

## **Response to Review Comments**

We thank the editor and reviewers for their efforts in making constructive remarks on our revised manuscript. Below you can find point-by-point replies to the the review comments. In the revised manuscript, revisions are highlighted by blue color. We hope that all of the Editor's and reviewers' concerns have been addressed adequately.

### ***Reviewer #2***

*The authors present future projection simulations for the Amundsen–Ross Sea region to assess projected changes in ocean circulation and sea-ice conditions using CMIP6 multi-model mean forcing. While the overall concept of the study is valuable, I have several substantial concerns regarding the robustness of the conclusions. I recommend major revision or reject with encouragement to resubmit.*

#### *1. Insufficient model–data agreement in the Amundsen Sea*

*The most critical issue is that the simulation does not achieve sufficient agreement with observations in the Amundsen Sea to justify their conclusion (title). Model–data comparison presented in Xie et al., 2024 (Fig. 2) shows a major mismatch: the simulated CDW intrusion is colder than 0 °C, whereas observations indicate temperatures exceeding 1 °C. No model–data comparison is shown in this manuscript for the Amundsen Sea. This discrepancy is large enough to call into question the reliability of the model's future projections. There is a substantial difference in their mean state. Without addressing this bias explicitly, it is difficult to place confidence in the projected future changes.*

We thank the reviewer for pointing out this important issue. We agree that the simulated CDW intrusion in the Amundsen Sea is colder than observed, as shown by the comparison in Xie et al. (2024). This cold bias may affect ice-shelf melting and meltwater release, which can in turn influence DSW formation through the transport of Amundsen Sea meltwater into the Ross Sea. We therefore evaluated this issue using Xie et al. (2025), where basal mass loss simulated by the same model was compared with satellite-based estimates for 2005–2014. The simulated total basal mass loss from the Amundsen Sea ice shelves is approximately 428 Gt yr<sup>-1</sup>. This value is in reasonable agreement with the estimate of 405 ± 56 Gt yr<sup>-1</sup> reported by Liu et al. (2015), and is only slightly lower than the estimates of 488 ± 58 Gt yr<sup>-1</sup> by Rignot et al. (2013) and 475 ± 87 Gt yr<sup>-1</sup> by Depoorter et al. (2013). This comparison suggests that the simulated Amundsen Sea ice-shelf meltwater production falls within the range of satellite-based estimates and is therefore not substantially underestimated in the model. This is also consistent with the fact that ice-shelf melting is not determined by CDW heat content alone, but also by how much CDW reaches the ice-shelf cavities, how frequently it does so, and how efficiently its heat is exchanged with the ice

base. These processes are controlled by bathymetric pathways, shelf circulation, eddy and tidal mixing, cavity geometry, and sub-ice-shelf circulation, many of which involve meso- and small-scale dynamics. Therefore, a cold bias in simulated CDW temperature does not necessarily translate linearly into an equivalent underestimation of integrated basal mass loss. The reasonable agreement between the simulated and satellite-based basal mass loss indicates that the model captures the overall meltwater production from the Amundsen Sea ice shelves reasonably well, despite the cold bias in CDW properties.

Meanwhile, we acknowledge that the original manuscript did not provide sufficient discussion of model performance in the Amundsen Sea and focused mainly on the simulation of DSW in the Ross Sea. To address this issue, we have added text in the revised Section 2.1 describing the cold bias in simulated Amundsen Sea CDW, together with the model's overall reasonable representation of ice-shelf basal melting (Lines 204–207).

