Blue color: reviewer comment

Dark color: Author response

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This is a review of the submission “Antarctic Tipping points triggered by the mid-Pliocene warm climate” of Blasco et al to Climate of the Past.

The paper is an interesting contribution to the body of work utilising the Pliocene Model Intercomparison Project Phase 2 simulations. It builds on a number of ice-sheet modelling experiments conducted for this period and takes some elements of its experimental design from previous ice sheet model Intercomparison efforts (e.g. PLISMIP). The paper is well written in terms of language and readability. The figures are clear and of high quality.

The study takes a perturbed parameter approach to considering the configuration of the Antarctic Ice Sheet (AIS) during the mid-Piacenzian. Results in the study are used to make inferences of potential tipping point thresholds that may have been passed in the mid-Piacenzian, leading to retreat of large sectors of the AIS. The study provides a step forward on the work of Dolan et al, and De Boer et al, who use a similar modelling framework for exploring uncertainty, in that it considers more thoroughly parameter uncertainty within one ice sheet model.

We thank the reviewer for the positive feedback and suggestions, which will contribute to improving the quality of our manuscript. Below you can find our response to each comment.

**General comments:**

The authors make good use of the data available through PlioMIP and provide a good overview of their results. My general feeling is that the results presented here present a pragmatic approach to understanding uncertainties in ice sheet predictions for this time period. I am less convinced that the overall model set up is sufficient to draw strong conclusions around Antarctic tipping points. Through necessity, the modelling framework needs to ignore certain climate-ice sheet feedbacks, but I think a more thorough assessment of these would be needed to draw robust conclusions on tipping points. It would be useful for the authors to elaborate further on the other ways of considering/modelling tipping points, and the limitations of their current study. This does not question the overall results of the study, which in my view are sound, but there is a reflection required on how these results are interpreted when considering future Antarctic ice sheet changes.

Indeed, by using only a stand-alone model, it is difficult to assess the role of climate-ice sheet interactions which could have an impact on tipping points of the Antarctic Ice Sheet (AIS). However, running coupled experiments requires overcoming several technical issues:

- The same way we needed to assess a range of unknown parameters which created a realistic present-day (PD) ice sheet, this has to be done also for the climate model.
- Even if the parameter space of the ice sheet and the climate models are constrained, once coupled, they can lead to different results than the reconstructions, which would require a new parameter constraint.

- Running coupled experiments needs large amounts of computing time and space.

The work of Berends et al., (2019) is a good example of a coupled model (HadCM3 with ANICE). However, in order to run these simulations, they needed to make a trade-off between a coupled model and ice-sheet resolution (40 km). This is a potential explanation why they do not simulate a retreat in the East Antarctic region. Here we aim to obtain a more profound understanding of processes related to ice dynamics in part through a higher spatial resolution (16 km).

We take into account some climate interactions, such as the surface melt-elevation feedback, by employing an atmospheric lapse-rate factor, and ice-albedo effects, which are considered within our ITM parameterisation. Nonetheless, probably one of the most important feedbacks which is not considered here would be the effect of freshwater flux (FWF) release from the AIS into the Southern Ocean (SO), which remains a matter of debate. Results from Sadai et al., (2020) show that accounting for Antarctic ice discharges increases SO temperatures. These results contradict those from Bintaja et al., (2017), where ice-shelf melt leads to a cooling of the SO and an expansion of sea ice area. This points to the need for a more profound understanding of ice-ocean related processes within models.

Regarding tipping points, we believe that our results are robust for the AIS. Tipping points are thresholds that, once reached, lead to positive-feedback mechanisms. Of course, ice sheet-climate interactions can hamper (or facilitate) reaching those thresholds. Assessing tipping points with a coupled ice-sheet-ocean model has not been done yet. Our results show that a 1 degree oceanic anomaly leads to a WAIS collapse and a 3 degree anomaly to a Wilkes collapse, consistent with other modelling results (McKay et al., 2022). We look forward to coupling an ice-sheet model together with an AOGCM in the future to improve our results and our understanding of the mPWP as well as Antarctic tipping-points, however, this is in the scope of future work. We have included the following discussion in the manuscript:

"Our forcing strategy based on an anomaly-snapshot method (i.e. one constant climatic snapshot from each AOGCM) ignores certain climate-interactions that could be relevant to the system. We take into account the surface melt-elevation feedback, by employing an atmospheric lapse-rate factor, and the albedo-melt feedback, which is considered within our ITM parameterisation. Nonetheless, probably one of the most important feedbacks not considered here is the effect of freshwater flux release from the AIS into the Southern Ocean. Results from Sadai et al. (2020) show that accounting for Antarctic ice discharges increases Southern Ocean temperatures, whereas in Bintanja et al. (2015) ice-shelf melt leads to a cooling of the Southern Ocean and an expansion of sea ice area. This points to the need for a more profound understanding of ice-ocean related processes within models.

