities, along with the specification of an eccentricity, determine the shape of a yield curve, passing through the origin, on which the stress state lies at typical strain rates. The ice strength in Hibler (1979) is approximated as:

$$P = P^* h A e^{-c^*(1-A)} \qquad (6)$$

where $P^* = 27.5$ N m^{-2}, $c^* = 20$, h is the sea ice thickness and A is its concentration. P^* is sometimes treated as a tunable parameter but P is most often within a factor of 10 of 10^5 N m^{-1} (Feltham (2008)). Regardless of the precise sub-critical rheology, the strength parameter P is the key scale for stresses that can be maintained within the sea ice.
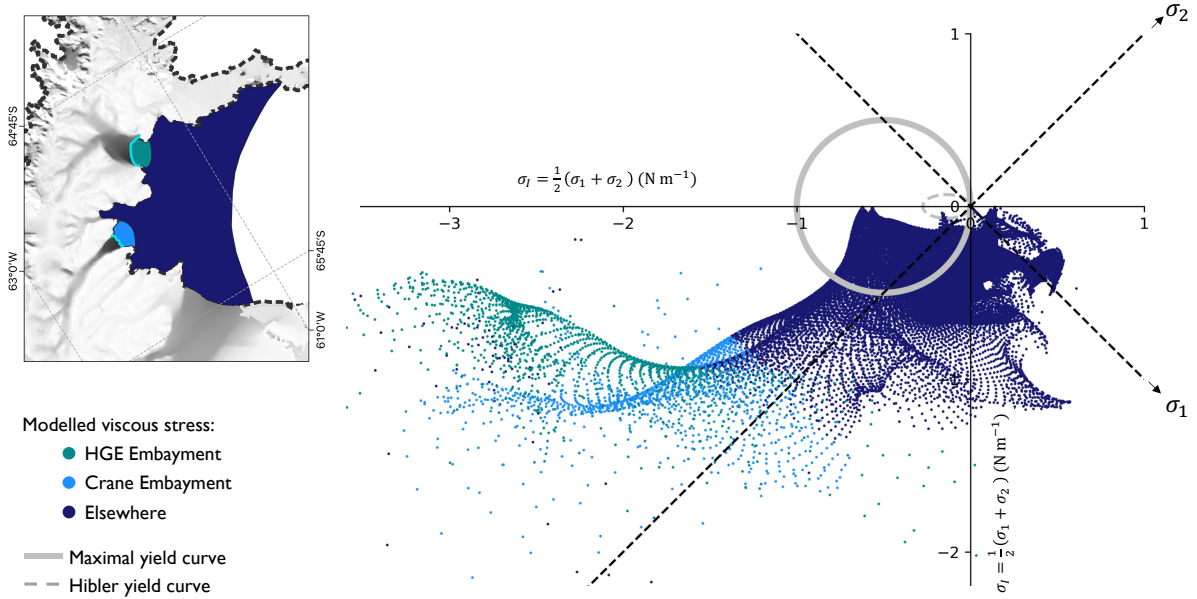
Figure 1: A comparison of viscous stresses in the modelled landfast sea ice and a possible yield curve for sea ice. The graph shows viscous stresses in the modelled landfast sea ice plotted as a function of "negative pressure" σ_I and "maximum shear stress" σ_{II} (Feltham (2008)). The colour of the points indicates where in the domain the modelled viscous stress is extracted - corresponding to regions on the inset map. The grey circle on the graph indicates a yield curve for a possible sea ice rheology of the form of eq. (5) with $P = 10^6$ N m^{-1} and eccentricity of 0. The grey dashed ellipse shows a yield curve with eccentricity of 2 and $P = 2.75 \times 10^5$ N m^{-1} as suggested in Hibler (1979).

We plot compressive and shear stress invariants within our 10 m-thick viscous sea ice (Fig. 1). We show on the same scale a possible but very generous yield curve for isotropic sea ice that is as strong in shear as it is in compression (this is not true and a real yield curve would be squashed vertically within the circles) with a strength of 10^6 N m^{-1}. (We also plot a more realistic yield curve with eccentricity of 2 and $P = 2.75 \times 10^5$ N m^{-1} suggested in Hibler (1979).) This shows that in the small embayments local to both the HGE and Crane glaciers, the viscous sea ice in our model holds a considerably larger amount of stress than is thought to be possible in real sea ice. This results in a higher buttressing effect.

Responses to general comments from Reviewer #1

We thank the reviewer for taking the time to read and comment on the article and for their valuable feedback. Their review is split into two components - a written part giving general feedback, and various specific comments in an annotated pdf of the manuscript. I have transcribed their annotations into the table at the bottom of this document.

Reviewer 1: This paper presents satellite-derived glacier speeds from 2014 and land-fast sea ice extent from 2002 till present. A numerical model is used to compute whether landfast sea ice (modeled as a thin meteoric ice shelf) could have provided sufficient buttressing to produce the observed glacier speedup. The answer to this question is no, following a standard modeling approach based on diagnostic runs quantifying instantaneous changes in glacier speed resulting from different boundary conditions. Additional hypothesis are then offered regarding potential causes of the glacier speedup, but these are no longer supported with numerical modeling.

Satellite estimates:
There are a lot of statements throughout the paper about pre/post 2011. But something that hasn't been shown is what the glaciers and glacier fronts did in terms of speed between 2002 and 2011 - how quickly did the system stabilize past the fast speed up in 2002? Was there any change in glacier speed around 2011 when the landfast sea ice settled in? And did the ice tongues only form past 2011 as mentioned in the paper? I don't think any of that was shown here, but is important for understanding the role of sea ice in the glacier dynamics in this bay.

The paper talks in a lot of detail about trends from 2014 but not clear what that reflects. Is that still recovering from 2002 speedup? is it reacting to 2011 landfast sea ice presence?

These are all very interesting points to consider! I agree that a greater analysis of the changes to glacier speed and calving front position covering the period before and after initial sea ice growth would provide greater insight into the effect of the sea ice. I have included some additional references to the literature that covers a period spanning pre- and post-2011 (namely: Wuite et al. (2015) and Rott et al. (2018)). However, I have not expanded very much on these points as the aim of the article is not really to fully review the effect of the landfast sea ice, rather to address the concept of sea ice buttressing. Similarly, we are not particularly concerned with what caused the glacier speed-up after the disintegration of the landfast sea ice in 2022. Further, this article does not presume to completely describe the mechanisms involved in the post-2014 trends, but does suggest as motivation for the modelling study that landfast sea ice can promote the growth of ice shelves that act as a control on upstream flow.

Previous papers have already shown similar satellite-derived information as shown here (and the studies are cited in this manuscript), so I wasn't clear on what the novelty here was. Making that explicit could help.

This is true - the novelty of the work does not lie greatly in the observations, other than them being slightly more focused on the HGE and Crane systems, as well as providing slightly more detail on the spatial pattern and magnitude of speed change. This was a comment raised by reviwer #3 as well. There is significant overlap between the observations presented here and in pre-prints elsewhere in the literature. However, we thought it was useful to present our additional observations as background and motivation to our modelling study. (This also allows us to do things like compare the modelled and observed speed changes at the same locations.) I have added the following sentence to the introduction:

"These results complement recent work by Sun et al. (2023) and Ochwat et al. (2023), which document many similar observations to those presented here."

Modeling:

There is no model validation, although Larsen B offers a rare opportunity in glaciology to actually validate a model in some sense. If the consensus is, that the Larsen B ice shelf breakup caused acceleration of outlet glaciers (and some models have showed that using similar techniques as here), then I would expect to see that validation here. That is, to see the model in this study first show that the removal of the ice shelf from a model tuned to pre 2002 velocities reproduces observed post 2002 speedup. If it does so, then I think the conclusions about the relative insensitivity of the land ice to landfast sea ice buttressing will be more robust.

The suggestion that there is no model validation is not entirely correct - this study is an exercise in validation. We ask the question of whether this land ice + sea ice model is able to reproduce the observations of speed change and the answer is no. However, I can in principle see the value in the kind of validation that is being suggested (with an experiment looking at the removal of the Larsen-B ice shelf). It might answer whether the geometry is set up correctly, or whether the sliding law we use is plausible. However, this does not have a great deal of relevance for our study as the geometry has changed, and we seek a sliding law that maximises the impact of the sea ice. More importantly, if we carried out that kind of validation, I think we would be limited to diagnostic modelling procedures like the ones we present here. I refer the reviewer to Figure 2 showing linear changes in ice speed with sea ice thickness to show that the model produces glaciers that are sensitive to changes in boundary stress - like a validation using the Larsen-B Ice Shelf would no doubt suggest.

There is an inconsistency in the modeling. The inversion uses ice flow speeds from 2021 when landfast sea ice was present, but the effect of the landfast sea ice itself is not included in the model at this point. So the tuning to velocities is done with the wrong setup/geometry. Further, it is unclear why the authors do the opposite experiment to nature. They take an (inconsistently) tuned state and then look at the effect of addition of an ice shelf, rather than the effect of the removal of an ice shelf. At the very least it would be good to explain the reasoning for that choice and an argument for why this procedure is generally reversible (especially considering potentially long lasting transients).

This is an astute point, and one that could be dealt with better in the article. Firstly, the fact we see no noticeable change in glacier flow with the addition of sea ice makes

the solution to the inverse problem in the case *without* the sea ice an almost equally good solution to the case *with* the sea ice. Hence, differentiating between the model initialisations in the two cases is not particularly meaningful. Taken together with Fig. 2d2 (now Fig 2f) (showing changes in speed to be linear in sea ice thickness) which shows that the addition of small amounts of sea ice cause changes comparable to taking away small amounts of sea ice, it is clear that the results would be the same had the experiment been performed the other way round. Had that been done, the experiments would just have taken substantially longer and perhaps been more difficult. It is true that the choice to do the experiments this way round assumes from the outset that the sea ice will not affect the glacier flow, but this assumption is validated by the results. I have added the following couple of sentences in the 'Modelling methods' section:

"The choice to do this presupposes that the inclusion of the landfast sea ice will do little to change the solution to the inverse problem and is necessary as the thickness of the landfast sea ice is not well constrained. We shall see that this assumption is validated by the results."

An alternative argument for why this consideration is not relevant also answers questions regarding modifications to the modelled glacier geometries. The argument we make in the paper is essentially a mechanical one: adding a thin layer of landfast sea ice in front of the glaciers has little impact on the glacier flow. It would take a considerable conspiracy of factors for this to not be true given slightly different solutions for the model control parameters C and ϕ, or, for example, the position of the grounding line, or the length of the ice shelves.

The modeling emphasis is on the glaciers that showed large change in observations, and the statement is that the modeled response after sea ice removal is not enough. How about the response of glaciers that showed no change in observations? Is the response to the sea ice removal in model larger than the observed change? Maybe you show something for Evans in a figure but there is no mention of this at all in the text. This is another opportunity to have a "control", or a validation of your model and setup.

Thank you for this suggestion. I have highlighted this by expanding the following line in the first paragraph of the section "Direct buttressing of grounded glaciers":

"These modelled percentage changes in speed are similar in magnitude on all glaciers including Evans, where we do not observe a substantial dynamic response (Fig. 1 g)". This is an indication in its own right that landfast sea ice removal was not the primary cause of the ice dynamic change observed on these glaciers.

3.2.2 talks about sea ice buttressing effect near the termini, but nowhere it is shown whether the (observed) loss of the ice tongues produces the observed grounded ice acceleration. I think the paper could go a bit further with the modeling experiments and show whether the ice tongue loss does reproduce the observations of speedup.

I think this would be a nice thing to do, though not here as the article is not particularly concerned with what caused the glacier acceleration. I am happy to leave the relationship between terminus retreat and speed change suggested but not fully explored.

In the end a hypothesis is suggested that basal melt rate change could have contributed to the glacier speed up - can you show with a model that the inferred change

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in melt rates over the duration of the change can indeed produce significant change in glacier speed over the observed time period?

I did not intend for this statement to be seen as much more than a possible suggestion that highlights the many different forcings at play in the region. I hope that it is a bit clearer given the modified structure that this is not central to the article, and hence would not require its own modelling study.

Methods: There is minimal methods section so it is sometimes quite hard to assess what the authors actually did.

For example, which points they chose to show time series, how representative those points are, what do the error bars (shaded ares) actually represent, etc.

It is clear from the reviewer responses in general that the article was not structured in the best way. To improve the readability, I have added a new "Observational methods" section that includes this extra information, as well as a fairly comprehensive "Modelling methods" section.

The sections 3.2.1 and 3.2.2 need to match corresponding sections/paragraphs in "Modeling setup" so that it is clear which modeling experiment will answer what question/hypothesis.

This is a good suggestion that should help the reader with which methods were used for which experiments. This has been implemented in the new "Modelling methods" section. However, rather than separating out methods sections corresponding to sections 3.2.1 and 3.2.2, I have added sentences making it clear which methods correspond to which results sections. Explanations of the specific experiments have been moved from sections 3.2.1 and 3.2.2, leaving these sections to focus on the results.

General: The study really tries to be concise but that is at the expense of clarity and detail. At many places justification of choices and any sort of reasoning is completely absent.

I hope that the new methods sections make things slightly clearer and that, in general, the reviewer finds the revised manuscript easier to read.

The paper tries to merge observations with modeling but doesn't succeed in joining the two together very well. Part of it is probably the presentation. It needs to be stated a bit more clearly what the role of the model is in this study and what exact question, provided by the observations, it aims to answer. And also how the model and observations complement each other. Part of this is probably the inconsistency between the time series from observations, but then diagnostic model, rather than time evolving one is used. I understand that this is what people have been doing now for a while and it is fairly standard, but at some point it would be good to start understanding transient responses.

A good example of the lack of joining model and observations together is that the modeling results are in no way compared visually to observations (e.g. in Fig 2, could you also add observed flow speeds before and after sea ice removal, in addition to the modeled ones?)

I have tried to make it clearer in the revised manuscript that the study aims to answer whether sea ice buttressing was a factor in the change in glacier dynamics seen after the sea ice evacuation, and that the observations provide motivation for this question. Regarding the simulation of transient responses, though in an ideal world we would carry these out, there are a couple of reasons why it is not appropriate here to do so. The most important of which is that we do not have an appropriate calving law. Hence, the only real ways of isolating the effect of the landfast sea ice buttressing given the large calving events that took place in the region are through the kind of basic mechanical arguments we make here.

It is a good suggestion to make the modelled and observed speed changes more visually similar. I have changed figure 2 in the way the reviewer has suggested. The figure is simplified, with no percentage speed changes shown, and ice speed data for the second quarter of 2020 and the last quarter of 2022 is plotted along with the modelled speeds.

The language is a bit clumsy, some long, confusing (ambiguous) sentences are present. Often times unclear what authors mean, some repetition is probably necessary.

I have tried to improve this in the revised version.

Terminology is also an issue, often times the authors use many different terms to refer to the same thing, introducing ambiguity. Also, when saying ice, in this particular study it is really important to specify every time whether you mean sea ice/meteoric ice.

This was an issue also raised by reviewer #2 - particularly regarding uses of 'ice' vs 'mélange' and 'ice shelf' vs 'ice tongue'. I have tried to commit more to particular vocabulary. I hope the reviewer finds the terminology in the modified manuscript less ambiguous.

Responses to specific comments from Reviewer #1

	Reviewer 1	
ID	Reviewer Comment	Response
1	Suggested change in title: effect, rather than impact is probably more accurate. "impact" suggests it is strong	I have implemented the change suggested by the reviewer.
2	Suggested change in abstract: again, effect	I have also implemented this change, and on a few other occasions throughout the article.

