We warmly thank the three reviewers for their constructive comments which help us to improve our manuscript. This document contains a point by point answer to each individual comment (referee comments italicised in green), followed by the manuscript in which modifications from the original version are highlighted.

Johannes Sutter

Quiquet and Dumas present the results of the GRISLI-LSCE contribution to ISMIP6, which is an extensive model intercomparison showing the 21st century evolution of the Antartic Ice Sheet (AIS) under a variety of climate scenarios (Seroussi et al. 2020). I think it is a worthwile excercise to present individual model contributions of ISMIP6 in depth, as due to page limitations and readability the main ISMIP6-paper can only illustrate the general findings of the model intercomparison in broad strokes. Therefore, in my opinion this manuscript is well suited for the scope of The Cryosphere.

An in-depth analysis as the authors attempt here should identify the key features as well as strenghts and weaknesses of the individual model contribution so the reader can appreciate the respective models skills and peculiarities when it comes to projecting the future evolution of the AIS.

The authors present interesting details regarding their model projections and how they differ from or agree with the ISMIP6 ensemble. The paper generally reads well and the figures are of good quality. To make this a valuable addition to the "TC-ISMIP6-canon" I would suggest a number of modifications and extensions mainly with regard to the Results-section as well as some stilistic overhaul to improve the general readability.

Thank you for your thorough reading and your positive appreciation. In the following, we provide a point by point response to your individual comment.

I will first list general comments pointing out where certain sections need more substance to elevate this manuscript above a mere documentation of GRISLI ISMIP6-results, followed by specific point by point edits/comments to the text.

1. (section 3.1 Present-day simulated ice sheet)
The authors discuss the modelled present day state of the AIS in detail covering mostly thickness and velocity changes in the different regions of the ice sheet. This gives a nice first impression as to how well GRISLI is capable to reflect the current available observations. If I understand correctly the underlying assumption of the initialisation procedure was to create an ice sheet in equilibrium with the late-20th century mean climate state as opposed to one with ongoing mass loss. If this is correct it could be stressed more, and the consequences of the initialisation for the projection runs (potentially to stable) should be discussed. Furthermore, it would be really interesting to hear the authors opinion on inverting for ice thickness versus inverting for surface velocity. How are the ice sheet’s future regional dynamics primed in the projections as a result of the inversion approach? What is the advantage/disadvantage of thickness inversion (e.g. realistic inital geometry/unrealistic flow patterns) in comparison to velocity inversion (e.g. realistic initial ice dynamics/unrealistic surface elevation)? Also, the authors focus a lot on ice shelf thickness and area changes which is important for buttressing and thus marine ice sheet stability. However, the ice thickness close to the grounding line is probably also an important indicator whether the initial ice sheet configuration is resistant to grounding line retreat or facilitates the latter. In general, it would be nice to have a more explicit discussion as to how the initial state of the ice sheet impacts the projections.

The fact that it produces an ice sheet in quasi-equilibrium with the present-day climate forcing is an important feature of our initialisation procedure and we agree that it should have been discussed more. In the method section, we have now added:
"It should be noted that such initialisation procedure produce an ice sheet in quasi-equilibrium with the late-20th century mean climate state. By construction it does not simulate the accelerated mass loss observed in the last decades (Rignot et al., 2019)."
And in the discussion:
"This methodology is thus not suited to reproduce the recent acceleration in mass loss, particularly important in West Antarctica (Rignot et al., 2019). For example, a simple cumulative value of the observed 2012-2017 loss rate (219 Gt yr^{-1}, The IMBIE team, 2018) from 2015 to 2100 will result in an Antarctic ice sheet contribution to sea level rise of 52 cm SLE. This number is much greater than the simulated contribution by GRISLI and more generally, it is much greater than any ISMIP6-Antarctica participating model simulated contribution. This highlights the importance of initial conditions for century scale projections."

About inverting the ice thickness or the ice velocity. Ice thickness (or surface elevation) inversion procedures should, in principle, provide an ice velocity close to the observations (as it should correspond to the balance velocity). Locally, it presents nonetheless some important differences with the observations, differences that can ultimately bias the projections. Compared to the inversion of ice thickness, the inversion of ice velocity can provide a mean to reproduce the recent trend in the observations. To date, only adjoint-based approaches have been followed to inverse the ice velocities. Instead of inverting ice velocities, in future developments of our model we plan to modify the target of the inversion procedure by adding the recent observed ice thickness changes to the observed ice thickness.
We added this in the discussion:
"Assimilation of surface velocities in transient ice sheet simulations are promising methodologies to overcome the limitations inherent to methods that assume steady state (Gillet-Chaulet, 2020). However, they require a complex modelling framework not currently implemented in our ice sheet model. In future developments of our model, we plan to modify the target of the inversion procedure by adding the recent observed ice thickness changes to the observed ice thickness. This would provide a more realistic initial state for the projections."

With respect to the initial state. It is not straightforward to assess the sensitivity of the results to the initial state. We only have one initial state after the initialisation procedure. An alternative could have been to perform multiple inversion procedure for different values of the enhancement factor for example as in Le clec'h et al. (2019). However, the whole initialisation procedure is relatively long to perform and we have done it only for one value of the enhancement factor (=1 which allows for a good performance of the initialisation procedure). This question of the sensitivity of the results to the initial state was part of the objective of the sensitivity experiments in which we apply uniform perturbation to the basal drag coefficient and/or to the enhancement factor. This part has been completely rewritten and extended.

2. (section 3.2.4)

The modelled grounding line response in the Ross and Filchner Ronne sectors seems to be very large for higher sensitivity runs if forced by e.g. NorESM1-M as discussed by the authors and shown in Figure 5 d. I suggest to expand the discussion of this response a little shedding light on the mechanisms and whether this response differs from the ISMIP6 ensemble substantially. Is this solely due to the strong forcing of NorESM1-M in these sectors or is there a model dependence if comparing the different ISMIP6 ensemble members?

The sector of the Ross ice shelf, together with the sector of the Totten ice shelf, are the two regions that present the largest ice thickness decrease when looking at the average response of the ISMIP6 participating models (Seroussi et al., 2020, Fig. 6a). The Filchner-Ronne ice shelf sector also shows a large ice thickness decrease although this decrease is more localised close to the grounding line. Our results are thus close to the average model response within the ISMIP6 ensemble for these regions. The Pine-Island sector is the one that present the largest standard deviation of ice thickness change amongst participating models (Seroussi et al., 2020, Fig. 6b), with some models that retreat substantially and other (like GRISLI) that not simulate any substantial changes. Here again, the response of GRISLI lies within the range of ISMIP6 models.

The strength of the oceanic forcing explains why this sector retreat in our simulations. For example, we have a much more limited retreat for IPSL-CM5A-MR since this model has a much smaller thermal forcing in the Ross basin.

We have added this discussion in Sec. 3.2.1 as it is the first time we show the pattern of retreat:
"For the variety of climate forcing used, the Ross and Totten sectors are the ones that most frequently present grounding line retreat and inland thinning. The Filchner-Ronne sector presents also an ice shelf thickness decrease although associated with a limited grounding line retreat. This is consistent with the average response of the ISMIP6 participating models (Fig 6 in Seroussi et al., 2020). The lack of sensitivity of the Pine Island sector is also a feature common to other participating models since the standard deviation of ice thickness change in this area is very high (> 200 m)."

3. (section 3.2.5) I think it is an important finding that ice shelf collapse does not seem to have a considerable effect until the year 2100 at least for GRISLI. Section 3.2.5 should be expanded by a discussion as to why this is the case. Did the authors carry out longer projections under ice shelf collapse (e.g. until the year 2300/3000)? Is MISI initialised in certain regions for longer simulation times? Or is the model setup so stable as to not allow MISI (doesn't seem to be the case if looking at Ross Sea grounding line retreat under NorESM RCP8.5 forcing). Is this result similar to the ISMIP6 model ensemble (i.e. do all models show negligible grounding line response to ice shelf collapse untill 2100 CE?), or how does GRISLI differ here? As of now this section is very short and does not really allow for an assessment how sensitive this GRISLI setup is with regard to removal of buttressing force.

The community paper only discussed the impact of ice shelf collapse under CCSM4 (medium oceanic sensitivity). For this forcing, the retreat mask by 2100 has removed ice shelves in the Peninsula and in the Pine Island sector, but affect only very marginally the other ice shelves. First, these sectors are poorly sensitive in GRISLI. Second, CCSM4 is one of the forcing that produces an ice volume evolution mostly driven by the increased precipitation (very limited oceanic forcing with respect to atmospheric forcing, Fig. 5). The ice shelf collapse induces a smaller ice extent (150000 km^2 reduction) compared to the standard experiment and, as a result, a smaller integrated surface mass balance. This is why for this forcing the ice shelf collapse is associated to a decrease of the Antarctic contribution with respect to the standard experiment, except in the last 15 years of the century. As a result the impact of the ice shelf collapse is limited with this forcing (2.6 mm SLE) when compared to the average ISMIP6 models (28 mm SLE). However, the standard deviation amongst the ISMIP6 models is also very large, suggesting that some models also show a low sensitivity to this process.

The retreat mask are computed from the outputs of climate models and do not go beyond 2100. Thus, we cannot perform longer experiments. However, we participated with GRISLI to the ABUMIP project in which we quantified the impact of ice buttressing on the simulated ice sheet. To do so, from an equilibrated initial state (different from the one used here), we removed the ice shelves and performed 500 yr simulations. We show in Sun et al. (2020) that GRISLI is able to simulate an important grounding line retreat of the West Antarctic ice sheet (including the Pine Island sector) when the buttressing force is removed.

We have expanded the discussion on the ice shelf collapse scenarios:
“A greater sensitivity to this process has been reported in Seroussi et al. (2020) (multi-model average of 28 cm SLE in 2100 under the CCSM4 forcing) although associated a wide spread of response amongst participating models. For most climate models, the retreat masks by 2100 have removed the ice shelves in the Peninsula and in the Pine Island sectors, but affect only very marginally the other ice shelves. In the standard experiments, these sectors show a low sensitivity to the oceanic forcing. In fact, even under the strongest oceanic forcings, GRISLI shows there a limited grounding line retreat. This suggests that the buttressing force is not the reason why the model does not retreat in these sectors. Instead, it is most likely the topographic biases in the initial state that make the model weakly sensitive to the oceanic conditions. Using a different initial state, we have shown in a recent intercomparison exercise (ABUMIP, Sun et al., 2020) that we were able to simulate large grounding line retreat when the buttressing induced by the ice shelves is removed.”

4. (Discussion)
Here, the authors discuss a parameter sensitivity study not shown in the results section. Is this on purpose? I would suggest to include a section in the Results and present the main findings of these experiments there. As for Figure 12 I suggest to include a graphical aid for the reader which delineates what the authors think is a realistic parameter range (e.g. good fit to present day observables). I assume the fringes of the parameter range would generate an ice sheet configuration which are not in agreement with the general present day features of the AIS.

This part has been moved to the results section. It has been considerably extended.

We have also performed an additional set of experiments for which we apply the perturbations to a control experiment. These perturbed control experiments helped us to define the range of acceptable values for the perturbations. To define this range we have selected the perturbed control experiments that show a mass change lower than 0.15% with respect to the standard control experiment (no perturbation). We chose 0.15% of mass change as it represents one tenth of the simulated ice loss in 2100 when using NorESM1-M under RCP8.5 with a medium oceanic sensitivity. The ranges now appear on the figure.

Point by point edits/comments:

general points:
-review your use of "important" (e.g. important acceleration, p1, l18) throughout the manuscript. Important for what? This is very implicit. I know what you mean but the word "important" should be replaced by an explanation of why the change is relevant throughout the manuscript.

Done.

-check throughout manuscript "consists in" and change to "consists of" where applicable.

Done.

-check your use of "pessimistic" and "optimistic" scenario and replace with e.g. "unmitigated" and "strong mitigation scenario" or alternatively just with the official CMIP abbrev.

Changed to “low/high emission scenario”

-check use of "All together" and replace by e.g. "Overall"

Done.

-check use of word "systematic" throughout the manuscript.

Done.

-you use the form "on the one hand ... on the other hand" exhaustively, especially in the second half of the manuscript. This is not technically wrong, but it would improve the reading experience if you use other forms to express contrasting things from time to time.

Done.

-for sake of readability I suggest to modify occurrences of ice volume changes and write in exponential form (e.g. 3e5 km3 instead of 300000 km3) and provide the sea level equivalent volume change in brackets right after.

We have changed the units, the volume change is now expressed as a mass in Gt. We have adopted an exponential form. However, we prefer to keep separating the discussion of total mass change and sea level equivalent as the two numbers show two different evolution.

Abstract:

p1,l2 this sentence could be changed to: The Antarctic ice sheet’s contribution to global sea level rise over the 21st century is of primary societal importance and remains largely uncertain as of yet.

Done

p1,l2-3: ISMIP6 itself suggests a range from negative to positive sea level contribution, while you write "from a few milimetres to more than one metre". This seems inconsistent to me.

We were referring to the list of papers cited in P2L6-8 of the original manuscript. However, since the ISMIP6 community paper is now published we should include it. Changed to:
“In particular, in the recent literature, the contribution of the Antarctic ice sheet by 2100 can be negative (sea level fall) by a few centimetres to positive (sea level rise) with some estimates above one metre.”

p1, l5-6 I suggest to omit: "While in a companion paper we present ..." and shorten the sentence to "Here, we present the GRISLI-LSCE contribution ...".

Done.

p1,l8 omit "of sea level equivalent".

We prefer not. It does not make sense to give a volume change in mm if there is no indication of area, does it?

p1, l9: suggest to rephrase to "... of the ice shelves resulting in grounding line retreat while increased precipitation partially mitigates or even overcompensates the dynamic ice sheet contribution to global sea level rise."

We have followed your suggestion.

p1, l12: change "retreats" to "retreat" and check use of retreats throughout the manuscript.

Done.

p1 l12-13: change to "... in ice sheet models for projections of the Antarctic ice sheet's evolution."

Done.

p1, l17 include reference of potential total sea level equivalen ice volume (e.g. ∼58.3 m BEDMAP2 or ∼57.9 m BEDMACHINE).

Done:
"Given its size, the Antarctic ice sheet represents the largest single potential contributor in the future, as it represents 58 m of sea level rise if melted completey (Fretwell et al., 2013; Morlighem et al., 2020)"

p1, l18 rephrase this sentence and include reference, suggestion: "While the ice sheet was probably in a quasi mass-equilibrium in the eighties (citation?), it has since then lost ice at an accelerated pace, reaching a yearly sea level contribution of up to 0.7 mm yr-1 during the last decade (...)"

Suggestion followed, reference Rignot et al. (2019).

p1, l21: replace "inexorably" with "irreversible".

Done.

p1, l22: change to "While the increase in mass loss is mostly associated with ocean warming, the increased precipitation ..."

Done.

p2, l3: "the projected sea level contribution"

Done.

p2, l4. please rephrase model formulation, unclear what you mean here. "Overall, the uncertainties related to XY"

Done.

p2, l9: "... contribution to ISMIP6-Antarctica in detail, while its …"

Done.

p2, l34: what about shorter timescales such as the one you are looking at here? Has GRISLI taken part in e.g. MISMIP? please elaborate.

No, we have not performed the MISMIP experiments. We have slightly expanded the presentation of GRISLI:
"For century timescales, with the same model version that the one used here, we participated to initMIP-Antarctica (Seroussi et al., 2019), ABUMIP (Sun et al., 2020) and LarMIP (Levermann et al., 2020). Slightly earlier version of the model has been used to simulate the evolution of the Greenland ice sheet until 2100 and 2150 (Peano et al., 2017; Le clec'h et al., 2019a)."

p3, l10: "... and the total velocity results from the addition of the …"

Done.

p3, l20: "initialisation procedure consists of ... which aims at determining the geographical …"

Done.

p3, l23: "... under a constant present day …"

Corrected.

p3, l31-32: please rephrase this sentence, unclear and poor style.

This sentence no longer exists. We now provide more information about the initialisation procedure.

p4, l9 "is derived from" ?

Changed.

p4,10. "The geothermal heat flux is taken from …"

Corrected.

p4, l19 "is derived from"

Changed.

p4, l30: "GCMs".

Corrected.

p5, l12: "... as the initial …"

Corrected.

p5, l15: unclear what you mean by " ... even though the time evolution has no incidence on the forcings."

Rephrased:
The *ctrl* experiment starts in January 1995 and ends in Decembre 2100, even though it uses a constant present-day climate forcing (RACMO2.3p2 averaged over 1979-2016).

p5,l15: if I understand correctly you are using annual forcing, so I guess you can omit *the specification of the month.*

Yes, you understand correctly. However, we prefer to keep the specification of the month, for consistency with the community paper and also because we believe it makes it easier to know exactly the length of the different simulations. For example it is not necessarily obvious to know if a 1995-2100 simulation includes the year 2100 or stops after the computations for the year 1999.

p5, l21: unclear: are they branched of from the historical experiment at 2014?

Rephrased:
"The different ice sheet projection experiments start in January 2015 and they are all branched from the end of the historical experiment *hist* (Decembre 2014). They end in Decembre 2100 (86 simulated years)."

p5, l27: using different sub-shelf melt rate sensitivities ..

Corrected.

p5, l28 : ...of the sub-shelf melt model calibrated …"

Corrected.

p6, l1: rephrase " In order to allow for the interpretation of the model response to the forcings, a control experiment, ctrl_proj , has been performed in addition to the ctrl experiment. As in the ctrl experiment …"

Done.

suggest to omit the month as it is not relevant for the simulations

We prefer to keep the month for consistency with the community paper and also it might provide a more precise idea on the beginning and end of the simulations.

p6,l 19: check your use of "important" and rephrase with an explicit description of what the relevancy is.

New version:
"There are large ice thickness underestimations, locally reaching more than 200 metres, in the Getz ice shelf region in the Amundsen sea and upstream the grounding line of the Filchner-Ronne ice shelf."

p6,l21: the extend

Rephrased:
"The ice front of the Ross and Filchner-Ronne ice shelves is located about 80 km away from the observations."

p6,l26: rephrase "location and magnitude" and check use of "important"

Reformulated:
"The model generally reproduces the pattern and the magnitude of the observed surface velocities, depicted in Fig. 3b, even if substantial errors remain (Fig. 3c)."

p6,l28: rephrase to "Surface velocities of the major tibutaries of the Ross ice shelf (Mercer- and Williams Glacier) and the Filchner-Ronne ice shelves (Foundation Glacier) are largely overestimated (include range here, e.g. up to factor 2 or what-ever it is)"

New version:
"Surface velocities of the major tributaries of the Ross ice shelf (Mercer and Williams glaciers) and Filchner-Ronne ice shelf (Foundation glacier) are largely overestimated (locally up to a factor 4 with errors larger than 1000 m yr^{-1})."

p6, l31. explicitly explain why ross ice shelf is largely over- and Ronne ice shelf under estimated.

These biases mostly come from the limitations of our initialisation procedure in which some glaciers can show important velocity errors. We added:
"The velocity errors for the grounded part of the ice sheet mostly explain the velocity errors for the floating ice shelves. Thus, the velocity in the Ross ice shelf is largely overestimated since its tributaries show generally a large ice velocity overestimation. The western part of the Ronne ice shelf shows an opposite behaviour with feeding glaciers showing a velocity underestimation."

p7,l2: which other regions could be affected by the 16 km resolution, i.e. where do you think the grid size plays a dominating role on projections?