#### References:

- Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J. T. M., Ligtenberg, S. R. M., van den Broeke, M. R., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, *Nature*, 502, 89–92, 2013.
- Liu, Y., Moore, J. C., Cheng, X., Gladstone, R. M., Bassis, J. N., Liu, H., Wen, J., and Hui, F.: Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves, *Proc. Natl. Acad. Sci. U. S. A.*, 112, 3263–3268, <https://doi.org/10.1073/pnas.1415137112>, 2015.
- Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice-shelf melting around Antarctica, *Science*, 341, 266–270, 2013.
- Xie, C., Zhang, Z., Chen, Y., Wang, C., and Zhou, M.: The response of Ross Sea shelf water properties to enhanced Amundsen Sea ice shelf melting, *J. Geophys. Res.-Oceans*, 129, e2024JC020919, 2024.
- Xie, C., Zhang, Z., Chen, Y., and Wang, C.: Substantial contraction of dense shelf water in the Ross Sea under future climate scenarios, *Geophys. Res. Lett.*, 52, e2024GL112581, 2025.

#### *2. Use of CMIP6 multi-model mean forcing and limitations of the ASL-related analyses*

*The authors rely on multi-model mean forcing and discuss impacts related to the Amundsen Sea Low (ASL), but the analyses do not sufficiently justify that the multi-model mean is appropriate for the conclusions drawn. Recent work by O'Connor et al., 2025 demonstrates that relatively small changes in northerly winds can strongly modify on-shelf conditions in the Amundsen Sea. A shift*

*of less than ~100 km (may be much smaller distance) or even a small change in wind strength can significantly alter heat transport, especially given that wind stress scales with the square of wind speed. Because of such nonlinearities, conclusions regarding “enhanced dense shelf water formation in the Ross Sea under future ASL trends” cannot be supported without careful examination. I think the full ensemble for each perturbation rather than relying solely on multi-model means is required.*

We thank the reviewer for raising this point. We agree that the ocean–sea ice–ice shelf system is highly nonlinear, and that its response to ASL-related wind perturbations can depend sensitively on the details of the atmospheric forcing. The recent study mentioned by the reviewer provides a good example of this sensitivity, showing that relatively small changes in local meridional winds can substantially modify coastal polynya activity, on-shelf hydrography, and ice-shelf melting in the Amundsen Sea (O’Connor et al., 2025). We therefore agree that the original manuscript did not sufficiently justify the use of the multi-model mean forcing, nor did it clearly state the limitations associated with this choice.

We have now clarified that our experiments are not intended to provide a full probabilistic projection of future DSW formation in the Ross Sea. Rather, they are designed as sensitivity experiments to examine the response of the coupled Ross–Amundsen Sea system to CMIP6-MME10 ASL-related wind changes. A full probabilistic projection would require a large ensemble of perturbation experiments based on individual CMIP6 models, which would be substantially more computationally demanding and is beyond the scope of the present study. We agree that a full ensemble of perturbation experiments based on each individual CMIP6 model would provide a more complete estimate of projection uncertainty. However, such an ensemble would not, by itself, identify which individual atmospheric model provides the most reliable representation of the realized future climate. We therefore focused on a different but directly relevant question: whether the CMIP6-MME10 provides a reasonable estimate of the atmospheric forcing fields used in our experiments.

To justify this choice, we have added a new evaluation of the selected CMIP6 models for the historical period 2005–2014. Following the performance-metric framework of Gleckler et al. (2008) and Naughten et al. (2018), we calculated the root-mean-square error (RMSE) of the monthly climatology from each CMIP6 historical simulation relative to ERA5 over the Ross Sea and Amundsen Sea, after linearly interpolating the CMIP6 fields to the ERA5 grid. The RMSE was calculated as:

