Review of: Quantifying the Uncertainty in the Eurasian Ice-Sheet Geometry at the Penultimate Glacial Maximum (Marine Isotope Stage 6) by Pollard *et al*

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1 Overview

Pollard *et al* present a reconstruction of the Eurasian Ice Sheet complex at the penultimate (MIS 6) glacial maximum. They accomplish this by using a plastic, steady state ice sheet model, ICESHEET, which creates ice sheet reconstruction using three main inputs – ice margin location, topography and basal shear stress. They develop a Bayesian statistical framework to test the ice sheet configuration by varying the basal shear stress. They calibrate the model framework by comparing with two reconstructions of the Eurasian Ice Sheet complex at the Last Glacial Maximum, namely ICE-6G and GLAC-1D. The sea level equivalent penultimate ice sheet volume after removing ruled out configurations is about 51 m, which is lower than previous dynamic ice sheet modelling exercises, but comparable to a previous result based on glacial isostatic adjustment methods.

As the creator of ICESHEET, I have been anticipating how Pollard *et al* would use my model (as a disclaimer, I did give some advice on how to run the model when the authors were starting up back in 2020). For various reasons, I personally decided against developing a Bayesian framework for my own ice sheet modelling exercises (*e.g.* Gowan et al., 2016, 2021), so I am very satisfied that Pollard *et al* have created a new way to use it. By using ICESHEET, it avoids many of the problems with other methods of ice sheet reconstruction (as described in the introduction), namely the large uncertainties in climate forcing for dynamic models, and the lack of physics in pure GIA loading models. The Bayesian framework that Pollard *et al* present provides a way forward to infer the ice sheet geometry of periods where there are few constraints on climate and sea level.

The manuscript is well written and easy to understand. Perhaps the main comment I have is that this study does not really introduce the geological observations that serve as the basis for the larger MIS 6 ice sheet compared to the last glacial cycle. For instance, we know that the ice sheet must have been much larger because the Baltic Sea was much larger in MIS 5e, even connecting to the White Sea for a time (*i.e.* Dalton et al., 2022). Having a paragraph or two introducing the geological basis would be of benefit to those interested in the ice sheet reconstruction but are not so aware of the penultimate glaciation.

2 Comments

2.1 Application to current ice sheets

When I developed my global ice sheet reconstruction (Gowan et al., 2021), I tuned the shear stress values to the present day Greenland and Antarctic Ice Sheets. Has the the Bayesian framework you developed also been applied to those ice sheets? If it is not too time consuming (*i.e.* a couple of weeks?), this would be a good test of the technique used here, as the basal shear stress can be determined directly from the present day configuration. If you anticipate such an exercise would take months, then I would regard this as optional.

2.2 Barents Sea area at LGM

The difficulty in fitting the LGM ice sheet in the Barents Sea with ICE-6G is not really surprising – in this area, the ICE-6G reconstruction starts with a high (and I would say unrealistic) ice thickness of nearly 5 km in the middle of the Barents Sea Ice Sheet at 26 ka. By way of comparison, the East Antarctica Ice Sheet only exceeds 4 km thickness in a few isolated places. This causes the topography in this area to be extremely depressed, which will mean that it will be harder to build up ice there with ICESHEET using realistic values of shear stress.

The result from GLAC-1D could also have issues, as we have no idea what metrics were used to tune it. GLAC-1D is an ensemble average of some unknown number of ice sheet model simulations (which we don't know because the details of the European component have never been published), and considering the likely lack of tuning parameters within the Barents Sea, could produce something that is not reflective of a real ice sheet configuration.

Though the usage of ICE-6G and GLAC-1D as a strategy to calibrate your model is fine (since they are two of the only available reconstructions of the ice sheet complex), keep in mind that these models might also not be realistic depictions of the ice sheet complex.