3	Line 12: "However, as the accompanying changes in viscous stress were small compared to local spatial variation": I'm not sure what you mean here at all	I apologise for the confusing sentence. I have replaced this with: "However, the accompanying changes to the distributions of viscous stress within the ice shelves were small compared to the widths of those distributions. Hence, this loss of buttressing is likely to have been a secondary process in the disintegration of the ice shelves compared to, for example, increased ocean swell or the same factors that brought about the initial landfast sea ice disintegration."
4	Line 34: citation of Rott et al., 2018: I don't understand how a 2018 paper can be used for a statement refering to 2022 desintegration	I have put the citation before the word "disintegration" (it was meant to refer to the growth of the ice shelves, rather than their disintegration post sea-ice evacuation but was in slightly the wrong place.)
5	Figure S1: The colors in S1 are really a bit too close to each other in tone to be able to tell which line is which. Multiple panels by 5 year segments, or additional timeseries of ice front positions along some lines are plausible ways how this could be visualized with better clarity	I have implemented this suggestion, and replaced Fig. S1 with one split into 4 panels, each with 5 years of sea ice front locations.
6	Line 49 "... sea ice was retained throughout the summer months" I don't think that is what Fig. 1a shows. It has sea ice edge from November (December) each year, but austral summer ends in February or so	The sentence at the start of the section "Sea ice area change" has been modified.
7	Line 49 "... and generally grew in extent each year through to 2017 when..." Again this is not clear from the figure, it seems it is more less staying the same in 2014-2016	Thank you for pointing out this inconsistency, this has been rectified in the modified article.
8	Line 51 "Between the 18th and 23rd of January 2022, the multi-year sea ice disintegrated..." provide reference	I have added a citation to Ochwat et al. (2023) here.
9	Line 51 "Satellite data show that there was modest surface melt ponding on the sea ice during the austral summers prior to the sea ice collapse, however, these melt ponds were more widespread and densely spaced across the entire sea ice area in 2021. Surface melt ponds were observed to be at their maximum extent in December 2021 immediately prior to the sea ice disintegration in January 2022." Is that shown here or elsewhere? Please clarify or provide reference	These lines have been removed from the manuscript. Ochwat et al. (2023) discuss the causes of the sea ice disintegration fairly extensively, and discussion of this at this point in the manuscript does little to help motivate the modelling.

10	Line 75 "At the grounded ice locations chosen for extraction of speed timeseries, ..." I think you need to comment a bit more on how you chose these locations and how representative they are	It is a good suggestion to make it clear in the article that nearby locations show similar signals. It should be clear from Figs 1b-c, which show trends that are compatible with the timeseries data nearby to the points we picked, and the new Figure 2, that the changes are more widespread than the locations we chose. I have added a sentence to the new "Observational methods" section explaining the choice: "These locations were chosen to be in the centre of the grounded ice streams, close to the grounding line but with enough room for a 1 km buffer along the flowlines that pass through them."
11	Referring to the "sign change" mentioned on line 77: This seems very small	I agree this signal is weak. I have softened the sentence a bit to say a "potential sign change", which is then qualified in the remainder of the sentence as before.
12	Referring to the "sign change" mentioned on line 77: do you mean sign change in acceleration?	We say "sign change in the ice speed trend" rather than "sign change in acceleration" to make it clear that we are looking over longer timescales.
13	Line 80 "...where the speed-up is most pronounced": I don't see where that is shown	This sentence was ambiguous, I did not mean that speed-up on was most pronounced at the grounding line, rather that speed-up was most pronounced on Hektoria, Green and Crane Glaciers. I have changed the sentence to read: "On Hektoria, Green and Crane Glaciers, where speed-up is most pronounced, we see speed changes extend up to 10 km upstream of the 2021 grounding line."
14	Line 81 "Overall, the speedup observed after the sea ice disintegration in January 2022 is more extensive than the region of slowdown observed between 2015 and 2022 (Fig. 1 d), and extends inland onto the grounded ice sheet (Fig. 1 e), therefore increasing the rate of ice discharge into the ocean": I am not sure what you are trying to say here. Are you comparing total ice discharge over the slowdown years with ice discharge over the much shorter period of speedup and claiming the latter is higher despite the short duration? If so, please clarify	This is a bit of an odd sentence but I think it does make sense - we are comparing the '*rate* of ice discharge' not the integrated discharge. But it's not particularly relevant so I have removed the sentence.
15	Figure 1 Figure 1 caption is really long. Probably best to split the manny (unrelated) panels to different figures, each with a brief caption, for clarity and readability.	I have shortened the caption but have kept the figure together for the time being.
16	Figure 1 f: the y axis on the actual panel says something different than what the description is here. Also, from the y label it is unclear what max is	I have changed the y-axis on the panel to read "Distance to the calving front (km)"

17	Figure 1 f - caption "Timeseries of distance to the calving front from a point on Hektoria Glacier…": Which point?	I have removed this reference to 'a point' on the glacier, and left the sentence saying the distance is measured along the white lines.
18	Line 89 "Hektoria and Green Glaciers were further exposed…": To what?	Good point, I'm not really sure what that means specifically. I have replaced this line with: "The HGE Ice Shelf retreated by a further 9 km between September and December 2022, decoupling the ice shelves of Hektoria and Green Glaciers."
19	Line 91 "The observations of the Larsen-B Embayment presented in this study and others (Ochwat et al., 2023) suggest that landfast sea ice permitted the growth of the floating ice/mélange tongues in front of HGE and Crane Glaciers over the period 2011 to 2022, which acted as a control on the upstream glacier dynamics.": I missed where you showed the glacier ice front position over the 2002-2022, so that we can see that the growth of ice tongues only occured after 2011 - or was that shown in a different paper? (Ochwat doesn't show that)	This is not explained very clearly in the article, so thank you for pointing out the confusion here. I have changed the first few sentences of the section 'Landfast sea ice buttressing' to read: "Previous studies focused on the area have shown ice speed changes on HGE and Crane Glaciers to be concurrent with changes in terminus position (Wuite et al., 2015; Rott et al., 2018) prior to 2011. In the case of HGE these changes fluctuated, while on Crane steady terminus advance accompanied steadily decreasing glacier speeds. Following the growth of persistent landfast sea ice in 2011, we see persistent terminus advance and decreasing speed - show here and elsewhere (Wuite et al., 2015; Rott et al., 2018; Ochwat et al., 2023). These observations, along with that of ice shelf disintegration after the sea ice evacuation in 2022, shown here and in Ochwat et al. (2023), suggests a coupling of landfast sea ice to glacier dynamics in which landfast sea ice permitted the growth of the ice shelves in front of HGE and Crane Glaciers prior to 2022 which acted as a control on the upstream flow. "
20	Line 105 "sea ice": maybe you should stick to the term landfast sea ice whenever that is the type of sea ice you are refereing to? This is just a suggestion but I think that would help the reader	Thank you for the suggestion, I have implemented the change throughout the manuscript.

21	Line 106: Also, I find the wording of point 1 quite confusing, it becomes clearer eventually when one reads the rest of teh paper, but rephrasing would be useful	Yes, I had difficulty properly articulating what I meant here, but the reviewer is right that it is important to get these points right. I have changed the points to: " 1) directly influencing the stress distribution in the glaciers such that the disintegration of the land-fast sea ice caused an instantaneous speed change on the grounded ice, and 2) reducing stresses in the ice shelves which would have otherwise been too great for the ice shelves to withstand. This latter mechanism is a second order effect of buttressing, the implication being that the disintegration of the landfast sea ice in turn caused the disintegration of the ice shelves via loss of buttressing, and hence the loss of the ice shelves as a control on the upstream dynamics." I hope these make more sense!
22	Line 106: I don't think this distinction makes much sense. The stresses in the land ice are coupled, both grounded and floating, and so a change of stress at the ice front translates to stress changes within the ice everywhere. You can then investigate all sorts of transient effects, but I don't think that is what is done here	You are right, the redistribution of stress as boundary conditions change happens across the whole glacier, not separately in the grounded and floating ice. This is the "direct buttressing" being referred to in point #1. The "indirect buttressing" of point #2 does indeed refer to a transient response in which buttressing were responsible for ice shelf stability. After that buttressing was taken away, this could have caused the ice shelves to disintegrate which, in turn, caused the grounded ice to speed up. Evidently, we cannot simulate this fully as we don't have an appropriate calving law, but we investigate whether the first part is plausible. We find that it is implausible, suggesting an alternative mechanism like increased ocean swell or buttressing from mélange. I hope the revised wording of points #1 and #2 make the distinction clearer.
23	Line 109 "This latter possibility is to be contrasted with other non-buttressing effects...": where, how?	In the mind of the reader.
24	Line 110 "... capacity of sea ice to bond fragments of mélange together, prevent small calving events at the glacier terminus and the export of icebergs": how is this influencing ice tongue stability if not through buttressing?	The 'buttressing' we refer to in analogy with ice shelf buttressing does not include these things. Instead, it refers to a change in viscous stress within the glacier due to the impact of sea ice on the stress boundary condition at the calving front.
25	Line 124 "At this point we do not include sea ice in the model geometry, so the glaciers terminate in open sea.": but the sea ice was there, so why does it make sense to assimilate to velocities observed in the presence of land fast sea ice, but not to include its effect (as a thin ice shelf as done below) when performing the inversion?	Good point. Please refer to the answer given to this question in the reviewer's general comments above.

26	Line 138 "Fig. S5": I don't see how the very patchy freeboard measurements inform about the smoothness of the stresses within the sea ice. Please elaborate on that.	Thank you for pointing out this mistake. The reference was supposed to be to Fig. S4 - the deformation field over the sea ice. I have changed this in the revised manuscript.
27	Line 141 "... relative abundances of meteoric and congelation ice...": are you talking about land ice now?	By "meteoric" I mean ice that originates from precipitation, rather than land ice.
28	Line 148 "... such an 'ice shelf' ...": maybe "modeled ice shelf"?	I have changed this to "...such landfast sea ice...".
29	Line 150 "... sea ice-like ice shelf ...": just pick a simple term for the modeled ice shelf and keep using the same term	Apologies for the confusing mixture of terminology. I have changed this to "landfast sea ice". Here, and throughout the rest of the modelling sections, context should make it clear whether we are referring to modelled or observed landfast sea ice.
30	Line 151 "... we use a regularised-Coulomb sliding law...": is that the same as sliding law used for the inversion? If not, please, justify	It was the same sliding law as used for the inversion, yes. I have not added anything to the manuscript because it doesn't really matter which sliding law is used in the inversion vs forward simulation as long as the basal stresses match in the two cases.
31	Line 160 "Again, this might lead to stiffer ice than in reality...": what do you mean by again? I think the key here is that still you are modeling a stronger buttressing effect than the sea ice can give, which is fine, given the conclusions of its inability to provide sufficient buttressing	I have removed the "Again" as it was a bit confusing. You are right about our ice providing greater buttressing.
32	Line 164 "...change smoothly...": do you mean smoothly as a function of sea ice thickness?	Yes. I have added "...as a function of landfast sea ice thickness..." to the sentence to make this clearer to the reader.
33	Line 169 "This is to be contrasted with the much larger $2-5\%$ changes in speed seen at the calving fronts and on the floating ice tongues in the simulations with sea ice thickness of 10 m (Fig. 2 b, c).": I don't understand this sentence. How is 2-5% much larger than 15-50%?	I meant to be referring to the change of $0-1\%$ of the grounded ice speed being smaller than the 2-5% on the floating ice. I have changed the sentence to read: "These changes in grounded ice speed are to be contrasted..."
34	Line 185 "now see that the sensitivity of grounded ice speed to changes in effective sea ice thickness is dwarfed in comparison to changes in the effective thickness of glacier ice.": I don't understand the last part of this sentence	I apologise for the confusion. I have replaced this with the sentence: "we now see that the sensitivity of grounded ice speed to changes in the effective thickness of landfast sea ice is minute in comparison to its sensitivity to changes in the effective thickness of glacier ice."
34	Figure 2: I m not sure if the panel c is necessary, it really doesn't show anything new that panel b wouldn't have already	This is a good point. These percentage changes in speed are not part of the revised Figure 2.

35	Figure 2 caption: Please add the glacier names on the plot	I have implemented this suggestion.
35	Line 189 "...the parts of the glaciers that showed speed increase in 2022...": it would be helpful to have in figure 3b a comparison figure to where along these profiles acceleration was observed. Spatial profile of acceleration is not clear from any figure in sufficient detail.	This is a good suggestion, and has been implemented in the revised figure 2.
35	Figure 3 caption "...artificial landfast sea ice...": what do you mean by artificial? modeled? prescribed?	I have removed the word 'artificial' as it wasn't adding anything. Though all of the reviewer's suggested alternatives are correct.
36	Figure 3 caption "...transects of data were collected...": specify modeled data (not to confuse with observed)	Good point. I have changed this to "...transects of modelled speeds were collected..."
37	Figure 3 caption - referring to glacier names: put these names on the plot, please	I have implemented this suggestion.
38	Line 203 "...thinner sections of ice...": sea ice of glacier ice? Please specify averywhere throughout the paper what you mean by ice when	I have added the word "glacier".
39	Figure 4 caption "...10m thick sea ice.": Is this linear? That is, does the addition of each additional 10 m produce comparable change in stresses? The formulation in the legend suggests that.	I am not sure what the reviewer is referring to here. It is the case that the speed changes are roughly linear with sea ice thickness, and probably stress too.
40	Line 216 "We cannot rule out the hypothesis that such processes were involved in the latter calving events on Crane Glacier and those on HGE starting in September 2022, though it seems likely that the effect would have been more due to the preceding loss of seaward sections of the ice tongues as opposed to this initial loss of sea ice buttressing.": I got a bit lost now. Are you trying to explain velocity changes on grounded ice? Why not repeat the same excercise, remove the floating ice tongues in the model and see what effect it has on the grounded ice in terms of instantaneous speedup?	I apologise, this is a confusing sentence. I am not trying to explain velocity changes on the grounded ice (in general, I don't have much interest in that). I am trying to explain changes to the calving behaviour of the ice shelves. I have changed this to read: "We cannot rule out the hypothesis that such processes were in part responsible for the elevated calving rate on Crane and HGE Ice Shelves starting in September 2022. However, if this were the case, it seems likely that the calving events themselves would have had a greater impact on subsequent calving rate than the loss of sea ice." which I hope is clearer.
41	Line 218 "... the effect ...": The effect of what?	Thank you for pointing out this confusion, this sentence was not well written. See my response to comment #40.
42	Figure 5 c: Is this T2m change or anomaly? make label consistent	I have changed the label on the figure to read 'anomaly'.

43	Figure 5: Please mark the date of fast ice breakup on plots a b and d. Also, if your timseries goes back enough, also mark the date of the 2002 ice shelf breakup	I have added vertical lines to the plots showing the dates of these events as suggested.
44	Line 262 "Observations of ice shelf basal melt rates": estimates	I have made the change as suggested.
45	Line 265 "A timeseries of the mean basal melt rate from this region shows": Also, it would be worth mentioning that these basal meltrates have not been validated, and if anything, similar estimates by Adusumilli at al have been shown to produce variability and order of magnitude larger than observed in situ on the neighboring Filchner-Ronne Ice Shelf.	Would it be possible to provide a reference for this?
46	Line 266 "0 ma^{-1}": I think you need to mention the giant ± 4 m a^{-1} uncertainty here	Very good point! I have added the uncertainty.
47	Line 351 "This leads us to suggest that the term "buttressing" should not be used in the context of sea ice in the way it is understood when applied to ice shelves.": I think I know what you mean here but it could be said in a less ambiguous way.	I think this is quite a precise statement. I don't want to say "People shouldn't use the term 'sea ice buttressing' ", but I do want to say "People shouldn't use the term 'sea ice buttressing' in a way analogous to ice shelf buttressing." Perhaps that would be better?
48	Figure S3: Figure S3: What is the vertical orange line on the western side of scar inlet? Did the calving front advance so much in less than a year from that vertical orange to the horizontal purple line further northwest?	Good spot! A new figure with updated calving fronts has replaced the old one.

