Response to Editor comments on "Mid-Holocene thinning of David Glacier, Antarctica: Chronology and Controls" by Stutz et al.

I would like to thank the reviewers for reviewing the re-submitted version of this article. The reviewers identify a number of minor outstanding issues but confirm that their previous comments have largely been addressed. However, on reading the revised version of the manuscript I feel that there are still a large number of points that require clarification. To this end, I have carried out my own review of the current version, my comments are below. I hope that you find my feedback constructive.

Pippa Whitehouse (Editor)

We would like to thank the editor for their comprehensive review of this article. We are pleased to hear the reviewers confirm their previous comments have largely been addressed. We hope our responses to comments improve the clarity of our study.

Major points

Model Setup: there appear to be two sets of sensitivity experiments carried out; in the first, the aim is to reproduce the modern behaviour of David Glacier (line 167), while the second investigates the controls on glacier retreat from an LGM state (more on this in the next main point).

With regard to the experiments that seek to replicate modern conditions: what climate forcing was used?

The climate forcing used in these experiments that seek to replicate modern conditions is the surface mass balance from RACMO2 of van Wessem et al., 2018. We include the statement "modelled surface mass balance" with citation (van Wessem et al., 2018), on line 214.

What parameters were tuned and what values do these parameters take? I could not see any results documented for this set of experiments.

We agree that our model tuning approach could be better documented. Ultimately, we are using these modern sensitivity experiments as a starting point in which to conduct deglaciation experiments.

We include on lines 214-217: We use modelled surface mass balance (van Wessem et al., 2018) and modern geometry (Howat et al., 2019; Fretwell et al.,1852013) to set the model up so that it replicates modern flow conditions and geometry at a steady state. We then tune the basal traction parameter so that we end up with appropriate ice surface thickness and velocities.

We include a table of parameters Table 1 and values used in this model tuning approach.

With regard to the experiments that investigate controls on glacier retreat: lines 215-216 suggest that the deglacial experiments are initialised using parameters tuned to replicate modern conditions – state clearly what these parameters are, what values they take, and provide justification that they are relevant for initialising the model under glacial conditions.

- Lines 208-213 provide justification that basal traction values and understanding of variation through time is poorly understood.

    - We include on line 216-217: 'We note here that as the ice surface evolves, basal traction evolves naturally - e. g. as the ice profile gets steeper or thicker, the basal traction evolves."
- Internal ice temperatures values and justification are provided on lines 244-248
- Accumulation values and justification are provided on lines 239-240

Separately, state what values are used for accumulation and temperature (ice? atmospheric? oceanic?) forcing in the deglacial experiments and whether they vary over the course of the experiments. I have tried to ascertain this information from the text but in places it is very confusing. E.g. text on lines 205-206 states that "transient changes in accumulation and internal ice temperature are tuned over the modelled period…" (what period?) "…to ensure a stable LGM configuration". How does this statement relate to the forcing applied in the deglacial experiments?

We scale RACMO2 accumulation values by 75%. Line 242-243.

We include on line 244-248: "For internal ice temperature, we increase this value through time to represent the relative increase in temperature though deglaciation. Knowledge of the internal ice temperature through deglaciation is poorly understood and for this study, we used values of -25◦C for the first 7,500 model years to -20◦C during the remaining 7,500 model years.

The modelled period is 15 kyr (line 264). We include on line 265-267: We run our experiments for 15 kyr to provide ample spin up time for glacial conditions. We force our model for 7.5 kyr to explore scenarios that, by the end of the modelled period, result in a configuration consistent with modern observations.

The statement on lines 235-236 relates to the forcing applied in the deglacial experiments by generally stating what approach we used to ensure a stable grounding line during the first 7,500 model years. We include on line 246-248: 'By accounting for changes in accumulation rate and internal ice temperatures during deglaciation, we are able to demonstrate these were accounted for and not responsible for driving modelled grounding line retreat.'

Further, we separate table S1 into two parts and include in main text. Now table 2: Experiment forcings and Table 3: Experiment results.

Deglacial sensitivity experiments: text on lines 112-114 clearly links the two main components of this study but justification for, and details of, the precise modelling experiments carried out is lacking or hard to track down within the text. Consideration of the following questions within the methods section would help clarify the study:

Based on previous reviewer suggestions, we have moved the results of our data – ice sheet model comparison (Section 3.5 and Fig. 8) within the results-chronology section in order to provide logical support for our modelling approach. We also introduce this logic on line 91 in the introduction.