2.3 Shear Stress values

Considering that the shear stress values are the main parameter that are varied, I think it would be a good idea to include figures showing the resulting optimal shear stress values plus the associated uncertainty in the main text (right now it is only shown in the appendix).

Looking at this, I think that the ensemble values for the cold based ice shear stress values are probably set to a range that is too high. If you look at the present day Antarctica ice sheet shear stress (Fig. 1), the interior of the ice sheet tends to actually have lower shear stress values than around the margins. This is likely because the precipitation is essentially zero when the ice sheet elevation gets above 3500 m, so there is no mechanism to increase the surface gradient (and therefore increase the basal shear stress). If a similar thing happened with the penultimate Eurasian Ice Sheet complex, you would expect the shear stress values in the middle of the ice sheet to be lower than the LGM. Using Antarctica as an analogue is not perfect, since it is an ice sheet with a relatively flat base in the interior, and mountains around the margins, which is the opposite of the Eurasian Ice Sheet Complex. Regardless, I would suspect a tendency of decreasing shear stress in the dome regions as the ice sheet grows larger than the LGM. The result of the high range (Figure 9 in the manuscript) is that the thickness of the ice sheet reaches 5 km, which is likely larger than is possible in reality.

If it is possible, I recommend running more simulations with an expanded (lower) range of Cold Based Ice Shear Stress values. I think this will result in a more realistic ice sheet configuration. The follow on to this is that I imagine the estimate of ice volume will also decrease.

2.4 Discussion

Perhaps a minor point, but the PGM results are compared against a reconstructed sea level curve by Waelbroeck et al. (2002) in a way that should be treated with caution. The Waelbroeck reconstruction is tuned assuming an ice volume sea level equivalent at the LGM of 130 m. The ice volume sea level equivalent will be always less than global average sea level for two reasons. First, the area of the ocean decreases as sea level falls, as continental shelf regions emerge. Secondly, the volume of the ocean basin also decreases due to GIA effects when the the water is taken out of the ocean. This means that as the ice sheets grow, it takes less ice volume to cause sea level to drop by the same amount. Estimates of sea level equivalent ice volume are therefore dependent on the choices of how to parameterize the Earth structure. The 130 m value is the result of a GIA model that is tuned against paleo sea level observations in Australia (Yokoyama et al., 2000). Australia is chosen as a good place to tune global ice sheet reconstructions, as it is a place that is expected to be close to global average sea level of around -120 m at the LGM. Recent assessments suggest the LGM sea level equivalent ice volume is likely closer to 114 m (Simms et al., 2019), a value comparable to my own analysis, which uses a different Earth model structure than Yokoyama *et al.* (Gowan et al., 2021). If this lower value is correct, which seems likely since it should be less than the near global average sea level values obtained from Australia, it will mean that the total sea level equivalent ice volume at the PGM is less than implied in the Waelbroeck curve, probably between 10-20 m.

On that note, it should be stated somewhere how the sea level equivalent ice volume is calculated (I am just guessing here that it is calculated based on modern ocean area).

2.5 Figure 6

I think this figure will need to be reworked in some way, or presented differently because even with my eagle-eyed vision, it is hard to see what is going on with these small plots. I think in the caption the plots need to be described better what they represent, because now it just looks like a cloud of coloured points and it is not easy to know exactly what relationship the parameters have with each other. By eye, there doesn't seem to be any clustering that would imply a relationship? Perhaps this is a consequence of the Latin Hypercube sampling, where variations happen with all parameters, so relationships between two parameters are hard to visualize? Also, I do not understand what the axes represent. Wouldn't it be better to plot it in terms of the actual values being varied (like from Table 1)?

Increasing the font size of the other figures is also recommended.

2.6 Code Availability

Please ensure that any modified versions of the ICESHEET code are made available.