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The ~~impact~~ effect of landfast sea ice buttressing on ice dynamic speedup in the Larsen-B Embayment, Antarctica

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Abstract. We observe the evacuation of 11-year old landfast sea ice in the Larsen-B Embayment on the East Antarctic Peninsula in January 2022, which was in part triggered by warm atmospheric conditions and strong offshore winds. This evacuation of sea ice was closely followed by major changes in the calving behaviour and dynamics of the ocean-terminating glaciers in the region. ~~Following~~ We show using satellite measurements that, following a decade of gradual slow-down, ~~satellite measurements show that~~ Hektoria, Green and Crane Glaciers have sped up by approximately 20-50% since February 2022, each increasing in speed by more than $100 \ \mathrm{m \, a^{-1}}$. Circumstantially, this is attributable to ~~the loss of floating ice/mélange tongues and~~ their transition into tidewater glaciers following the loss of their ice shelves. However, a question remains as to whether the landfast sea ice itself could have acted to provide direct buttressing to the glaciers prior to its disintegration. We use diagnostic ~~model~~ simulations to estimate the buttressing effect of the landfast sea ice in the Larsen-B Embayment and its ~~impact~~ effect on the speed of Hektoria, Green, Evans and Crane Glaciers. The results show that direct landfast sea ice buttressing had a negligible impact on the dynamics of the grounded ice streams. Additionally, ~~our results~~ we show that the loss of landfast sea ice buttressing likely produced noticeable changes to the flow speeds of the rheologically weak ice ~~tongues~~shelves, which could have diminished their stability over time. However, ~~as the accompanying changes in viscous stress were small compared to local spatial variation,~~ the accompanying shifts in the distributions of viscous stress within the ice shelves were only minor, indicating that this loss of buttressing is likely to have been a secondary process in the ~~disintegration of the ice tongues~~ ice shelf disaggregation compared to, for example, increased ocean ~~melting or swell~~ swell or the drivers of the initial landfast sea ice disintegration.

1 Introduction

The Antarctic Ice Sheet lost $2,671$ Gt of ice mass between 1992 and 2020 contributing $7.4\,\mathrm{mm}$ towards global sea level rise
20 (Otosaka et al., 2023), with almost all of this loss attributed to ocean-driven ice dynamic processes (Slater et al., 2021). The
Antarctic Peninsula (AP) is one of the most rapidly changing parts of the Antarctic Ice Sheet due to its exposure to increasing
air temperatures relative to a warm baseline (Trusel et al., 2015; Banwell et al., 2021), increased ocean forcing (Smith et al.,
2020), decrease in ice shelf area (Cook and Vaughan, 2010), and changes in wind and sea ice conditions (Christie et al., 2022;
Fraser et al., 2023).

25 The Larsen-B Embayment, located on the East AP - bordered by Seal Nunataks in the north and Jason Peninsula in the south
- contains 12 major glaciers that flow into the Weddell Sea. Over the last 30 years, satellites have observed major changes in
this region. Following a period of relative stability in the 1990~~'~~'s, the collapse of the Larsen-B Ice Shelf in 2002 (Scambos
et al., 2004) caused an immediate eight-fold increase in speed (1.0 to $2.8\,\mathrm{km\,a^{-1}}$) on the Jorum, Crane and Hektoria, Green,
Evans Glaciers which were previously buttressed by the ice shelf (Rignot et al., 2004). Though continued buttressing by the
30 Larsen-B remnant in Scar Inlet prevented the neighbouring Flask and Leppard Glaciers from speeding up in 2002/3, their ice
discharge was 42% higher by 2013 relative to 1995 (Wuite et al., 2015).

Following the ice shelf collapse in 2002, first-year sea ice formed annually during the austral winter in the Larsen-B Em-
bayment, however, it remained ice free each year during the summer months. In 2011, the winter sea ice became landfast,
and persisted continuously for 11-years (Christie et al., 2022) before it suddenly disintegrated in January 2022 and was evac-
35 uated from the embayment (Ochwat et al., 2023). During the weeks and months following the landfast sea ice evacuation,
the floating ice ~~/mélange tongues~~ shelves that had developed on the Hektoria/Green/Evans (HGE) glacier system and Crane
Glacier ~~disintegrated (Rott et al., 2018)~~ (Rott et al., 2018) disintegrated, and their tributary glaciers increased in flow speed
(Ochwat et al., 2023). There are clear visual parallels between the clearance of landfast sea ice in 2022 and the disintegration
of the Larsen-B Ice Shelf 20 years earlier, and the subsequent dynamic responses of these glaciers. However, uncertainty re-
40 mains about the mechanisms driving the increased ice speeds on HGE and Crane in the latter case, particularly regarding the
~~"buttressing"~~ "buttressing" role that the landfast sea ice was able to provide the glaciers prior to collapse (Sun et al., 2023;
Ochwat et al., 2023).

Here, we present observations of the spatial pattern of ice speed change before and after the landfast sea ice disintegration
in January 2022, along with measurements of glacier calving front location, landfast sea ice extent and thickness amongst
45 others. ~~We then investigate the~~ These results complement recent work by Sun et al. (2023) and Ochwat et al. (2023), which
document many similar observations to those presented here, though we focus on the glaciers that showed the greatest dynamic
response after 2022 - namely Crane and Hektoria/Green/Evans. These observations form the background and motivation for
an investigation into the buttressing capacity of the landfast sea ice ~~using~~ in which we perform simple diagnostic modelling
experiments ~~which aim~~ aiming to quantify the redistribution of ~~stresses as sea ice thickness is changed in~~ stress as landfast
50 sea ice of varying thickness is added to the Larsen-B Embayment.~~Monitoring and understanding the mechanisms driving both
long and short-term glacier speed change is important for accurately projecting the future evolution of Antarctic glaciers .~~.

2 Observations

2.1 ~~Sea ice area change~~

2.1 Observational methods

55 We collected satellite-derived datasets over the period 2002-2023 to assess changes in landfast sea ice extent, ice shelf extent and ice flow speed across the Larsen-B Embayment and the glaciers that terminate there. We used multi-spectral optical Landsat-8 imagery to visually identify and delineate the landfast sea ice edge in the Larsen-B Embayment in November each year from 2002 to ~~2022 (~~2022. We used this Landsat-8 data, and additional Sentinel-1 Synthetic Aperture Radar (SAR) backscatter images, to manually delineate the calving front location of each glacier feeding the Larsen-B Embayment (Fig. 1

60 ~~a~~f, Fig. ~~S1). These observations show that, since its formation in winter 2011, the sea ice was retained throughout the summer months, and generally grew in extent each year through to 2017 when its seaward margin entered a period of fragmentation and regrowth until 2022. Between the 18th and 23rd of January~~ S3). Before the first calving events of 2022, the ~~multi-year sea ice disintegrated and was evacuated out of the Larsen-B Embayment, leaving open ocean. Satellite data show that there was modest surface melt ponding on the sea ice during the austral summers prior to the sea ice collapse, however, these melt ponds~~

65 ~~were more widespread and densely spaced across the entire sea ice area in 2021. Surface melt ponds were observed to be at their maximum extent in December 2021 immediately prior to the sea ice disintegration in January 2022.~~

2.2 ~~Ice dynamic and calving response~~

calving fronts were difficult to define precisely, with a smooth transition from consolidated ice shelf to landfast sea ice through a region of ice mélange. However, this does not impact our understanding of the timings of the calving events. We applied

70 intensity tracking techniques to ~~Interferometric Wide~~ single-look complex Sentinel-1 SAR data collected in Interferometric Wide-swath (IW) mode~~Sentinel-1a/b Synthetic Aperture Radar (SAR) data~~, to produce a ~~7-year~~ 8-year record of ice speed over the 12 outlet glaciers in the study region ~~(Hogg et al., 2017; Davison et al., 2023). We report linear trends in ice speed over the domain for the period October 2014 to October 2021 (Fig. 1 d) and October 2021 to~~ from January 2015 to April 2023 ~~(Fig. 1 e). Timeseries of mean ice speed were extracted for~~ (Davison et al., 2023). We extracted timeseries of ice speed

75 averaged over 1 km-long flowline segments on 12 glaciers flowing into the Larsen-B Embayment, and used a Kalman smoother with an identity transition matrix ~~was used~~ to filter the results (1 a-c) (Wallis et al., 2023). These locations were chosen to be in the centre of the grounded ice streams, close to the grounding line but with enough room for a 1 km buffer along the flowlines that pass through them. Uncertainty indicators in these speeds were calculated by scaling the reciprocal signal-to-noise ratio in the cross-correlation field with the ice speed (Lemos et al., 2018).

80 ### 2.2 Landfast sea ice area change

Our data show that the landfast sea ice went through phases of growth and decay during the period 2002-2011, with sea ice covering the entire embayment at times, and only the smaller pro-glacial embayments at others (Fig. S1). After its formation

3

2.3 Ice dynamic and calving response

Our velocity measurements show that between October 2014 and January 2022 Hektoria, Green and Crane Glaciers slowed by approximately $100 \, \mathrm{m \, a^{-1}}$ (Fig. 1 b, d), with smaller decreases in speed on Evans (Fig. 1 c, d), Punchbowl, Jorum and Melville Glaciers (1 b, Fig. S2). Over the same period Flask Glacier sped-up slightly by 5% ($30 \, \mathrm{m \, a^{-1}}$), and the remaining 4 glaciers exhibited fairly stable speeds on annual timescales (1 c, Fig. S2).

We used Landsat-8 and Sentinel-1 images to manually delineate the calving front location of each glacier feeding the Larsen-B Embayment (Fig. 1 f, Fig. S3). During the period of steady or declining speeds between 2014 and 2021 we observe progressive advance of the calving front on the majority of glaciers in the study region. Hektoria and Crane Glaciers advanced the furthest, with approximately $12 \, \mathrm{km}$ and $7 \, \mathrm{km}$ of growth observed between 2015 and 2021 respectively, though this advance was not monotonic. The Larsen-B remnant in Scar Inlet is the only calving front to have continually advanced between 2015 and 2021, growing by $6 \, \mathrm{km}$. The remaining glaciers experienced changes in calving front position of $3 \, \mathrm{km}$ or less between 2014 and 2022.

Following the sea ice disintegration disintegration of the landfast sea ice, we observe a large speed-up on Green and Crane Glaciers beginning in February 2022 and accelerating from June/July 2022 (Fig. 1 b, e), followed by a speedup on Hektoria Glacier beginning in July 2022 (Fig. 1 b, e), though this glacier exhibits a more varied signal. At the grounded ice locations chosen for extraction of speed timeseries, we see changes in speed between January and December 2022 of $35.5 \pm 10.4\%$ on Hektoria Glacier, $46.9 \pm 7.0\%$ on Green Glacier and $17.8 \pm 5.5\%$ on Crane Glacier. We also see a potential sign change in the ice speed trend on Evans and Jorum (Fig. 1 c, e) Glaciers in early 2022 from negative to positive, though the changes in speed are comparable to historical variability in the ice speed data. Speed changes extend up to 10 km upstream of the 2021 grounding line on On Hektoria, Green and Crane Glaciers, where the speed-up is most pronounced, speed changes extend up to 10 km upstream of the 2021 grounding line. Our velocity measurements show that there was no pronounced change in speed of Leppard, Flask, Starbuck, Pequod, Melville, Mapple or Punchbowl Glaciers discernible from the variability in ice speed over the preceding decade (Fig. 1 c, e, Fig. S2). Overall, the speedup observed after the sea ice disintegration in January 2022 is more extensive than the region of slowdown observed between 2015 and 2022 (Fig. 1 d), and extends inland onto the grounded ice sheet (Fig. 1 e), therefore increasing the rate of ice discharge into the ocean.

The large dynamic changes on Crane and Green Glaciers were preceded immediately by a period of terminus retreat in February 2022 of $6 \, \mathrm{km}$ and $12 \, \mathrm{km}$ on the Crane and HGE Ice Shelves respectively (Fig. 1 f). Crane Ice Shelf continued to calve during the period of acceleration and, by the end of our study period, had retreated $12 \, \mathrm{km}$ relative to its maximum position
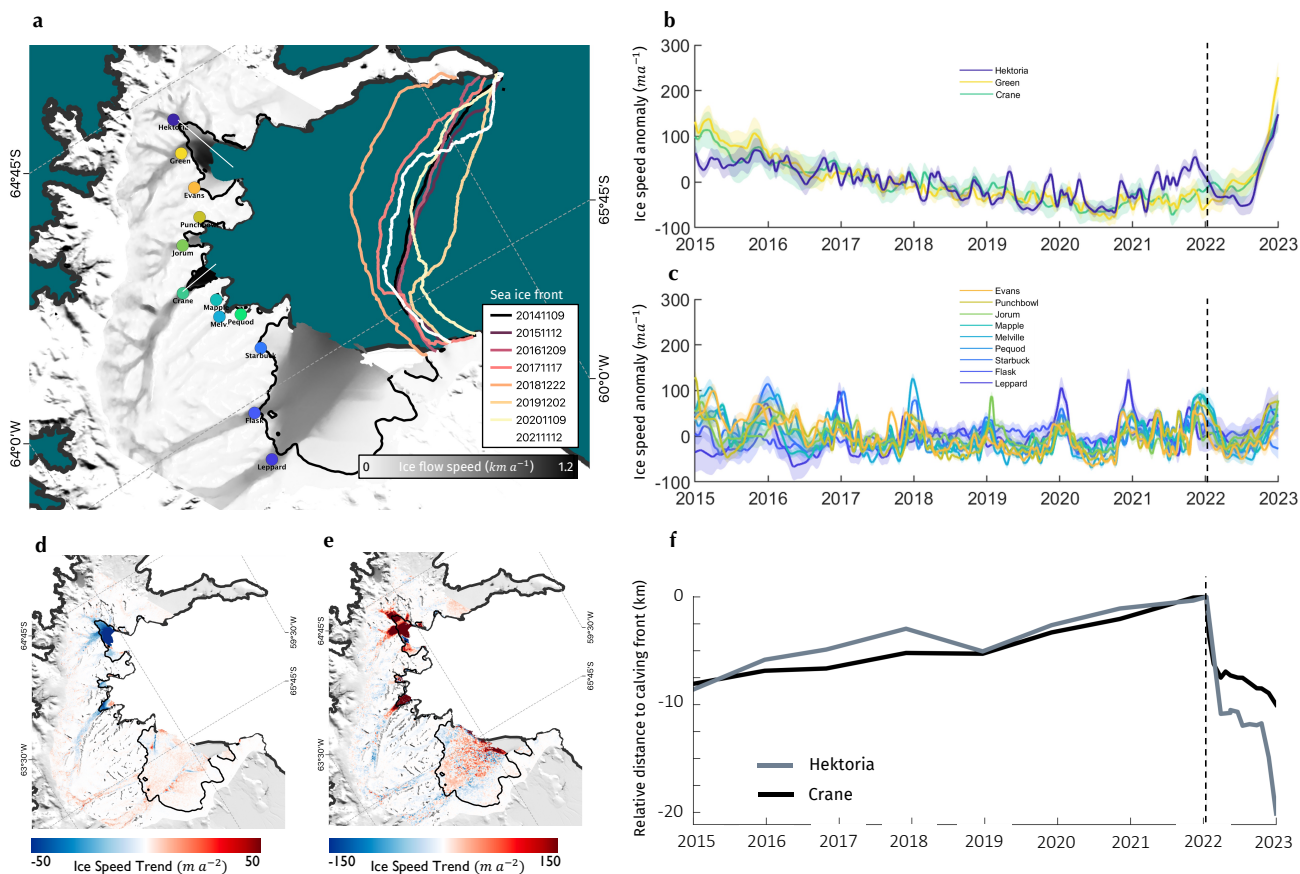
Figure 1. Ice Speed and speed change map of the Larsen-B Glaciers. a) Inverse-error-weighted mean ice speed of glaciers flowing into the Larsen-B Embayment on the East Antarctic Peninsula, measured between October 2014 and April 2023 ~~using Interferometric Wide (IW) mode synthetic Aperture Radar (SAR) data acquired by the Sentinel-1a/b satellites (~~(greyscale map). Grounding line location (~~constituting~~ that of Wallis et al. (In Prep.) in HGE and Crane, and the MEaSUREs InSAR-derived grounding line elsewhere (Mouginot et al., 2017)) is shown with the solid black line. ~~The locations at which ice speed timeseries (b-c) were extracted on Hektoria, Green, Evans, Punchbowl, Jorum, Crane, Mapple, Melville, Pequod, Starbuck, Flask and Leppard Glaciers are shown with coloured cirlees.~~ Coloured lines show the landfast sea ice fronts, measured annually between November 2014 and November 2021. b) Ice speed anomaly (signal minus the timeseries mean) from January 2015 to January 2023 on Hektoria, Green and Crane Glaciers. c) Ice speed anomaly on the other glaciers shown in (a). For the plots in (b-c), data was extracted over 1 km long segments of flowlines with centrepoints shown by the circles in (a)~~and a Kalman smoother was used along with a 30-day moving average to smooth the data~~. The uncertainties shown are 1σ either side of the mean. d) A map of the observed rate of change in ice speed between October 2015 and October ~~2021, prior to the sea ice disintegration event.~~ 2021. e) A map of the observed rate of change in ice speed between October 2021 and April 2023, spanning the ~~sea ice~~ disintegration event in February 2022. f) Timeseries of ~~distance to the~~ calving front ~~from a point~~ distance on Hektoria Glacier (grey line) and Crane Glacier (black line) from January 2015 to January 2023. These distances are measured along the white lines shown in (a). Datapoints are annual between 2015 and 2022, and monthly thereafter. Black dashed lines in panels (b, c, f) show the 18th January 2022, the start of the break up of the landfast sea ice in the Larsen-B Embayment.

