Response to Anonymous Referee #1

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We would like to thank Referee #1 for their helpful feedback on our work. The reviewer's comments are in black and our responses are in blue. Excerpts from the improved manuscript are italicised.

Comments by Reviewer #1

This paper provides a detailed modelling study of the effect that the Shirase Coast Ice Rumples have on the flow of the Ross Ice Shelf. The work looks technically sound and well carried out. The main issue I have with this paper is that it's a bit hard to see the forest for the trees. Specifically, there results are shown several ways and numerous figures are given that show various aspects of the with and without the rumples, but the discussion is fairly thin its not clear that it makes the case that ice rumples matter. Other than the fact the that the rumples will affect the velocity and the stress distributions in somewhat different ways with different assumptions in model parameters, it's not really clear to me whether they are essential features contributing to the overall stability of the ice shelf. Yes, the details of the shelf will differ depending on whether they are present,but does that really matter. I would think this manuscript would be much improved if some kind of big picture statements could be made about the influence of the rumples on long-term stability (even if turns out the ice shelf behaves roughly the same, albeit with some changes in the details). This seems to be what Table 3 indicates (mass flux differences of only a few percent, which may still reflect transients from the abrupt and somewhat unphysical removal (actual ungrounding might be followed by regrounding due to the increased flux).

The magnitude of the flow resistance provided by the SCIR is quite large, given their low relief and relatively low basal traction. This was an important conclusion in Still et al. (2019). Here, we are concerned that the snap-shot like approach used in that paper (and by everybody else who investigates whether or not particular pinning points "matter") could be misleading. It could cause us to overestimate the importance of individual features because it does not allow for other compensating (re-balancing) effects. With these kinds of concerns in mind, we did not make any claim about the importance of these particular features. Is a 1% change in the volume of the RIS due to the presence of the SCIR large? We thought the possible interaction between pinning points (their effects on thickness and stresses) and driving stress and traction in grounded ice was interesting and would argue that this may be what is really important but as the reviewer notes, more work is required to investigate the connection.

We have added an additional paragraph to the discussion to include some big picture statements on the influence of the Shirase Coast Ice Rumples (SCIR) on long-term ice shelf stability:

The magnitude of the flow resistance currently provided by the SCIR is of the same order of magnitude as the flow resistance provided by the larger and more well-grounded Roosevelt, Crary and Steershead Ice Rises (Still et al., 2019). This finding alone does not reveal how important the SCIR are to RIS stability. If an unstable ice shelf configuration is required for irreversible grounding line retreat (Weertman, 1974; Schoof, 2007), then the simulations imply that the SCIR are unimportant to stability (SCIR removal results in a transition to a new steady-state), despite the relatively large flow resistance they provide. This is due to a regional redistribution of ice thickness and resistive stresses. The redistribution, which itself depends on embayment geometry, moderates the sensitivity of the coupled ice sheet–ice shelf system to the ice rumples. Similar redistributions should be expected for changes to other, individual pinning points. If stability is associated with crevasse and rift formation (Bassis and Ma, 2015; Borstad et al., 2017; Lai et al., 2020), the SCIR generate shear and tensile stresses that form crevasses and therefore the removal of pinning points may be expected to improve stability, although changes to shear stresses elsewhere may promote crevasse and rift formation in those locations. If stability is associated with ice shelf thickness (Gudmundsson et al., 2019), the SCIR cause a regional redistribution of mass with a net effect of about a 1% change in ice shelf mass, implying very little impact on long-term stability.

Mass flux differences in Table 3 do not reflect transients from pinning point removal - the system has reached a new steady-state without the ice rumples. We have improved line 160 to make this clearer: *The steady-state reference model is perturbed by excavating the bathymetry beneath the SCIR to prevent mechanical contact between the ice and seafloor, and stepped forward for 150 years with a timestep of one year. By 150 years, the rate of change in ice shelf volume is $<$0.001%, indicating that the model has reached a new steady-state.*

We agree that complete removal of the pinning points is unphysical. It is, however, the correct approach for quantifying the net effect of the SCIR on the momentum budget: we want to calculate the difference in resistive stresses, with and without the contribution of the ice rumples. We clearly did not explain this well enough in the original manuscript and have tried to improve it in several ways:

Abstract, lines 1-5: *Ice rises and rumples, sites of localised ice-shelf grounding, modify ice shelf flow by generating lateral and basal shear stresses, upstream compression and downstream tension. Studies of pinning points typically quantify this role indirectly, through related metrics such as a buttressing number. Here, we quantify the dynamic effects of pinning points directly, by comparing model-simulated stress states in the Ross Ice Shelf (RIS) with and without a specific set of pinning points located downstream of the MacAyeal and Bindschadler Ice Streams (MacIS and BIS, respectively).*

Introduction, line 44: *Altogether, the ice shelf is a coupled system in which a change in any specific location may, though the momentum and mass balances, drive change in resistive stresses and ice thickness elsewhere. The aim of the present work is to quantify the complete system of mass and momentum adjustments caused by a specific set of pinning points in the RIS, West Antarctica.*

Introduction, line 63: *We take a different approach to examine the dynamical role of pinning points. Our aim is to quantify the complete pinning point contribution to ice dynamics, and we do this by performing numerical model simulations of ice-shelf and ice-stream flow with and without a collection of lightly grounded,* *low relief ice rumples (hereafter called the Shirase Coast Ice Rumples, SCIR). Differences between two steady states – with and without the SCIR – show how the coupled system responds to their presence, including a repartitioning of resistive stresses and a redistribution of ice mass.*

It might be good to remove a figure or table or 2 and put less emphasis on the all of the details, many of which have to do with the response to the abrupt removal of a bedrock feature, which not going to happen in reality. It's still a good thought experiment, so more discussion about the effect of the rumples on overall ice stability. How would the RIS be different in a parallel universe where the bathymetric features that give rise to the rumple did not form?

The purpose of the model experiments is to "quantify the specific contribution [of the SCIR] to flow dynamics." There are two ways to do this, (1) a force budget analysis and (2) removing the features from a calibrated model, finding a new steady state, and subtracting one from the other. A third, related, approach is to compute a buttressing number. We've done all three and the results are not identical.

We would like to be clear that the model has not been used to conduct a thought experiment. It has been used to isolate specific terms in a non-local force balance. It may be that using the word *experiment* to describe the calculations muddles this and we have replaced it with *simulation* wherever this seemed to help. It is also possible that the word *removal* is itself unhelpful to our cause because it sounds like the "parallel universe" we did not set out to create.

We have refocused the abstract and introduction section to state more emphatically that we are quantifying the specific contribution of the Shirase Coast Ice Rumples to the flow dynamics of the Ross Ice Shelf and tributary ice streams, rather than conducting a 'thought experiment':

Abstract, line 2: *Here, we quantify the dynamic effects of pinning points directly, by comparing model-simulated stress states in the Ross Ice Shelf (RIS) with and without a specific set of pinning points located downstream of the MacAyeal and Bindschadler Ice Streams (MacIS and BIS, respectively).*

Introduction, line 64: *Our aim is to quantify the complete dynamical effect of a set of pinning points and we do this using numerical model simulations of ice shelf and ice stream flow with and without a collection of lightly grounded, low relief ice rumples downstream of the Shirase Coast (hereafter called the Shirase Coast Ice Rumples, SCIR). Differences between two steady states – one with and one without the SCIR – show how the coupled system responds to their presence, including repartitioning of resistive stresses and redistribution of ice mass.*

Please see our response to the previous comment for our statements on the influence of the Shirase Coast Ice Rumples (SCIR) on overall ice shelf stability.

Along these lines, is 150 years a long enough period to get rid of all transients associated with the step-removal of the topo.

Yes, the rates of change in model ice volume, thickness, and speed were tracked to identify when a $\sim$steady state had been achieved. We have clarified this in the text (line 160):

The steady-state reference model is perturbed by excavating the bathymetry beneath the SCIR to prevent mechanical contact between the ice and seafloor, and stepped forward for 150 years with a timestep of 1 year.

By 150 years, the rate of change in ice shelf volume is <0.001%, indicating that the model has reached a new steady-state.