Added:
"More generally, spatial resolution could explain most of velocity errors in the coastal regions where topography together with spatially variable surface mass balance and sub-shelf melt exert a strong control on simulated velocities."

p7,9-10: suggest to provide names of ice sheet models which use velocity inversion in ISMIP6 so the reader can compare in Seroussi et al. 2020.

The initialisation procedure used by the different model is listed in Tab. 3 of Seroussi et al. (2020). Velocity inversion is used in DA and DA+ models. We now provide a few examples:
"[…] ice sheet models that use the velocities in their initialisation procedure (e.g. JPL1_ISSM, UTAS_ElmerIce)."

p7,l21 "mass balance uncertainties" - please specify regions with large mass balance uncertainties so the reader can grasp where these are relevant.

There are large mass balance uncertainties all over Antarctica primarily due to the sparse distribution of observational data (e.g. GLACIOCLIM-SAMBA). P7L21 of the original manuscript discusses the biases in the Amery region and it is not intended to discuss Antarctic-wide biases.
We have added some elements for the biases in the Amery region:
"This inconsistency can be due to surface mass balance overestimation in the forcing in this area. This overestimation could be corroborated by the fact that another regional climate model than the one used here simulates a surface mass balance 30% smaller than RACMO2.7 in the Amery region (Agosta et al., 2019)."

p7,l33 "... acceleration of ice volume loss over the course of the century."

Corrected.

p8,l1 as suggested in the general points please write volume changes in exponential form and provide sea level equivalent changes right after in brackets.

We have kept separated the discussion for the total mass change from the ice mass contributed to sea level rise. We changed the notation though.

p8,l6 "(i.e. above floatation)"

Thanks for noticing. Corrected.

p8,l9 This is not necessarily the whole story as mass gains in grounded ice above sea level could overcompensate mass change in marine ice sheet regions. Please elaborate.

Locally, this is indeed possible. However, when looking at the spatially integrated numbers, such overcompensation is not reached in the experiments discussed here.

p8,l9 : rephrace to "ice shelve volume is shrinking over the course of the century"

Done.

p8,l10 : please elaborate "ambivalent"

Reformulated:
“This means that the ice shelves are reducing in volume for all forcings while the grounded ice volume can increase or reduce depending on the forcing used.”

p8,l11 replace "perpetual" with "constant"

Replaced.

p8,l18 what is the reason for the decresased surface mass balance in HadGEM2-ES? If I plot precip alone over the AIS I get an ~30% increase. From Seroussi et al. 2020 I gather that surface mass balance anomalies are computed from "changes in precipitation, evaporation, sublimation, and runoff".

The HadGEM2-ES surface mass balance anomalies in the future are positive for elevated areas (>2000m) but negative for the coastal areas. The anomalies have been indeed been computed from precipitation minus evaporation minus runoff. We do not have locally the different variables to check but it is possible that the model simulate increased runoff in the future.

p8,l18 I assume you mean: basal melting underneath ice shelves is increasing?

Yes, we have followed your suggestion.

p8,30: "... wide spread thickening of the grounded ice sheet"

Corrected.
p8,31: rephrase to "When using NorESM1-M this thickening is present to a lesser extent and compensated by the thinning that results from the grounding line retreat in some areas (Ross or Totten ice shelves for example)."

Thanks, done.

p9,l7: "Similar to CMIP5 climate models, the CMIP6 …"

Changed to: "Similarly to CMIP5 climate models, the CMIP6 [...]"

p9,l10 is this also the case for the ISMIP6 ensemble or a specific feature of your model?

The CMIP6 model results have not been studied yet within the ISMIP6 ensemble.

p9,16 "largest" instead of "greater"??

Yes, corrected.

p9,l19: "maintain" what?

We meant: "[…] are able to survive in the course of the century."

p9,l24-25: please rephrase these sentences, I know what you mean, but the formulation as it stands is unclear.

Reformulated:
"However, compared to the high emission scenario, the simulated total ice mass evolution using the low emission scenario is closer to the mass evolution of the control experiment. This means that, in this case, the simulated ice sheet changes in the future are dampened with respect to an higher emission scenario."

p9,l29: again, "maintain" what??

We meant: "[...]" are able to survive until the end of the century [...]"

p10,l2: "The computation of the sub-shelf melt rate ..."

Done.

p10,l2 unclear what you mean by "largely derived". I guess the basal melt rate is tuned to observational data.

Clarified:
"[…] is a parametrisation tuned to reproduce a combination of observational datasets (Jourdain et al., 2019)."

p10,l13: "the NorESM1-M forcing under RCP8.5 ..."

Corrected.

p10,l26-28: please completely rephrase this sentence.

Rephrased:
"These models show a limited sub-shelf melt (Fig. 5b) and one of the smallest ice mass loss in the future (Fig. 7a). Thus, they produce a large ice shelf extent with respect to the other climate models. CNRM-ESM2 and CNRM-CM6-1 also simulate a pronounced atmospheric warming in the future. This warming is indirectly visible in Fig. 5a since the precipitation increase is primarily driven by

the increased temperature. The atmospheric warming together with the large ice shelf extent explain why the CNRM-ESM2 and CNRM-CM6-1 models show the largest mass loss resulting from ice shelf collapse."

p10,l30: suggest to omit "Respective" in section header

Done.

p11,l12-14. Please rephrase.

Rephrased:
"Conversely, the total ice mass change (Fig. 11a) mostly reflects the mass loss from the ice shelves which respond primarily to the oceanic forcing. The ice shelf mass loss in the OO experiments can be large with an important acceleration in the last 20 years of the century. This late response might be a reason why the volume above floatation is not drastically different from the control experiment in the OO experiments."

p11,l19: suggest to rephrase to : "Modelled grounded ice surface velocity changes are limited with the notable ..."

Suggestion followed.

p11,l26: "Another way ... this century …"

Corrected.

p11,l27: replace "different natures" with "different causes"

Done.

p12,l1: replace "somehow" with a quantification.

The quantification is given at the beginning of the sentence ("a few centimetres"). We have replaced "somehow" by "slightly":
"In East Antarctica there is a widespread very small (a few centimetres) negative dynamical contribution to ice thickness change (ice thinning) that slightly moderates the ice thickening due to increased precipitation."

p12, l4: unclear what you mean by "in line". Close to ensemble mean?

Yes, rephrased:
"Although close to the ensemble mean of the ice sheet models participating in [...]"

p12,l8 :"(e.g. Bamber et al. ...)"

Corrected.

p12,l28: "Such an approach ..." please quantify "much more computationally expensive"

Added:
"Such approach is much more computationally expensive since it requires multiple regional climate model simulations. For example, the MAR regional climate model (Agosta et al., 2019) requires

about 15 days to compute 100 years (C. Agosta, personal communication). That is why this approach has been discarded so far for the Antarctic ice sheet where [...]”

p13,l1: "While the atmospheric forcing ...

Done.

p13,l13: "providing the means to investigate"

Corrected.

p13,l20: "partly mitigating or over-compensating the effect of loss of buttressing due to ice shelf melt."

Done.

p13,l23: "do not drastically change the simulated ice sheet volume ..."

Corrected.

p13,l24: "...emission scenarios..."

Corrected.

p13,l24: replace "present" with "exhibits"

Done.

General point for the volume figure captions:

you often use the sentence " Simulated ice volume change for the historical experiment hist (1995-2015), the control experiments ctrl (solid grey lines) and ctrl_proj (dashed grey lines) and for the projections using climate models run"
which is a bit bulky and only after that the description of what the panels show follows.
For sake of readability I suggest to modify the respective captions so it reads: "Simulated ice volume change and sea level contribution for projections XYZ ..." and in the end include a sentence stating that the plots begin with the historical run and that ctrl and ctrl_proj are depicted in gray (dashed and solid).

Thanks for the suggestion. We have followed your advice.

Figure 9: How come that for some experiments the AIS sea level contribution is negative for ice shelf collapse in comparison to standard approach? This should be discussed in the results! It seems only those runs which show AIS growth in standard approach show a relative AIS mass loss in the shelf collapse scenarios.

It is true that it is counter-intuitive. For some climate forcings, the ice shelf collapse scenario produces a local thickening in the vicinity of some grounded line. This is mostly related to local non-linearities. We have added the following:
“The impact of the ice shelf collapse scenario on the sea level contribution ranges from -8 to +17 mm SLE. This range is much smaller than the range of the simulated sea level contribution for the different climate models (-50 to 70 mm SLE). Surprisingly, for some models, the ice shelf collapse

scenario contributes negatively to the sea level contribution (e.g. UKESM1-0-LL). This is most probably due to local non-linearities of grounding line dynamics. However this effect is limited to small changes in the grounded volume.”

CCSM4 shows a negative contribution to future sea level rise with an evolution very similar to CNRM-CM6-1, CNRM-ESM2 and CESM2. However, while the shelf collapse scenario increases the contribution to sea level rise in 2100 for CNRM-CM6-1, CNRM-ESM2 and CESM2, it has a negligible impact on CCSM4. It is therefore not obvious to draw a general conclusion.

Figure 12: it would help if you indicate the parameter range which produces a "realistic" present day ice sheet with respect to observations for present day forcing, so the reader can identify which parameters are still "OK" to use. Also please remove double brackets e.g. ((a) and (b)) -> (a and b).

We have added a vertical grey band for the acceptable range (volume change in perturbed control with respect to the standard control lower than 0.15%). Double brackets removed.

References

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Anonymous Referee #2

1 General comments

This paper is based on the Ice Sheet Model Intercomparison project (ISMIP6) on the Antarctic ice sheet. The results of individual ice-sheet model GRISLI are discussed. Apart from the standard experiments described in Seroussi et al., 2020, forcings derived from some CMIP6 model simulations are implemented in this study. Furthermore, experiments with atmospheric forcing only and oceanic forcing only are taken to study their roles separately. Finally, the authors did sensitivity tests on the basal friction coefficient and enhancement factor to address the influence of initial conditions.

Thank you for your careful reading. In the following we provide a point by point response to your comments.

Generally, I believe studies based on individual models could be a good complement or further study beyond the intercomparison paper (Seroussi et al., 2020). For example, by implementing different schemes in the single model, uncertainties could be better understood. Though, it's not clear to me what the strong points of this paper are. I have a few concerns about this paper:

• The main results and the induced conclusions are in line with the model intercomparison paper and don't add more information. Therefore I'm not sure why is it important to publish the single model result? There should be more discussion about the regions where the GRISLI model shows different behavior compared to the mean ISMIP6 model results. (See also specific comments).

We acknowledge that the conclusions of our paper are not drastically different from the one in Seroussi et al. (2020). This is in part due to the fact that GRISLI shows a model response close to the mean of the ensemble of ISMIP6 participating models. However, beyond the general conclusion, we think that papers that show an individual group contribution to a large intercomparison exercise have three main advantages:

- Documentation. The model response to the forcings is clearly reported in a single model paper while this information can be buried in the community paper. The documentation of a specific model response is important to analyse any further studies that use this model.
- Climate forcing uncertainty quantification. The community paper is best suited for a quantification of the sensitivity to the choice of the ice sheet model while the sensitivity to the climate forcing is better shown for individual model.
- Model bias description. Very limited information on individual model biases is given in the community paper. Such issues are more extensively discussed in a single model paper.

We have added these ideas in the introduction section:
"The analysis of a single model response to the different forcing scenarios presents some important added value with respect to the community paper of Seroussi et al. (2020). First, single model paper allows for a documentation of a specific model response to the forcings while this information can be buried in the community paper given the large material to cover. Second, the community paper is best suited for a quantification of the sensitivity of the projections to the choice of the ice sheet model. The sensitivity to the climate forcing is better shown for individual ice sheet model. Third, single model paper can provide a more complete information of model biases."

• Apart from the standard experiments introduced in Seroussi et al., 2020, the authors added sensitivity experiments on basal drag coefficient and enhancement factor by simply changing the value proportionally. The experiments are only shortly described in the discussion without any

contribution to the conclusions. The authors didn't work deeper in this direction of studying the uncertainties from initial conditions.

Seroussi et al. (2020) only describe the results for Tier 1 and Tier 2. These experiments are limited to CMIP5 climate forcing and only cover a subset of the sensitivities to RCP/SSP scenarios, sub-shelf melt calibration and shelf collapse scenarios. Excluding the "open" experiments (which are mutually exclusive with the "standard" experiments), Seroussi et al. (2020) discuss 12 different experiments. Here we discuss 60 experiments from which new features not discussed in Seroussi et al. (2020), such as results for the CMIP6 forcing and atmospheric and oceanic only experiments.

We added this in the introduction:
"Thanks to a relatively low computational cost, we performed the full list of experiments of ISMIP6 described in Nowicki et al. (2020), where Seroussi et al. (2020) only cover a subset of these experiments."

In addition, we also performed 38x2 additional experiments with a perturbed basal drag coefficient and 17x2 additional experiments varying the flow enhancement factor. We have completely rewritten the description of the results of these perturbed experiments. This part has been also largely extended and we think it brings valuable information on the choice of the initial ice sheet state. However, in order to fully explore the sensitivity of the model results to the initial state we would have needed different initial state. For example, we could have run multiple initialisation procedures for different values of the flow enhancement factor as in Le clec'h (2019). However, the whole initialisation procedure is relatively long to perform and we have done it only for one value of the enhancement factor (=1 which allows for a good performance of the initialisation procedure).

2 Specific comments

Hyphenation should be used between adjective-noun pairs, such as "ice-sheet model", please check through the manuscript.

Hopefully corrected, unsure for some cases. There is a great variety of spellings in the published literature, even among native speakers. Eventually, the Copernicus language editing service will be able to correct the mistakes that we might have overlooked.

P1L10: 'sub-shelf basal melt' is a repeated expression. → 'sub-ice-shelf melting/melt rates'.

Corrected.

P1L22: 'increased in mass loss' → 'acceleration of mass loss'

Corrected

P2L3: 'ice sheet dynamics' → 'ice-sheet dynamics', again, please check through

Done.

P2L2: '....remains largely uncertain' need references.

We though that the 9 references in the following sentence should suffice. We have nonetheless added a reference to the special report of the IPCC (Oppenheimer et al., 2019).

P2L2: delete 'Thus, altogether' ?

Changed for “Overall”.

P2L5: a wide spread in the prediction/assessment of the magnitude

Corrected.

P2L9: cite Seroussi et al., 2020

Done.

*P3L10: I wonder if the total velocity is a weighting function of SIA and SSA as Bueler and Brown, 2009 described or simply added the two velocities? In the later case, the reference should be Winkelmann et al., 2011 (*https://doi.org/10.5194/tc-5-715-2011*).*

It is a simple addition indeed. We have added the reference to Winkelmann et al. (2011).

P3L24: ’and impose’

Done.

P3L28: ’basal drag coefficient reduced for ice thickness overestimation’, so is the next sentence ’basal drag coefficient remains...’

Corrected.

P3L28: ’e.g. basal drag reduced for ice thickness overestimation’: how does the coefficient reduce corresponding to the thickness change? The authors should describe the formula clearly, or supply the related references. Similarly, in the sentence of L30, ’The ice thickness mismatch...is used to modify the basal drag coefficient for the next iteration.’ How does the ice thickness mismatch modulate the basal drag coefficient?

We now give more information on the manuscript, including the two main equations.

P3L33: ’Le clec’h et al. (2019)’→’(Le clec’h et al., 2019)’

Corrected.

section 2.2 Model and initialisation: Sensitivity experiments are taken for basal drag coefficient and the enhancement factor, however, the enhancement factor is not introduced in this section. I think it’s necessary to describe the parameter, how it influence the stress field and what value do you use in the standard simulations.

We have added the following:
“As in most large-scale ice sheet models, GRISLI uses a flow enhancement factor to artificially account for ice anisotropy (Quiquet et al., 2018). In the model, we specify the value of this enhancement factor for the SIA velocity and we use a fixed ratio to determine its smaller SSA counterpart. For the experiments presented here (except in Sec. 3.2.7), we use a flow enhancement factor of 1 (no SIA enhancement) and a ratio close to 1 for the SSA (1.2:1).”

P4L8: ’an observational dataset’→’a combination of observational datasets’

Done.

P4L25: 'of' → 'at'

Corrected.

P4L25–: I suggest to give the non-local quadratic parameterisation formula instead of only refer to the paper. The manuscript heavily discussed the influence of ocean forcing, such as 'sub-shelf melt rates sensitivity to temperature' and the uncertainties related to the 'low','high' and 'medium' methods. However, It's not explained what's the parameter, and what do 'low','medium' and 'high' mean.

Ok, we have substantially rewritten the description of the sub-ice-shelf melt parametrisation, providing the equation and more details on the calibration.

P4L28, In the standard experiments, the gamma (sensitivity parameter) has been calibrated to reproduce the total amount of observed sub-ice-shelf melt rate around Antarctica (Rignot et al., 2013).

Thanks, we have clarified this.

P4L33, also because there are dense observational data available in Pine Island glacier.

Added.

P5L3: Maybe also label the standard calibration as MeanAnt to be consistent with Jourdain et al., 2019.

Done.

P5L4: The first sentence need a reference.

Added, Scambos et al. (2009).

P5L7: I didn't find 'SC' used thereafter. Is the sentence needed?

Right, removed.

P5L13: 'climate forcings (surface temperature...)' is surface temperature implemented as a forcing?

Yes it is. The model is thermo-mechanically coupled and surface temperature is a boundary condition for the temperature diffusion.

P5L15: Which forcing is used for the ctrl experiment?

RACMO2.3p2 averaged over 1979-2016. Precision added in the manuscript.

P6L8: delete 'namely GRISLI' ?

Done.

P6L11: 'These errors are the results of ...' I guess the errors are also from the iterative procedure of initialisation?

Not directly since we restart from the observations for the ice thickness: the errors are simply due to the drift during the 65-yr relaxation. Of course the chosen map for basal drag coefficients will drive this drift.

P6L15: What do you mean by 'most of the time' ?

Simplified:
"The differences over the East Antarctic plateau are smaller than a few metres but increases towards the ice margins or in the vicinity of major ice streams (e.g. Amery ice shelf tributaries)"

P6L19 Figure 1: It's not easy for me to tell the yellow color from white. It seems that in the Amundsen sea embayment, there are ∼50 m underestimation of ice thickness in the Getz ice shelf region but ∼50 m overestimateion in Pine Island glacier and Thwaites glacier?

We have changed the colour palette, hopefully it is now clearer. Yes, we have ~50 m overestimation in Pine Island and Thwaites glacier regions. The error in the Getz ice shelf region is slighly larger, reaching 200 m locally.

P6L20 'the Filchner-Ronne ice shelf grounding line' → grounding line of the Filchner-Ronne ice shelf

Done.

P6L30: 'The velocity errors for the grounded part...' Why?

For a large upstream flux, mass conservation will favour a large downstream flux as well.

P6L31: 'Thus,...' need a more detailed explanation.

We give slightly more information:
"Thus, the velocity in the Ross ice shelf is largely overestimated since its tributaries show generally a large ice velocity overestimation. The western part of the Ronne ice shelf shows an opposite behaviour with feeding glaciers showing a velocity underestimation."

P6L7: It's declared in the section 2 that the initialisation method is same with Le clec'h 2019, where the basal drag coefficient is also modulated by velocity. But here you does not have any constraints on the velocities?

It is exactly the same methodology as in Le clec'h et al. (2019). There is no constraints on velocities in Le clec'h et al. (2019).

P7L20: 'This inconsistency can be due to...' Why? Could you give more specified explanation?