in ~~Dec~~ December 2022. ~~Hektoria and Green Glaciers were further exposed, and their ice shelves decoupled, by a further retreat~~

5

~~of the~~ The HGE Ice Shelf ~~by~~ retreated by a further 9 km between September and December ~~2022.~~2022, decoupling the ice shelves of Hektoria and Green Glaciers.

3 ~~Sea~~ Landfast sea ice buttressing

~~The observations of the Larsen-B Embayment presented in this study and others (Ochwat et al., 2023) suggest that~~ Previous studies focused on the area have shown ice speed changes on HGE and Crane Glaciers to be concurrent with changes in terminus position (Wuite et al., 2015; Rott et al., 2018) prior to 2011. In the case of HGE these changes fluctuated, while on Crane steady terminus advance accompanied steadily decreasing glacier speeds. Following the growth of persistent landfast sea ice in 2011, we see persistent terminus advance and decreasing speed - show here and elsewhere (Wuite et al., 2015; Rott et al., 2018; Ochw. These observations, along with that of ice shelf disintegration after the sea ice evacuation in 2022, shown here and in Ochwat et al. (2023), suggests a coupling of landfast sea ice to glacier dynamics in which landfast sea ice permitted the growth of the ~~floating ice /mélange tongues~~ ice shelves in front of HGE and Crane Glaciers ~~over the period 2011~~ prior to 2022 ~~,~~which acted as a control on the upstream ~~glacier dynamics.~~ flow. However, it is unclear the extent to which the landfast sea ice could have itself acted to buttress the upstream glaciers, and whether the growth of the ice ~~tongues~~ shelves is attributable to the ~~buttressing effect of~~ *buttressing* effect of landfsat sea ice as opposed to other mechanisms by which landfast sea ice can confer stability to regions of ice mélange.

Recent observational reports of the January 2022 evacuation of landfast sea ice from the Larsen-B Embayment provide conflicting accounts of the possible buttressing effect the landfast sea ice could have had. Ochwat et al. (2023) suggest that the growth of the ice ~~tongues~~ shelves during the residency of the landfast sea ice, the potential dampening ~~by the sea ice~~ of ice speed in Scar Inlet and the immediate speed up of certain ice ~~tongues~~ shelves following the collapse of the landfast sea ice is evidence of its buttressing effect. However, Sun et al. (2023) suggest that the limited immediate response of the glaciers to the landfast sea ice evacuation, and the potential plastic rheological response of the landfast sea ice to sudden changes in upstream stress are reason to believe ~~sea ice~~ any buttressing was minimal.

In the context of ice shelves, "buttressing" refers to the hypothetical difference in englacial stress with and without the ice shelf (Gudmundsson, 2013; Fürst et al., 2016). To be consistent, we take "buttressing" to have the same meaning in the context of landfast sea ice. Consequently, there are two ways that ~~a loss of~~ landfast sea ice buttressing could have contributed to the observed speed changes on the HGE and Crane Glaciers: 1) directly influencing the stress ~~state of the grounded ice~~ distribution in the glaciers such that the ~~increases in speed after January 2022 cannot be fully accounted for by the loss of the ice tongues or other external influences~~disintegration of the landfast sea ice caused an instantaneous speed change on the grounded ice, and 2) reducing ~~longitudinal~~ stresses in the ice ~~tongues, contributing to their stability over the time the sea ice was present and indirectly controlling the upstream glacier speed. This latter possibility~~shelves which would have otherwise been too great for the ice shelves to withstand. This latter mechanism is a second order effect of buttressing, the implication being that the disintegration of the landfast sea ice in turn caused the disintegration of the ice shelves via loss of buttressing, and hence the

loss of the ice shelves as a control on the upstream dynamics. This is to be contrasted with other non-buttressing ~~effects that mechanisms by which the landfast sea ice could~~ influence the stability of the ice ~~tongues~~shelves, such as ~~the capacity of sea ice to bond~~ by bonding fragments of mélange together, ~~prevent~~ preventing small calving events at the glacier terminus~~and~~, stopping the export of icebergs, and ~~to dampen~~ dampening swell-induced loading cycles.

Here, we use the BISICLES ice sheet model (Cornford et al., 2013) to directly investigate these possible effects for the glaciers that exhibited the most pronounced changes in dynamic behaviour after January 2022 – namely the HGE system of glaciers and Crane Glacier.

3.1 ~~Model set-up~~Modelling methods

BISICLES is a finite-volume, adaptive mesh model that solves a discretised form of the shallow-stream approximation to the momentum balance equations:

$$\boldsymbol{\nabla} \cdot [\phi h \bar{\mu} (\boldsymbol{\nabla}\boldsymbol{u} + (\boldsymbol{\nabla}\boldsymbol{u})^{\top} + 2(\boldsymbol{\nabla}\cdot\boldsymbol{u})\mathcal{I})] - C f(u)\boldsymbol{u} - \rho_i g h \boldsymbol{\nabla}s = 0, \tag{1}$$

where u is the ice speed, h is the ice thickness, s is the ice surface elevation, $\mathcal{I}$ is the identity operator, $f(u)$ is a function parametrising our sliding law, C is a scalar 'basal slipperiness' field, ρ_i is the density of ice, g is the acceleration due to gravity, $\bar{\mu}$ is the vertically-averaged effective ice viscosity and the scalar field ϕ is an 'stiffness' that scales $\bar{\mu}$. We use Glen's flow law with an exponent of 3, Hooke's form of the rate factor (Cuffey and Paterson, 2010) and an internal energy field generated from a continent-wide thermomechanical spin-up in the calculation of the effective ice viscosity. Simulations were carried out at a maximum of $125 - 250$ m resolution.

Initially, we set up a model domain with geometry approximately reflecting the HGE and Crane basins of the Larsen-B Embayment, using a combination of smoothed bedrock elevations according to Huss and Farinotti (2014), grounding line positions timestamped for the year 2021 (Wallis et al., In Prep.) and surface elevations from the Reference Elevation Model of Antarctica (REMA) digital elevation model (DEM) (Howat et al., 2019) which is timestamped to May ~~2015, and grounding line positions timestamped for the year 2021 (Wallis et al., In Prep.).~~ 2015. Contemporary grounding line locations are required as there has been significant grounding line retreat on these glaciers since the MEASURES InSAR grounding line datasets were produced (Wallis et al., In Prep.). The REMA DEM does not reach the edge of the HGE and Crane Ice Shelves as they were in 2021, so we filled this gap by extrapolating the DEM along flowlines. We performed an inversion for basal ~~traction~~slipperiness (C) and ~~enhancement factor~~ stiffness (ϕ) fields using ~~mean observed~~ observations of ice speed across the HGE and Crane basins ~~in~~ averaged over 2021 (Cornford et al., 2015). At this point we ~~do not include~~ did not include the landfast sea ice in the model geometry, so the glaciers terminate in open sea. ~~As this inverse problem is ill-posed, we use~~ The choice to do this presupposes that the inclusion of the landfast sea ice will do little to change the solution to the inverse problem and is necessary as the thickness of the landfast sea ice is not well constrained. We shall see that this assumption is validated by the results. We

used regularisation with a Tikhonov operator that approximates the gradients of the control fields to ~~ensure the problem is not underdetermined and improve its conditioning~~ improve the conditioning of the problem. L-curve analysis (Hansen, 1994) was

185 used to select an appropriate level of regularisation (Fig. A1). ~~We~~ The gaps in time between the surface elevation, grounding lines and ice speed data used for the inversions meant that a certain amount of 'relaxation' of the geometry was required. We ran 5 inverse problems separated by a year of thickness evolution. Fig S6 shows geometry and control fields at the end of the model initialisation. We note that, as the thickness and bedrock data in this region of Antarctica is very poorly constrained, the geometry we construct should be considered plausible as opposed to fully accurate. As such, our conclusions are subject

190 to change under replication using different glacier geometries. Given the potential influence of unknown deviations in the real geometry from the data available to us, we avoid performing transient simulations ~~,~~ which risk amplifying the impact of these uncertainties which, for the basic mechanical arguments made here, are not likely to be important.

To simulate the effect of the landfast sea ice in the embayment, we assume that it can be treated as a thin ice shelf with the

195 same constitutive ice rheology as the upstream glaciers. Considering a range of length- and time-scales, sea ice is typically treated as a visco-plastic ~~(Hibler, 1979) or elasto-visco-plastic material (Hunke and Dukowicz, 1997)~~(e.g. Hibler (1979)) or elasto-plastic material (e.g. Hunke and Dukowicz (1997)). This captures a material that is strong in compression and weak in extension and shear ~~in which long-term viscous internal creep deformation is coupled with an elastic response to sudden loading and~~ dominated by plastic deformation in thin-ice-covered leads or pressure ridges. Regarding the landfast sea ice that

200 inhabited the Larsen-B Embayment prior to 2022, satellite images show a fairly uniform, unbroken ice coverage with a smooth deformation field ~~not confined to leads~~ (Fig. ~~S5~~S4). This suggests incompressible flow with stress continuity between the landfast sea ice edge and the glacier calving fronts ~~, and largely viscous or elastic~~ and largely smooth deformation over its decade of residency, though indications of ~~a~~ larger-lengthscale plastic response to sudden loading have been observed (Sun et al., 2023).

205 ~~In turn, any viscous deformation~~ Any sub-critical viscous deformation internal to the sea ice is controlled by a rheology which depends on the relative abundances of meteoric and congelation ice, with differences in crystal structure and the presence of brine-inclusion leading to a lower effective viscosity in the latter case. Similarly, surface melt-induced porosity in the meteoric ice lower its effective viscosity relative to glacier ice. The use of the same formula for the effective viscosity of land and sea ice, along with the assumption of viscous deformation, means that our treatment is to likely provide an upper bound to

210 the buttressing strength that unbroken landfast sea ice could exert on the upstream glaciers. We provide additional evidence in support of this claim in Sec. 4.1.

After setting up the model domain in the way described above, we add such ~~an 'ice shelf'~~ modelled landfast sea ice between the glacier calving fronts and the observed seaward limit of the multi-year landfast ice (Fig. 2 a). We then recalculate ice speed

215 over the domain by solving the stress-balance equations in this new configuration~~, and compare~~. We compare these along flowline transects with the speed in the absence of the ~~sea ice-like shelf~~ landfast sea ice (Fig. 2 b-d) ~~. For these~~ and also with flowline transects of quarterly-averaged speed observations from before and after the landfast sea-ice evacuation. We show

speed observations smoothed with a 5 km window from the second quarter of 2021 (the last before the sea ice evacuation - excluding the months October-December 2021 where high surface melt rendered the data unreliable) and the last quarter of 2022. The transects of observations are cut off at the most land-ward calving front position observed during the quarter, or at the edge of our speed observations (which coincide with the edge of the REMA DEM). This gives us the results of Sec. 3.2.1.

For the simulations, we use a regularised-Coulomb sliding law (Schoof, 2005; Joughin et al., 2019) with a threshold ice speed of $u_o = 300\ \mathrm{m\,a^{-1}}$, ensuring basal stresses so that sliding is plastic on much of the grounded ice. This ensures that basal stresses remain relatively unchanged as landfast sea ice is introduced resulting in enhanced changes to the viscous stress and greater ice speed change. Our choice of $u_o = 300\ \mathrm{m\,a^{-1}}$ is based on the speeds of tributary glaciers flowing into HGE and Crane Glaciers, though a choice of an even lower threshold makes little difference to the main results (Sec. A3). This was carried out for landfast sea ice thicknesses of 1 m, 2 m, 5 m and from 10 m to 50 m in increments of 10 m – a range that extends beyond what one might expect to be realistic landfast sea ice thicknesses in the study region. CryoSat-2 radar altimetry observations show the landfast sea ice had a mean freeboard under 1 m over the period 2013 to 2020 (Fig. S5), implying an approximate sea ice thickness under 10 m. We choose chose to model the landfast sea ice as uniform in thickness, despite these data suggesting otherwise, as the data do not extend to the critical zone at the glacier calving front. This should do little to change the conclusions of the modelling results. The sea ice was assumed to be of vertically and horizontally uniform temperature of $-5\ ^\circ\mathrm{C}$. Again, this might This is likely to lead to stiffer ice with greater buttressing strength than in reality as observations of surface melt (Ochwat et al., 2023) indicate that the sea ice might be better modelled as temperate.

Additionally, we assess the sensitivity of grounded ice speed to changes in the thickness of the landfast sea ice compared to the thickness of the glaciers themselves (Sec. 3.2.1). This gives us some intuition as to where any changes in geometry that occurred in 2022 might have led to changes in glacier speed. We treat the stiffness ϕ as a proxy for ice thickness (h) as, to first order, perturbations to these quantities each have the same effect on vertically-integrated effective viscosity. We consider two 1 km-radius circular regions on the grounded ice of Hektoria and Crane Glaciers (Ω_H and Ω_C respectively) and define the function $\mathcal{J}$ as the mean ice speed over these regions. We then calculate the magnitude of the gradient of $\mathcal{J}$ with respect to ϕ using standard adjoint-based methods (Sec. A2). To ensure that we are not aliasing an atypical part of the solution space, we find these sensitivities for 6 realisations of the control variables C and ϕ corresponding to solutions of the inverse problem with different amounts of regularisation.