A more sophisticated approach would include direct coupling between an AOGCM and our ice-sheet model. However, besides more computational resources, this would require constraints not only on our ice-sheet model parameters, but also on those of the AOGCM. The work of Berends et al. (2019) is a good example of a coupled model. However, in order to run these simulations, one trade off is a lower ice-sheet resolution (40 km). This is a potential explanation why they do not simulate a retreat in the East Antarctic region. Here we aim to obtain a more profound understanding of processes related to ice dynamics in part through a higher spatial resolution (16 km)."

The authors make very few comments about the comparison of their results for PlioMIP2 and those already published for PlioMIP1 in terms of any significant changes between the climatological forcing. This is possibly beyond the scope of this study, but it would be interesting to try and assess the impact of the changes to boundary conditions between PlioMIP1 and 2 and their effect on Antarctica. While the ice sheet boundary condition remained the same, others (e.g. topography, ocean gateways) did not. Are there any systematic changes within the climatologies that would have an impact on the spread of sea-level predictions here?

We agree with the reviewer's opinion that a comparison between PlioMIP1 and PlioMIP2 provides an interesting framework to understand how updated boundary conditions affect the AOGCM and the AIS, however this is indeed behind the scope of our study.

In the following figure (Figure A) from Haywood et al., (2021), they show the multi-model annual mean surface temperature and precipitation for PlioMIP1 and PlioMIP2 and its differences. The main outcome in the Antarctic region and Southern Ocean is that PlioMIP2 models simulate warmer temperatures and a similar precipitation pattern. Thus we would expect a  smaller AIS than from PlioMIP1.