The control experiment should ideally have no drift in ice thickness as it is based on the assumption that the ice sheet is at equilibrium. In the Amery region we have an ice thicknening in the control, suggesting that the ice velocity should be higher. However, the ice velocity is already too high when compared to the observations. This inconsistency can be the results of a too high mass balance in the climate forcing.
We have rephrased this idea:

“The ice thickening during the control experiment could suggest an underestimation of the ice velocity, i.e. underestimation of the ice export, which seems in contradiction to the overestimation of the simulated ice velocity with respect to the observations. This inconsistency can be due to surface mass balance overestimation in the forcing in this area.”

P7L24: ’1000 km3 ’ Could you use consistent unit when mentioning the mass change? km3 , Gt or sea level equivalent? Right now all of the three units are implemented, making it hard to compare.

Sea level equivalent and total ice mass (or volume) can not be used interchangeably, since only a fraction of the total mass (or volume) contributes to sea level rise. However, we have switch for total mass (in Gt) change instead of total volume (in km^3). In doing so, the mass balance and the total mass are given in a comparable unit.

P7L26: ’...and Filchner-Ronne ice shelves’. Upstream Pine Island, Getz and Totten ice shelves are also quite high? It’s not easy to tell from Figure 2d.

The colour palette in these maps have been changed. We have added:
“Although more localised, the changes in Pine Island, Getz and Totten areas can be larger than one hundred metres per year.”

P7L32: Using ’MeanAnt’ same as Jourdain et al., 2019 instead of ’sub- shelf...dataset’ will make it much easier to follow.

We have added the label *MeanAnt*.

P8L27 & Figure 5: ’For both forcings,...’ For NorESM1-M the ice-shelf thinning of Totten ice shelf is more pronounced?

For both forcing this ice shelf has disappeared by 2100.

P8L31: delete the second ’also’.

Done.

P8L33 & Figure 5: This is a very interesting figure which could compare to the Figure 6 of Seroussi et al., 2020. There the mean model result shows an important thinning as well as acceleration in Pine Island, Thwaites and Totten glacier, while the model result for these regions are all quite stable here. However, the explanation here ’ This is likely due to the fact that our control experiment tends to produce an ice thickening in this region (Fig. 5b) which tends to stabilise this region, resulting in a smaller sensitivity’ is insufficient. Why do you have a thickening trend in the control experiment and why it results in a smaller sensitivity to climate forcings? I noticed from the equations that GRISLI implement linear basal friction law. Brondex et al., 2019 claimed that the Pine Island glacier is sensitive to the sliding laws and an exponent of 8 is suggested for the region. As descriptions of models are listed in Seroussi et al., 2020, I hope the authors can have a more specific discussion.

We have added the following elements:
“Our model does not simulate substantial changes in the Pine Island glacier area. In this region, there is a thickening of the ice sheet during the control experiment (Fig. 2b) with underestimated surface velocities (Fig. 3c). These biases can be due to the inferred basal drag coefficient during the initialisation procedure that leads to an underestimation of the velocities. The linear friction law implemented in our model can also result in an underestimation of the velocity (Brondex et al.,

2019). Finally, the biases can also be the result of the complex topographic setting that might not be well captured at 16 km. The underestimated ice sheet velocity at the grounding line in this area, together with the thickening bias, result in a small sensitivity to oceanic warming. However, for other intercomparison exercices we have shown that our model is able to produce a grounding line retreat in this area (Sun et al., 2020).

For the variety of climate forcing used, the Ross and Totten sectors are the ones that most frequently present grounding line retreat and inland thinning. The Filchner-Ronne sector presents also an ice shelf thickness decrease although associated with a limited grounding line retreat. This is consistent with the average response of the ISMIP6 participating models (Fig 6 in Seroussi et al., 2020). The lack of sensitivity of the Pine Island sector is also a feature common to other participating models since the standard deviation of ice thickness change in this area is very high (>~200 m)."

P9L6: From Figue 6 and Figure 3,4, we can see UkESM1 has more total mass loss compare to NorESM1, and their surface and basal mass balance have similar trend, why NorESM1 has ∼20 mm sea level contribution and UkESM has negative contribution? Is it because of the spatial distribution of forcing?

Until 2080, UKESM1 shows a larger surface mass balance than NorESM1 (about 200 Gt/yr difference early in the century) and a smaller basal mass balance than NorESM1 (reaching about 1000 Gt/yr difference circa 2050). With this, it is somehow expected that UKESM1 shows the largest total mass loss (ice shelf melting) but the smallest sea level contribution to sea level rise when compared to NorESM1. The spatial distribution of the forcing can explain partly the difference (NorESM1 has only a larger SMB than UKESM1 at the margins) but it is most probably of the second order in this case.

P9L13: The first sentence can be removed.

Done.

P9L16: 'scenarios'

Corrected.

P9L16: 'The model that...' the colors for the three models are really similar.

We have changed the colours used for the different models.

P9L30: Again, the comparison with the ensemble model results could be interesting.

No map showing the impact of the scenario is shown in Seroussi et al. (2020). However, the response in term of ice sheet contribution to sea level rise is discussed for two climate forcing. We have added the following in the manuscript:
"In Seroussi et al. (2020), two climate forcings (NorESM1-M and IPSL-CM5A-MR) were evaluated for both the RCP2.6 and the RCP8.5. The simulated contribution to sea level rise in the ISMIP6 ensemble is very similar to the GRISLI response: no change in grounded ice mass for NorESM1-M but an increase in grounded ice mass for IPSL-CM5A-MR under RCP8.5 with respect to RCP2.6. CNRM-CM6-1 shows a response similar to the one of the IPSL-CM5A-MR since the grounded ice mass is increasing under the SSP585 with respect to the SSP126."

P11L17: 'NorESM1-M climate forcing' → 'NorESM1-M climate forcing under RCP8.5'

Done.

P11L18: How does the decrease of surface velocity of ice shelves associated with ice thinning?

It is more the thinning that induces a velocity reduction (the SSA velocity is positively correlated with the ice thickness). Locally, the ice thinning in the vicinity of the grounding line can induce a smaller ice flux feeding the ice shelf.

P11L31: From Figure 11b, the dynamic contribution in West Antarctica has strong spatial variabilities, e.g. thinning of Siple coast and thickening in Amundsen sea region.

Yes it does although the positive contribution in the Amundsen sea region are generally small (less than 10 metres). We have added the following:
"In West Antarctica, the dynamical contribution has a strong spatial variability. It can reach up to more than 50 metres decrease in ice thickness and [...]"

P12L8: '...suggested in other studies' Could you give the numbers from these references?

We now refer to the IPCC special report here:
"A relatively moderate Antarctic ice sheet contribution to future sea level rise by 2100 has also been suggested in other studies since the IPCC special report on the ocean and cryosphere in a changing climate (Oppenheimer et al., 2019) reported a range from 30 to 280 mm SLE (RCP8.5)."

P12L9: 'One reason for this disagreement...This methodology is thus not suited...' Why this type of initialisation cause the disagreement? And is this the only reason causing disagreements?

By construction, a methodology that produces an ice sheet in equilibrium under present-day climate cannot, at the same time, reproduce the recent observed acceleration of mass loss. Other source of uncertainties are listed in the discussion and, notably, the sub-ice-shelf melt model since the largest simulated mass loss among ISMIP6 participating model is systematically obtained with ice sheet models that use their own sub-ice-shelf melt model (open experiments) instead of the standard ISMIP6 approach.

P12L19: Enhancement factor appears here for the first time. It should be defined in the methodology. And the author should explain why this parameter is interesting for a sensitivity test.

The enhancement factors are describe in the methodology section now.

Figure 12: Explain in the caption or in the text what's the meaning of positive and negative percentages.

We have added the following:
"The perturbation starts from +100% (i.e. a doubling of the base value) to -90% (i.e. a reduction to 10% of the base value)."

P13L8: '...when using the same forcing' I don't think the parameterisations in the open experiments are using the same forcing. At least for PICO, PICOP and Plume, ocean temperature and salinity are used instead of thermal forcing.

The ISMIP6 thermal forcing is also computed from the ocean temperature and salinity. But it is true that in the standard experiments, the ice sheet models do not use directly the temperature and salinity as forcing. We have changed the sentence to:

“when using forcings elaborated from the same climate model realisations.”

P13 section Conclusion: There is not much new information comparing to the Seroussi et al., 2020 paper.

GRISLI is not an outsider within the ISMIP6 ensemble and as a result the numbers given in the conclusion are not out of the ISMIP6 range. We have added few elements regarding the additional sensitivity tests we performed:
“Finally, with additional simple sensitivity tests we have shown that the simulated ice sheet contribution to sea level rise by 2100 could be largely affected by changes in ice-sheet mechanical properties such as basal dragging. Given the weak understanding on such processes, they could also represent a large source of uncertainty.”

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Fuyuki Saito

This paper presents a detail of ISMIP6 Antarctic ice experiments using a numerical ice-sheet model GRISLI. In my opinion, it is worthwhile to present detail results of an individual model to participate an intercomparison project, because the corresponding main paper usually focuses on general feature among the participants. I think this paper is fairly well written with some exception below, and can be accepted with minor revision.

Thank you for your positive evaluation. We address your concerns in the following.

There is one relatively major point in the manuscript, which is argued on the experiments shown in Figure 12. In the text the author mentioned that (P12L16): 'A uniform reduction of the basal drag coefficient by 30% leads to a 13000 km3 total volume reduction contributing to about 50 mmSLE in 2100. This means that, with our model, it is unlikely to obtain a significantly different ice volume change for slightly different basal initial conditions.' I do agree the former sentence, but I am not sure what the authors mean in the latter. Is 50 mmSLE insignificant? Or, is 30% change in the basal drag coefficient already too large to be worried about that expected contribution is much smaller than 50 mmSLE? The authors do not provide the inferred basal drag coefficient map in the manuscript. Le clec'h et al. (2019) present the basal drag coefficient map, but for GRISLI Greenland simulation. In this basal drag coefficient map, at least in Greenland ice sheet, the coefficients seem to vary more than a factor thousand. If this factor holds true also for Antarctica, 30% changes in the coefficient may be far smaller than the variation of the coefficients. I appreciate if the author extend this discussion to describe clearer from the experiment design. Moreover, there are not enough information about the sensitivity experiment for the ice enhancement factor, which should be extended.

We agree. As in Le clec'h et al. (2019), the basal drag coefficient in Antarctica shows a very high spatial variability. This coefficient can vary from ~1 to 10^5 Pa yr m^{-1}. However, in practice a value above 10^3 Pa yr m^{-1} produce very limited sliding velocities. Also, the absolute value of the basal drag coefficient has none or a limited impact in the interior of the ice sheet, where the SSA velocity is small anyway, but is very important in the coastal regions, where the ice streams are located.

Our approach is very simple as we applied a uniform perturbation. It allows for an artificial speed-up of the ice streams but it is not suited to investigate realistic changes that could occur in the future. For example, for a realistic ice sheet, it can be envisioned that a grounded point switches from a state where it slowly flows to an ice stream state. In this case, in the model, it means that the basal drag coefficient switches from a value greater than 1000 to lower than 100 Pa yr m^{-1}. To test such phenomenon in the model we could apply a random noise in the basal drag coefficient with much larger perturbation than the one we used here.

The problem is that we only have one map for the basal drag coefficients, being the one obtained after the initialisation procedure. Ideally we should have tested alternative maps. However, if such alternative maps not resulting from our inversion were used, it would have resulted in unwanted drift in the control simulation. The use of these maps would be difficult to justify.

We added a number of new simulations in order to get an idea of what range of values for the uniform perturbation is acceptable. We now perform new ctrl_proj simulations in which the basal drag coefficient (and the enhancement factor) is perturbed in the same way as the NorESM1-M projection shown in the initial version of the manuscript. We computed the volume drift of these perturbed ctrl_proj experiments and compared it to the volume drift in the standard ctrl_proj experiment. We consider that a 0.15% difference between the standard ctrl_proj experiment and the perturbed one is acceptable. We chose 0.15% of the volume difference since it corresponds to 10%

of the change in volume simulated in 2100 using NorESM1-M under RCP8.5 (medium oceanic sensitivity meanAnt).

This discussion has been moved from the discussion section to the results section. It has been largely rephrased and extended as well.

Minor points:

P3L9. the abbreviation SSA should be inserted as SIA.

Added.

P3L9 and Eq.(2) It is confusing to describe SSA is as a sliding law while a linear till parameterization (2) is used as sliding velocity. Better to explain clearer.

We simply rephrased to:
“For temperate regions, we assume a linear basal friction (Weertman, 1957):”

Sect 3.1 and others. There are not a few names of glaciers and the region without explanation. I know that this journal is the Cryosphere and many readers are familiar with such local names, however, I really appreciate if the author show a map of these locations for better understanding of result description.

We have added a map as Fig. 1.

P7L3, about RMSE of simulated velocity fields. I am interested in the relative rank of RMSE of simulated topography (thickness) by GRISLI. I suspect that the dispersion in the simulated topography by the participants are smaller than that of the velocity, but I want to know whether GRISLI's errors are both large or only velocity is large among the participants.

The RMSE of simulated ice thickness was given in P6 L22-23 of the original manuscript. It is about 120 metres and it is the 5th lowest in the ISMIP6 ensemble (21 models). As a result, compared to the other participating models, only the velocity error is large for GRISLI.

P7L14, resemblance of patterns between Fig.1a and b. Why not show a figure of correlation?

Not sure what you meant. The spatial correlation between two 2D variables is a scalar right? We computed a Pearson correlation of 0.24 between the two variables shown in Fig 1a and b. We have added this value in the main manuscript. This relatively low value can be explained by the noisy signal of the ice thickness difference between the end of the historical experiment and the observations.
To visualise this correlation we could plot the thickness difference at the end of the *ctrl_proj* as a function of the thickness difference at the end of the historical experiment *hist*. We show this figure in this response (Fig. R1). We are unsure if this will bring additional value? If yes, we would be happy to add such a figure in the paper.

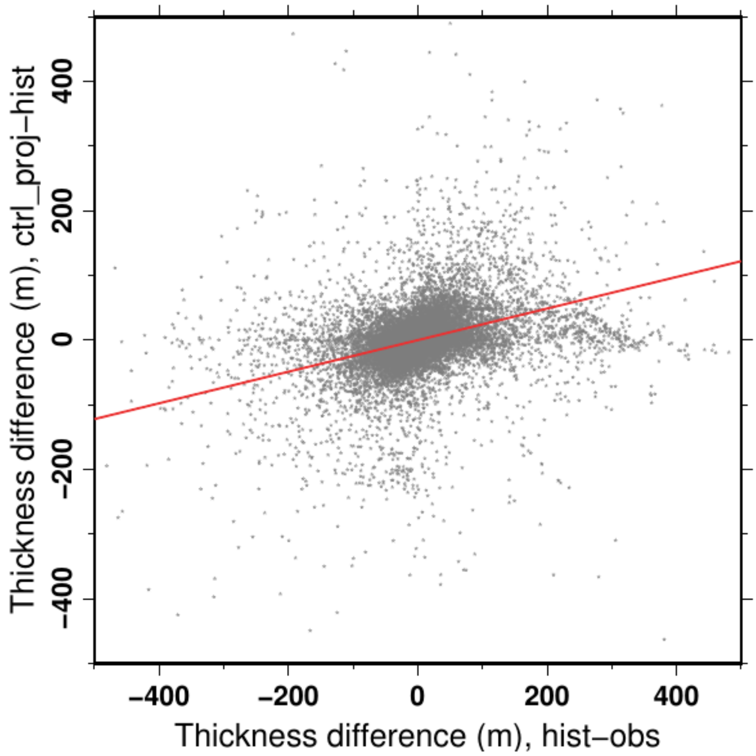

Figure R1: Ice thickness difference at the end of the control experiment ctrl_proj with respect to the end of the historical experiment as a function of the ice thickness difference at the end of the historical experiment with respect to observations (Frettwell et al., 2013). The red line represents the linear regression with a correlation value at 0.24.

P8L12 '... suggesting increased precipitation in the future'. As far as I understand the experiment protocol and the mentioned in the next sentence, changes in simulated ice sheet volume never suggests the precipitation increasing, but it originates from the boundary condition. Please rewrite this part.

Modified for:
"In addition, except under the HadGEM2-ES forcing, the Antarctic contribution to global sea level rise is always smaller than under the control experiment under constant present-day forcing. This suggests that the climate forcing computed from the GCMs in the future leads to a larger integrated total mass balance compared to our reference present-day mass balance. In fact, most GCMs simulate an increase in precipitation in Antarctica related to the projected warming."

Figure 2 and other velocity figures. The range of smallest velocity color (white) is not explicitly written. Or I suspect that it is from +1 m/yr to -1 m/yr, because there are three color boxes between 10 and 100 or 100 and 1000 while only 2 between 1 and 10.

We have changed the colour scale. The range -1 to 1 m/yr is white. This is now specified in Fig. 3 (former Fig. 2).

Figure 6 and other evolution figures. Adding numbers of sea-level equivalent height to the ice volume axis (a) will help to compare with (b).

We are not sure what you want us to do here. To express the volume shown in (a) in sea-level equivalent instead of in km^3 (or Gt)? We prefer not to do so as it might appear confusing for the reader to express in cm SLE a volume change that is not contributing to sea level rise. What we could do instead is to express all the volume changes in Gt instead of using the sea-level equivalent. However, we think that most people are interested in the sea-level equivalent so we prefer to use this unit. In order to facilitate the comparison of the two panels, we have added the conversion factor (1 mm SLE = 372 Gt) in the figure captions when applicable.

Figure 11b. I do not understand the rule of annotations in the color bar between 0.1 to 10 and -0.1 to +0.1.

We have changed the colour scale. The range from -0.1 to 0.1 m is white. This is now specified in the caption.

The GRISLI-LSCE contribution to ISMIP6, Part 2: projections of the Antarctic ice sheet evolution by the end of the 21st century

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Abstract.

~~Of primary societal importance, the ice sheet~~The Antarctic ice sheet's contribution to global sea level rise over the 21st century is of primary societal importance and remains largely uncertain as of yet. In particular, ~~the~~ in the recent literature, the contribution of the Antarctic ice sheet by 2100 ~~ranges from a few millimetres to more than one metrein the recent literature~~can be negative (sea level fall) by a few centimetres to positive (sea level rise) with some estimates above one metre. The Ice Sheet Model Intercomparison Project for CMIP6 aimed at reducing the uncertainties on the fate of the ice sheets in the future by gathering various ~~ice sheet~~ ice-sheet models in a common framework. ~~While in a companion paper we present the GRISLI-LSCE contribution to ISMIP6-Greenland~~Here, we present here the GRISLI-LSCE contribution to ISMIP6-Antarctica. We show that our model is strongly sensitive to the climate forcing used, with a contribution of the Antarctic ice sheet to global sea level rise by 2100 that ranges from -50 mm to +150 mm of sea level equivalent. Future oceanic warming leads to a decrease in thickness of the ice shelves ~~and implies grounding line retreats~~ resulting in grounding line retreat while increased precipitation partially mitigates ~~the~~ or even overcompensates the dynamic ice sheet contribution to global sea level rise. Most of ice sheet changes over the next century are dampened under low greenhouse gas emission scenarios. Uncertainties related to ~~sub-shelf basal melt~~ sub-ice-shelf melt rates induce large differences in simulated grounding line ~~retreats~~retreat, confirming the importance of this process and its representation in ~~ice sheet models for the~~ ice-sheet models for projections of the Antarctic ice sheet's evolution.