- Why did you decide to carry out your own modelling experiments?
    - We provide justification for this in the opening paragraph of section 4-Results-Deglacial sensitivity experiments. We include that no prior detailed modelling has been undertaken for the David Glacier catchment (line 94).
- Are you seeking to address specific research questions?

- We provide these two questions on lines 378-380.

- Specifically, why do you seek to investigate the role of basal melt?
  - We now clarify the justification in the text.
  - We state our general justification (without including reference to our chronology or data-ice sheet model comparison) on line 253-255
    - Further justification included on lines 255-256
    - Lines 334-340 suggest a paleo-thinning mechanism linked to a process driven from the ocean (e.g. elevated sub-ice shelf melt from relatively warm ocean water) rather than accumulation changes.
- and lateral buttressing?
  - In the introduction (from line 66), we direct the reader to many studies that support this amalgamated nature of the ice sheet in the western Ross Sea. As this grounded ice retreated, buttressing conditions would have changed and hence we investigate buttressing and basal melt as the two likely processes driving the dynamic outlet glacier response we see in our chronologies.
- Why do you think they are the most important factors controlling ice stream dynamics in this setting?
  - Changes in ocean-driven basal melt and buttressing in the seward extension of the glacier, as explained above.
- What experiments were carried out, what values were used for each parameter, what is your justification for using these parameter choices / combinations? (Include a table in the main text)
  - We split table S1, include more detail on experiments, values used for each parameter, and justification. This table 2 will be moved into the main text.
- You mention that grounding line retreat is initiated by progressively increasing sub-ice-shelf melt or decreasing lateral buttressing (lines 221, 331) – is the progressive change carried out within the course of a single numerical experiment or do you carry out many experiments with constant forcing to identify the threshold for triggering grounding line retreat?
  - We clarify this on line 381-82

Site information: Field sites are first mentioned in the results – consider introducing them in methods section 2.1: Field and laboratory methods. The location of some sites is not clear from the main text, e.g. Cape Phillipi, and it is not clear when fieldwork was carried out.

Sites are now introduced in section 2.1. Location of Cape Phillipi is marked in figure S5.

Interpretation: for readers whose expertise does not lie in cosmogenic exposure dating, some aspects of the interpretation of the field data (sections 3.2 and 3.3) warrant additional explanation or supporting references. Check statements/text on lines 241, 243, 249, 250, 251-252, 263.

We include additional explanation and supporting references line in the methods section (Lines 105-115).

Lines 298-299: we clarify and include an additional reference to strengthen this statement.

Data-model comparisons: some comparisons made in the text are not supported by evidence in the figures. E.g., "the magnitude of modelled elevation change matches well with the surface exposure data" (line 315) – this statement is not supported by the information shown in figure 8.

We quantify the comparison to strengthen the statements on line 365-370:

Similarly, "at the LGM, the expanded David glacier had… a grounding line that was pinned on the David Fjord bathymetric sill" (lines 405-407) – modelling profiles in figures 9-11 have the glacial grounding line location well offshore, not pinned on the David Fjord bathymetric sill (assuming I have correctly identified the location of the sill).

We fix this error: "…and a stable grounding line near Coulman Island (Licht et al., 1996, Domack et al., 1999, Shipp et al., 1999, Mckay et al., 2008).

In addition, more care is needed to avoid making comparisons between the model predictions and the timing of ice sheet change recorded by the exposure data (see lines 348, 350, 364-365, 472-473, 487). The flowline sensitivity experiments simply apply a step change in forcing, they do not seek to replicate the evolution of forcing during the Holocene. A better approach may be to compare observed and modelled *rates* of thinning; the latter are not reported in the main text, but various statements claim 'good agreement' (lines 407-408, 473). You could also discuss what the modelling reveals about the *relative timing* of grounding line retreat and upstream thinning.

We agree that a better approach may be to compare observed and modelled rates of thinning. These comparisons are compiled in Table 3. Further, we expand on the thinning rate comparison for Mt. Kring and Hughes Bluff in section 5.2, lines 449-453.

Combined forcing: several statements imply that interactions between enhanced sub-ice shelf melt and reduced lateral buttressing are required to initiate grounding line retreat and/or retreat is triggered at lower threshold values when forcings are combined (see lines 15, 347, 366, 486). These results are not rigorously demonstrated by the results shown in the current manuscript.