As noted above, the flux changes are relatively small, especially compared with everything else going on these ice streams over 150 year, so why do we care if our bottom line is sea level rise estimation. Especially if the this the difference between all or nothing. Maybe a good-enough pinning point representation is fine. I am not saying this is the case, rather I want to see the case made based on the overall system response, not just in the details presented here.

We do present the overall system response in the manuscript, with a focus on the connection between the pinning points and the grounded ice streams. If the end-goal is sea level rise estimation, then the presence of the Shirase Coast Ice Rumples alone will have a negligible impact on the contribution to sea level rise. This is in part due to the redistribution of stresses and mass that the study aimed to examine. However, there are quite a few ice rises and rumples embedded in Antarctic ice shelves, more than 500 (Matsuoka et al., 2015; Moholdt and Matsuoka, 2015), and collectively these features will have a significant impact on mass flux into Antarctic ice shelves.

I think with a bit for refocussing and wordsmithing this could be an excellent paper

Thank you. We have revised the abstract, introduction and discussion sections to, we hope, be more clear about the rationale for the experiment design and connections with ice shelf stability. These changes are noted throughout our responses to both Reviewer 1 and Reviewer 2.

Line 59. Given we are getting much more frequent time series, it would be good soften the limited snap-show view statement, even if it may apply here. (At least go with snap-show viewS plural since we have very detailed time series for some areas).

Changed as suggested.

Line 66. Hyphenate ice-sheet and ice-shelf, and separate with En dash (I think the Endash is currently there).

We have added hyphens as suggested, although we prefer 'ice-sheet and ice-shelf system' rather than 'ice-sheet–ice-shelf system'.

Equation 3 – Its disappointing to see this sliding law still being used. Why not use at least Weertman if not Coulomb plastic. At least add some discussion on the implications and validity of this this choice.

We used a linear Budd-type friction law (Budd et al., 1979). This friction law is extensively used by the ISSM community (Bondzio et al., 2016; Seroussi et al., 2017; Haubner et al., 2018; Schlegel et al., 2018; Smith-Johnsen et al., 2020). The Coulomb plastic friction law may be more appropriate for application to ice streams, however this is currently not implemented in ISSM. The Weertman friction law (Weertman, 1957) intends to describe ice motion over hard bedrock and therefore is less appropriate for the fast-flowing Ross ice streams that lie over soft subglacial till with water present. In addition, the Weertman friction law has been tested in ISSM by Seroussi and Morlighem (2018) and they stated *"This friction law induces a sharp discontinuity in basal friction at the grounding line that is not realistic and not appropriate for problems investigating grounding line evolution but remains nevertheless widely used in the community (Brondex et al., 2017)".*

During model tuning we tested different values of the friction law exponents p and q. As a general rule, (p, q) = (3,1) is appropriate for high normal stresses ($>$ 500 kPa) (Budd et al., 1979) while (p, q) = (1,1) is commonly used in ice sheet models to improve model stability (e.g., Morlighem et al., 2010; Bondzio et al., 2016). This is one reason why we used (p, q) = (1,1). We also found that (p, q) = (1,1) provided a more realistic representation of ice flow near the grounding line for our model of the Ross Ice Shelf and tributary ice streams than (p, q) = (3,1).

We have added two paragraphs into the discussion section that consider the implications of our choice of friction law:

The choice of friction law and its coefficients determine ice stream speeds and mass flux across the grounding line. The Budd-type friction law (Budd et al., 1979) used here is a common choice in ISSM applications, where it has been found to improve model stability and representation of grounding line migration (Seroussi and Morlighem, 2018). The grounding line is more sensitive to change than would be the case for other possible friction laws (Tsai et al., 2015; Brondex et al., 2017; Joughin et al., 2019).

The inferred basal friction coefficient α encapsulates the mechanical and thermal properties of the ice/bed interface in a single, spatially varying, parameter. Individual physical processes that control basal sliding (e.g., till deformabililty, presence of subglacial meltwater, bedrock bumps) are therefore hidden within the friction coefficient distribution. Without additional parameterisations to account for change in these processes over time, α is held fixed. Given the apparent dynamical connections between pinning points and basal traction on grounded ice (identified here and by Nias et al. (2016)), improved representation of sliding and of the processes responsible for basal friction are likely to lead to new insights into the behaviour of the coupled system.