1 Introduction

The Greenland and Antarctic ice sheets are now the largest source for the observed global mean sea level rise behind the thermosteric and the glacier contributions (Nerem et al., 2018). Given its size, the Antarctic ice sheet represents the largest single potential contributor in the future~~. If~~ , as it represents 58 m of sea level rise if melted completey (Fretwell et al., 2013; Morlighem et al., 2020 . While the ice sheet ~~has probably displayed~~ was probably in a quasi mass-equilibrium in the eighties (Rignot et al., 2019), it has ~~shown, since then , an important acceleration in mass loss, reaching up to an equivalent of~~ since then lost ice at an accelerated pace, reaching a yearly sea level contribution of up to 0.7 mm yr^{-1} ~~of global sea level rise for~~ during the last decade (The IMBIE team, 2018; Rignot et al., 2019). The largest changes are observed in West Antarctica with increased ice discharge (Gardner et al., 2018) and increased ice shelf mass loss (Paolo et al., 2015). These recent changes might have already triggered mechanical instabilities (Favier et al., 2014) that could led to an inexorable irreversible retreat of the grounding line over large sectors of the ice sheet. If the increased in While the acceleration of mass loss is mostly associated with oceanic condition changesocean warming, the increased precipitation related to climate change can partially mitigate the ice sheet contribution to sea level rise in the future (Palerme et al., 2017; Medley and Thomas, 2019).

Despite significant advances in our understanding of ice sheet ice-sheet dynamics (Pattyn et al., 2017), the projected sea level contribution of the Antarctic ice sheet in the future by numerical models remains largely uncertain . Thus, altogether, (Oppenheimer et al., 2019). Overall, the uncertainties related to model formulation, parameter choice and external forcing, lead to a wide spread in the assessment of the magnitude of the Antarctic ice sheet contribution to global sea level rise by 2100, ranging from only a few millimetres to more than one metre (Golledge et al., 2015; Winkelmann et al., 2015; Ritz et al., 2015; DeConto anc which can be either negative (sea level fall) by a few centimetres or positive (sea level rise) with some estimates above one metre (Golledge et al., 2015; Winkelmann et al., 2015; Ritz et al., 2015; DeConto and Pollard, 2016; Schlegel et al., 2018; Edwards et al., 2019; . While the different ice sheet ice-sheet models seem to respond consistently to atmospheric changes, oceanic changes translate instead into largely different model responses (Seroussi et al., 2019)(Seroussi et al., 2019, 2020).

The Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6, Nowicki et al., 2016), endorsed by the Coupled Model Intercomparison Project – phase 6 (CMIP6), is an international effort that aims at providing estimates of the Greenland and Antarctic ice sheet contributions to global sea level rise by the end of the century. Such intercomparison of models is useful to reduce the uncertainties related to ice sheet ice-sheet dynamics since a variety of ice sheet ice-sheet models have participated in ISMIP6, spanning a range of model complexities and using various initialisation techniques to infer the initial conditions used for the projections. The analysis of the different responses amongst participating ice sheet ice-sheet models is done in Goelzer et al. (2020) for the Greenland ice sheet and in Seroussi et al. (2020) for the Antarctic ice sheet. With the same ice sheet ice-sheet model (GRISLI, Quiquet et al., 2018) and a similar ice sheet ice-sheet initialisation procedure, we participated in both ISMIP6-Greenland and ISMIP6-Antarctica. This paper aims at presenting the GRISLI-LSCE contribution to ISMIP6-Antarctica in detail, while its companion paper (Quiquet and Dumas, submitted) presents the ISMIP6-Greenland contribution. Thanks to a relatively low computational cost, we performed the full list of experiments of ISMIP6 described in (Nowicki et al., 2020), where Seroussi et al. (2020) only cover a subset of these experiments.

The analysis of a single model for all response to the different forcing scenarios allows to improve our understanding of the role of the forcing uncertainties in the simulated ice sheet changes. presents some important added value with respect to the community paper of Seroussi et al. (2020). First, single model paper allows for a documentation of a specific model response to the forcings while this information can be buried in the community paper given the large material to cover. Second, the community paper is best suited for a quantification of the sensitivity of the projections to the choice of the ice-sheet model. The sensitivity to the climate forcing is better shown for individual ice-sheet model. Third, single model paper can provide a more complete information of model biases.

In Sec. 2 we describe the ice sheet ice-sheet model used for the GRISLI-LSCE contribution and how the model has been initialised. In this section, we also present the ISMIP6 forcing methodology and we describe the complete list of experiments performed. The Antarctic ice sheet simulated by GRISLI for all the different experiments are presented in Sec. 3. Sec. 4 is a broader discussion of these results and we conclude in Sec. 5

2 Methods

2.1 Model and initialisation

The experiments shown here were performed with the 3D thermo-mechanically coupled ice sheet ice-sheet model GRISLI. Solving the mass and momentum conservation equations together with the heat equation, the model computes the evolution of the Antarctic ice sheet geometry and ice physical characteristics. The model is fully described in Quiquet et al. (2018) where the model has been shown to be capable of simulating grounding line migration of the Antarctic ice sheet at the glacial-interglacial timescale. For century timescales, with the same model version that the one used here, we participated to initMIP-Antarctica (Seroussi et al., 2019), ABUMIP (Sun et al., 2020) and LarMIP (Levermann et al., 2020). Slightly earlier version of the model has been used to simulate the evolution of the Greenland ice sheet until 2100 and 2150 (Peano et al., 2017; Le clec'h et al., 2019a) . In the following we only provide the main equations useful for the discussion of the model results.

In GRISLI, the ice sheet is only composed of incompressible ice with a constant and homogeneous density. The mass conservation equation reads

$$\frac{\partial H}{\partial t} = BM - \nabla\left(\bar{\mathbf{U}} H\right)$$

$$\frac{\partial H}{\partial t} = M - \nabla\left(\overline{\boldsymbol{U}} H\right), \tag{1}$$

with H the local ice thickness, BM the M the total mass balance and $\bar{\mathbf{U}}$ $\overline{\boldsymbol{U}}$ the vertically averaged horizontal velocity vector. $\nabla\left(\bar{\mathbf{U}} H\right)$ $\nabla\left(\overline{\boldsymbol{U}} H\right)$ is thus the ice flux divergence.

Velocities are computed using asymptotic *shallow* zero-order approximations, namely the shallow ice approximation (SIA) and the shallow shelf approximations (SSA). For the entire grid, the SSA is used as a sliding law (Bueler and Brown, 2009) and the total velocity is results from the addition of the SIA and the SSA velocities as in Winkelmann et al. (2011). Floating ice shelves are assumed to have no friction at the base (SSA driven ice flux). Conversely, grounded cold based regions show an infinite friction (SIA driven ice flux). For temperate regions, we assume a linear till below the ice sheet that allows for a viscous deformation (Weertman, 1957):

$$\tau_\mathbf{b} = -\beta\, \mathbf{U_b}$$

basal friction (Weertman, 1957):

$$\boldsymbol{\tau_b} = -\beta\, \boldsymbol{U_b}, \qquad (2)$$

where τ_b is the basal drag, β is the basal drag coefficient and $\mathbf{U_b}$ $\boldsymbol{U_b}$ is the basal velocity. The basal drag coefficient is spatially variable but constant in time (except in specific cases such as during the inversion procedure).

As in most large-scale ice-sheet models, GRISLI uses a flow enhancement factor to artificially account for ice anisotropy (Quiquet et al., 2018). In the model, we specify the value of this enhancement factor for the SIA velocity and we use a fixed ratio to determine its smaller SSA counterpart. For the experiments presented here (except in Sec. 3.2.7), we use a flow enhancement factor of 1 (no SIA enhancement) and a ratio close to 1 for the SSA (1.2:1).

Calving is based on a simple threshold criterion where ice thickness at the front reaching a minimal value is automatically calved.

For model initialisation, we followed a similar approach as in the initMIP-Antarctica experiments (Seroussi et al., 2019). The initialisation procedure is consists of an iterative method which aims at finding determining the geographical distribution of the basal drag coefficient (β in Eq. 2) that yields the minimal ice thickness error with respect to the observations. The procedure is described in Le clec'h et al. (2019b) and we only provide here a general description. We first compute an ice sheet thermal regime that is in equilibrium with the present-day climate forcing. To this aim, we run a 60 kyr experiment under a perpetual constant present-day climate forcing and imposing impose a fixed topography. For this thermal equilibrium experiment, the basal drag coefficient comes from a previous model realisation (Levermann et al., 2020) and is left unchanged. Using the inferred thermal state at the end of the 60 kyr, we performed multiple 120-yr long experiments. Each iteration consists in of a first step of 20 years with fixed grounding line position during which the basal drag coefficient is interactively adjusted on a yearly timestep so that it compensates the ice thickness error with respect to the observations (e.g. basal drag coefficient reduced for ice thickness overestimation). The second step is a 100 year long experiment with a freely evolving grounding line during which the basal drag coefficient remains at its last computed value during the first step. The ice thickness mismatch with respect to the observations at the end of the 100 simulated years is used to modify the basal drag coefficient for the next iteration. This correction consists in having an ice flux on the simulated topography as close as possible to the balance flux on the observed topography Le clec'h et al. (2019b). To do so, we modify the velocity so that the corrected vertically averaged velocity $\overline{\boldsymbol{U}^{\mathrm{corr}}}$ is related to the simulated vertically averaged velocity $\overline{\boldsymbol{U}}$ as

$$\overline{\boldsymbol{U}^{\mathrm{corr}}} = \overline{\boldsymbol{U}} \times \frac{H}{H^{\mathrm{obs}}}, \qquad (3)$$

with H and H^{obs} the simulated and the observed ice thickness. Only the basal velocity is corrected ($\boldsymbol{U_b^{\text{corr}}}$) when modifying the basal drag coefficient and we use the following relationship to infer the basal drag coefficient for the next step β^{new}:

$$\beta^{\text{new}} = \beta^{\text{old}} \times \frac{\boldsymbol{U_b}}{\boldsymbol{U_b^{\text{corr}}}}, \tag{4}$$

with β^{old} the basal drag coefficient of the previous step.

For the experiments shown here we have performed 15 iterations. At the end of the initialisation procedure, we use the last inferred basal drag coefficient together with the corresponding thermal state to run a relaxation experiment of 65 years with a free evolving grounding line. The simulated ice sheet after this relaxation experiment is used as the initial condition for the historical experiment (*hist*, see Sec. 2.3). It should be noted that such initialisation procedure produce an ice sheet in quasi-equilibrium with the late-20th century mean climate state. By construction it does not simulate the accelerated mass loss observed in the last decades (Rignot et al., 2019).

Our reference ice thickness and bedrock topography is the Bedmap2 dataset (Fretwell et al., 2013). This dataset is used as the initial topography for the 65-yr relaxation experiment used to define the initial state for the historical simulation. The ice thickness in Bedmap2 is also used as a target for the iterative initialisation procedure. Our reference present-day surface mass balance comes from RACMO2.3p2 (van Wessem et al., 2018) averaged over 1979-2016. The reference present-day oceanic forcing used to compute the ~~sub-shelf~~ sub-ice-shelf melt rates (more details available in Sec. 2.2) ~~comes from an observational dataset~~ is derived from a combination of observational datasets (Jourdain et al., 2019), averaged over 1995-2017. These reference atmospheric and oceanic forcing are used during the initialisation procedure and for the relaxation and control experiments (*ctrl* and *ctrl_proj*, see Sec. 2.3). The geothermal heat flux is ~~the one of~~ taken from Shapiro and Ritzwoller (2004). The model is run on a Cartesian grid at 16 km resolution covering the Antarctic ice sheet using a polar stereographic projection. Glacial isostatic adjustment has been neglected in this work.

2.2 ISMIP6-Antarctica forcing methodology

The ISMIP6-Antarctica working group has elaborated and distributed atmospheric and oceanic forcings in addition to a detailed methodology on how to implement these forcings in individual ~~ice sheet~~ ice-sheet models (Nowicki et al., 2020). Since we have strictly followed the suggested forcing methodology we only provide here the main principles and the reader is invited to refer to Nowicki et al. (2020) for more details.

For ~~ice sheet~~ ice-sheet model projections, the ISMIP6-Antarctica working group has provided a set of yearly climate fields ~~elaborated~~ derived from various general circulation models (GCMs). The climate fields cover the 1950-2100 period.

- The atmospheric forcing consists ~~in~~ of yearly surface mass balance and surface temperature (skin temperature) anomalies with respect to the 1995-2014 mean. The surface mass balance has been computed from the GCM outputs as the total precipitation minus the evaporation and runoff and regridded to the 16 km resolution grid. The anomalies have to be added on top of the reference present-day climatology.

– The oceanic forcing ~~consists in~~ is the thermal forcing, i.e. the ambient temperature minus the ambient temperature ~~of~~ at the freezing point. In the standard ISMIP6-Antarctica approach, which we follow with GRISLI, the thermal forcing is used to compute ~~sub-shelf~~ sub-ice-shelf melt rates using a non-local quadratic parametrisation as described in Jourdain et al. (2019). ~~For each GCM output, the parametrisation has been calibrated so that it can reproduce the observational dataset around Antarctica. Three estimates for the temperature sensitivity are provided (*low*, *medium* and *high*) for each GCM. In addition, an alternative calibration has been performed for selected GCM. This alternative calibration only uses~~ This parametrisation defines 16 sectors based on the Antarctic drainage basins extended into the open ocean. For each grip point (x,y) of the model, belonging to a specific sector, the sub-ice-shelf melt rate m is

$$m(x,y) = \gamma_0 \times K \times \left(TF(x,y,z_{\text{draft}}) + \delta T_{\text{sector}}\right) \times \left|\langle TF \rangle_{\text{draft} \in \text{sector}} + \delta T_{\text{sector}}\right| \quad (5)$$

where K is a constant that depends on physical properties of water, $TF(x,y,z_{\text{draft}})$ is the thermal forcing at the ice–ocean interface, $\langle TF \rangle_{\text{draft} \in \text{sector}}$ is the averaged thermal forcing for the ice shelves of the sector, and δT_{sector} is a sector-specific temperature correction. γ_0 is a parameter calibrated to reproduce the observed melt rate in the observations for $\delta T_{\text{sector}} = 0°K$. Once γ_0 is found, a δT_{sector} correction is computed to reduce the sector-specific biases.
γ_0 is estimated in two different ways. In one approach, γ_0 is calibrated to reproduce the total Antarctic melt rate (Rignot et al., 2013; Depoorter et al., 2013). This version is labelled *MeanAnt* in Jourdain et al. (2019). An alternative calibration (labelled *PIGL*) consists in using a subset of the observational data, restricted to the Pine Island glacier ~~basin. This was~~ sector. This is motivated by the fact that the Pine Island glacier has undergone a substantial grounding line retreat related to an increased ~~sub-shelf melting~~ sub-ice-shelf melting rates in the recent years (Jenkins et al., 2018). ~~When calibrated to reproduce the observations for this basin, the parametrisation~~ Also, there are dense observational data available in this sector. The *PIGL* calibration produces a higher melt rate response for a given change in thermal forcing than the ~~reference parametrisation calibrated for the whole dataset. The experiments that use this~~ *MeanAnt* calibration. Here, the experiments that used the *PIGL* calibration are labelled *PIGL* ~~in the following.As for the standard~~ while all the other experiments use the *MeanAnt* calibration.
For both *MeanAnt* and *PIGL*, the γ_0 probabilistic distribution is computed with a random sampling of the melt rates in the observations. For each calibration, three ~~temperature sensitivities are provided,~~ possible values of γ_0 are thus given: the 5$^{\text{th}}$ percentile, the median and the 95$^{\text{th}}$ percentile. These results in different oceanic sensitivity to thermal forcing and are referred as *low*, *medium* and *high* ~~, for the *PIGL* calibration.~~ oceanic sensitivity in this manuscript.

Surface melt can generate ~~ice shelf~~ ice-shelf collapse through hydrofracturing (Scambos et al., 2009). These processes are poorly understood and generally not accounted for in large-scale ~~ice sheet~~ ice-sheet models such as GRISLI. ISMIP6-Antarctica working groups have provided the participants with scenarios for ~~ice shelf~~ ice-shelf collapse in the future following the methodology of Trusel et al. (2015). With these scenarios, the retreat in time of the ~~ice shelf~~ ice-shelf front is imposed. These scenarios are not necessarily used and only the experiments labelled *shelf collapse* (hereafter *SC*) make use of them.

2.3 List of experiments

The ~~ice sheet~~ ice-sheet state (i.e. ice thickness and internal thermomechanical conditions) at the end of the initialisation procedure (Sec. 2.1) is used as the initial condition for a control experiment *ctrl* and for the historical simulation *hist*. For the control experiment *ctrl*, the climate forcings (surface temperature, surface mass balance and thermal forcing) are left unchanged for the duration of the experiment at their present-day values used during the initialisation procedure (no anomalies are imposed). The *ctrl* experiment starts in January 1995 and ends in Decembre 2100, even though ~~the time evolution has no incidence on the forcings~~it uses a constant present-day climate forcing (RACMO2.3p2 averaged over 1979-2016). Instead, the historical simulation *hist* uses the time varying climate forcing described in Sec. 2.2 from January 1995 to Decembre 2014. Although it could have been possible to run multiple historical simulations for each GCM output available, it has been asked to participating models to run only one historical simulation using the NorESM1-M climate forcing. NorESM-1-M was chosen because it is one of the CMIP5 models that best reproduce the present-day Antarctic climate change (Barthel et al., 2020).

The different ~~ice sheet projection experiments~~ ice-sheet projection experiments start in January 2015 and they are all branched ~~to the~~ from the end of the historical experiment *hist* ~~in~~ (Decembre 2014~~and they~~). They end in Decembre 2100 (86 simulated years). The complete list of experiments in ISMIP6-Antarctica is shown in Tab. 1. Because few CMIP6 models were available when elaborating the ~~ice sheet~~ ice-sheet forcing, most of the experiments make use of CMIP5 models. Four CMIP6 models are nonetheless used (Tier 2). Some climate models were run under two scenarios for future greenhouse gas evolution, a ~~pessimistic~~ high emission scenario (RCP8.5 for CMIP5 models and SSP585 for CMIP6 models) and ~~an optimistic~~ a low emission scenario (RCP2.6 for CMIP5 models and SSP126 for CMIP6 models). For each climate forcing, three experiments using different ~~sub-shelf melting~~ sub-ice-shelf melt rate sensitivity to temperature change (*low*, *medium* and *high*) are performed. In addition, the parametrisation of ~~sub-shelf~~ the sub-ice-shelf melt model calibrated against the Pine-Island glacier area (*PIGL*) is used for four CMIP5 models under RCP8.5. The ~~ice shelf~~ ice-shelf collapse scenario related to hydrofracturing is also used for all the climate forcing under the ~~pessimistic~~ high emission scenario. Finally, in order to disentangle the role of atmospheric versus oceanic forcing, a series of experiments also consists in using only one or the other of these forcings.

In order to ~~facilitate~~ allow for the interpretation of the model response to the forcings, ~~an other~~ a control experiment, *ctrl_proj* , has ~~also~~ been performed in addition to the *ctrl* experiment. As ~~for~~ in the *ctrl* experiment, the climate forcings remain constant with no anomaly with respect to the present-day climate used for the initialisation procedure. However, the *ctrl_proj* starts from the end of the historical simulation in January 2015 where the *ctrl* experiment uses the initial state instead. In doing so, the *ctrl_proj* experiment resembles a projection experiment, except that it uses no anomaly for the climate forcing.

3 Results

While the comparison of the various participating ice sheet ice-sheet models response has been fully described in Seroussi et al. (2020), we aim here at describing the response of one individual model , namely GRISLI, to the various forcings available in ISMIP6-Antarctica. A map of Antarctica with the names of the different regions discussed in the following is shown in Fig. 1.