We respectfully disagree that the results do not demonstrate that, compared with individual forcings, a better geometric fit and closer comparison with thinning rates is achieved in the combined forcing experiments. We do agree that the text can be expanded to clarify our combined forcing approach. We include clarifying text at lines 259-261 & 403-406.

Section 5.1: I agree with reviewer 2 that the information in this section provides useful motivation for your study and hence, with the exception of the final paragraph, material should be moved to the opening section of the manuscript.

We incorporate this useful motivation material to the introduction. We incorporate the final paragraph of section 5.1 into section 5.4 to draw stronger connections to summary figure 12.

Writing style: there are several places where the text is implicit rather than explicit, leaving the reader to guess what you are talking about. E.g. Instead of saying "Given the inferred intimate link between the expanded David Glacier and grounded ice in the Ross Sea…" (lines 325-326), this could read, "Given that ice from David Glacier coalesced with grounded ice in the Ross Sea…". Look out for other instances.

We agree and include this suggestion.

Minor Comments

Comments on the text

Many statements in the first paragraph of the introduction require supporting references

We now include further supporting references in first paragraph.

Line 39: suggest "…require a correction for *the ongoing response to* millennial…"

We agree with and include this suggestion.

Lines 38-43: it is not clear how "a geological perspective on ice sheet behaviour" (lines 31-32) addresses the issues raised in this point

We agree and re-write this point for clarity. Lines 41-48.

Lines 44-49: your study does not address the role of short-term climate variability

We agree and remove this text.

Lines 85-87: additional explanation is needed to explain how samples with "subglacial origins" are used "to track the upper ice surface through time"

We clarify this on lines 104-115

Line 100: "the PRIME lab" – what does PRIME stand for?

We include 'Purdue Rare Isotope Measurement Laboratory (PRIME lab)' on line 128-129.

Lies 125-126: please justify your use of a flowline model to represent ice *sheet* flow and clarify the implications of the assumptions stated on line 126

We remove 'sheet' and replace ice sheet interior with 'grounded portion the model domain'. Further, we remove 'shelf'

Line 132: incorrect units for gravitational acceleration

We now include 'm/s^2' for gravitational acceleration.

Line 134: the exponent in equation 4 should be (1-n)/(2n)

We now include (1-n)/(2n) for the exponent in equation 4.

Lines 153-154: when you talk about 'lateral buttressing' I think you are referring to buttressing by ice rather than buttressing by, e.g., fjord margins – make this clear

On line 180, we replace 'such as lateral buttressing' with 'associated with MISI'. The following statement on lines 181 provides the context for lateral buttressing and we add '…a reduction in lateral buttressing *from adjacent, coalesced ice* is expected…'

Line 164: clarify what you mean by an "ice stream-parallel width"

We include clarification on line 190 and lines 193-194

Line 172: indicate the location where tributary mass flux is injected on relevant figures

We include the location of tributary ice on Figure 2.

Line 196: W12 is not a GIA model, it is an ice sheet reconstruction (that was created with the purpose of using it to drive a GIA model). A similar comment applies to the "prescriptive post-glacial rebound model" mentioned on line 303

We make the correction to line 226-7 and 352-3.

Lines 197-202: throughout this section you refer to 'ice surface elevation', but elevation is usually defined in terms of a height above sea level – you do not clarify what assumptions you make about sea level. I suggest referring to 'ice thickness' rather than 'ice surface elevation' throughout this paragraph. Ice thickness is defined relative to the bed (regardless of the absolute elevation of the ice surface or the bed) and ice thickness change is what is recorded by the exposure data.

We agree and the model requires an estimate/calculated upper ice surface elevation to run. We include the following statement to provide justification for our approach to model input. Line 229: 'introduce uncertainty involving variable along flow isostatic response and dynamic topography associated with the long-term evolution of the Antarctic subglacial topography.' Further, we include "calculated" when referring to the model input s, surface elevation 229 and 232.

Lines 202-204: text on the timing/processes responsible for retreat should be in the next paragraph

We agree and have moved this statement to line 255-264.

Line 222: is the 7.5 kyr spin-up prior to, or included within, the 15 kyr model run?

We clarify this on line 266-7.

Line 224: what is the temporal frequency of the sub-ice-shelf melt rate perturbations?

We clarify this on line 268-9.

Lines 266-267: text is unclear

We improve clarity on lines 313-315

Line 275: what does '320' refer to?