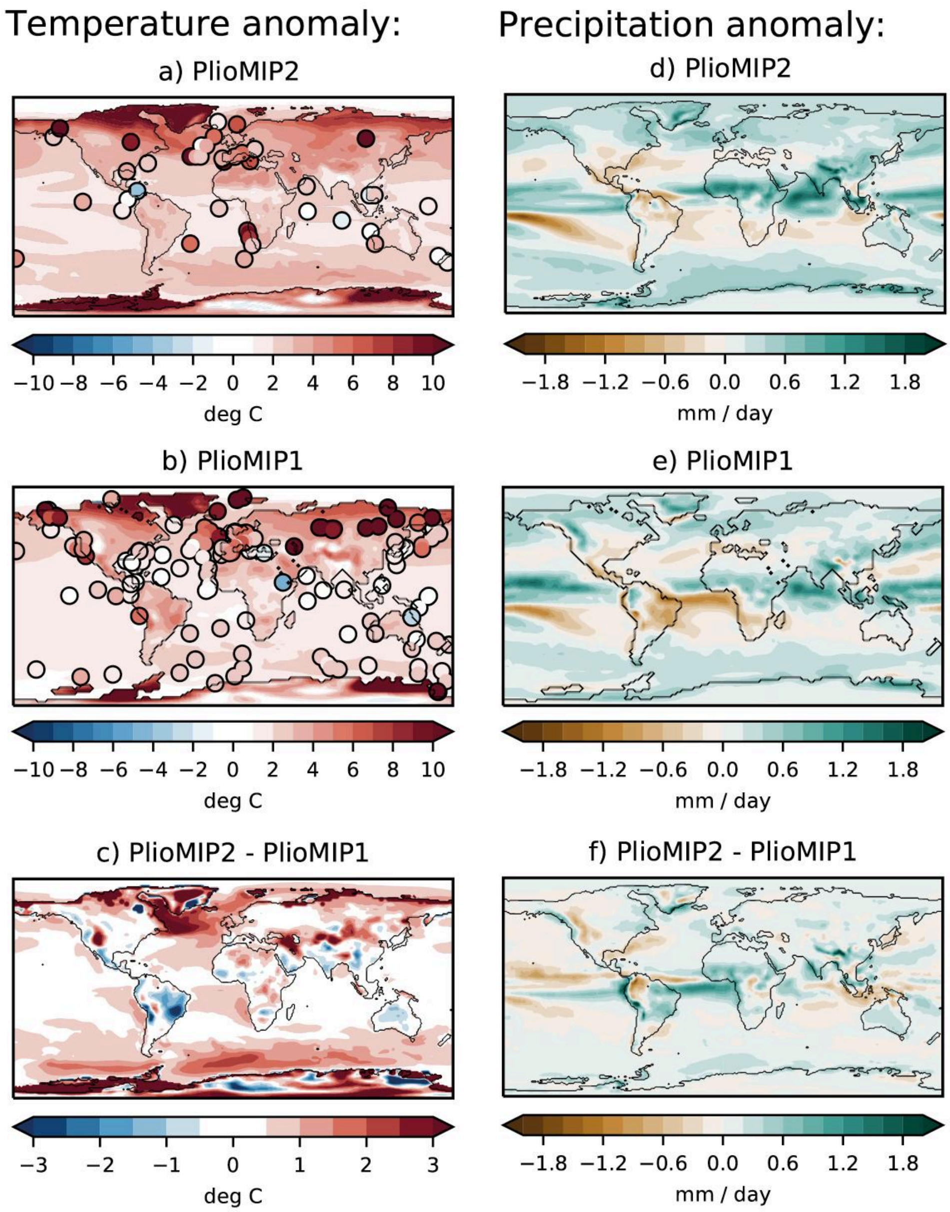


Figure A from Haywood et al., (2021): *"(A) PlioMIP2 and (B) PlioMIP1 multi-model annual mean surface air temperature (SAT) differences (over land) and sea surface temperature (SST) differences (over oceans) in °C, compared to the pre-industrial era. (C) Difference between PlioMIP2 and PlioMIP1 multi-modal means (°C). (D) PlioMIP2 and (E) PlioMIP1 multi-model annual mean total precipitation rate (mm/day) differences (compared to the pre-industrial era). (F) Difference between PlioMIP2 and PlioMIP1 multi-modal means (mm/day). Circles represent proxy-derived SST and SAT anomalies in (A) from McClymont et al. (2020) and Salzmann et al. (2013) respectively. Proxy-derived SST and SAT anomalies in (B) from Dowsett et al. (2010) and Salzmann et al. (2013) respectively."*

Finally, it would be beneficial for the authors to provide a brief summary of non-sea level related records that could help assess whether or not ice-retreat in certain areas would be expected during the mPWP.

Indeed we focused mainly on sea-level related records in the manuscript, as we did not find an extensive bibliography related to non-sea level related records. We hope that the following updated paragraph in the introduction provides clarifications on the expected retreat of Wilkes basin during mPWP :

“One key question in Antarctic reconstructions and simulations is whether the Wilkes Basin retreated or not during the mPWP (Wilkes basin illustrated in Fig. 8 and Fig. S3). Today, the WAIS and the Greenland Ice Sheet (GrIS) sum up to make a total of 10 mSLE (Morlighem et al., 2017, 2020). Thus, in order to achieve a sea-level rise far beyond 10 mSLE, a significant response in the EAIS is required. Marine records close to the Wilkes basin reinforce the hypothesis of such a retreat. Deposition of ice- rafted debris close to the Wilkes basin shows enhanced iceberg activity during the mPWP (Patterson et al., 2014; Bertram et al., 2018). This can be interpreted as a consequence of ice-sheet retreat with its related calving events. In addition, land-based sediment records of the EAIS show low concentrations of cosmogenic isotopes, which indicate that land-based regions experienced minimal retreat during the mPWP (Shakun et al., 2018). This points to a response of marine-based regions to explain high sea-level records”

**Specific comments:**

L4: the use of mid-Pliocene Warm Period is no longer the most up-to-date way of referring to this time interval (see the note on terminology in Dowsett et al 2023, Stratigraphy). Please also refer to Haywood et al (2020) for the definition of the time period used for PlioMIP2 - mid-Piacenzian warm period (3.264 to 3.025 million years ago).

Thank you for this clarification. We will update the terminology in the next submission of the manuscript.

L37: Such rather than Suc

Corrected. Thank you!

L50: Sea-level estimates noted here are inconsistent with those in the abstract.

We changed it for consistency.

L170: Sentence missing ending

Fixed.

L185: Do all simulations used or tried reach the steady-state condition required? It would be useful to note this as it is unclear from Figure S2 - were any excluded if they did not reach a steady-state?

Yes, our PD spin-up of $10^6$ years is sufficiently long to ensure that our ice sheet reaches a steady present-day state as shown in the following Figure 1. This point will be made clearer in the manuscript.