Finally, to examine the component of ice shelf stability due to the buttressing of landfast sea ice (Sec. 3.2.2) we further study the case in which 10 m of landfast sea ice is added to the embayment. We look at how strain rates and stresses near the glacier termini change. Principal strain rates ε_1 and stresses σ_1 (the largest eigenvalues of the strain rate and stress tensors local to each parcel of ice) were calculated and compared for the HGE and Crane ice shelves for 10 m of landfast sea ice vs 0 m.
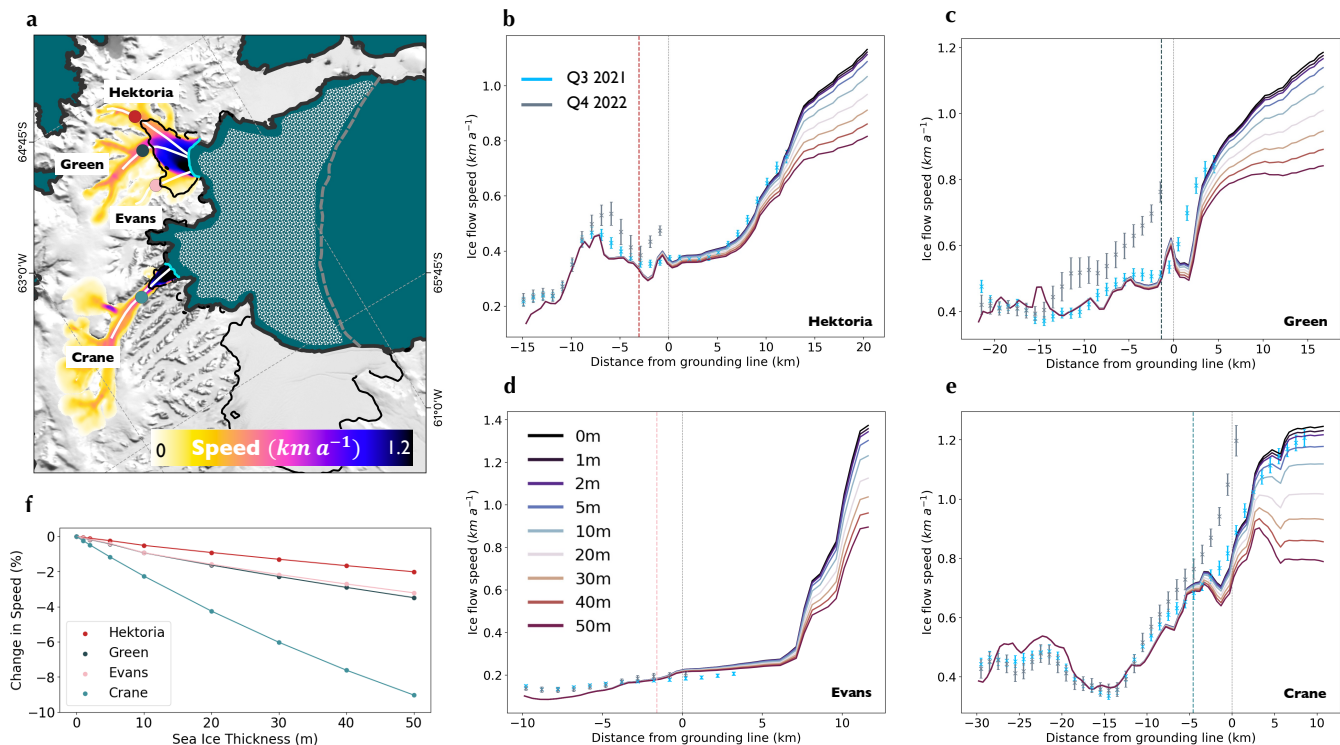
Figure 2. Modelled changes in speed with varying ~~landfast~~ sea ice thickness. (a) The Larsen-B Embayment. Flow speeds following the inversions for ~~enhancement factor~~ stiffness and basal slip coefficient fields over the Hektoria and Crane basins. The patterned area bound by the embayment walls and the grey dashed line ~~shows the maximum extent of the~~ indicates where landfast sea ice ~~– where sea ice~~ was added during the simulations. Coloured circles on the glaciers show where timeseries of speed were extracted in Fig. 1. Flowlines used to extract speeds for different landfast sea ice thicknesses (~~d~~b-e) are shown in white. ~~Cyan lines show the glacier terminus positions according to the model geometry and the~~ The basemap is the MODIS Mosaic of Antarctica (Haran et al., 2021). (~~b~~b-e) Modelled ice speeds for different landfast sea ice thicknesses, where dark blue indicates 0 m and dark red indicates 50 m~~sea ice thickness~~, along the flowlines shown in (a): Hektoria (b.~~1~~), Green (~~b.2~~c), Evans (~~b.3~~d) and Crane (~~b.4~~e). Thin, vertical, grey dashed lines show the positions of the grounding lines, and coloured vertical lines show the positions of the corresponding circles in (a). ~~(c) A repeat of (b) with percentage speed changes relative to zero sea~~ Points plotted in cyan show the ice ~~shown instead of~~ speed measured along these transects in the third quarter of 2021 - smoothed with a 5 km window. Points plotted in grey show the equivalent for the last quarter of 2022. (~~d~~f) ~~Ice speed (c.1) and percentage~~ Percentage change in modelled ice speed ~~change (c.2)~~ for different landfast sea ice thicknesses at the locations with ~~corresponding colour~~ colours shown in (a).

3.2 Modelling results

3.2.1 Direct buttressing of grounded glaciers

Transects located approximately along flowlines of four glaciers that accelerated in 2022 show that speeds ~~change smoothly~~ along the glaciers ~~when sea ice is added into~~ change smoothly as a function of landfast sea ice thickness in the embayment (Fig. 2 ~~b-d~~b-e). However, these changes in speed are strongly attenuated upstream of the calving front. At the grounded-ice locations used to produce the timeseries in Fig. 1 b, we see instantaneous ice speed changes on the order of 0-1% with the addition of a
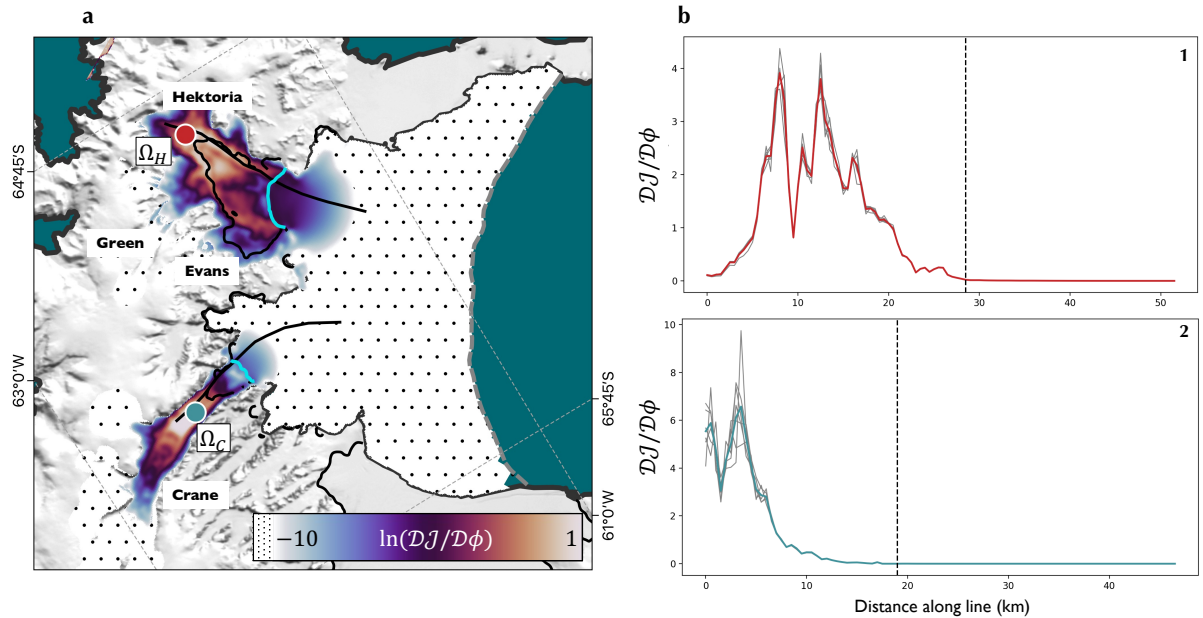
Figure 3. Sensitivity of ice speed to changes in effective ice thickness. (a) Magnitudes of differential sensitivities of ice speed in the locations marked by the coloured circles to change in stiffness across the domain. The black spotted area shows where the sensitivity is under e^{-10}. Cyan lines show the boundaries between the glacier termini and the start of the landfast sea ice according to the model geometry. Black lines show where transects of modelled speeds were collected to produce the graphs in (b)-(c). The basemap is the MODIS Mosaic of Antarctica (Haran et al., 2021). (b) Magnitudes of sensitivities along the transects shown in (a). Black dashed lines show the location along the transect of the glacier terminus: Hektoria (b.1) and Crane (b.2). Grey lines indicate the different realisations of the control variables C and ϕ, while coloured lines show the mean sensitivities. Note: data is presented logarithmically in (a) and linearly in (b).

realistic upper limit of 10 m thick landfast sea ice, and a speed change of 0-6% with the highly unlikely ~~sea ice~~ thickness of 50 m (Fig. 2 ~~b, c, d~~ b-f). This is considerably below the 15-50% speed change observed on these glaciers (Fig 1 b, Fig. 2 b-e) after January 2022. ~~This is~~ These changes in grounded ice speed are to be contrasted with the much larger $2-5\%$ changes in speed seen at the calving fronts and on the floating ice ~~tongues~~ shelves in the simulations with landfast sea ice thickness of

260 10 m (Fig. 2 ~~b, c~~ b-e). These modelled percentage changes in speed are similar in magnitude on all glaciers including Evans, where we do not observe a substantial dynamic response (Fig. 1 g). This ~~indicates~~ is an indication in its own right that landfast sea ice removal was not the primary cause of the ice dynamic change observed on these glaciers.

265 In the range $0-50$ m, the addition of ice in the Larsen-B Embayment produces changes in speed that vary approximately linearly with thickness (Fig. 2 ~~d). Using the adjoint to the linearised stress balance equations, we can directly compare the magnitudes of gradients in ice speed with respect to ice thickness across the whole domain (Sec. A2). This gives us intuition as to where changes in ice geometry that occurred in 2022 might have led to changes in glacier speed. We treat ice enhancement factor (ϕ) as a proxy for ice thickness (h) as, to first order, perturbations to these quantities each have the same effect on vertically-integrated effective viscosity. To ensure that we are not aliasing an atypical part of the solution space, we find these~~

11

270 ~~sensitivities for 6 realisations of the control variables C and ϕ corresponding to solutions of the inverse problem with different amounts of regularisation. f).~~ We invert this relationship and look, in Fig. 3~~shows~~, at the magnitudes of gradients of ice speed at two locations (Fig. 3 a), with respect to effective thickness, assuming 10 m of landfast sea ice.

~~Sensitivity of ice speed to changes in effective ice thickness. (a) Magnitudes of differential sensitivities of ice speed in the locations marked by the coloured circles to change in enhancement factor across the domain. The black spotted area shows~~

275 ~~where the sensitivity is under e^{-10}. Cyan lines show the boundaries between the glacier termini and the start of the artificial landfast sea ice according to the model geometry. Black lines show where transects of data were collected to produce the graphs in (b). The basemap is the MODIS Mosaic of Antarctica (Haran et al., 2021). (b) Magnitudes of sensitivities along the transects shown in (a). Black dashed lines show the location along the transect of the glacier terminus: Hektoria (b.1) and Crane (b.2). Grey lines indicate the different realisations of the control variables C and ϕ, while coloured lines show the mean sensitivities.~~

280 ~~Note: data is presented logarithmically in (a) and linearly in (b).~~

Though Fig. 2 shows that changes in landfast sea ice thickness result in non-zero changes to ice speed along the whole glacier length, we now see that the sensitivity of grounded ice speed to changes in ~~effective sea ice thickness is dwarfed~~ the effective thickness of landfast sea ice is minute in comparison to its sensitivity to changes in the effective thickness of glacier ice. This can be seen especially clearly in transects taken along shear margins of Hektoria/Crane Glaciers and out into the

285 landfast sea ice (Fig 3 b.1, b.2). The map of logarithmic sensitivity (Fig 3 a) shows the landfast sea ice in the ~~glacier~~ pro-glacial embayments to have an impact on the grounded ice, though this diminishes quickly further out to sea. These results further suggest that direct landfast sea ice buttressing of the parts of the glaciers that showed speed increase in 2022 is likely to have been negligible.

3.2.2 Buttressing of the floating ice ~~tongues~~shelves

290 ~~To examine the component of ice tongue stability due to the buttressing of sea ice, we first consider how strain rates near the glacier termini change with the addition of 10 m thick sea ice to the embayment (Fig. 4).~~ Despite the fact that speeds in these regions change by a mean of under 4% except very close to the calving fronts when 10 m of landfast sea ice is added to the embayment (Fig. 2~~c),~~), there are changes in principal strain rates ~~increase by between 5% and 10% across large~~ across parts of the HGE and Crane Ice Shelves on the order of 10% (Fig. 4 ~~a~~a-b), with ~~increases of 15% concentrated 2.5 km and~~

295 ~~3.5 km inland of the HGE and Crane calving fronts respectively~~changes largest in the seaward-most parts of the shear margins. Together with Fig. 2~~b and c~~, this indicates that the buttressing effect of 10 m of landfast sea ice in the embayment is enough to produce ~~a noticeable~~ some dynamic response on the weak floating ice. The important question for the Larsen-B glacier system that remains is whether this change could have destabilised the ~~floating ice tongues~~ ice shelves of HGE and Crane Glaciers.