Typo, is removed.

Line 277: "at a number of sites in Antarctica" – summarise the geographic distribution

We summarise the geographic distribution on lines 325-330

Line 293: specify that you are talking about the East Antarctic Ice Sheet

We include EAIS on line 341.

Line 302: "forward ice sheet models" – explain, or simplify the terminology

We simplify by removing 'forward' on line 351.

Line 308: "its neighbouring grid cell" – surely each cell has several neighbours?

We include 'cells' on line 355.

Line 318: "which impact rate of retreat" – retreat of what? Suggest delete

We agree and delete 'which impact rate of retreat'

Line 335: "modelled surface reconstructions place the upper ice surface ~300 metres above…" – what experiment does this text relate to, what time does it relate to?

We clarify on line 389.

Line 345: please clarify what is pinned to the sill

We clarify on line 400.

Line 352: what are you referring to by the phrase "meltwater parameterization"?

We clarify on line 412

Lines 353-354: "a general fit to modern sub-ice shelf melt rates and basal stress" – are these known for David Glacier, if so, please report values and confirm the fit with your modelling

We report modern sub ice shelf melt rates (with citation) on lines 385-6 and justify our use of sub-ice shelf melt rates prescribed in our modelling approach.

While basal stress is poorly constrained/understood in general, the resultant modelled basal stress approaches 100 kPa. The general discussion on this item is found on lines 208-213 and the support for appropriate use of basal traction parameter and resultant modelled basal stress values is supported by the findings of Zoet et al., 2012 (lines 222-225).

Lines 411-412: please provide evidence to support your statement that stability of the grounding line implies stability of the Drygalski Ice Tongue

We provide support to this statement on line 443-447.

Lines 415-416: text on the Terra Nova Bay polynya is not relevant to this study

We respectfully disagree and include further justification on lines 441-446

Lines 445-446: is the "stable position" mentioned here related to the bathymetric sill mentioned on line 444? How does mention of these stable positions link to opening text in this paragraph, which is about unstable retreat?

We remove the use of stable and replace it with pinning point. We make similar changes elsewhere to ensure the proper use of 'stable'.

Line 447-454: as suggested by one of the reviewers, link this paragraph more closely to the modelling that you have carried out

We now provide a clearer link on line 487-489

Line 464: "The modelled grounding line initially retreats to a location where a large GZW has been documented by Lee (2019)" – be more specific about when this happens and the location of the GZW; there is no reference to a GZW identified by Lee (2019) in fig. 12

We provide more information on lines 500-501

In fig 12. caption, we now include grounding zone features: triangles with age constraints (orange) and without age constraints (green) of Lee (2019)

Lines 488-489: “Data-model mismatches highlight enduring questions…” – be more specific/explicit about what questions you are referring to

We remove “enduring questions” and clarify on line 370.

Line 492: “Our data constrain…” – what aspect of the glacier do your data constrain?

We clarify on line 532.

Comments on Figures

Figures 3 and 5: why are some ages in bold, why are some italicised?

We include in the caption: Bold ages indicate Holocene age and italicised ages indicate bedrock age.

Figures 4, 6 and 7: please explain the y-axis caption ‘Relative Elevation’

On line 279, we establish use of ‘above the ice’ throughout text and link with ‘relative elevation’ usage in captions for Figs 4,6,7.

Fig. 8: it is difficult to differentiate between some lines; the pale blue line in the lower plot does not appear to be represented in the legend; it is not clear how the 12 models listed in the legend are related to the six studies referenced on lines 303-304

The model output for PSU_2018 was coloured incorrectly in the legend and Fig 8A. For consistency, we change the colour of PSU_2018 to match the pale blue colour of Fig 8B.

We agree that we can link the 11 models listed in the legend to the referenced studies on lines 353. We synchronise the names in the text and add qualifiers to differentiate model within each reference. 11 legend items appear as Pollard2016, Pollard2017, Pollard2017-ELRA, Pollard2018, Kingslake2018, Kingslake2018-WDC, Argus2016, Lowry2019-Cool, Lowry2019-Warm, Lowry-EMV, Lowry2019-Avg.

Figures 9-11: three sites are mentioned in the caption, but I only see two on the figures in (A)

We separate them for clarity (as in Fig S6).