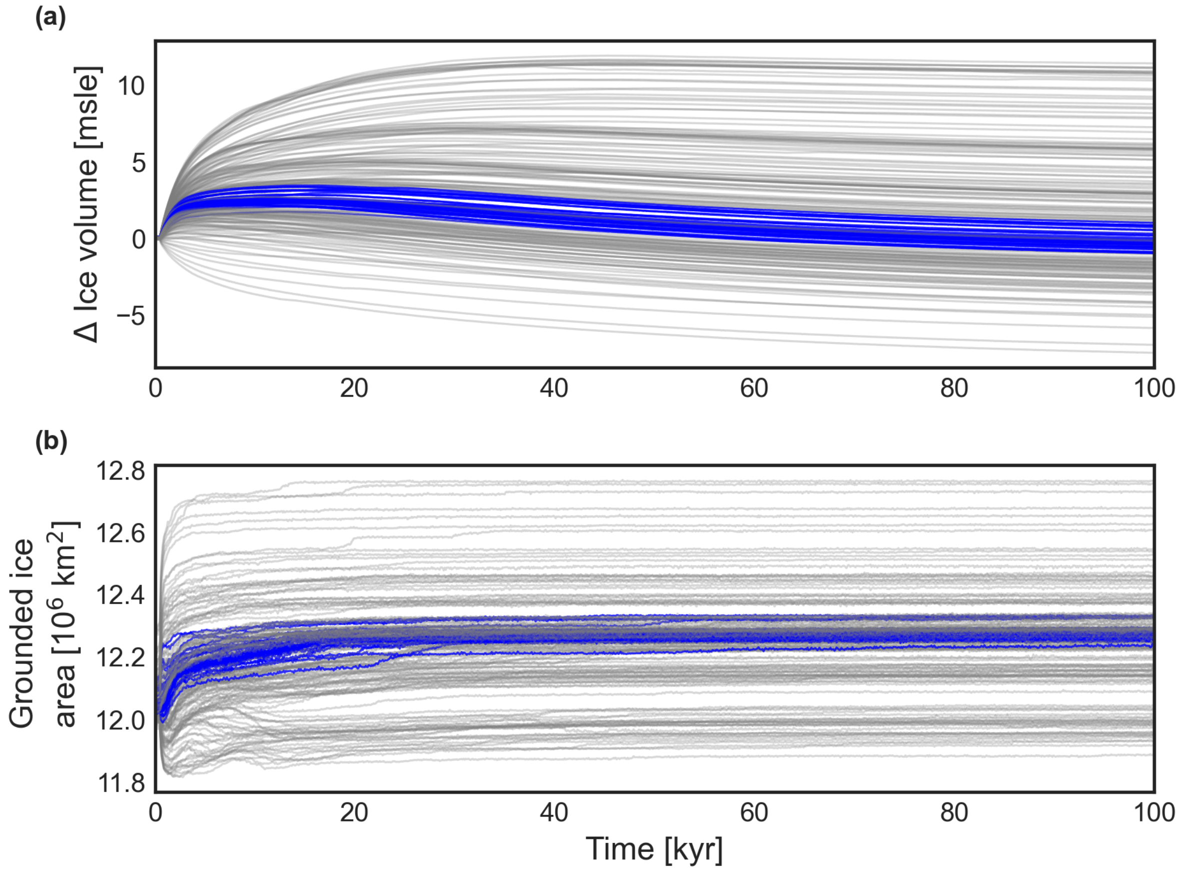


*Figure 1: Temporal evolution of the (a) ice-volume difference in terms of msle with respect to PD; (b) grounded-ice extent under PD climatological conditions. Blue lines represent simulations that differ less than 1 mSLE and 2.5 106 km2 with observations (a deviation of 2% from observed values) and are considered for mPWP simulations.*

L195 onwards: use X rather than times.

Changed.

L214: perhaps use ‘assess the spatial origin’

Done.

L246: can you clarify what defines ‘high probability’ in this context?

We have specified now with numbers.

L274: missing end bracket

Fixed.

L325: Comparison with Dolan et al is useful, but it is unclear from the way it is written if the authors infer that they agree or disagree with the overall conclusion of a high climate model dependency of AIS reconstructions. Please consider alternative phrasing. The quoted sea level figures for ‘simulations which are not close to tip’ needs further elaboration.