Best Regards,
Evan J. Gowan

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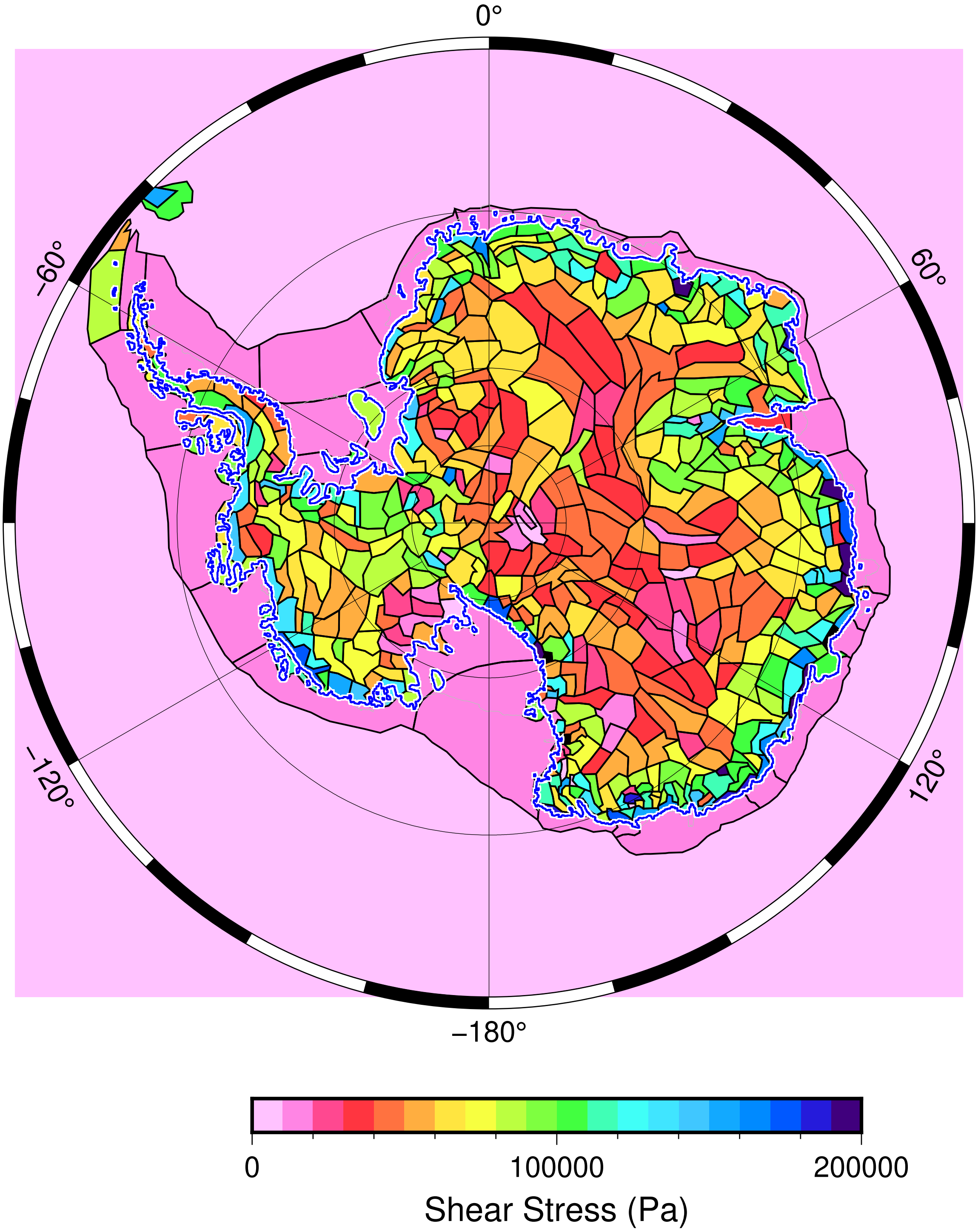

Figure 1: Present day basal shear stress values for Antarctica in PaleoMIST (Gowan et al., 2021)