3.1 Present-day simulated ice sheet

The map of ice thickness error with respect to the observations at the end of the historical simulation is shown in Fig. 2a. These errors are the results of ice thickness changes during the 65 years of relaxation at the end of the initialisation procedure and during the 20 years of the duration of the historical simulation. The differences appear relatively noisy since the model has a tendency to simulate smoother ice thickness gradients than observations. The differences over the East Antarctic plateau are most of the time no greater smaller than a few metres but increases towards the ice margins or in the vicinity of major ice streams (e.g. Amery ice shelf ice-shelf tributaries). In East Antarctica, the Amery and Totten ice shelf ice-shelf regions display the largest error where it can locally approach 500 metres. The ice thickness is generally overestimated in the the Amery region, while it is underestimated in the Totten region. While the errors are relatively localised in East Antarctica, they are more widespread in West Antarctica. There are important large ice thickness underestimations, locally reaching more than 200 metres, in the Getz ice shelf ice-shelf region in the Amundsen sea and upstream the grounding line of the Filchner-Ronne ice shelfgrounding line. . The Pine Island glacier area shows an ice thickness overestimation of about 50 metres. Except for the Filchner ice shelf, the ice thickness of the ice shelf is slightly underestimated (error lower than 30 metres). The extents ice front of the Ross and Filchner-Ronne ice shelves are overestimated by is located about 80km. All together km away from the observations. Overall, these discrepancies, integrated over the whole ice sheet, lead to a an ice thickness root mean square error with respect to the observations of about 120 metres (5th lowest error amongst the 21 participating models).

The simulated surface velocity magnitude at the end of the historical simulation is shown in Fig. 3a. The model generally reproduces the location pattern and the magnitude of the observationsobserved surface velocities, depicted in Fig. 3b, even if important substantial errors remain (Fig. 3c). The largest errors are located in fast flowing areas and they can be positive (overestimation) or negative (underestimation). Amongst the largest errors are the large overestimation of the ice velocity for Surface velocities of the major tributaries of the Ross ice shelf (Mercer and Williams glaciers) and Filchner-Ronne ice shelf (Foundation glacier) are largely overestimated (locally up to a factor 4 with errors larger than 1000 m yr^{-1}). Conversely, there is an important a large underestimation of the ice velocity, locally greater than 1000 m yr^{-1}, for the Pine Island ice shelf ice-shelf tributaries. The velocity errors for the grounded part of the ice sheet mostly explain the velocity errors for the floating ice shelves. Thus, the velocity in the Ross ice shelf is largely overestimated while the velocity in since its tributaries show generally a large ice velocity overestimation. The western part of the Ronne ice shelf is underestimatedshows an opposite behaviour with feeding glaciers showing a velocity underestimation. The Amery ice shelf is an exception: the grounded velocity errors are positive while their floating counterparts are negative. This ice shelf is narrow and very confined with a complex sub-shelf melt sub-ice-shelf melt rate pattern which makes it difficult to model for a large scale ~~ice sheet~~ ice-sheet model at 16 km horizontal resolution. ~~All together~~ More generally, spatial resolution could explain most of velocity errors in the coastal regions where topography together with spatially variable surface mass balance and sub-ice-shelf melt exert a strong control on simulated velocities. Overall, the root mean square error with respect to the observations is about 270 m yr^{-1} (3rd largest error amongst the 21 participating models). When computing the error for the logarithm of the velocity in order to reduce the importance of fast flowing regions with respect to slowly flowing regions, the performance of GRISLI with respect to the other participating models slightly improves (6th largest error). This suggests that the model shows the largest disagreement with respect to the observations in fast flowing regions. Our initialisation procedure aims at finding the basal drag coefficient that minimises the ice thickness error with respect to the observations but it does not have any constraints on the simulated velocities. As a result, it is not surprising that we obtain a low RMSE in ice thickness together with a larger RMSE in surface velocities with respect to other ~~ice sheet~~ ice-sheet models that use the velocities in their initialisation procedure ~~.~~ (e.g. JPL1_ISSM, UTAS_ElmerIce).

Even though our initialisation procedure aims at providing a simulated ice sheet in equilibrium with our reference present-day climate, a drift is nonetheless simulated at the century scale. Fig. 2b shows the ice thickness change from 2015 to 2100 in the control experiment *ctrl_proj*. The pattern of ice thickness change resembles the one of the ice thickness error with respect to observations (Fig. 2a). In particular the regions with the largest errors with respect to observations are the one producing the largest ice thickness change in the control simulation. The model drift over the 2015-2100 period can be explained for a large part by the simulated velocity errors with respect to observations (Fig. 3c): thickening (e.g. Pine Island glacier region) is generally associated to an underestimation of the velocity while thinning (e.g. Filchner ~~ice shelf~~ ice-shelf tributaries) is associated to an overestimation of the ice velocity. One exception is the Amery region in East Antarctica where the grounded velocities are overestimated while there is an increase in ice thickness in the control experiment. The ice thickening during the control experiment could suggest an underestimation of the ice velocity, i.e. underestimation of the ice export, which seems in contradiction to the overestimation of the simulated ice velocity with respect to the observations. This inconsistency can be due to a surface mass balance ~~errors or an underestimation of the ice flux at the grounding line~~overestimation in the forcing in this area. This overestimation could be corroborated by the fact that another regional climate model than the one used here simulates a surface mass balance 30% smaller than RACMO2.7 in the Amery region (Agosta et al., 2019). Because of compensating errors, the ice thickness change, integrated over the duration of the control experiment, leads to a negligible total ice ~~volume~~ mass change (less than 1000 ~~km^3~~Gt). However, the ice volume above floatation shows a negative trend (Fig. 4) which means that there is a mass transfer from the grounded to the floating part of the ice sheet in the control experiment. The model drift in the control experiment *ctrl_proj* in ~~term~~ terms of surface velocity is shown in Fig. 3. The velocity changes for the grounded areas are generally limited to a few metres per year except for some ice streams feeding the Ross and Filchner-Ronne ice shelves. Although more localised, the changes in Pine Island, Getz and Totten areas can be larger than one hundred metres per year. Since the ice shelves show a larger velocity magnitude, they also show the largest absolute velocity changes (a few hundred metres locally).

3.2 Ice sheet evolution projections

3.2.1 Ice sheet evolution for CMIP5 models using RCP8.5

The evolution of the ice volume total ice mass change for the different CMIP5 models under the pessimistic greenhouse gas emission scenario high emission scenario for greenhouse gases (RCP8.5) and using the sub-shelf sub-ice-shelf melt parametrisation calibrated over the Antarctic wide dataset Antarctic-wide dataset (*MeanAnt*) is shown in Fig. 4. The total ice volume mass (Fig. 4a) is decreasing for the six CMIP5 models and for most models there is an acceleration in volume of ice mass loss in the course of the century. HadGEM2-ES produces the largest ice volume loss (greater than 300000 km^3mass loss (about 30×10^3Gt in 2100) while CSIRO-Mk3 produces the smallest loss (lower then 50000 $km^3$$50\times10^3$Gt). The sub-shelf sub-ice-shelf melt rate sensitivity to temperature change constitutes an important source of uncertainty for the forcings that produce the largest volume mass loss: for NorESM1-M and HadGEM2-ES the differences between the *low* and *high* oceanic sensitivity corresponds to a volume mass difference of about 100000 km^3 100×10^3Gt.

The volume change contributing to sea level rise (e.g. i.e. above floatation) shows a different evolution than total ice volume mass (Fig. 4b). While the total ice volume mass change is always negative, the simulated Antarctic contribution to sea level rise in 2100 for the CMIP5 models can be either positive, e.g. ~ 60 mm of sea level equivalent (mmSLEmm SLE) for HadGEM2-ES, or negative, e.g. -45 mmSLE mm SLE for CCSM4. This means that the ice shelves are systematically reducing in volume shelf volume is shrinking for all forcings over the course of the century while the grounded ice volume has an ambivalent response to the forcingscan increase or reduce depending on the forcing used. In addition, except under the HadGEM2-ES forcing, the Antarctic contribution to global sea level rise is always smaller than under the control experiment under perpetual constant present-day forcing, suggesting increased precipitation . This suggests that the climate forcing computed from the GCMs in the future leads to a larger integrated total mass balance compared to our reference present-day mass balance. In fact, most GCMs simulate an increase in precipitation in Antarctica related to the projected warming. This has important consequences on the ice sheet ice-sheet integrated surface mass balance and, as a result, the difference in term terms of precipitation change amongst the GCMs explains the large spread in simulated Antarctic ice sheet contribution to global sea level rise. Fig. 5 shows the evolution of the surface mass balance (Fig. 5a) and basal mass balance (Fig. 5b) over the next century, integrated over the ice sheet, for the different climate forcings. Despite a considerable interannual variability, the surface mass balance is generally slightly increasing by 15% to 25% (400 to 900 Gt yr^{-1} increase), except for HadGEM2-ES where it shows a slight decrease of about 200 Gt yr^{-1}. Instead, the basal mass balance is always decreasing melting underneath ice shelves is increasing for the different GCMs leading to an increase in mass loss by about 100% (e.g. 1500 Gt yr^{-1} increase for IPSL-CM5A-MR) to more than 200% (e.g. 5000 Gt yr^{-1} increase for HadGEM2-ES). The lack of precipitation increase in HadGEM2-ES combined with an increase sub-shelf melt sub-ice-shelf melt rate explains why this forcing produces the largest Antarctic contribution to future sea level rise.

The spatial pattern of ice thickness change in 2100 with respect to 2015 for a selection of climate forcings is shown in Fig. 6. For this figure, in order to better illustrate the impact of the forcings, the projected ice thickness change has been corrected for the ice thickness change in the control experiment *ctrl_proj* (shown in Fig. 2b). Fig. 6a is for a forcing that produces a large increase in grounded ice volume (~~CCSM4~~CESM2) under RCP8.5 while Fig. 6b is for a forcing that produces a reduction in both the total and the grounded ice volume (NorESM1-M). For both forcings, the Ross, Filchner-Ronne and Amery ice shelves show ~~important~~ ice thinning, amplified in NorESM1-M with respect to ~~CCSM4. However CCSM4~~ CESM2. However CESM2 shows a more pronounced thinning for the Larsen and Fimbul ice shelves, illustrating the spatial heterogeneity amongst the different forcings. Associated with the increased surface mass balance in the course of the century (Fig. 5a), ~~CCSM4~~ CESM2 produces a wide spread ~~ice~~ thickening of the grounded ice sheet. When using NorESM1-M this thickening is ~~also presents~~ present to a lesser extent ~~but it is also~~ and compensated by the thinning that results from the grounding line retreat in some areas (Ross or Totten ice shelves for example). Our model does not simulate ~~important~~ substantial changes in the Pine Island glacier area. ~~This is likely due to the fact that our control experiment tends to produce an ice thickening in this region~~ In this region, there is a thickening of the ice sheet during the control experiment (Fig. ~~6b) which tends to stabilise this region, resulting in a smaller~~ 2b) with underestimated surface velocities (Fig. 3c). These biases can be due to the inferred basal drag coefficient during the initialisation procedure that leads to an underestimation of the velocities. The linear friction law implemented in our model can also result in an underestimation of the velocity (Brondex et al., 2019). Finally, the biases can also be the result of the complex topographic setting that might not be well captured at 16 km. The underestimated ice sheet velocity at the grounding line in this area, together with the thickening bias, result in a small sensitivity to oceanic warming. However, for other intercomparison exercises we have shown that our model is able to produce a grounding line retreat in this area (Sun et al., 2020).

For the variety of climate forcing used, the Ross and Totten sectors are the ones that most frequently present grounding line retreat and inland thinning. The Filchner-Ronne sector presents also an ice shelf thickness decrease although associated with a limited grounding line retreat. This is consistent with the average response of the ISMIP6 participating models (Fig 6 in Seroussi et al., 202 . The lack of sensitivity of the Pine Island sector is also a feature common to other participating models since the standard deviation of ice thickness change in this area is very high (> 200 m).

3.2.2 Ice sheet evolution for CMIP6 models using SSP585

Because CMIP6 models have shown a much larger climate sensitivity than their CMIP5 counterparts (Forster et al., 2020), it is interesting to compare the projected Antarctic ice sheet evolution under the CMIP6 forcings with respect to the CMIP5 experiments discussed previously. In Fig. 7, we show that the CMIP6 forcings produce an ice sheet evolution in the range of what we simulate with the CMIP5 forcings. Three models produce very little ~~ice volume~~ total ice mass change with an evolution very similar to the CCSM4 CMIP5 model. Only UkESM1 produces a relatively ~~important total ice volume reduction (-250000 km^3~~large total mass reduction (-230$\times$10^{3}Gt) although not associated with a positive ice sheet contribution to sea level rise (about -10 ~~mmSLE). Alike other~~ mm SLE). Similarly to CMIP5 climate models, the CMIP6 models simulate an increase in the integrated surface mass balance (Fig. 5a) that partly compensate the mass loss due to ~~sub-shelf~~ sub-ice-shelf melting (Fig. 5b). Thus, the new generation of climate projections do not seem to support fundamentally different Antarctic evolution in the future with respect to the previous climate projections.

3.2.3 Ice sheet evolution for RCP2.6 and SSP126

~~The forcing dataset provided by the ISMIP6-Antarctica working group allows for an evaluation of the impact of the future evolution of the greenhouse gas emission on the Antarctic ice sheet response.~~ In Fig. 8 we show the ~~ice volume~~ total ice mass change under three climate models that have run for a ~~pessimistic~~ high (RCP8.5 or SSP585) and ~~an optimistic~~ a low(RCP2.6 or SSP126) emission scenario for greenhouse gases. The total ~~ice volume~~ mass loss is systematically smaller when using the ~~optimistic scenario~~low emission scenarios. The model that produces the ~~greater volume~~ largest mass loss, NorESM1-M, also shows the most pronounced response to the choice of the scenario. For this model, even if the volume loss contributing to global sea level rise remains almost unchanged, there is a drastic reduction in total ice ~~volume~~ mass loss when using the ~~optimistic~~ low emission scenario. In this case, the ice shelves are able to ~~maintain~~ survive in the course of the century. For the other two models, ~~IPSL-CM51-MR~~ IPSL-CM5A-MR and CNRM-CM6-1, the main consequence of the use of the ~~optimistic~~ low emission scenario is a reduction of the volume above floatation relative to the volume simulated when using the ~~pessimistic~~ high emission scenario. This is related to the smaller precipitation amount in the colder ~~optimistic~~ low emission scenario. As a result, by the end of the century, the Antarctic ice sheet contribution to global sea level rise is larger (about 30~~mmSLE~~ mm SLE) in the ~~optimistic~~ low emission scenario with respect to the ~~pessimistic~~ high emission one. However, ~~the use of the optimistic scenariosystematically produces ice volume evolution~~ compared to the high emission scenario, the simulated total ice mass evolution using the low emission scenario is closer to the ~~one~~ mass evolution of the control ~~experiments~~experiment. This means that, in this case, the simulated ice sheet changes in the future are dampened with respect to an higher emission scenario.

The impact of the greenhouse gas scenario on the spatial distribution of ice thickness change across 2015-2100 is shown in Fig. 6. ~~On the one hand,~~ NorESM1-M using the RCP8.5 scenario (Fig. 6b) produces drastically thinner ice shelves than when using the RCP2.6 scenario (Fig. 6c). The Ross ice shelf is thus able to ~~maintain~~ survive until the end of the century with minimal thickness change under the RCP2.6 scenario. ~~On the other hand,~~ The grounded parts of the ice sheet show an opposite response: the RCP2.6 scenario leads to almost no change in thickness ~~for the grounded parts of the ice sheet whereas under RCP8.5~~ whereas a slight widespread thickening is simulated under RCP8.5, related to increased precipitation.

3.2.4 ~~Ice sheet evolution using the Pine-Island glacier calibrated sub-shelf melt parametrisation~~

In Seroussi et al. (2020), two climate forcings (NorESM1-M and IPSL-CM5A-MR) were evaluated for both the RCP2.6 and the RCP8.5. The simulated contribution to sea level rise in the ISMIP6 ensemble is very similar to the GRISLI response: no change in grounded ice mass for NorESM1-M but an increase in grounded ice mass for IPSL-CM5A-MR under RCP8.5 with respect to RCP2.6. CNRM-CM6-1 shows a response similar to the one of the IPSL-CM5A-MR since the grounded ice mass is increasing under the SSP585 with respect to the SSP126.

3.2.4 Ice sheet evolution using the Pine-Island glacier calibrated sub-ice-shelf melt parametrisation

~~Sub-shelf melt rate computation in ice sheet~~ The computation of the sub-ice-shelf melt rate in ice-sheet models is one of the largest source of uncertainty. The standard approach in ISMIP6-Antarctica is a parametrisation ~~largely derived from observational data~~ tuned to reproduce a combination of observational datasets (Jourdain et al., 2019). However, the choice of the dataset used to calibrate the parametrisation can lead to substantial differences in the ~~sub-shelf~~ sub-ice-shelf melt model. Fig. 9 shows the simulated ~~ice volume~~ total ice mass change when using the ~~sub-shelf~~ sub-ice-shelf melt parametrisation calibrated to reproduce the mean Antarctic melt rate (reference, *MeanAnt*) or calibrated to reproduce the Pine Island's grounding line melt rate (*PIGL*). The *PIGL* calibration produces higher melt rates and much greater ~~volume~~ mass loss than the reference calibration. For the medium oceanic sensitivity, the use of the *PIGL* calibration leads to an additional total ~~volume loss of 200000 to 300000 km^3~~ mass loss of 200 to 300×10^3Gt and an additional contribution to global sea level rise of about 40 to 50~~mmSLE~~ mm SLE with respect to the ~~reference~~ *MeanAnt* calibration. In addition, with the *PIGL* calibration, the model shows a much larger sensitivity to the oceanic forcing as the difference from a low to a high oceanic sensitivity can be as large as ~~350000 km^3~~ 350×10^3Gt (100 ~~mmSLE~~mm SLE) when using the CCSM4 forcing.

Amongst the different experiments, the NorESM1-M under ~~rcp8~~RCP8.5 using the *PIGL* calibration for the ~~sub-shelf~~ sub-ice-shelf melt rate with a high oceanic sensitivity produces the largest Antarctic contribution to global sea level rise by 2100. The spatial distribution of ice thickness change over 2015-2100 for this experiment is shown in Fig. 6d. The pattern is similar to the one obtained with the reference ~~sub-shelf~~ sub-ice-shelf melt model (Fig. 6b) but with a much larger decrease in ice thickness. In particular, the grounded line retreats much further inland in the Ross and Filchner-Ronne sectors when using the *PIGL* calibrated ~~sub-shelf~~ sub-ice-shelf melt model with the high oceanic sensitivity.