The original text read as follows:

“Contrary to Dolan et al. (2018), we find that the climatologies yield a higher uncertainty (~7 msle) than the dynamical configuration, if parameters are constrained with PD observations. Dolan et al. (2018) obtain more than 10 msle between different ice-sheet models, whereas we obtain less than 2 msle differences for simulations which are not close to tip, and up to 5 msle differences for CESM1.0.5 due to its proximity to tip or not in the Wilkes basin (Error bars Fig. 5). Thus, a large ensemble parameter constraint like in our study, helps considerably to reduce uncertainty from ice-sheet models"

We changed it to:

“Dolan et al., (2018) find that climatic uncertainty leads to more than 10 msle. Our results yield a smaller uncertainty (~7 msle). However, the climatic outputs used by Dolan et al., (2018) belonged to the PlioMIP1 experimental setup whereas ours belonged to the PlioMIP2 experimental setup. Ice-sheet models uncertainty leads to more than 10 msle in Dolan et al., (2018) and deBoer et al., (2015). Our results suggest that the uncertainty associated with ice dynamics within an ice-sheet model is less than 2 msle for the majority of AOGCMs. Nonetheless, we find up to 5 msle differences for CESM1.0.5, where different dynamic configurations can lead to a retreat of the Wilkes basin (error bars in Fig. 5).”

L331: the statement that ISMIP6 simulations around tipping points over the next century being consistent with the results presented here seems a little ungrounded, given that these results are for a steady state following thousands of years.

Indeed, since it can lead to misinterpretation the paragraph was removed from the discussion section.

L364: Regarding the note around cooler conditions prevailing before the mPWP, it would be useful to provide some further context on this. Do you mean the MIS M2 event? Throughout this period there will have been orbital forcing that is not taken into account here.

Yes, we refer to the MIS M2 event (~ 3.3 Ma BP). We wanted to highlight that during that time cooler conditions prevailed allowing the ice sheet to extend to modern-like configurations (Berends et al., 2019). We have rephrased the paragraph as follows:

“The mPWP was preceded by a large global glaciation during Marine Isotope Stage M2 ca. 3.3 Ma BP (Rohling et al., 2014; Stap et al., 2016). During that period, the AIS evolved towards a modern-like configuration (Berends et al., 2019). Therefore, starting from PD initial conditions can help to assess the realism of the simulated mPWP from the AOGCMs. For instance, if the retreat of Wilkes basin is a necessary condition for an accurate mPWP representation, then only 3 out of 12 AOGCM models can be considered to realistically simulate warm Pliocene conditions, according to our simulations.”

L417: use of “irreversible retreat” terminology should perhaps be reconsidered here in reference to the Pliocene, as WAIS has clearly advanced since then. However, I am not clear if this sentence does refer to the mPWP or PD – it would benefit from rephrasing I think.

We rephrased it to “[...] and that even a lowering of PD precipitation could lead to a potential retreat of marine basins” to avoid any confusion.

L419: Is this Pliocene only here, and does it include both ice-sheet initial conditions?

No, it is only starting from PD conditions. We therefore rephrased it to:

“Finally, our simulated sea-level contributions ranged from 1.8 mSLE to 9.6 mSLE considering the whole ensemble starting from PD conditions, and 15.5 mSLE to 25.6 mSLE when starting from PRISM4 conditions.”

Fig 6: Just for clarity, does 100% probability mean that all simulations agreed? Do any of the results presented reach that 100% mark, or are they mostly between 80% and 100%. It could be useful to have a distinction in colour for when they do all agree.

Yes, 100% means all the simulations agree. We changed the figure and colorbar accordingly.