Line 102, Equation 4. Are you actually updating the model with this height above flotation effective pressure? It's not clear that this is appropriate for Siple Coast (or maybe anywhere) since most boreholes indicate effective pressures near zero.

The effective pressure N is updated at each time step as the ice thickness changes.

Lines 118-125, please change all instances of resolution to posting - most of these data sets have nothing like this resolution (especially the bed products).

We have modified the sentence about the ice velocity datasets to clarify that the **grid** resolution of the Landsat 8 and Measures velocity datasets is 750 m and 900 m, respectively.

In the Supplementary Material lines 7-9, we stated that: *"The Bedmap2 sub-ice shelf bathymetry used to create the model geometry is interpolated from limited resolution (55 km) point measurements onto a 1 km grid (Fretwell et al., 2013). Predictably, the depth of the water column beneath the RIS is incorrect in some areas and this poses particular problems where the seafloor is unrealistically shallow."* This provides the justification for modifying the Bedmap2 bathymetry in the model geometry to ensure that the Ross Ice Shelf pinning points have the correct area of grounding.

Paragraph beginning at line 131. It's unclear without looking at the supplement whether you are inverting for B on the floating ice and alpha on the grounded, or B on both. The text seems to indicate the latter, but Figure 2 seems to indicate the former since no value of B is shown on the grounded ice. Please clarify in main text. Along those lines, inversion for both B and alpha can be problematic. Yes, you will always get less model-data mismatch, but that's not necessarily a better fit since you have introduced an extra degree of freedom.

We inverted for $\bar{B}$ on floating and grounded ice. In Figure 2, we included $\bar{B}$ for floating ice only to make the point that the velocity of the floating ice shelf is primarily controlled by $\bar{B}$ while the velocity of grounded ice is primarily controlled by the inferred friction coefficient. We used two separate inversions to infer $\bar{B}$ and α and did not invert for both parameters at the same time.

We have modified this part of the method, line 133, as follows:

1. ***First inversion for $\bar{B}$ for floating and grounded ice***. *The initial estimate is a uniform $\bar{B}$ of* 1.6×10^8 *Pa s$^{1/3}$, corresponding to an ice temperature of -16.7°C...*

Line 149. A 2-year time step with speeds that potentially move ice 750 m (Fig. 1) through elements with 500-m dimension seems a bit dangerous with respect to CFL. Please justify.

The mesh was manually refined near pinning point perimeters to achieve a finer mesh resolution. Using the mesh generation algorithm implemented in ISSM, a **minimum edge length of 500 m** was assigned. In combination with anisotropic mesh refinement according to the distribution of velocity gradients, this resulted in a mesh resolution of approximately 1 km over the Shirase Coast Ice Rumples (ice velocity = 200 m/a), and a mesh resolution of approximately 3 km in the fast-flowing narrow of Bindschadler Ice Stream where ice velocity exceeds 600 m/a. The central Ross Ice Shelf, where velocities exceed 750 m/a has the coarsest mesh resolution (up to 10 km). The simulations were stable and we satisfied the CFL condition.

It was incorrect to state that the mesh resolution was 500 m when this was actually the minimum possible edge length specified when generating the mesh. In the manuscript (Line 81), we have rewritten this as:

Mesh resolution ranges from approximately 1 km over pinning points, ice stream shear margins and the grounding line, to approximately 10 km over the inland ice sheet and central ice shelf.

Line 174: As a point that extends beyond this sentence, nothing is mentioned about whether any regularization has been applied in the inversions. Even if none has, that should be stated. Specific to this sentence, regularization might have smoothed out the friction coeff, so no manual adjustment would have been required.

We applied Tikhonov regularisation. Rather than performing an L-curve analysis, the weighting was chosen such that we were able to capture the flow velocity gradients generated by the smallest ice rumples, but with an appropriate level of regularisation to avoid overfitting to noise in the velocity data (i.e., we reproduced the velocity gradients near the Shirase Coast Ice Rumples but have not reproduced any of the artefacts in the MEaSUREs velocity dataset, or the discontinuity between the MEaSUREs and Landsat 8 velocity datasets. The goal was to use the minimum amount of smoothing required to resolve velocity gradients generated by the smallest ice rumples in the domain.