300 The simulations exhibit a smooth redistribution of stress when the landfast sea ice is added, however this is unrealistic for ~~the case of an ice tongue formed of ice mélange~~ highly crevassed ice shelves where thicknesses can vary considerably from place to place. ~~Stress continuity instead concentrates stress in the~~ Continuity instead ensures that the vertically-integrated stress is concentrated in thinner areas. It is possible that small changes in the ~~vertically-integrated~~ this stress would surpass the load-
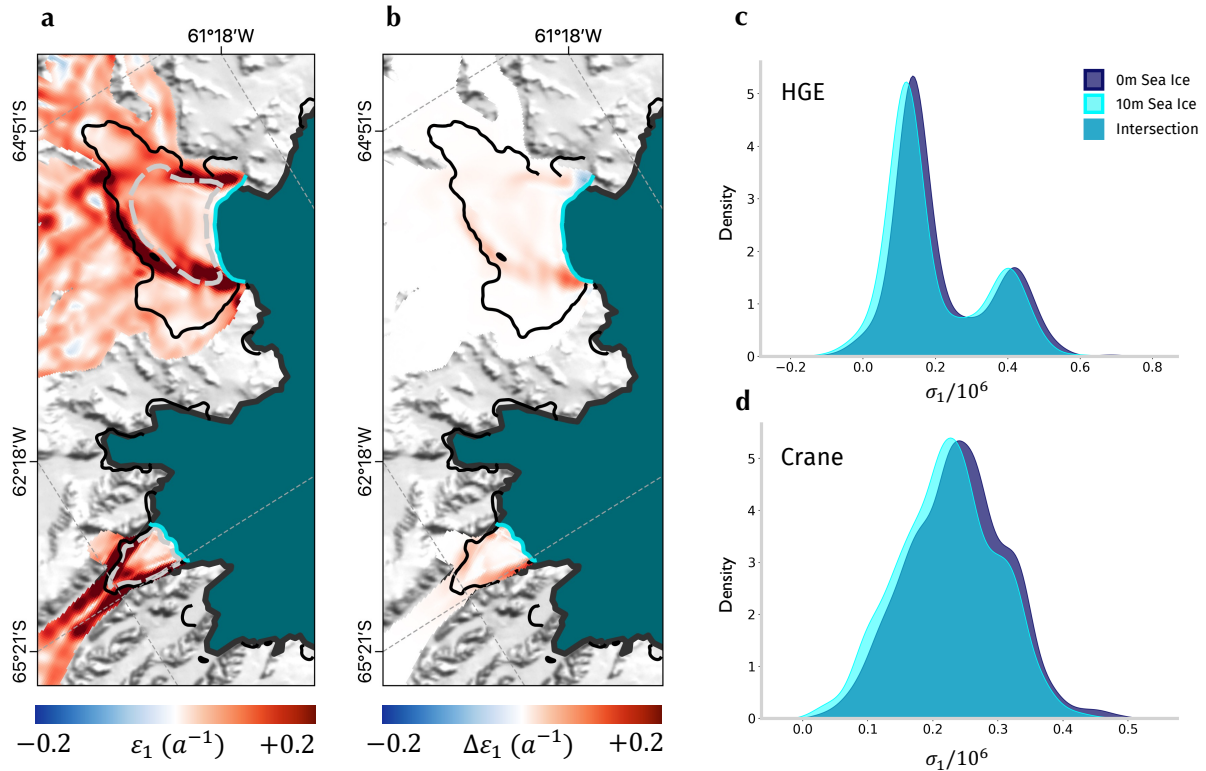
Figure 4. Change in the modelled strain rates and stresses in response to the addition of 10 m thick landfast sea ice. (a) ~~Percentage change in principal~~ Principal strain rate ~~when~~ across the HGE and Crane Ice Shelves with 10 m thick landfast sea ice~~is added at 10 m compared~~. (b) Difference in principal strain rate across the HGE and Crane Ice Shelves with no sea ice compared to 10 m. (~~bc~~-d) Histograms of principal stress for 10 m thick landfast sea ice (~~blue~~cyan) compared with ~~no sea ice~~ 0 m (~~red~~navy) and their overlap (~~purple~~)over the HGE and Crane Ice Shelves respectively. These graphs are produced for the floating ice regions bounded with the grey dashed lines in (a)~~: HGE (b.1) and Crane (b.2) Glaciers~~.

bearing capacity of these thinner sections of glacier ice, causing the ice ~~tongue~~ shelf to break up. To assess how plausible

305 this is, we compare the distributions of vertically-averaged principal viscous stresses across the ice shelves with and without

10 m thick landfast sea ice (Fig. 4 ~~b).~~ c-d). We see on both HGE and Crane Glaciers that the addition of the landfast sea ice

reduces the mean principal stress, however this ~~change~~ shift is small compared to the variance of stresses within the ice shelves.

Assuming that weaknesses in the ice shelves are not ~~spatially concentrated~~ concentrated in a small region, it is improbable,

therefore, that the ice ~~tongues~~ shelves were stable prior to the landfast sea ice removal and that ~~the sea ice~~ this removal caused

310 a large enough perturbation in viscous stress to account for the spatially extensive ice shelf break-up that was observed.

The above analysis relates to instantaneous changes in the stresses and strain rates within the floating ice that result from a

loss of landfast sea ice buttressing. We have suggested that the distributions of principal stresses within the floating ice change,

but by an amount that is unlikely to have led to the rapid collapse of the ice shelves such as seen on the Crane and HGE

13

315 Glaciers. However, changes in strain rate (Fig. 4 ~~a~~a-b) can have implications for ice shelf stability on longer timescales. For example, increased ice shelf thinning rates, resulting from enhanced velocity gradients, can lessen its robustness to fracturing. Additionally, elevated strain rates can lead to faster changes to the glacier ~~geomeotry~~geometry. We cannot rule out the hypothesis that such processes were ~~involved in the latter calving events on Crane Glacier and those on HGE~~ in part responsible for the elevated calving rate on Crane and HGE Ice Shelves starting in September ~~2022, though~~ 2022. However, if this were the

320 case, it seems likely that the ~~effect would have been more due to the preceding loss of seaward sections of the ice tongues as opposed to this initial loss of sea ice buttressing~~calving events themselves would have had a greater impact on subsequent calving rate than the loss of sea ice.

3.3 ~~What impact does sea ice have on glacier ice?~~Environmental drivers

~~Landfast sea ice allows ice shelves to grow initially by providing a barrier to icebergs that, having calved from the glacier
325 terminus, would otherwise drift away. Sea ice formation between these icebergs can bond them together, and to the glacier calving font, forming a rigid ice mélange with material properties determined by the size and density of the icebergs, and the strength of the sea ice bonds. These tongues can get progressively more robust over time as icebergs calving upstream are more tightly constrained and sea ice thickens. It is evident, therefore, that]DiscussionGiven the abundance of landfast sea ice fringing the fast-flowing margin of the Antarctic Ice Sheet (Fraser et al., 2021), and the potentially large contribution of ice dynamics to
330 future changes in Antarctic mass balance (Joughin and Alley, 2011; Pattyn and Morlighem, 2020), understanding how changes in landfast sea ice extent and thickness alters the dynamic behaviour of glaciers is evidently valuable. The sudden evacuation of the sea ice from the Larsen-B Embayment, and the changes in dynamics of HGE and Crane Glaciers that followed, has provided us with a natural opportunity investigate these relationships. The concurrency of the evacuation of the sea ice and the observed changes in calving behaviour and dynamics of the upstream glaciers demonstrates the crucial impact of sea ice in the
335 region, however our modelling results suggest that the component of this due to buttressing, as it is understood in the context of ice shelves, is likely to have been minimal.~~

3.3 ~~What impact does sea ice have on glacier ice?~~Environmental drivers

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340 calving font, forming a rigid ice mélange with material properties determined by the size and density of the icebergs, and the strength of the sea ice bonds. These tongues can get progressively more robust over time as icebergs calving upstream are more tightly constrained and sea ice thickens. It is evident, therefore, that~~ The aim of this article is to address the potential buttressing capacity of landfast sea ice in ~~an embayment can stabilise ice tongues through the twin mechanisms of inhibiting the export of floating icebergs and increasing the strength of bonds between them. If this landfast sea ice disintegrates, the visible calving of
345 mélange at the seaward end of the ice tongue will increase through the first mechanism and, if ocean or atmospheric conditions led to~~ light of its self-evident relationship to glacier stability shown by recent events in the ~~break-up of sea ice within the ice~~

tongue itself, some level of fragmentation of the mélange would also be expected. This is perhaps the mechanism responsible for the partial fragmentation of the Crane and HGE ice tongues concurrently with the sea ice evacuation, which led to the speed-up of Crane and Green Glaciers.

350 Additionally, and perhaps more importantly for the additional calving events seen on the Crane Ice Shelf in the months following the sea ice evacuation, and those on Hektoria and Green Glaciers in Septemeber 2022, sea ice can act to attenuate ocean swell that originates outside of the embayment (e.g. Voermans et al. (2021)). This occurs through scattering of ocean waves from heterogeneities in the ice cover, and the dissipation of wave energy, for example by the elastic plate-bending of the sea ice at different lengthscales and the short wavelength fracturing of ice near its margin (Squire, 2020). Without the sea ice,

355 ocean swells cause higher-amplitude flexural loading cycles that can lead to brittle failure (Holdsworth and Glynn, 1978; Massom et al., 20 .

3.3 ~~Environmental drivers~~

~~Environmental forcing over the Larsen-B Embayment. (a-c) Wind velocity and air temperature data over the period 2000-2022.~~
~~(a) 2022 wind speed anomaly (signal compared to timeseries mean) extracted from the purple box shown in (c). (b) 2 m air~~
360 ~~temperature anomaly extracted from the yellow box shown in (c). (c) Normalised wind direction anomaly (vector field) and 2 m~~
~~air temperature anomaly (colour) over the Larsen-B Embayment in 2022 compared to the 2000-2022 mean. (d-e) CryoSat-2~~
~~swath-mode ice shelf basal melt rate observations from November 2010 to January 2022 over Scar Inlet in the Larsen-B~~
~~Embayment. (d) Timeseries of mean monthly basal melt rate in Scar Inlet (indicated with a blue box in (c)). (e) Mean basal~~
~~melt rate over the Scar Inlet (shown by the blue box in (c)) between November 2010 and January 2022.~~

365 ~~To examine the~~ Larsen-B Embayment. However, we briefly diverge here to note a couple of interesting climatic factors that may have played a part in the 2022 landfast sea ice fragmentation and the subsequent dynamic response of the glaciers. To examine these, we looked at air temperature ~~, wind speed and basal melt-rate data~~ and wind velocity data from ERA5 reanalysis over the Larsen-B Embayment ~~.~~ between 2000 and 2022 and estimates of basal melt-rate from swath mode CryoSat-2 radar altimetry data acquired between November 2010 and January 2022 (Gourmelen et al., 2017).

370

ERA-5 reanalysis data suggests that annual mean surface air temperatures over the 11 years of landfast ice persistence had been steadily increasing at a rate of $0.25°C\,a^{-1}$ over the Vaughan and Exasperation Inlets (Fig. 5 b). By 2022, the air temperature had increased to $2°C$ above the 2000-2022 mean in the Larsen-B Embayment. ERA-5 temperature data shows an even more pronounced localised peak in the air temperature anomaly over the Larsen-B Embayment in the months prior to

375 the landfast sea ice disintegration~~, indicating that this increase in air temperature led to extensive surface meltwater ponding on the sea ice in the embayment in 2022, beyond that observed in previous years. These observations indicate that the~~. These data suggest the possibility that the landfast sea ice in the Larsen-B Embayment was ~~simply~~ unable to persist through a longer and more intense melt season than it had encountered in previous years, brought about by trends in atmospheric conditions~~, than it had encountered in previous years.~~. Additionally, ERA-5 wind velocity data suggest there were anomalously strong

380 north-westerlies over the Anarctic Peninsula in 2022 compared to the 2000-2022 mean (Fig 5 c). These strong offshore winds
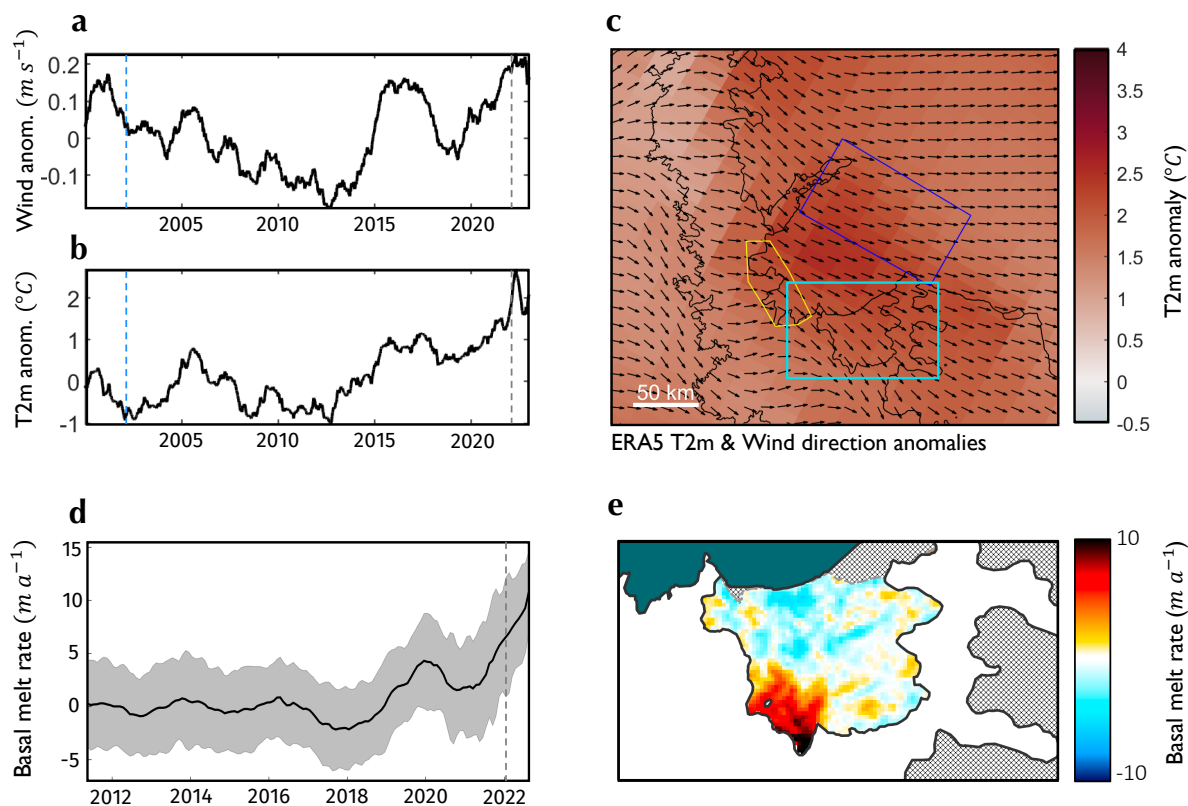
Figure 5. Environmental forcing over the Larsen-B Embayment. (a-c) Wind velocity and air temperature data over the period 2000-2022. (a) 2022 wind speed anomaly (signal compared to timeseries mean) extracted from the purple box shown in (c). (b) 2 m air temperature anomaly extracted from the yellow box shown in (c). (c) Normalised wind direction anomaly (vector field) and 2 m air temperature anomaly (colour) over the Larsen-B Embayment in 2022 compared to the 2000-2022 mean. Vertical blue dashed lines indicate March 2002 - when the Larsen-B Ice Shelf disintegrated, and vertical grey dashed lines show January 2022 when the landfast sea ice disintegrated. (d-e) CryoSat-2 swath-mode ice shelf basal melt rate observations from November 2010 to January 2022 over Scar Inlet in the Larsen-B Embayment. (d) Timeseries of mean monthly basal melt rate in Scar Inlet (indicated with a blue box in (c)). The vertical grey dashed line shows January 2022. (e) Mean basal melt rate over the Scar Inlet (shown by the blue box in (c)) between November 2010 and January 2022.

~~would have aided the evacuation of the sea ice~~ could well have contributed to the landfast sea ice disintegration, and would have aided its evacuation from the embayment ~~following its disintegration,~~ before it could re-freeze as pack-ice.