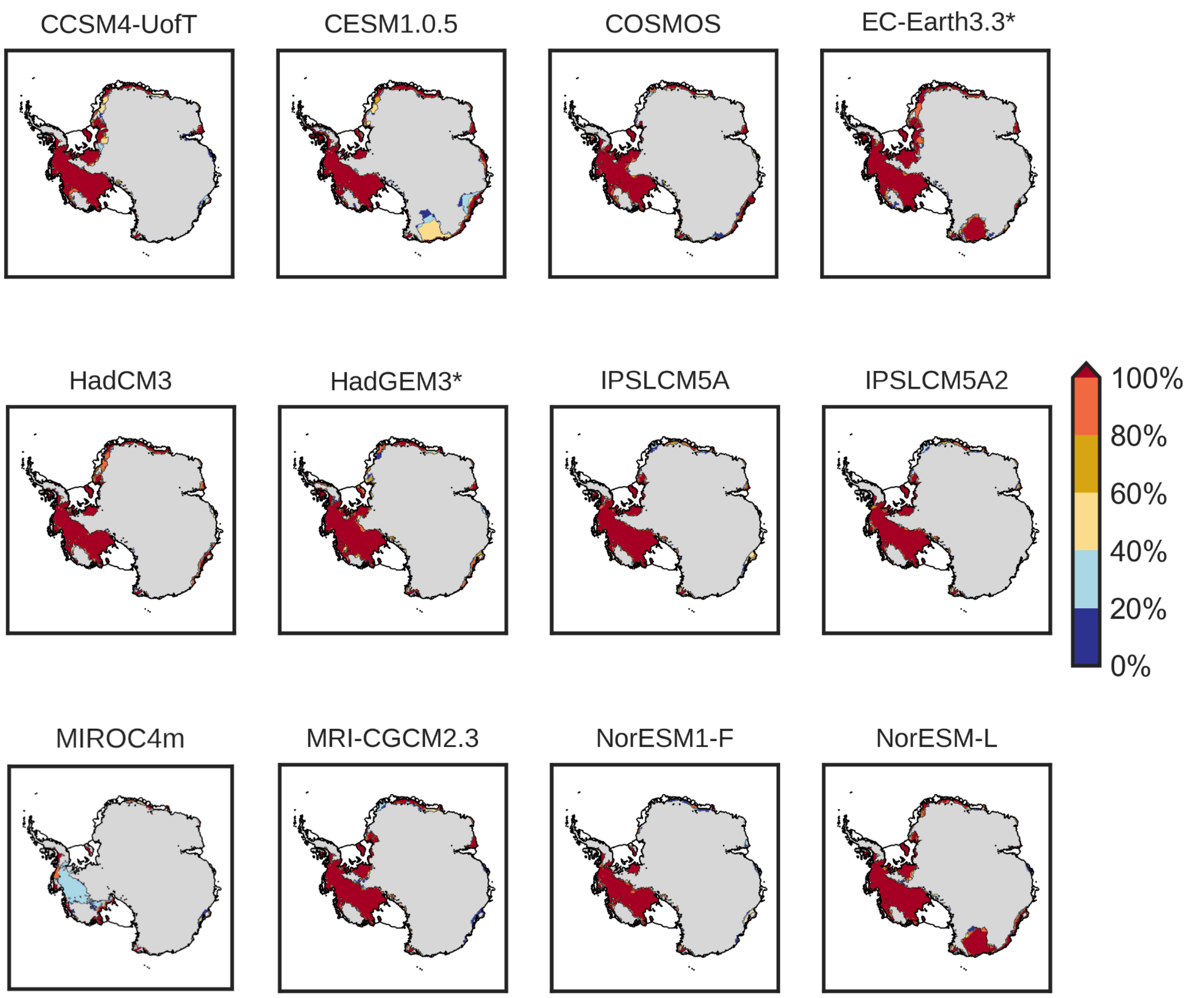

*Figure 6: Ice-collapsed probability of the ensemble for every AOGCM. Darkred/Blue colors indicate a high/low probability of a collapsed region. Gray colors show grounded ice for all the ensemble simulations.*

Table S1: additional comma in caption

Done.

**References:**


- *Berends, C. J., et al.: Modelling ice sheet evolution and atmospheric $CO_2$ during the Late Pliocene, Clim. Past, https://doi.org/10.5194/cp-15-1603-2019, 2019.*
- *Sadai, S., et al.: Future climate response to Antarctic Ice Sheet melt caused by anthropogenic warming, Sci. Adv., https://do.org/10.1126/sciadv.aaz1169, 2020.*
- *Bintanja, R., et al.: The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice, Annals of Glaciology, https://doi.org/10.3189/2015AoG69A001, 2017.*
- *McKay, D. A., et al.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, Science, https://doi.org/10.3189/10.1126/science.abn7950, 2022.*
- *Haywood, A. M., et al.: PlioMIP: The Pliocene Model Intercomparison Project, Past Global Changes Magazine, https://doi.org/10.22498/pages.29.2.92, 2021.*
- *Shakun, J. D., Corbett, L. B., Bierman, P. R., Underwood, K., Rizzo, D. M., Zimmerman, S. R., Caffee, M. W., Naish, T., Golledge, N. R., and Hay, C. C.: Minimal East Antarctic Ice Sheet retreat onto land during the past eight million years, Nature, 558, 284–287, https://doi.org/s41586-018-0155-6, 2018.*