3.2.5 Ice sheet evolution using the ~~ice shelf~~ ice-shelf collapse scenario

Fig. 10 shows the impact of the imposed ~~ice shelf~~ ice-shelf collapse scenario on the ~~ice volume~~ total ice mass evolution when using different GCM forcings. Such scenarios lead to an increase in the total ~~volume~~ mass loss (Fig. 10a) but have, most of the time, a ~~negligible~~ small impact on the ice volume contributing to global sea level rise (less than 16 ~~mmSLE~~ mm SLE in 2100, Fig. 10b). This means that the ~~ice shelf~~ ice-shelf collapse scenarios mostly impact the floating ice volume but, on the century time scale, they do not imply a destabilisation of the grounded ice sheet in our model. The largest response is obtained for CNRM-ESM2 and CNRM-CM6-1. These models show a limited sub-ice-shelf melt (Fig. 5b) and one of the smallest ice mass loss in the future (Fig. 7a)~~with a limited sub-shelf melt (Fig. 5b). However, they simulate an important~~ . Thus, they produce a large ice-shelf extent with respect to the other climate models. CNRM-ESM2 and CNRM-CM6-1 also simulate a pronounced atmospheric warming in the future~~(~~. This warming is indirectly visible in Fig. 5a since the precipitation increase ~~shown in~~

~~Fig. 5a) that lead to an important ice shelf fracture~~is primarily driven by the increased temperature. The atmospheric warming together with the large ice-shelf extent explain why the CNRM-ESM2 and CNRM-CM6-1 models show the largest mass loss resulting from ice-shelf collapse.

The impact of the ice shelf collapse scenario on the sea level contribution ranges from -8 to +17 mm SLE. This range is much smaller than the range of the simulated sea level contribution for the different climate models (-50 to 70 mm SLE). Surprisingly, for some models, the ice shelf collapse scenario contributes negatively to the sea level contribution (e.g. UKESM1-0-LL). This is most probably due to local non-linearities of grounding line dynamics. However this effect is limited to small changes in the grounded volume.

A greater sensitivity to this process has been reported in Seroussi et al. (2020) (multi-model average of 28 cm SLE in 2100 under the CCSM4 forcing) although associated a wide spread of response amongst participating models. For most climate models, the retreat masks by 2100 have removed the ice shelves in the Peninsula and in the Pine Island sectors, but affect only very marginally the other ice shelves. In the standard experiments, these sectors show a low sensitivity to the oceanic forcing. In fact, even under the strongest oceanic forcings, GRISLI shows there a limited grounding line retreat. This suggests that the buttressing force is not the reason why the model does not retreat in these sectors. Instead, it is most likely the topographic biases in the initial state that made the model weakly sensitive to the oceanic conditions. Using a different initial state, we have shown in a recent intercomparison exercise (ABUMIP, Sun et al., 2020) that we were able to simulate large grounding line retreat when the buttressing induced by the ice shelves is removed.

3.2.6 ~~Respective role~~ Role of atmospheric versus oceanic forcing

Future global warming has ambivalent impacts on the evolution of the Antarctic ice sheet. On the one hand, the Southern Ocean is expected to warm in the future, leading to ice shelf thinning and calving eventually associated to grounding line destabilisation. On the other hand, the increase in moisture content associated with atmospheric warming can lead to increased precipitation and thickening of the ice sheet. To disentangle the respective role of the oceanic forcing with respect to the atmospheric forcing, we have run the ~~ice sheet~~ ice-sheet model for four climate forcings using alternatively only one or the other of the forcing (ocean only, OO, or atmosphere only, AO). The results in ~~term of volume~~ terms of total mass change is shown in Fig. 11. The AO experiments produce an increase in total ice ~~volume~~ mass where the OO experiments show a decrease (Fig. 11a). The Antarctic contribution to global sea level rise is ~~systematically~~ smaller than the control experiment *ctrl_proj* for the AO experiments while the OO experiments produce a contribution relatively close to the control experiment *ctrl_proj*, although slightly larger. The CCSM4 model produces the largest surface mass balance increase (Fig. 5a). Interestingly, the Antarctic contribution to sea level rise with this model is almost identical when using the full forcing (Fig. 4b) or when using the atmospheric forcing only (Fig. 11b). This suggests a negligible role of the ocean for this model to explain the Antarctic ice sheet contribution to sea level rise in the future. To a lesser extent this is also the case for the MIROC-ESM-CHEM model.

Conversely, the total ice volume mass change (Fig. 11a) mostly reflects the loss of volume of mass loss from the ice shelves which , unsurprisingly, mostly responds respond primarily to the oceanic forcing. The ice shelf volume ice-shelf mass loss in the OO experiments can be large but it is mostly occurring with an important acceleration in the last 20 years of the century. This late response might be a reason why the volume above floatation is not drastically different from the control experiment in the OO experiments.

3.2.7 Simulated change in ice dynamics

The ice sheet ice-sheet surface velocity change in 2100 with respect to 2015 using the NorESM1-M climate forcing under RCP8.5 with the medium oceanic sensitivity is shown in Fig. 12a. Associated with ice thinning (Fig. 6b), the remaining ice shelves show a large decrease in surface velocity. Grounded ice shows only limited changes in surface velocity Modelled grounded ice surface velocity changes are limited with the notable exception of the ice streams feeding the Ross ice shelf that show a substantial acceleration (several hundred metres per year). The acceleration in this area is due to the grounding line retreat simulated by the model under this climate scenario. The pattern of simulated ice velocity change is consistent with results from other ice sheet ice-sheet models (Seroussi et al., 2020) and remains similar for the other forcings: systematic decreased ice shelf decreased ice-shelf velocity and increased grounded velocity only for scenarios that produce a grounding line retreat in the future.

An other Another way to quantify the dynamic changes over the this century is to integrate in time the mass conservation equation (Eq. 1). In doing so, the total ice thickness change from 2015 to 2100 is the superposition of two terms of different naturescauses: the integral of the mass balance related to climate forcings (calving and surface and basal mass balance) and the integral of the ice flux divergence. The integral of the ice flux divergence can be seen as the dynamic dynamical contribution to ice thickness change. Such dynamic dynamical contribution is shown in Fig. 12b for the NorESM1-M climate forcing with the medium oceanic sensitivity. Generally the dynamic dynamical contribution follows the simulated change in surface velocity. In West Antarctica, the dynamic contribution dynamical contribution has a strong spatial variability. It can reach up to more than 50 metres decrease in ice thickness and as such explain most of the simulated ice thickness change shown in Fig. 6b. In East Antarctica there is a widespread very small (a few centimetres) negative dynamic dynamical contribution to ice thickness change (ice thinning) that somehow moderate the ice thickening due to increased precipitation.

To further assess the sensitivity of the simulated ice sheet evolution to the mechanical parameters used in the model, we performed a set of additional sensitivity experiments. In these new experiments, we apply a uniform perturbation of either the basal drag coefficient (Eq. 2) or the SIA flow enhancement factor. These perturbations are imposed abruptly at the end of the year 2045. We perform perturbed control experiments *ctrl_proj* and perturbed projections using the NorESM1-M climate forcing under RCP8.5 with a medium oceanic sensitivity. Fig. 13 shows the mass change in 2100 for the perturbed experiments with respect to their standard counterpart. Fig. 13a,b is for a basal drag coefficient perturbation that starts from +100% (i.e. a doubling of the base value) to -90% (i.e. a reduction to 10% of the base value). Fig. 13c,d shows the effect of changing the value of the enhancement factor from 0.4 to 6 (1 being the standard value). The perturbed control experiments are used here to define a range of acceptable perturbations. Thus, in Fig. 13, the vertical grey band shows the range of perturbations that implies a 0.15% total mass change in the perturbed *ctrl_proj* with respect to the standard *ctrl_proj*. 0.15% has been chosen as it represents one tenth of the mass loss simulated using NorESM1-M under RCP8.5 with a medium oceanic sensitivity. For the basal drag coefficient, the acceptable perturbations lead to an additional sea level contribution ranging from about -30 to +30 mm SLE, with respect to the standard value of 20 mm SLE. The perturbation produces thus considerable ice sheet changes. For the enhancement factor, the effect of the perturbation is even larger as it ranges from -50 to +50 mm SLE. These sensitivity experiments show that any change in the Antarctic ice-sheet mechanical properties (basal dragging or ice flow) in the course of the century can have a substantial impact on the ice sheet contribution to sea level rise. The total mass change is relatively less impacted by the perturbations. They induce a change in total mass of -12×10^3 to $+12\times10^3$Gt for the basal drag coefficient and of -30×10^3 to $+25\times10^3$Gt for the enhancement factor, with respect to a standard mass loss in 2100 of -165×10^3Gt. The total ice mass is less impacted by the perturbations than the mass contributing to sea level rise because the ice shelves respond first to the increase sub-ice-shelf melt rate.

These simple sensitivity experiments can also be used to quantified the importance of the choice of the mechanical parameters for the projections. For the basal drag coefficient, the perturbations lead to a change in the sea level contribution that is almost identical for the projection experiments and for the control experiment. This means that the effect of climate change is not amplified for different values of the basal drag coefficient. As a result, with our model, the projected contribution to sea level rise is only weakly affected by the choice of the basal drag coefficient. For the enhancement factor, this does not hold: a larger (respectively smaller) enhancement factor leads to larger (respectively smaller) ice sheet contribution to sea level rise. However, if the difference can be as large as 50 mm SLE for an enhancement factor of 4, it is nonetheless small in the vicinity of the reference value of 1.

4 Discussion

~~Although in line with results from other ice sheet~~ Although close to the ensemble mean of the ice-sheet models participating in ISMIP6-Antarctica, the contribution of the Antarctic ice sheet to global sea level rise simulated by GRISLI is relatively limited. Amongst the different experiments, the largest contribution by 2100 is 150 ~~mmSLE~~ mm SLE (NorESM1-M *PIGL* with a high oceanic sensitivity) while most experiments produce a contribution no greater than 80 ~~mmSLE. If a~~ mm SLE. A relatively moderate Antarctic ice sheet contribution to future sea level rise by 2100 has also been suggested in other studies ~~(Bamber et al., 2019; Edwards et al., 2019, e.g.), it~~ since the IPCC special report on the ocean and cryosphere in a changing climate (Oppenheimer et al., 2019) reported a range from 30 to 280 mm SLE (RCP8.5). However, this seems nonetheless in contradiction with the acceleration in mass loss reported by modern observational techniques Rignot et al. (2019). One reason for this disagreement is that we use a data assimilation procedure that produce an initial condition in quasi-equilibrium with present-day forcing. This methodology is thus not suited to reproduce the recent acceleration in mass loss, particularly ~~important~~ large in West Antarctica ~~(Rignot et al., 2019).~~ where it has been estimated to 48 Gt yr^{-1} per decade for 1979-2017 (Rignot et al., 2019). For example, a simple cumulative value of the observed 2012-2017 loss rate (219 Gt yr^{-1}, The IMBIE team, 2018) from 2015 to 2100 will result in an Antarctic ice sheet contribution to sea level rise of 52 cm SLE. This number is much greater than the simulated contribution by GRISLI and more generally, it is much greater than any ISMIP6-Antarctica participating model simulated contribution. This highlights the importance of initial conditions for century scale projections.

Assimilation of surface velocities in transient ~~ice sheet~~ ice-sheet simulations are promising methodologies to overcome ~~such limitations (Gillet-Chaulet, 2020) even though~~ the limitations inherent to methods that assume steady state (Gillet-Chaulet, 2020). However, they require a complex modelling framework not currently implemented in our ~~ice sheet model. Alternatively, to assess the sensitivity of the modelresponse to the inferred basal drag coefficient, we also perform a set of projections with a uniform perturbation of this parameter after the year 2045. Around its reference value, the perturbation leads mostly to a linear ice volume change (Fig. 13a,b). A uniform reduction of the basal drag coefficient by 30% leads to a 13000 km^3 total volume reduction contributing to about 50 mmSLE in 2100. This means that, with our model, it is unlikely to obtain a significantly different ice volume change for slightly different basal initial conditions. We perform a similar sensitivity experiments but for the enhancement factor and we draw similar conclusion (Fig. 13c,d).~~ ice-sheet model. In future developments of our model, we plan to modify the target of the inversion procedure by adding the recent observed ice thickness changes to the observed ice thickness. This would provide a more realistic initial state for the projections.

The GRISLI ~~ice sheet~~ ice-sheet model, similarly to other ISMIP6-Antarctica participating models, simulate an ice sheet contribution to global sea level in 2100 that can be either positive or negative, depending on the climate forcing used. This is related to the fact that the climate models simulate an increase in precipitation in the future over Antarctica. An important difference with ISMIP6-Greenland forcing methodology lies in the fact that the atmospheric forcing is much more simplified in ISMIP6-Antarctica. The ISMIP6-Greenland atmospheric scenarios has been elaborated from a regional climate model forced at its boundary by the different GCMs. The atmospheric forcing fields (namely surface temperature and surface mass balance anomalies) are further corrected by the surface elevation changes using time-evolving vertical gradients computed from the regional climate model. Such approach is much more computationally expensive ~~and~~ since it requires multiple regional climate model simulations. For example, the MAR regional climate model (Agosta et al., 2019) requires about 15 days to compute 100 years (C. Agosta, personal communication). That is why this approach has been discarded so far for the Antarctic ice sheet where the GCMs anomalies are used directly with no downscaling with a regional climate model and no vertical correction. The use of an approach similar to ISMIP6-Greenland would be ~~an important~~ a significant step forward for the next exercise for Antarctica given the importance of the atmospheric forcing for the Antarctic contribution to future sea level rise.

~~Although~~ While the atmospheric forcing is an important driver for the Antarctic evolution, the oceanic forcing remains the major source of uncertainty for future projections. ~~On the one hand~~Thus, using a different calibration strategy, the *PIGL* ~~sub-shelf~~ sub-ice-shelf melt model produce a much larger ice sheet retreat than the standard calibration ~~. On the other hand~~*MeanAnt*. In addition, Seroussi et al. (2020) also show that the ~~ice sheet~~ ice-sheet models that use their own approach to compute the ~~sub-shelf~~ sub-ice-shelf melt in place of the standard ISMIP6-Antarctica melt model are the models that produce generally the largest Antarctic contribution to future sea level rise. Thus, the participating models that use the standard approach all simulate a loss in ice volume above floatation lower than 40 ~~mmSLE~~ mm SLE in 2100 using NorESM1-M under RCP8.5 with a medium oceanic sensitivity. At the same time, four models that use their own approach simulate a much greater loss, ranging from about 75 to 225 ~~mmSLE~~mm SLE, when using ~~the same forcing~~forcings elaborated from the same climate model realisations. This highlights the need for a better understanding of this process, since the various parametrisations used in ~~ice sheet~~ ice-sheet models lead to largely different simulated ~~sub-shelf melt~~ sub-ice-shelf melt rates (Favier et al., 2019).

5 Conclusions

In this paper, we have presented the GRISLI-LSCE contribution to ISMIP6-Antarctica, providing ~~a mean~~ the means to investigate the impact of the climate forcing on one individual ~~ice sheet~~ ice-sheet model. We showed that the ~~volume~~ total mass change simulated by 2100 is strongly dependant on the general circulation model used to force the ~~ice sheet~~ ice-sheet model. On the one hand, the total ice ~~volume is systematically~~ mass is decreasing in the course of the century for all the climate forcings evaluated, primarily because of ~~a reduction in ice shelf volume. The volume~~ ice-shelf mass loss. The mass loss can be as low as ~~100000 km^3~~ 100×10^3Gt to as high as ~~700000 km^3~~ 700×10^3Gt. On the other hand, the ice volume contributing to sea level rise can be either positive (sea level rise) or negative (see level fall). We simulate a range of ~~ice sheet~~ ice-sheet contribution to global sea level rise by 2100 from about -50 ~~mmSLE~~ mm SLE to +150 ~~mmSLE~~mm SLE. Increased precipitation simulated by most of the climate models in the future tend to increase the grounded ice volume, partly mitigating or over-compensating the effect of ~~ice shelf reduction~~loss of buttressing due to ice-shelf melt. By the end of the century, we simulate the largest changes in ice thickness and ice dynamics in the Filchner-Ronne and Ross basin with only moderate changes elsewhere. The geographical pattern of these changes remains mostly consistent amongst the different climate forcings. The CMIP6 climate models do not ~~change drastically the simulated ice sheet~~ drastically change the simulated ice-sheet volume in the future with respect to the CMIP5 models. Under low greenhouse gas emission ~~scenario~~scenarios, the Antarctic ice sheet ~~present~~ exhibits much less ice ~~volume~~ mass changes suggesting that the ~~ice sheet volume~~ ice-sheet mass loss could be mitigated with a reduction in greenhouse gas emission. The oceanic forcing is a major source of uncertainty since the use of the melt model calibrated against the Pine-Island glacier data instead of the standard calibration produces a much faster ~~ice shelf~~ ice-shelf retreat and, as a result, a larger ice sheet ~~volume~~ contribution to sea level rise in the future. This process has to be carefully assessed when performing future projections of the Antarctic ice sheet. Finally, with additional simple sensitivity tests we have shown that the simulated ice sheet contribution to sea level rise by 2100 could be largely affected by changes in ice-sheet mechanical properties such as basal dragging. Given the weak understanding on such processes, they could also represent a large source of uncertainty.

6 Data availability

The GRISLI outputs from the experiments described in this paper are available on the ~~zenodo~~ Zenodo repository with digital object identifier 10.5281/zenodo.3819782 (Quiquet and Dumas, 2020). The outputs in the ~~zenodo~~ Zenodo repository are the standard GRISLI outputs on the native 16 km grid and, as a result, they may slightly differ from the post-processed outputs available on the official CMIP6 archive on the Earth System Grid Federation (ESGF). In order to document CMIP6's scientific impact and enable ongoing support of CMIP, users are obligated to acknowledge CMIP6, the participating modelling groups, and the ESGF centres (see details on the CMIP Panel website at http://www.wcrp- climate.org/index.php/wgcm-cmip/about-cmip). The forcing datasets are available through the ISMIP6 wiki and are also made publicly available via https://doi.org/xxx.