A higher weighting of the Tikhonov regularisation cost function may have smoothed the friction coefficient over all of the ice rumples in the SCIR complex, however, the degree of regularisation required to smooth out the friction coefficient over the ice rumples (a 200 km^2 area) would result in a loss of spatial detail elsewhere in the model domain. For example, the individual sticky spots along MacIS and BIS would not be resolved, and neither would the different density of sticky spots along MacIS and BIS.

We have added the following information to 2.2 Model initialisation: *The inverse method seeks to minimise the value of a cost function, a measure of the misfit between observed and modelled ice velocities, integrated over the whole model domain. Terms in the cost function include absolute and logarithmic misfits, and a third regularisation term is included to prevent physically unrealistic variations in* $\bar{B}$ *and* α *over short spatial scales.*

Figure 3. With all of the map view figures in the main manuscript, nobody should have to skip to the supplement to see the locations of profiles. Please show in on or more figures in the main text.

We have moved the profile locations and flux gate locations from the supplement to the first figure in the main manuscript. The improved figure is included at the end of this document (Fig. 1).

Line 186. Remove the word 'very' the numbers are similar, but given the uncertainties, some of this may be due to chance, so just keep it at 'similar'.

Changed as suggested.

Section 3.3 Another sentence or two here of introduction and why these equations are being given would be appropriate.

We have added the following statements to introduce the resistive stress calculations at the beginning of Section 3.3. *The non-local nature of the ice shelf momentum balance is examined in detail by computing the distribution of resistive stresses acting on RIS flow. The gravitational driving stress* τ_d *must be balanced by resistive stresses including the longitudinal stress* $\bar{R}_{ll}$*, transverse stress* $\bar{R}_{lt}$*, and the lateral shear stress* $\bar{R}_{tt}$*. Resistive stresses are computed using flow-following longitudinal* $\dot{\epsilon}_{ll}$*, transverse* $\dot{\epsilon}_{tt}$ *and shear* $\dot{\epsilon}_{lt}$ *strain rates from the model via Glen's flow law...*

Table 1. How is their basal shear stress, however small, when the ice rumple is removed (where is the traction coming from). Maybe this is just an artifact of the force budget computation, but some kind of explanation is required (zero to within errors?).

For floating ice without the ice rumples, basal drag should equal zero or fall within the uncertainty range of zero given the model-derived datasets used for the force budget calculations. Uncertainty in the force budget calculation arises from: (1) the errors in the modelled velocity data and strain rates; (3) the modelled ice thickness; and (3) the inferred inverse rate parameter $\bar{B}$.

This is presented in detail in Still et al. (2019) and referenced in the manuscript.

Although error propagation is not applicable to model-generated data (because there are no "measurement" errors to propagate), $\mathbf{F}_e$ (and therefore basal drag) is likely to fall within the uncertainty range of 0 given the large uncertainty bounds around $\mathbf{F}_e$ computed from observational datasets for Crary Ice Rise, Steershead Ice Rise, the SCIR and Roosevelt Island).

Line 192. Minor point, but since 10b is referenced before 10a, they should be swapped, especially since there is no other compelling reason for the current ordering.

We have switched the order in the revised manuscript. Please see Fig. 2 (in this document) for the updated figure.