Figures 9-11: the top plots in (B) are very confusing. The two sets of y-axes labels imply that a particular melt rate translates into a specific % reduction in lateral buttressing – is this correct? In figure 9, the legend suggests that melt rates are kept constant, but the plotted lines suggest that both melt rate and % of lateral buttressing vary with time. Similar comments can be made for figures 10 and 11; it is not clear what is actually represented by the coloured lines plotted in these figures.

We offer two y-axes, not to imply that one impacts another, rather to co-view forcings in one plot, relative to model years. The legend in figure 9B, incorrectly implies that melt rates are kept constant, whereas ‘% reducing’ in lateral buttressing is held constant at 0%. We include discrete model names (M1, S1, MS1, etc) in the legend for clarity between figures, tables and text. For Figure 11B (top panel), we include dashed lines in the legend.

Figures 9-11: it is not appropriate to plot the exposure ages on the same figure as the output from the sensitivity experiments without careful caveat. The implication of plotting the exposure ages is that the x-axis represents some specific time in the past. However, the model output does not represent a specific time, it simply documents the response of a flowline to a step change in forcing.

We offer 382-383 as our careful caveat. We include a shorter version in each caption

Fig. 9: what does '0% reduction' refer to – no reduction in buttressing or no reduction in melt rate?

0% reduction refers to no reduction in lateral buttressing. Through our changes proposed above, both in the legend and caption, we believe this will add clarity.

Fig. 10: ice profiles in the top plot of Fig. 10A ('0% reduction') do not agree with plots of ice surface elevation change or grounding line migration in Fig. 10B. Fig. 10A also disagrees with text on line 342 which says that retreat occurs when buttressing is reduced by 4%

Thanks for pointing this out. It was a plotting error, has been fixed, and is now consistent with the text.

Fig. 11B: not clear how to interpret the six experiments shown by the six different lines; why are there only three lines in subsequent plots, and why are the two types of forcing seemingly applied at different times?

We hope that the changes proposed above, both in the legend and caption, have improved clarity. The forcings are applied at different times. We include a description of this 255-263.

Fig. 12: the upper plot is not a map of "Holocene thinning". It would be useful to include the position of B' in plot (A) to help relate the two figures. The caption to (B) refers to retreat between 11 ka and 5.5 ka, but plotted ice profiles relate to 13 ka and 4.5-5.5 ka.

We change the caption to more accurately represent the figure: "Map of David Glacier, Terra Nova Bay and surrounding areas. Synthesis map…"

We note that B' is indicated in the top right of figure 12A.

We include: A) Map of David Glacier, Terra Nova Bay and surrounding areas. Synthesis map focused on two phase retreat between 13 ka and 5.5 ka…'. We remove '4.5 ka' beneath red line depicting near modern position of grounding line.

General Comments

Check that all acronyms are defined, especially those used in figures

In all cases check it is clear whether 'surface' refers to bedrock or ice

Check the grammar of all text and figure captions. There are several instances of singular/plural errors and in a number of places the text does not make sense or is ambiguous

Check the use of brackets in conjunction with references in the text and figure captions

Use a consistent number of significant figures throughout the text, figures, and tables

We thank the editor for these general comments and have made careful checks to ensure consistency and accuracy.

Comments on Supplementary Material

Fig. S3/S4: ensure that the orientation of the photo is stated in all cases

In fig S3, we add: 'West facing oblique…'. In fig S4, we add: A) West facing oblique…, C) North facing view of moulded…, D) North facing view of…, E) West facing view of…

Figure S6: does the accumulation profile in the top plot relate to modern or palaeo conditions? Do the ice velocity and ice sheet profiles in the lowest two plots relate to modern or palaeo conditions? What is the implication of the different size yellow triangles?

The accumulation profile in the top plot relates to modern conditions. Ice velocity and ice sheet profiles in the lowest two plots relate to palaeo conditions. We include: '…modelled palaeo-ice surface and velocity of…' in caption.

We include the same colour and description for the triangles as in figure 12: triangles with age constraints (orange) and poorly constrained without age data (green) of Lee (2019)

Table S1: there are some inconsistencies in the text description of the modelling results. For example, why is the grounding line retreat rate for experiment MS1 described as 'rapid' when the value listed is less than half the value listed for experiments MS2 and MS3, where the retreat is described as 'moderate'?

We have fixed this error by including: 'moderate' modelled retreat behaviour for experiment MS1 and 'rapid' modelled retreat behaviour for experiment MS2 and MS3.