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Table 1. List of ISMIP6-Antarctica experiments performed in this work. The three oceanic sensitivities are low, medium (med) and high. The experiments that use the sub-shelf melt parametrisation calibrated against the Pine Island glacier data are labelled *PIGL*. The experiments that use the imposed ~~ice shelf~~ ice-shelf collapse scenario due to hydrofracturing are labelled *SC*.

exp_id	scenario	GCM	Ocean	
exp05	RCP8.5	NorESM1-M	Med	Core experiments – Tier 1
exp06	RCP8.5	MIROC-ESM-CHEM	Med	
exp07	RCP2.6	NorESM1-M	Med	
exp08	RCP8.5	CCSM4	Med	
exp09	RCP8.5	NorESM1-M	High	
exp10	RCP8.5	NorESM1-M	Low	
exp12	RCP8.5	CCSM4	*SC* Med	
exp13	RCP8.5	NorESM1-M	*PIGL* Med	
expa05	RCP8.5	HadGEM2-RS	Med	Extended ensemble – Tier 2
expa06	RCP8.5	CSIRO-Mk3	Med	
expa07	RCP8.5	IPSL-CM5-MR	Med	
expa08	RCP2.6	IPSL-CM5-MR	Med	
expb06	SSP585	CNRM-CM6-1	Med	CMIP6 extension – Tier 2
expb07	SSP126	CNRM-CM6-1	Med	
expb08	SSP585	UKESM1-0-LL	Med	
expb09	SSP585	CESM2	Med	
expb10	SSP585	CNRM-ESM2-1	Med	
expc01	RCP8.5	NorESM1-M AO	Med	Ocean only (OO) and Atmos. only (AO) – Tier 3
expc03	RCP8.5	NorESM1-M OO	Med	
expc04	RCP8.5	MIROC-ESM-CHEM AO	Med	
expc06	RCP8.5	MIROC-ESM-CHEM OO	Med	
expc07	RCP2.6	NorESM1-M AO	Med	
expc09	RCP2.6	NorESM1-M OO	Med	
expc10	RCP8.5	CCSM4 AO	Med	
expc12	RCP8.5	CCSM4 OO	Med	

exp_id	scenario	GCM	Ocean	
expd01	RCP8.5	MIROC-ESM-CHEM	High	Ocean sensitivity – Tier 3
expd02	RCP8.5	MIROC-ESM-CHEM	Low	
expd03	RCP2.6	NorESM1-M	High	
expd04	RCP2.6	NorESM1-M	Low	
expd05	RCP8.5	CCSM4	High	
expd06	RCP8.5	CCSM4	Low	
expd07	RCP8.5	HadGEM2-RS	High	
expd08	RCP8.5	HadGEM2-RS	Low	
expd09	RCP8.5	CSIRO-Mk3	High	
expd10	RCP8.5	CSIRO-Mk3	Low	
expd11	RCP8.5	IPSL-CM5-MR	High	
expd12	RCP8.5	IPSL-CM5-MR	Low	
expd13	SSP585	CNRM-CM6-1	High	
expd14	SSP585	CNRM-CM6-1	Low	
expd15	SSP585	UKESM1-0-LL	High	
expd16	SSP585	UKESM1-0-LL	Low	
expd17	SSP585	CESM2	High	
expd18	SSP585	CESM2	Low	
expd51	RCP8.5	NorESM1-M	*PIGL* Low	
expd52	RCP8.5	NorESM1-M	*PIGL* High	
expd53	RCP8.5	MIROC-ESM-CHEM	*PIGL* Med	
expd54	RCP8.5	MIROC-ESM-CHEM	*PIGL* Low	
expd55	RCP8.5	MIROC-ESM-CHEM	*PIGL* High	
expd56	RCP8.5	CCSM4	*PIGL* Med	
expd57	RCP8.5	CCSM4	*PIGL* Low	
expd58	RCP8.5	CCSM4	*PIGL* High	
expe06	RCP8.5	NorESM1-M	*SC* Med	Ice shelf collapse – Tier 3
expe07	RCP8.5	MIROC-ESM-CHEM	*SC* Med	
expe08	RCP8.5	HadGEM2-RS	*SC* Med	
expe09	RCP8.5	CSIRO-Mk3	*SC* Med	
expe10	RCP8.5	IPSL-CM5-MR	*SC* Med	
expe15	SSP585	CNRM-CM6-1	*SC* Med	
expe16	SSP585	UKESM1-0-LL	*SC* Med	
expe17	SSP585	CESM2	*SC* Med	
expe18	SSP585	CNRM-ESM2-1	*SC* Med	

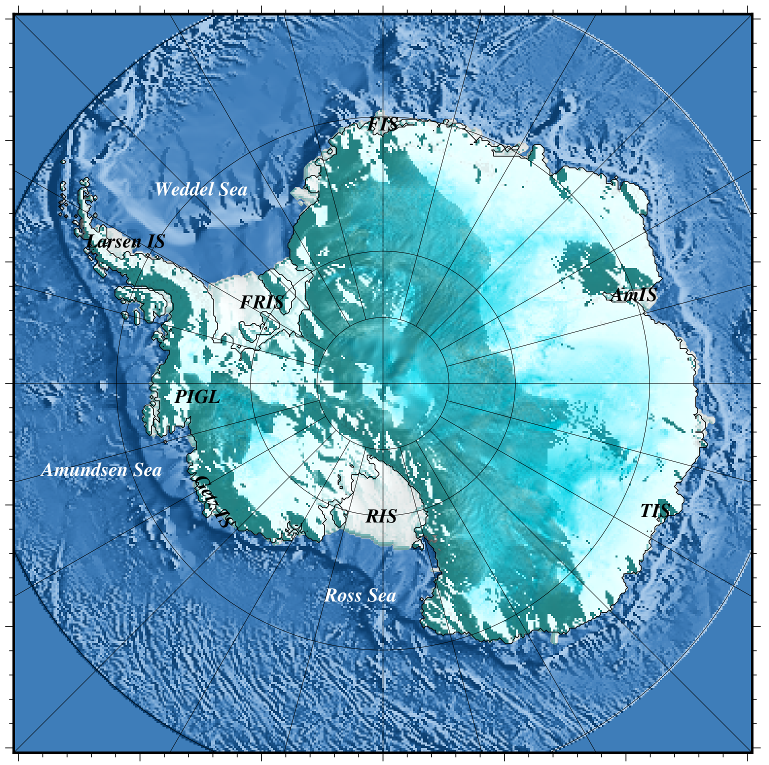

Figure 1. The Antarctic ice sheet with the major ice shelves discussed in the text: Larsen ice shelf, Filchner-Ronne ice shelf (FRIS), Pine Island glacier ice shelf (PIGL), Getz ice shelf, Ross ice shelf (RIS), Totten ice shelf (TIS), Amery ice shelf (AmIS) and Fimbul ice shelf (FIS).

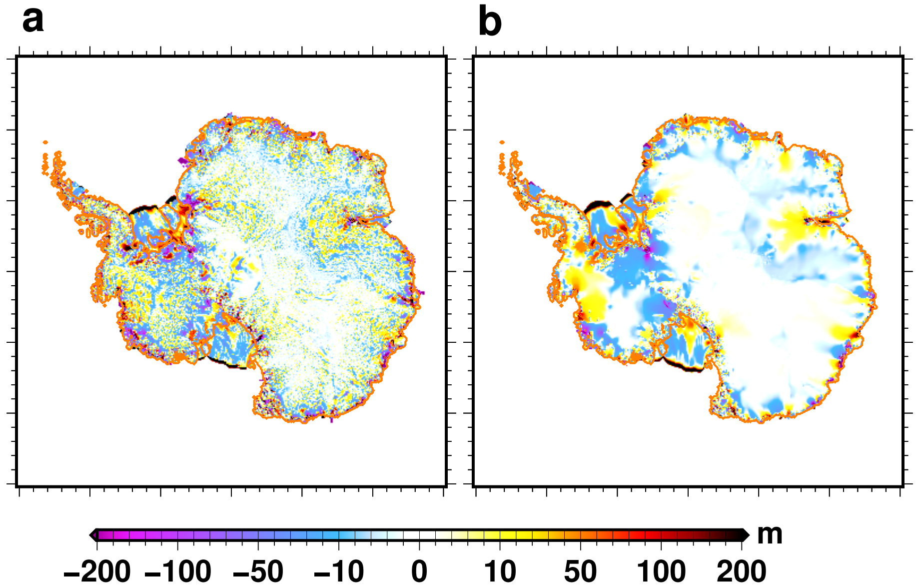

Figure 2. Ice thickness difference: **(a)** end of the historical experiment *hist* with respect to observations (Fretwell et al., 2013); **(b)** end of the control experiment *ctrl_proj* with respect to the end of the historical experiment *hist*. The orange line shows the present-day grounded line. The Pearson correlation coefficient between (a) and (b) is 0.24.

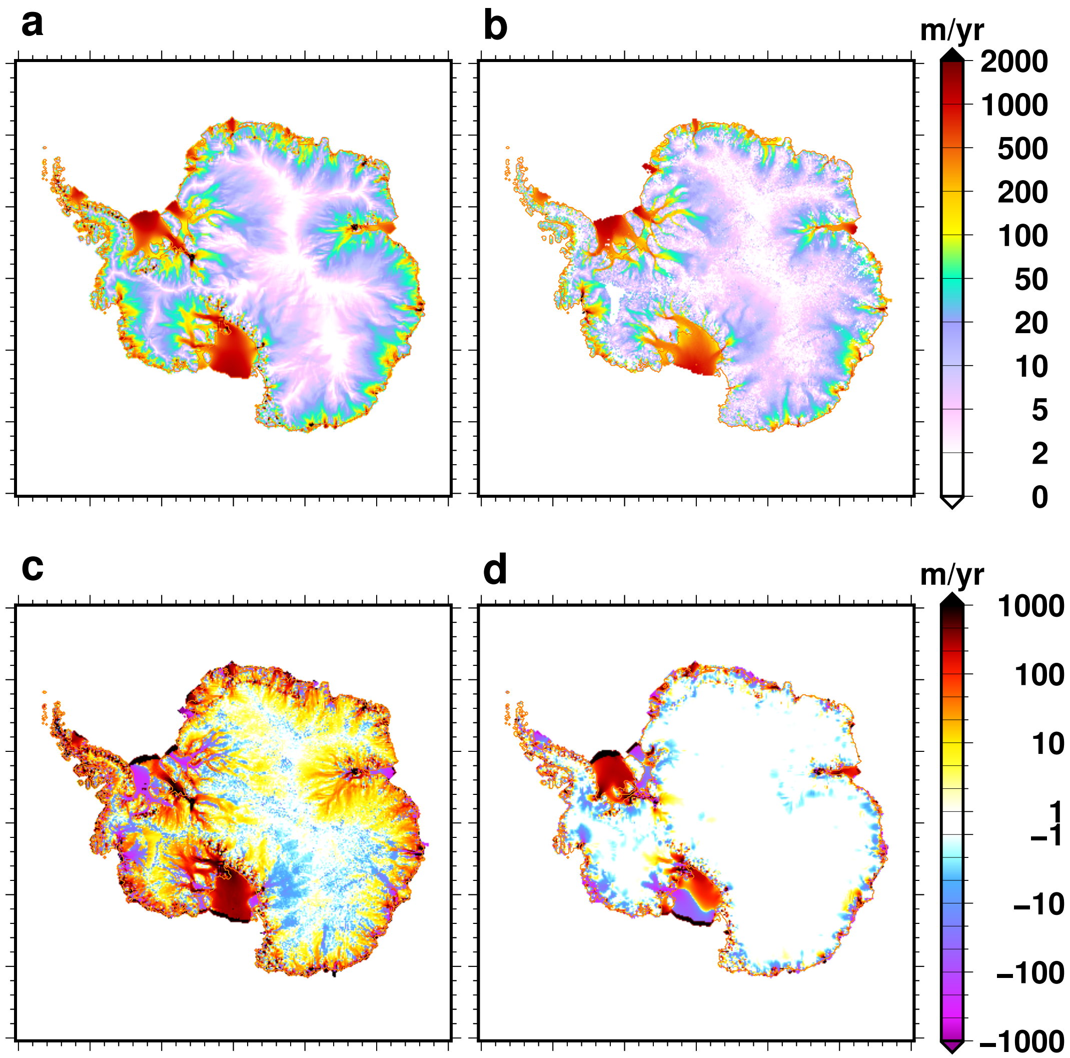

Figure 3. Surface velocity magnitude: **(a)** simulated at the end (2011-2015) of the historical experiment *hist*; **(b)** in the observational datasets of Rignot et al. (2011); **(c)** difference between (a) and (b). The surface velocity magnitude change from 2011-2015 to 2096-2100 in the control experiment *ctrl_proj* is shown in **d**. We use a 5 year mean for the simulated velocity to reduce the impact of interannual variability. The range -1 to 1 m yr^{-1} is set to white for velocity difference (**c** and **d**).

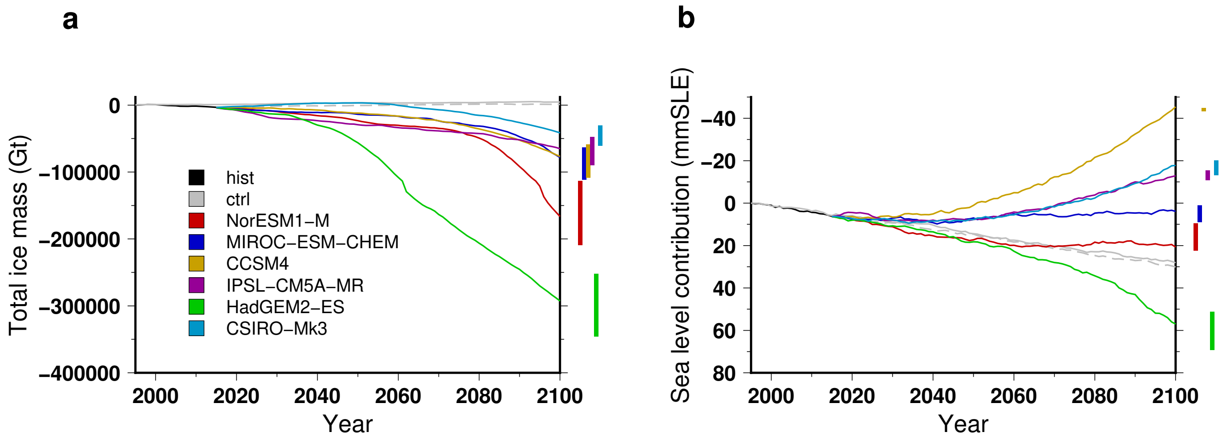

Figure 4. Simulated total ice ~~volume~~ mass change ~~for the historical simulation *hist*~~ (~~1995-2015~~**a**) ~~, the control experiments *ctrl* (solid grey lines)~~ and ~~*ctrl_proj*~~ ice volume contributing to sea level rise (~~dashed grey lines~~**b**) ~~and the~~ for projections under the different CMIP5 forcings using the RCP8.5 scenario and the medium oceanic sensitivity~~: **(a)** total ice volume change~~. The evolutions begin with the historical simulation *hist* (1995-2015) and ~~**(b)** ice volume contributing to sea level rise~~the control experiments *ctrl* and *ctrl_proj* are depicted in grey (solid and dashed, respectively). For each projection experiment the vertical bar shows the minimal and maximal ~~volume change~~ changes associated with the oceanic forcing sensitivity to temperature change (*low* and *high*). The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

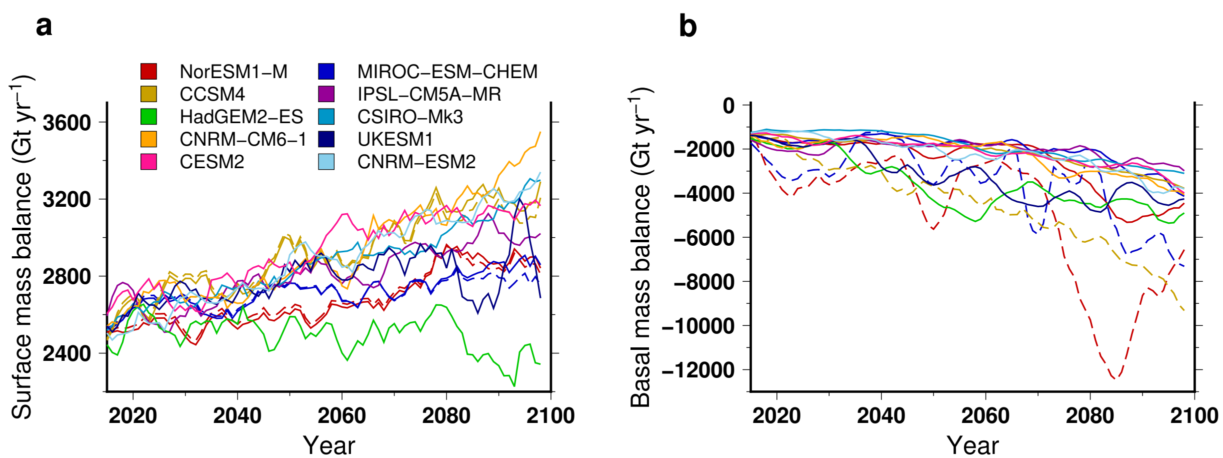

Figure 5. Simulated surface mass balance **(a)** and basal mass balance **(b)**, integrated over the ice sheet, for different CMIP5 and CMIP6 climate forcings using the RCP8.5 scenario and SSP585 scenario, respectively. The projection experiments shown in this figure use the medium oceanic sensitivity. The solid lines stand for the experiments that use the sub-shelf melting parametrisation calibrated against all the Antarctic data while the dashed lines are for the experiments that use a parametrisation calibrated against Pine-Island area data only. For this figure we use a 5-year running mean in order to smooth the interannual variability.

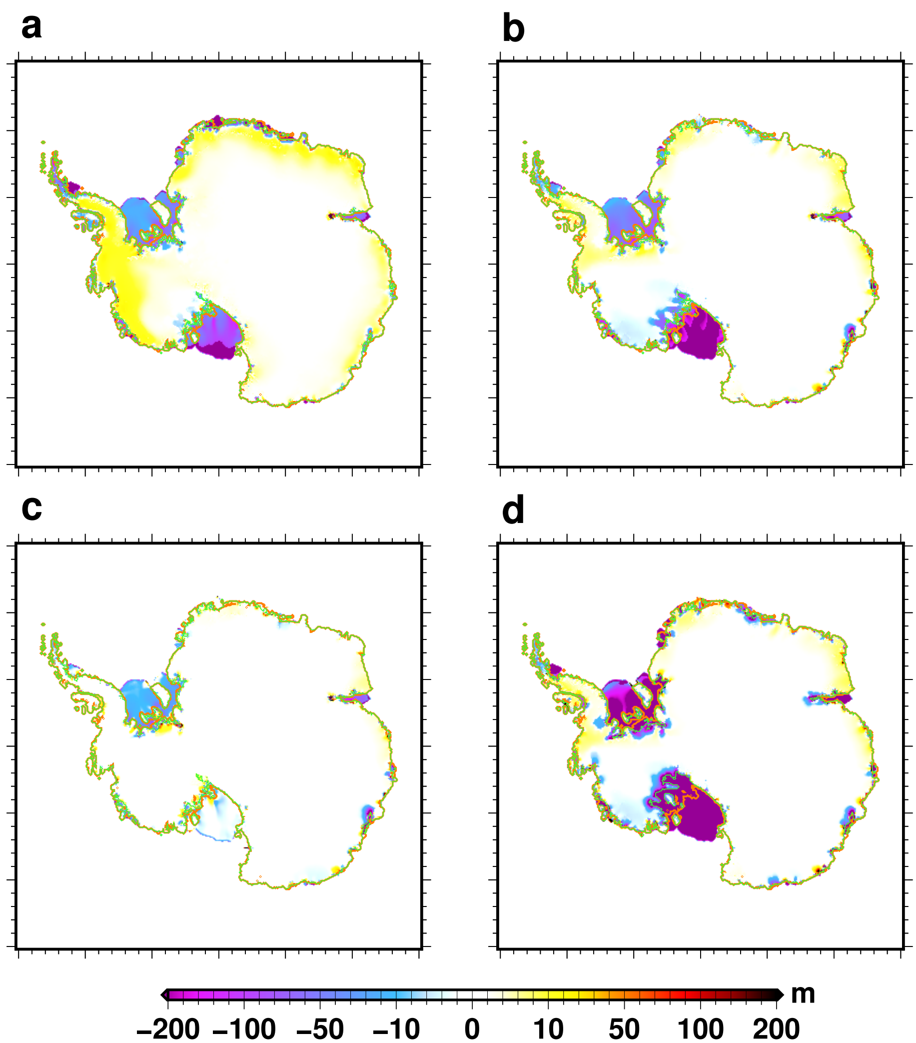

Figure 6. Simulated ice thickness change (2100 - 2015) for: **(a)** CESM2 (SSP585); **(b)** NorESM1-M (RCP8.5); **(c)** NorESM1-M (RCP2.6) and; **(d)** NorESM1-M (RCP8.5) *PIGL*. The orange line shows the the present-day grounded line and the light green line represents its simulated position in 2100. The medium oceanic sensitivity has been used here, except for the *PIGL* experiment (d) for which we use the high oceanic sensitivity. The ice thickness change shown here is corrected for the ice thickness change (2100-2015) in the control experiment *ctrl_proj*.