Updated figures

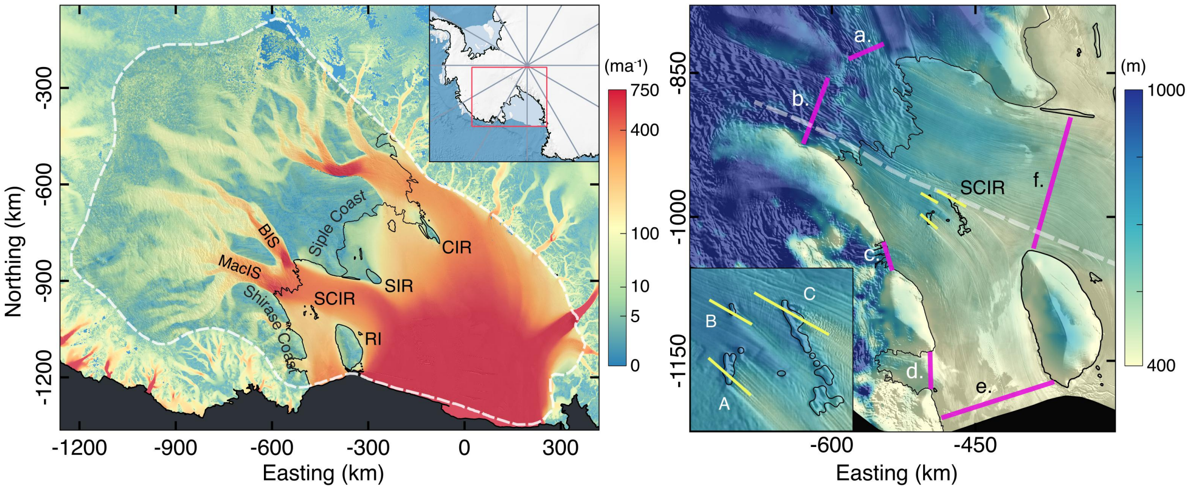

Figure 1: Pinning points in the RIS and the model domain boundary. In panel (a), large pinning points are labelled: SCIR = the Shirase Coast Ice Rumples, RI = Roosevelt Island, SIR = Steershead Ice Rise and CIR = Crary Ice Rise. The colour map of surface ice velocity magnitude is from the MEaSURES velocity dataset (Rignot et al., 2011). The black line indicates the grounding zone (Bindschadler et al., 2011). Panel (b) shows the along-flow cross-sections intersecting the SCIR in Figs. 3 and 10 and the gates used for mass flux calculations in Table 3. The colour map of ice thickness is from the Bedmap2 compilation (Fretwell et al., 2013). In each figure from hereon, datasets are mapped with a Polar Stereographic Projection with a central meridian of 0° and a standard latitude of 71°S, and in most cases, overlayed onto the MODIS MOA (Haran et al., 2014).

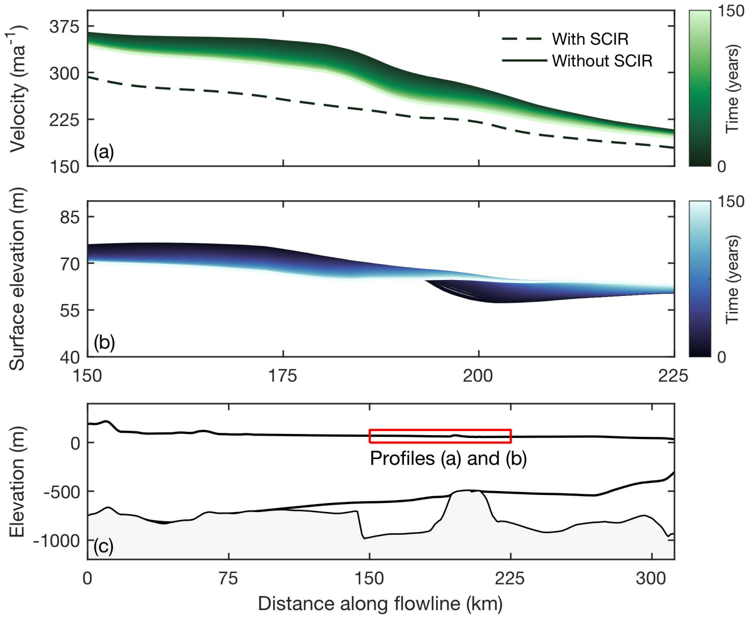

Figure 2: The adjustment in (a) the along-flow surface gradient and (b) ice velocity in response to removal of the SCIR. The 'time' variable refers to the number of years after removal of the SCIR from the model domain. In (b), the difference between the dashed profile (flow speeds with the SCIR) and the profile at 0 years represents the instantaneous speed-up due to removal of the SCIR. (c) demonstrates the location of the profiles in (a) and (b). The location of (c) is indicated in Fig. 1b.

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