~~Observations~~

385   Estimates of ice shelf basal melt rates ~~produced~~ over Scar Inlet, the last remaining remnant of the original Larsen-B Ice Shelf, ~~from swath mode CryoSat-2 radar altimetry data acquired between November 2010 and January 2022 (Gourmelen et al., 2017), show that spatially~~ show that the highest melt rates are located at the grounding line (Fig. 5 d). A timeseries of the mean basal melt rate from this region shows that the rates were fairly constant at ~~$0\,\mathrm{m\,a^{-1}}$~~ $0 \pm 4\,\mathrm{m\,a^{-1}}$ for the majority of the period from

2010 to 2018, however, after 2018 there was an increase in the basal melt rate with a further pronounced increase from around

2 m a^{-1} in January 2021 to around 10 m a^{-1} in January 2023 (Fig. 5 e). While there is an absence of direct ocean temperature measurements during the period around 2021, it is possible that the strong offshore winds shown by the ERA5 data (Fig. 5 a) drove an upwelling in ocean circulation bringing warm water up from depth, in addition to blowing out the disintegrated sea ice. If this proxy is representative of changes in ocean temperature across the Larsen-B Embayment then it ~~strongly~~ indicates that widespread increased grounding line ablation ~~also had an important~~ could have had a role to play in the rapid calving of the ~~floating ice tongues~~ ice shelves and ice dynamic response of HGE and Crane Glaciers~~, in addition to the removal of the consolidating effect that the sea ice provided~~. It is also plausible that the mélange adjacent to HGE was exposed to these higher melt rates, which may have contributed to its disaggregation in 2022. While the basal melt rates observed on Scar Inlet since 2020 of up to 10 m a^{-1} (Fig. 5 d) have not yet caused a notable speedup on Flask and Leppard Glaciers, which may be in part explained because they remain buttressed by the laterally constrained ice shelf remnant, these basal melt rates are comparable to those observed on ice streams flowing into the Amundsen Sea Sector of West Antarctica (Shean et al., 2019). If sustained or even increased in the future, these basal melt rates may suggest that a dynamic response on these glaciers could be expected in the longer-term. ~~The role of changing ocean conditions is known to have an impact on the ice dynamic response of the Antarctic Ice Sheet, therefore, this study further demonstrates the importance of acquiring long-term, continuous, multi-year ocean temperature measurements to assess the impact of this processes.~~

4 Discussion

Given the abundance of landfast sea ice fringing the fast-flowing margin of the Antarctic Ice Sheet (Fraser et al., 2021), and the potentially large contribution of ice dynamics to future changes to Antarctic mass balance (Joughin and Alley, 2011; Pattyn and Morlighem), understanding how changes in landfast sea ice extent and thickness alters the dynamic behaviour of glaciers is evidently valuable. The sudden evacuation of the landfast sea ice from the Larsen-B Embayment, and the changes to the dynamics of HGE and Crane Glaciers that followed, has provided us with a natural opportunity investigate these relationships. The concurrency of the evacuation of the landfast sea ice and the observed changes in calving behaviour and dynamics of the upstream glaciers demonstrates the crucial impact of landfast sea ice in the region, however our modelling results suggest that the component of this due to buttressing, as it is understood in the context of ice shelves, is likely to have been minimal.

4.1 The use of a viscous flow model

The conclusions of this article rely on the assertion that model we chose to use, which treats landfast sea ice in the same way as the land ice, gives an upper bound on the buttressing that the landfast sea ice could provide. We discuss in Sec. 3.1 some of the reasons why this is likely to be true. Here, we provide additional evidence for this by comparing stresses in the modelled landfast sea ice to plausible yield stresses in a widely used visco-plastic sea ice model; namely that of Hibler (1979). In general, sea ice rheology is modelled as being plastic in the case of large deformation due to the opening of cracks, raising of pressure ridges and shearing along crack boundaries. In the case of small-scale deformation, the rheology is sometimes argued to be

elastic, reflecting the interaction of floes as they bump into each other (Coon et al., 1974) or viscous, as an approximation to the random jostling of small floes together (Hibler, 1977). The continuity of speed across the glacier/landfast sea ice boundary, as well as the smooth deformation field we observe (Fig. S4) indicates that the deformation of the landfast sea ice in the Larsen-B Embayment, if not dominated by internal viscous deformation, is unlikely to have been in such a sub-critical regime. The

425   model of Hibler (1979) uses a rheology of the form:

$$\sigma_{ij} = 2\eta\dot{\varepsilon}_{ij} + [(\zeta - \eta)\dot{\varepsilon}_{kk} - \frac{P}{2}]\delta_{ij} \tag{2}$$

where P parametrises the strength of the ice and $\zeta \equiv \zeta(\dot{\varepsilon}_{ij}, P)$ and $\eta \equiv \eta(\dot{\varepsilon}_{ij}, P)$ are bulk and shear viscosities respectively. These are decreasing functions of strain rate invariants such that the stress states for typical strain rates lie on an elliptical yield curve. We define $\sigma_I \equiv \frac{1}{2}(\sigma_1 + \sigma_2)$ and $\sigma_{II} \equiv \frac{1}{2}(\sigma_2 - \sigma_1)$, where $\sigma_{1,2}$ are the principal stresses. Assuming isotropic ice,

430   the yield curve then can be plotted as a function of σ_I and σ_{II} (Feltham, 2008). This curve passes through the origin, has major axis width of P and centre at $(-P/2, 0)$ and an eccentricity that depends on the relative strength of the ice in shear and compression.

The ice strength itself is approximated as:

$$P = P^* h A e^{-c^*(1-A)} \tag{3}$$

435   where $P^* = 2.75 \times 10^4 \, \mathrm{N\,m^{-2}}$, $c^* = 20$, h is the sea ice thickness and A is its concentration. P^* is sometimes treated as a tunable parameter but P is greater than a factor of 10 away from $10^5 \, \mathrm{N\,m^{-1}}$ (Feltham, 2008). Regardless of the precise sub-critical rheology, the strength parameter P is the key scale for stresses that can be maintained within the landfast sea ice.

We consider a yield curve for the landfast sea ice in the Larsen-B Embayment with $P = 10^6 \, \mathrm{N\,m^{-1}}$ and eccentricity of 0.

440   We consider this to be a 'maximal' yield curve as P is likely to be smaller in reality, and sea ice is generally far weaker in shear than in compression. (We also plot a more realistic yield curve with eccentricity of 2 and $P = 2.75 \times 10^5 \, \mathrm{N\,m^{-1}}$ suggested in Hibler (1979).) We compare the viscous stresses in the modelled landfast sea ice to this yield curve, paying special interest to the pro-glacial embayments in front of the HGE and Crane Ice Shelves (Fig. 6). In large part, the viscous stresses lie far outside the yield curve, and those in the proglacial embayments all do. This indicates that the stresses born by the landfast sea ice in

445   our model are substantially larger than would be expected of real landfast sea ice. Hence, our modelled ladfast sea ice has a considerably greater buttressing capacity than could be expected from a more realistic and well-known model.

4.2   What impact does sea ice have on glacier ice?

We have seen that, given a definition of buttressing analogous to that of ice shelves, landfast sea ice does not have the ability to buttress glaciers - essentially due to its relative thinness. However, there is a clear link between the landfast sea ice and the

450   stability of the glaciers in the region. As mentioned in Sec. 3, one way in which this could occur is through the promotion of
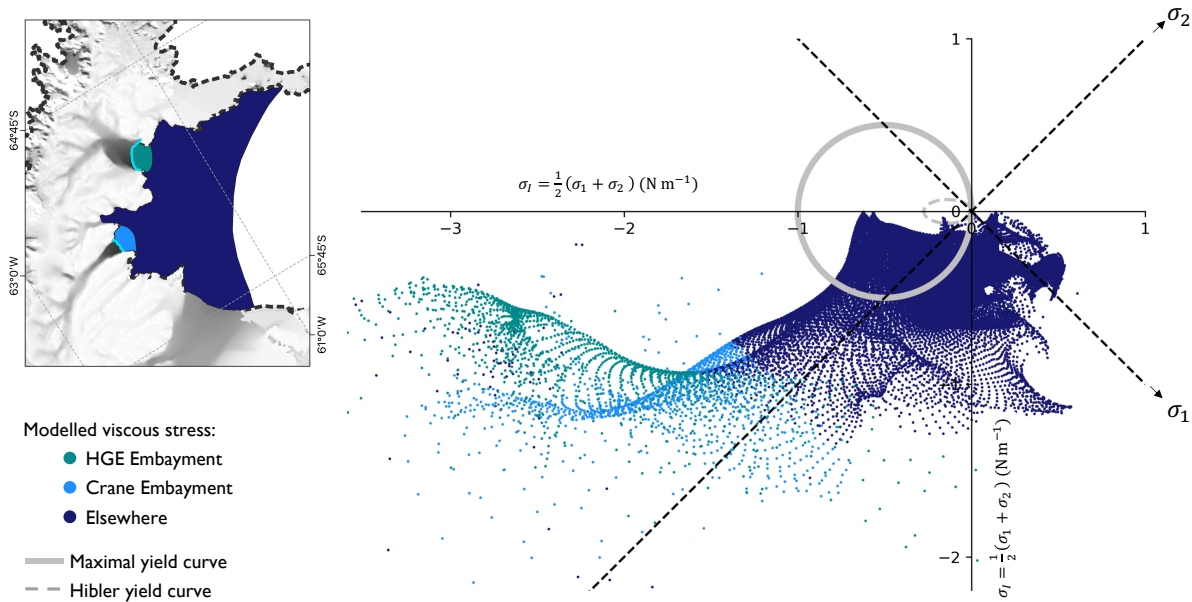
Figure 6. A comparison of viscous stresses in the modelled landfast sea ice and a possible yield curve for sea ice. The graph shows viscous stresses in the modelled landfast sea ice plotted as a function of "negative pressure" σ_I and "maximum shear stress" σ_{II} (Feltham, 2008). The colour of the points indicates where in the domain the modelled viscous stress is extracted - corresponding to regions on the inset map. The grey circle on the graph indicates a yield curve for a possible sea ice rheology of the form of eq. (3) with $P = 10^6 \, \mathrm{N \, m^{-1}}$ and eccentricity of 0. The grey dashed ellipse shows a yield curve with eccentricity of 2 and $P = 2.75 \times 10^5 \, \mathrm{N \, m^{-1}}$ as suggested in Hibler (1979).

ice shelf growth, for example by the following mechanism. Landfast sea ice allows ice shelves to grow initially by providing a barrier to icebergs that, having calved from the glacier terminus, would otherwise drift away. Sea ice formation between these icebergs bonds them together, and to the glacier calving font, forming a rigid ice mélange with material properties determined by the size and density of the icebergs, and the strength of the sea ice bonds. These proto-ice shelves get progressively more

455 robust over time as icebergs calving upstream are more tightly constrained and sea ice thickens. Such a mechanism would lead to ice shelves with no clear boundary in thickness or rigidity separating them from the landfast sea ice - such as those in the HGE and Crane Glaciers prior to 2022 - rather a gradient in those properties. Hence, landfast sea ice confined to an embayment could stabilise ice shelves through the twin mechanisms of inhibiting the export of icebergs and increasing the strength of bonds between them. If this landfast sea ice disintegrates, the visible calving of mélange at the seaward end of the ice shelf

460 would increase through the first mechanism and, if ocean or atmospheric conditions led to the break-up of sea ice within the ice shelf itself, some level of fragmentation of the mélange would also be expected. This is perhaps the process responsible for the partial fragmentation of the Crane and HGE ice shelves concurrently with the landfast sea ice evacuation, which led to the speed-up of Crane and Green Glaciers.

465   Perhaps more importantly for the additional calving events seen on the Crane Ice Shelf in the months following the landfast sea ice evacuation, and those on Hektoria and Green Glaciers in Septemeber 2022, sea ice can act to attenuate ocean swell that originates outside of the embayment (e.g. Voermans et al. (2021)). This occurs through scattering of ocean waves from heterogeneities in the ice cover, and the dissipation of wave energy, for example by the elastic plate-bending of the sea ice at different lengthscales and the short wavelength fracturing of ice near its margin (Squire, 2020). Without the

470 sea ice, ocean swells cause higher-amplitude flexural loading cycles that can lead to super- and sub-critical brittle failure (Holdsworth and Glynn, 1978; Massom et al., 2018). The observations of immediate fragmentation of weak seaward parts of the ice HGE and Crane Ice Shelves in January 2022 and the continuation of enhanced calving on the HGE and Crane Ice Shelves months after the evacuation of the landfast sea ice is compatible with the idea that the ice shelves were not capable of withstanding the elevated swell.

475 **4.3   Wider implications for the interaction of glaciers with landfast sea ice~~on glaciers~~**

The results presented here are relevant to a certain limit of landfast sea ice and glacier conditions. Namely: i) the landfast sea ice existed in a relatively enclosed embayment, ii) it was likely to have been relatively thick due to its multi-year persistence over the previous 11-years in a relatively cold ocean, iii) it appeared spatially coherent and deformed smoothly and iv) the inflowing ice shelves were rheologically weak. How well the specific results generalise depends on how well these variables

480 apply to the situation under consideration. However, the conclusion that unbroken landfast sea ice has limited capacity to directly buttress glaciers is likely to hold in general ~~for unbroken, landfast sea ice~~ as the conditions explored here are consistent with a 'maximum buttressing' example. (The exception is in the rheology of the ice shelves, where stiffer ice may be more capable of transmitting stress upstream.~~Additionally, the assumption of stress continuity within the sea ice does not hold for all sea ice conditions, for example for pack ice or ladfast sea ice with large fractures. In such cases, for example, short period~~

485 ~~stress transfers and elastic response of ice floes could lead to greater buttressing. Such a situation has been investigated, for example by Robel (2017), in the context of fjord-like geometries.~~)

In recent decades, the general picture of Antarctic sea ice has been one of regional fluctuation and relative continental stability, with sea ice extent (SIE) increasing slightly between the early 1970s and the mid 2010s (Turner et al., 2022). 2014

490 saw the beginning of a fall in SIE, culminating in a record Antarctic sea ice low in 2022 (Turner et al., 2022), which already looks set to be exceeded by even lower sea ice extent in 2023. Several studies have indicated the importance of sea ice in maintaining glacier stability in Antarctica and Greenland (Arthur et al., 2021; Christoffersen et al., 2012), and the results of this study do little to suggest otherwise - merely highlighting that this importance is unlikely to stem from its ability to buttress glaciers in the way an ice shelf can buttress a grounded ice stream. However, to more accurately judge the extent to which

495 landfast sea ice stabilises ice shelves, a greater understanding of the mechanisms by which this happens is required. To help with observational and modelling studies that aim to do this, work should be carried out to close the gaps in landfast sea ice extent, ~~sea ice~~ concentration, and altimetry measurements at the critical zone near glacier calving fronts. For example, knowledge of sea ice thickness at the point of contact with the calving front, along with calving front morphology would help

better our understanding of processes in which sea ice might inhibit iceberg calving via its influence on torques at the glacier front.