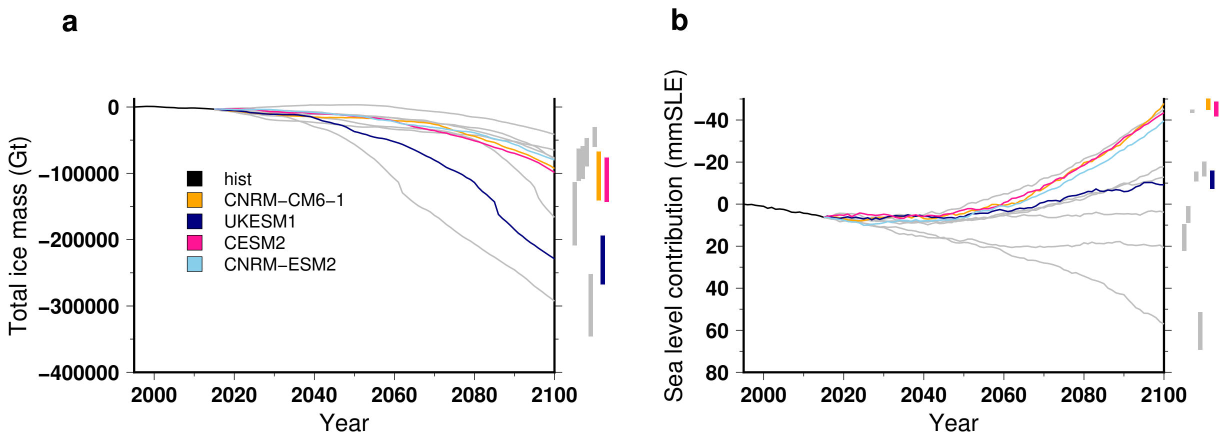

Figure 7. Simulated total ice ~~volume~~ mass change ~~for the historical experiment *hist*~~ (~~1995-2015~~**a**) and ~~the~~ ice volume contributing to sea level rise (**b**) for projections under the different CMIP6 forcings using the SSP585 scenario and the medium oceanic sensitivity~~: **(a)** total ice volume change and **(b)** ice volume contributing to sea level rise~~. The evolutions begin with the historical simulation *hist* (1995-2015). For each projection experiment the vertical bar shows the minimal and maximal ~~volume change~~ changes associated with the oceanic forcing sensitivity to temperature change (*low* and *high*). The grey lines are the ~~volume change~~ changes under the CMIP5 forcings shown in Fig. 4. The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

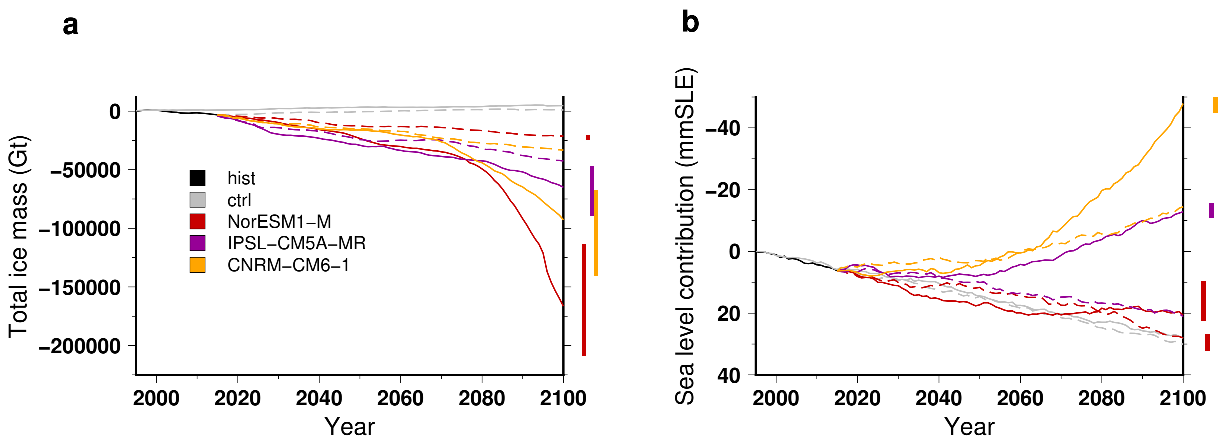

Figure 8. Simulated total ice ~~volume~~ mass change ~~for the historical experiment *hist*~~ (~~1995-2015~~**a**) ~~, the control experiments *ctrl* (solid grey lines)~~ and ~~*ctrl_proj*~~ ice volume contributing to sea level rise (~~dashed grey lines~~**b**) ~~and~~ for ~~the~~ projections using climate models run under a ~~pessimistic greenhouse scenario~~ high (solid lines, RCP8.5 for NorESM1-M and IPSL-CM5A-MR, and SSP585 for CNRM-CM6-1) and ~~an optimistic greenhouse scenario~~ a low (dashed lines, RCP2.6 for NorESM1-M and IPSL-CM5A-MR, and SSP126 for CNRM-CM6-1) emission scenario for greenhouse gases with a medium oceanic sensitivity~~, expressed as: **(a)** total ice volume change~~ . The evolutions begin with the historical simulation *hist* (1995-2015) and ~~**(b)** ice volume contributing to sea level rise~~the control experiments *ctrl* and *ctrl_proj* are depicted in grey (solid and dashed, respectively). For each projection experiment ~~,~~ the ~~right-hand side~~ vertical bar shows the minimal and maximal ~~volume change~~ changes associated with the oceanic forcing sensitivity to temperature change (*low* and *high*). The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

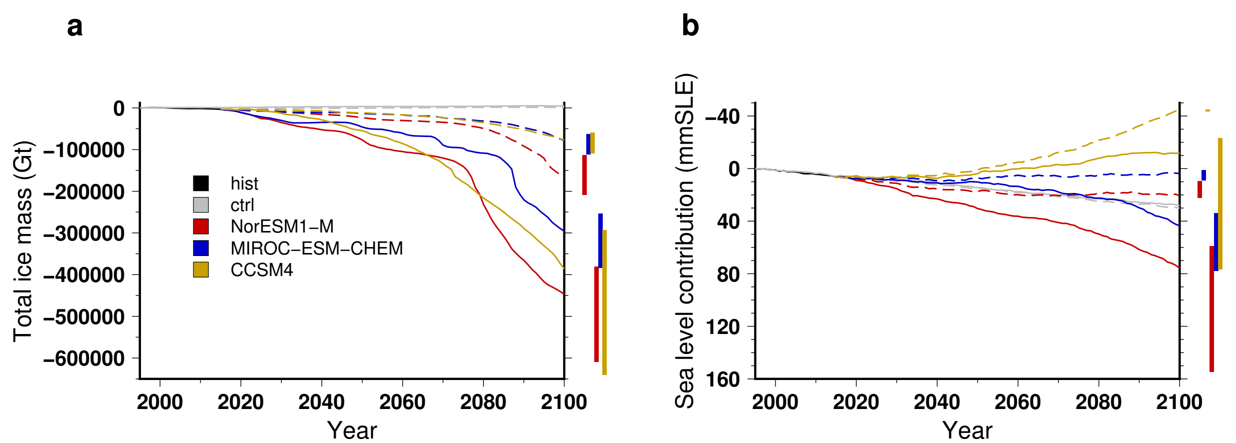

Figure 9. Simulated total ice ~~volume~~ mass change ~~for the historical experiment *hist*~~ (~~1995-2015~~**a**) ~~, the control experiment *ctrl_proj*~~ and ice volume contributing to sea level rise (~~solid grey line~~**b**) ~~and the~~ for projections under the different CMIP5 forcings using the RCP8.5 scenario and the medium oceanic sensitivity. For the projections, the solid lines stand for experiments that use a sub-shelf melting rate parametrisation calibrated against the Pine-Island glacier area only (*PIGL*) while the dashed lines stand for experiments that use the sub-shelf melting rate parametrisation calibrated against the Antarctic-wide dataset (*MeanAnt*). The ~~volume change is expressed as: **(a)** total ice volume change~~ evolutions begin with the historical simulation *hist* (1995-2015) and ~~**(b)** ice volume contributing to sea level rise~~the control experiments *ctrl* and *ctrl_proj* are depicted in grey (solid and dashed, respectively). For each projection experiment the vertical bar shows the minimal and maximal ~~volume change~~ changes associated with the oceanic forcing sensitivity to temperature change (*low* and *high*). The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

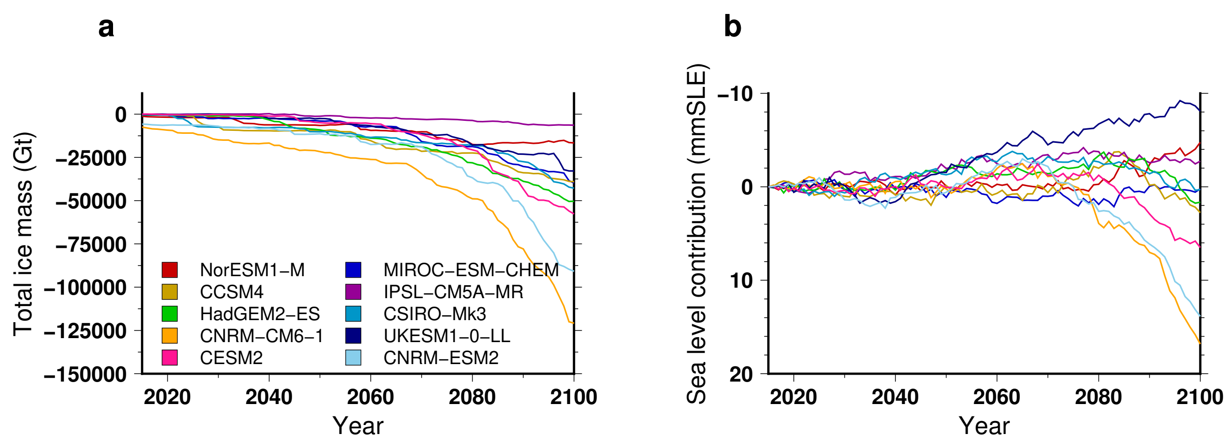

Figure 10. Simulated ice volume difference between the shelf collapse scenario ~~(*SC*)~~ and the standard approach for the projections under different CMIP5 and CMIP6 forcings using the RCP8.5 scenario and SSP585 scenario, respectively. The volume change is expressed as: **(a)** total ice ~~volume~~ mass change and **(b)** ice volume contributing to sea level rise. The projection experiments shown in this figure use the medium oceanic sensitivity. The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

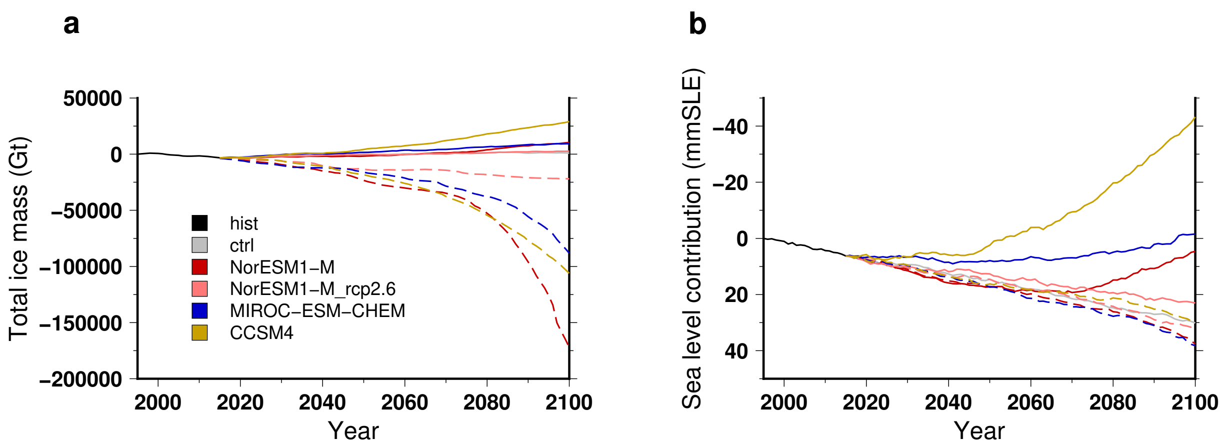

Figure 11. Simulated total ice ~~volume~~ mass change ~~for the historical experiment *hist*~~ (~~1995-2015~~**a**) ~~, the control experiment *ctrl_proj*~~ and ice volume contributing to sea level rise (~~solid grey line~~**b**) ~~and the~~ for projections under the different CMIP5 forcings using the RCP8.5 scenario and the medium oceanic sensitivity. For the projections, the solid lines stand for experiments under atmospheric forcing change only (no change in sub-shelf melting rates) while the dashed lines stand for experiments under oceanic forcing change only (no change in surface mass balance nor surface temperature). The ~~volume change is expressed as: **(a)** total ice volume change~~ evolutions begin with the historical simulation *hist* (1995-2015) and ~~**(b)** ice volume contributing to sea level rise. The projection~~ the control experiments ~~shown~~ *ctrl* and *ctrl_proj* are depicted in ~~this figure use the medium oceanic sensitivity~~grey (solid and dashed, respectively). The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.

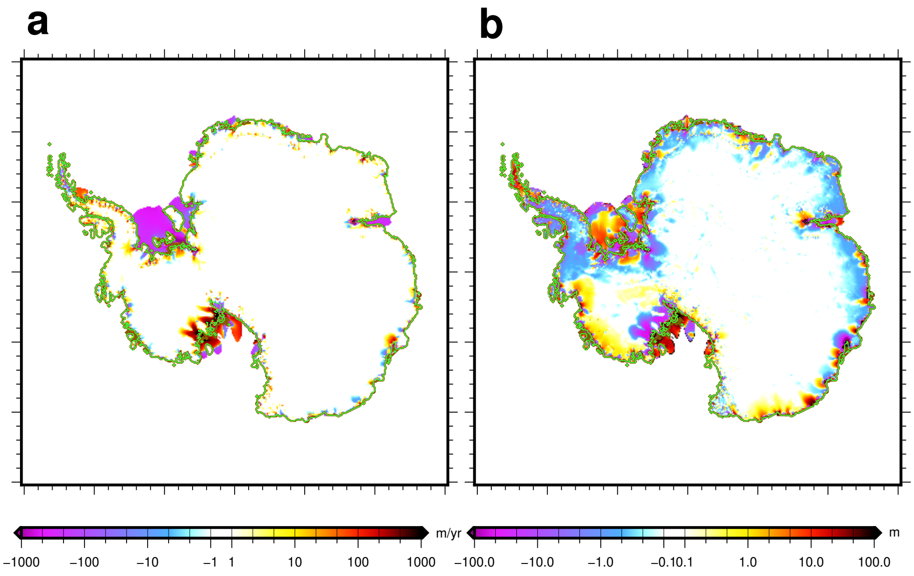

Figure 12. **(a)**: Simulated surface velocity change during the projection run (2096-2100 with respect to 2015-2019) using NorESM1-M forcing under RCP8.5 with a medium oceanic sensitivity. **(b)**: change in the dynamic dynamical contribution to ice thickness change in 2100 (see text for definition) for this same experiment. For both panel, we corrected the changes by the ones simulated in the control experiment *ctrl_proj* over the same period. The range -1 to 1 m yr^{-1}, respectively -0.1 to 0.1 m, is set to white in **(a)**, respectively **(b)**.

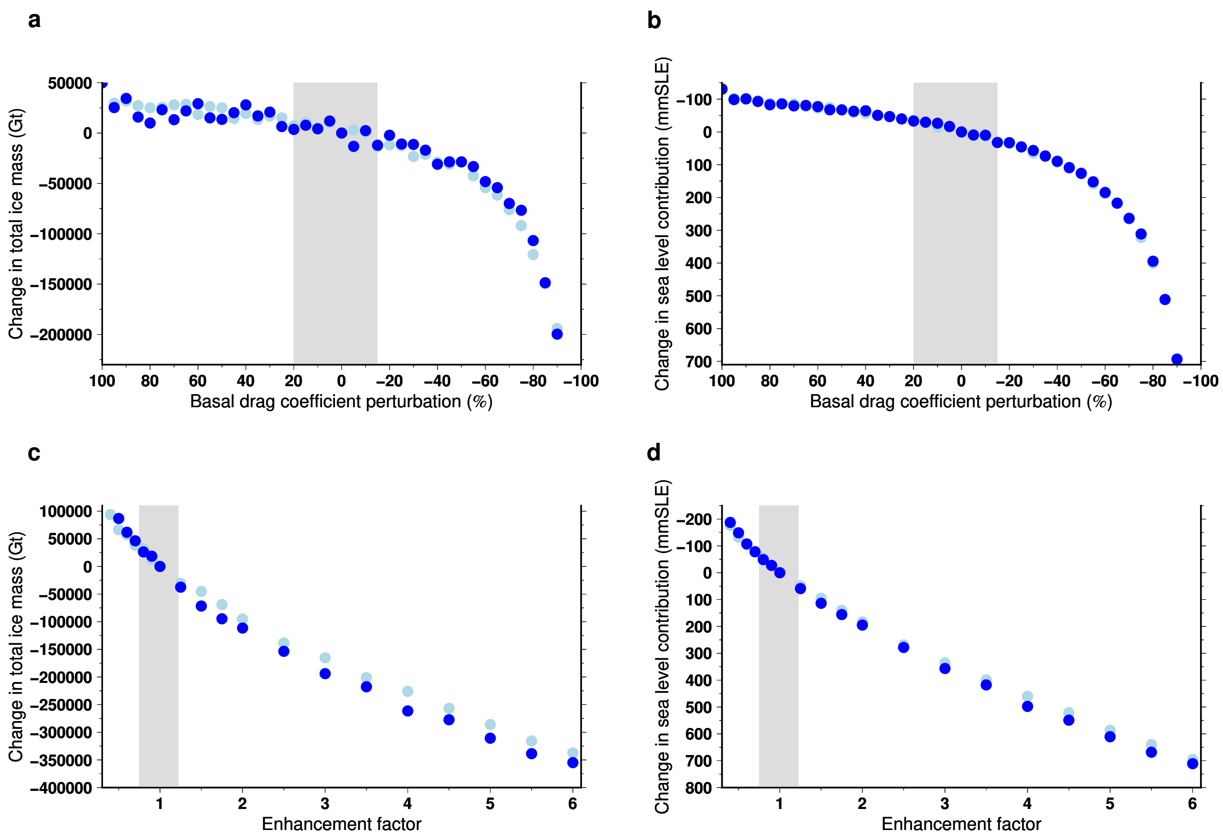

Figure 13. Change in ice volume for a modification of the basal drag coefficient (~~(a)~~ **a** and ~~(b)~~**b**) and different values of the enhancement factor (~~(c)~~ **c** and ~~(d)~~**d**). In this figure, each dot represents the ~~ice volume~~ difference in 2100 with respect to the standard ~~projection~~ experiment (~~zero~~ no basal drag coefficient perturbation and enhancement factor at 1). The ~~climate forcing used for this figure is~~ dark blue dots are projection experiments that use NorESM1-M under RCP8.5 with a medium oceanic sensitivity. The ~~perturbation is~~ light blue dots are control experiments *ctrl_proj*. Some control experiments can be hidden by the projection experiments if they imply a similar volume change. The perturbations are applied starting at year 2045. The vertical grey band stands for the range of perturbations that produce a 0.15% of total mass change in the perturbed control experiment with respect to the standard control experiment. The difference is expressed in total ice ~~volume~~ mass (~~(a)~~ **a** and ~~(c)~~**c**) and ice volume contributing to sea level rise (~~(b)~~ **b** and ~~(d)~~**d**). The sea level contribution can be expressed as a mass using 1 mm SLE = 372 Gt.