4.4 Limitations and future work

~~As discussed above, our treatment of~~

The geometry used in our modelling experiments was one in which glacier ice gave way suddenly to sea ice. In reality, in early January 2022, the boundaries between the HGE and Crane Ice Shelves and the landfast sea ice ~~in this study is necessarily simplified. We argue that the results represent an upper bound on the buttressing capacity of the ice assuming viscous rheology, however, this may not be the case. For a one-dimensional ice stream/shelf, assuming stress continuity, the solution to the stress balance is unique given a lateral boundary condition. Hence, the specification of a particular constitutive relation has no impact on the stress distribution and a plot like Fig. 4 b would be unchanged. Fig. 3 a suggests that the sea ice~~ in front of them were less obvious. The transition between glacier and sea ice involved stages of increasingly rarefied mélange including icebergs of a range of sizes. It is quite possible that this transition zone has the dual properties of being able to supply meaningful buttressing to the upstream ice shelf through interactions between icebergs, and being itself vulnerable to the loss of landfast sea ice. Idealised configurations of this kind were investigated in Robel (2017). It is very possible that the dynamics of these regions played a role in the destabilisation of the parts of the HGE and Crane Ice Shelves that disintegrated immediately after the ~~centre of the ice shelf, where the flow is close to one-dimensional, has greatest impact on upstream flow. This indicates that the prescribed constitutive relation, whether viscous, elastic or plastic might alter the results of the experiments less than expected. However, future work should look to determine the deviation in stress solutions given different constitutive relations in a full two- or three-dimensional setting. Smooth deformation fields over the~~ landfast sea ice ~~suggest that stress continuity is a good assumption (Fig. S5). However, if stresses in the sea ice are not continuous, e.g. if choking of sea ice floes were a major component of its movement, it is possible that the buttressing capacity of the ice could exceed that predicted in this study.~~ evacuation. That these regions of mélange diaggregated at the time of the sea ice disintegration could suggest a buttressing of them by the landfast sea ice and hence a second order buttressing effect of the landfast sea ice on the glaciers. However, it seems more likely, though more mundane, that the more rarefied parts of the mélange would be susceptible to the same forcing as the landfast sea ice so disintegrated in January 2022 for the same reasons. Future work should look in greater detail at the mechanisms by which landfast sea ice can interact with glaciers through such transitional zones of ice mélange, as these might be key to the coupling in embayment and fjord-like geometries.

The sensitivities presented in Fig. 3 are reported for a number of realisations of the control fields C and ϕ. This is because, by looking at solutions corresponding to different amounts of regularisation, we hope to show that the spatial pattern of ice speed sensitivities is typical for solutions near the misfit minimum. A more complete picture of the sensitivities might be obtained in future by looking at the curvature of ice speed around the solution, i.e. the principal components of the Hessian matrix. At present, such analysis is difficult to achieve in BISICLES, but is possible for models employing automatic differentiation (e.g. Recinos et al. (2023)). Additionally, this would enable a more exact computation of the gradient, rather than the linear

approximations used here (Goldberg and Sergienko, 2011).

535   Additional observations will help to further our understanding of the relative importance of the components of the effect of landfast sea ice on the stability of floating glacier ice. We see in the sensitivity maps (Fig. 3) a focussing of the effect of landfast sea ice thickness close to the glacier termini~~(Fig. 2 a).~~. This suggests that the buttressing component of the effect of landfast sea ice on the ~~glacier tongues was concentrated in the small embayments local~~ ice shelves is concentrated close to the glaciers. This is in contrast to the ~~component due to the~~ attenuation of ocean swell~~which relies on~~, which occurs across the
540 full extent of sea ice in the embayment and beyond (Ochwat et al., 2023). Future observations of sea ice growth in the small embayments, e.g. seasonally, vs the Larsen-B Embayment as a whole, and the impacts on the calving behaviour of Hektoria and Crane Glaciers can help shed more light on the relative importance of these processes on the growth of ~~mélange tongues~~ice shelves.

5   Conclusions

545 Our results show that multi-year landfast sea ice which has been present in the Larsen-B Embayment for the last 11-years, following the ~~catastrophic~~ collapse of the Larsen-B Ice Shelf in 2002, completely disintegrated between the 18th and 23rd of January 2022. This was followed in February with the onset of major ice dynamic speedup events and changes in the calving behaviour of glaciers flowing into the Larsen-B Embayment. Hektoria, Green and Crane Glaciers have sped up by approximately 15-50% since February 2022 and, with the most pronounced increase of approximately 240 m a^{-1} on Green
550 Glacier upstream of the grounding line. These glaciers lost the majority of their floating ice shelves, that had built up over the preceding decade, by the end of 2022, with the largest retreats of 12 km and 6 km on HGE and Crane Glaciers immediately following the loss of the landfast sea ice.

    Model simulations suggest that the increases in speed on the now tidewater parts of Hektoria, Green and Crane Glaciers are not due to the loss of direct mechanical buttressing supplied by the landfast sea ice that formerly covered the Larsen-B
555 Embayment. However, ~~that~~ the landfast sea ice undoubtedly had an effect on the floating parts of these glacier systems. This effect can be partitioned into the bonding of mélange by sea ice in the ice ~~tongues~~shelves, the dampening of ocean swell that would otherwise cause high amplitude stress cycles in the ice ~~tongues~~ shelves, and the buttressing that reduces ~~longitudinal~~ internal stresses. The modelling and observations presented here suggest that direct buttressing of the landfast sea ice could have been large enough to have had a dynamic impact on the floating ice, but that the disintegration of the ice shelves is unlikely
560 to have been related to the associated small changes in viscous stress. This leads us to suggest that the term ~~"buttressing"~~ "buttressing" should not be used in the context of sea ice in the way it is understood when applied to ice shelves. However, a ~~full visco-elastic~~ more complete model of the glaciers, ice shelves and landfast sea ice (including the transition zone of ice mélange~~tongues and sea ice~~) is required to fully quantify the relative importance of the effects of sea ice on floating glacier termini, along with further observations of sea ice/ice shelf interactions in the Larsen-B Embayment and elsewhere.

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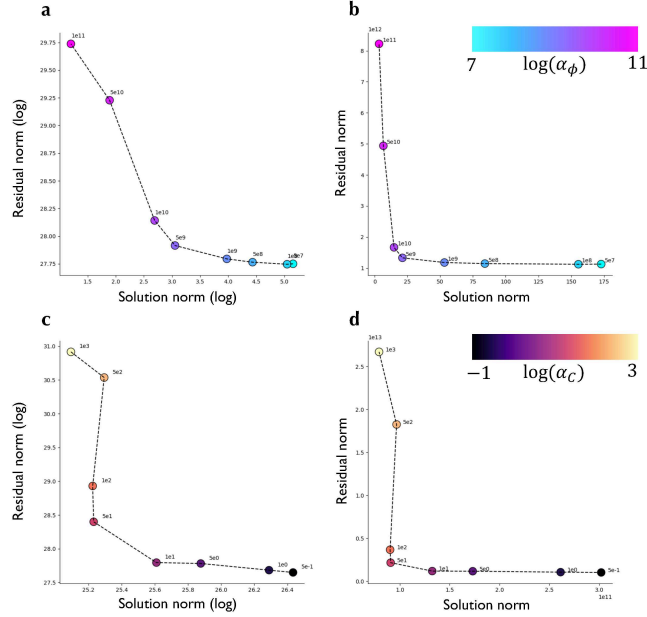
715 Appendix A: Additional model details

A1 L-curve analysis

Figure A1. L-curves for the choice of regularisation parameters. (a) L-curve for α_ϕ. (b) modified L-curve for α_ϕ. (c) L-curve for α_C. (d) modified L-curve for α_C.

As discussed briefly in Sec. 3.1, we use a form of Tikhonov regularisation to replace the ill-posed inverse problem with a 'nearby' well-posed one, with an operator that calculates spatial gradients of C and ϕ. The inverse problem can be written:

$$\underset{C,\phi}{\mathrm{argmin}}\left\{\int_\Omega |u-u_o|^2 d\Omega + \alpha_\phi \int_\Omega |\nabla\phi|^2 d\Omega + \alpha_C \int_\Omega |\nabla C|^2 d\Omega\right\}, \quad \text{s.t.} \quad G(u,C,\phi)=0 \tag{A1}$$

720   where u is the modelled ice speed, u_o is the observed ice speed, and $G(u,C,\phi)=0$ are the shallow-stream momentum balance equations ÷

$$\nabla\cdot[\phi h\bar{\mu}(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^\top + 2(\nabla\cdot\boldsymbol{u})\mathcal{I})] - Cf(u)\boldsymbol{u} - \rho_i gh\nabla s = 0,$$

where h is the ice thickness, $\mathcal{I}$ is the identity operator, $f(u)$ is a function parametrising our sliding law, ρ_i is the density of ice, g is the acceleration due to gravity and s is the ice surface elevation. Eq. (A1) (1). This is approximately solved in BISICLES
725   using a non-linear conjugate gradient method.

28

We use L-curve analysis to find optimal values of α_C and α_ϕ (Fig. A1). This is a heuristic method that posits that the optimal values of the regularisation parameters lead to a solution that balances sensitivities of the misfit and regularisation parts of the cost function to changes in their relative weights (Hansen, 1994). Given the tendency for L-curve analysis to over-regularise, we take the values to the immediate right of the position of maximum curvature in the L-curves, namely $\alpha_C = 1$, $\alpha_\phi = 10^9$.

A2 Calculating gradients of ice speed using the model adjoint

Fig. 3 displays the gradient of the functional:

$$J(u(C,\phi)) = \int |u| \, d\Omega_{HC}$$

with respect to the field ϕ, where . Here, the domain Ω_{HC} is a union between the neighbourhoods marked by coloured circles (Ω_H and Ω_C) in Fig. 3 a. We write $J(u(C,\phi))$ as $\tilde{J}(C,\phi)$, a pure functional of C and ϕ. The Gâteaux derivative of $\tilde{J}(C,\phi)$ with respect to ϕ in the direction $\delta\phi$ can be written:

$$\langle D\tilde{J}, \delta\phi \rangle = \lim_{\epsilon \to 0} \frac{\tilde{J}(C,\phi+\epsilon\delta\phi) - \tilde{J}(C,\phi)}{\epsilon}.$$

We approximate this as

$$\langle D\tilde{J}, \delta\phi \rangle \approx \int \delta\phi \times \bar{\mu} h \boldsymbol{\nabla}\boldsymbol{\lambda}\left(\boldsymbol{\nabla}\boldsymbol{u} + (\boldsymbol{\nabla}\boldsymbol{u})^\top + 2(\boldsymbol{\nabla}\cdot\boldsymbol{u})\mathcal{I}\right) \, d\Omega \tag{A2}$$

where the vector field $\boldsymbol{\lambda}$ are is a vector field of lagrange multipliers that solve solves the adjoint eqution:

$$-\boldsymbol{\nabla}\cdot[\phi h\bar{\mu}(\boldsymbol{\nabla}\boldsymbol{\lambda} + (\boldsymbol{\nabla}\boldsymbol{\lambda})^\top + 2(\boldsymbol{\nabla}\cdot\boldsymbol{\lambda})\mathcal{I})] + C\boldsymbol{\lambda} = \begin{cases} \hat{\boldsymbol{u}}, & \text{in } \Omega_{HC} \\ 0, & \text{elsewhere} \end{cases} \tag{A3}$$

with reflection boundary conditions on the domain boundary:

$$\hat{\boldsymbol{n}} \cdot \boldsymbol{\lambda} = 0,$$
$$\hat{\boldsymbol{t}} \cdot \boldsymbol{\nabla}\boldsymbol{\lambda} \cdot \hat{\boldsymbol{n}} = 0$$

(where $\hat{\boldsymbol{n}}$ and $\hat{\boldsymbol{t}}$ are normal and tangent vectors to the boundary respectively).

A more detailed exposition of this kind of procedure is given in Morlighem et al. (2013). To construct (A3), we have neglected non-linearities in the dependence of $\bar{\mu}$ on $\boldsymbol{u}$, and in the sliding law (Goldberg and Sergienko, 2011). The field we show in Fig. 3 comes from interpreting eq (A2) as the projection of the functional gradient along the direction $\delta\phi$ with the standard

L_2 inner product. Hence, the gradient shown in Fig. 3 is the field:

750 $\quad \bar{\mu} h \boldsymbol{\nabla}\boldsymbol{\lambda} \left(\boldsymbol{\nabla}\boldsymbol{u} + (\boldsymbol{\nabla}\boldsymbol{u})^{\top} + 2(\boldsymbol{\nabla}\cdot\boldsymbol{u})\mathcal{I} \right)$

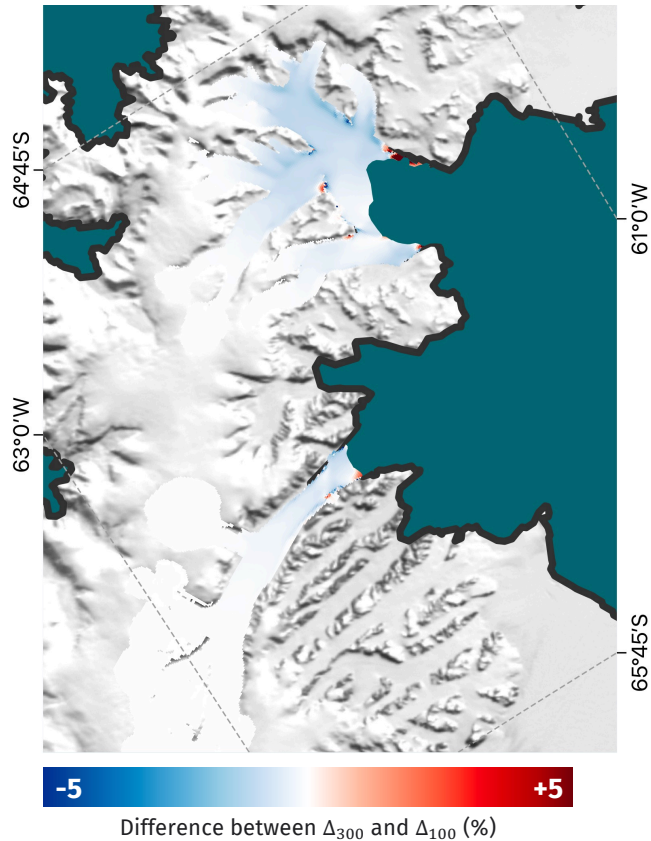## A3 Sensitivity to sliding physics

Figure A2. Difference between Δ_{100} and Δ_{300} - the percentage change in ice speed with the addition of 50 m of landfast sea ice for $u_o = 100 \text{ m a}^{-1}$ and $u_o = 300 \text{ m a}^{-1}$ respectively. The background image is the MODIS MOA (Haran et al., 2021), and the black line is the glacier boundary according to Mouginot et al. (2017).

For the simulations presented in this article, we used a Regularised-Coulomb sliding law for basal stress $\boldsymbol{\tau}_b$ in terms of basal ice velocity $\boldsymbol{u}_b$ of the form:

$$\boldsymbol{\tau}_b = - \left(\frac{|\boldsymbol{u}|_b}{|\boldsymbol{u}_b|/u_o + 1} \right)^m \frac{\boldsymbol{u}_b}{|\boldsymbol{u}_b|} \tag{A4}$$

755 with a Weertman-like exponent of $m = 1/3$ and a threshold ice speed of $u_o = 300 \text{ m a}^{-1}$ that represents a transition between viscous and plastic sliding (Joughin et al., 2019). This sliding law is physically plausible for the fast-flowing glaciers under

consideration, and allows for the greatest change in grounded ice speed with the small changes to viscous stress at the calving front brought about by the addition of sea ice. The value of u_o is the main control on how far these speed changes propagate upstream of the grounding line.

760   To ensure the conclusions of this study are independent of the chosen u_o, we also consider a value of $u_o = 100 \, \mathrm{m\,a^{-1}}$. For values of both $100 \, \mathrm{m\,a^{-1}}$ and $300 \, \mathrm{m\,a^{-1}}$, the percentage difference in speed between ~~between~~ the cases of no sea ice and $50 \, \mathrm{m}$ of sea ice was calculated. We call these Δ_{100} and Δ_{300} respectively. Fig. A2 shows the difference between these quantities.

We see that the difference is below 1% across the HGE and Crane basins. The transects shown in Fig. 2 ~~e~~f indicate changes in grounded ice speed with the addition of $50 \, \mathrm{m}$ of landfast sea ice and a threshold ice speed of $300 \, \mathrm{m\,a^{-1}}$ is on the order of

765   5% where speed measurements were made.