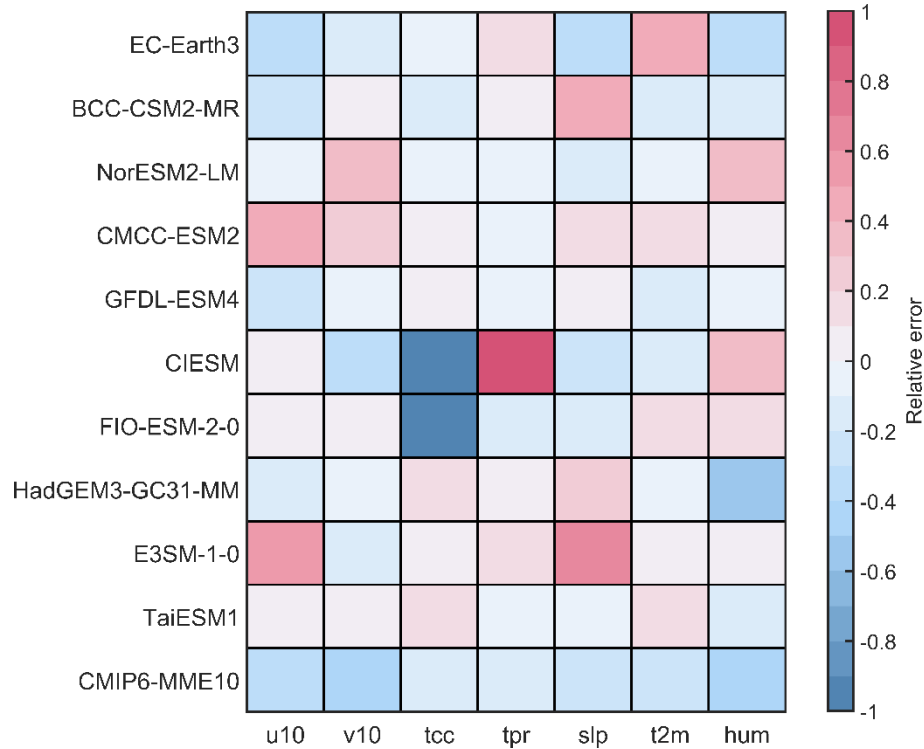
$$\text{RMSE}_{\text{CMIP6},v} = \sqrt{\frac{1}{N_x \cdot N_y \cdot T} \sum_{i,j,t} (v_{\text{CMIP6}}^{i,j,t} - v_{\text{ERA5}}^{i,j,t})^2}, \quad (1)$$

where  $\text{RMSE}_{\text{CMIP6},v}$  denotes the RMSE of a CMIP6 model (including CMIP6-MME10) for atmospheric variable  $v$ ,  $v_{\text{CMIP6}}^{i,j,t}$  and  $v_{\text{ERA5}}^{i,j,t}$  are the monthly climatological values from the CMIP6

model and ERA5 at grid point  $(i, j)$  and month  $t$ , respectively.  $N_x$  and  $N_y$  are the numbers of grid points in the zonal and meridional directions, and  $T(=12)$  represents the 12 monthly climatological fields. The evaluated variables include all atmospheric variables used to force our ocean–sea ice–ice shelf model: 10-m zonal wind component (u10), 10-m meridional wind component (v10), total cloud cover (tcc), total precipitation rate (tpr), sea-level pressure (slp), 2-m air temperature (t2m), and relative humidity (hum). For each variable, the RMSE of each model was then normalized by the median RMSE across the selected models to obtain a relative error (RE):

$$\text{RE}_{\text{CMIP6},v} = \frac{\text{RMSE}_{\text{CMIP6},v} - \text{median}(\text{RMSE}_v)}{\text{median}(\text{RMSE}_v)}, \quad (2)$$

where  $\text{median}(\text{RMSE}_v)$  denotes the median RMSE across all selected models (excluding CMIP6-MME10) for variable  $v$ . The median rather than the mean RMSE was used to reduce the influence of models with unusually large errors on the normalization. For example, a RE of 0.5 indicates that the given model has a RMSE 50% higher than the median across selected models for the given variable. Similarly, a RE of -0.5 indicates a RMSE 50% lower than the median. Models in better agreement with ERA5 will consistently have RE values that are relatively negative.



**Figure 3.** Relative error (RE) for the 10 CMIP6 models and the multi-model mean (CMIP6-MME10). The RE of each model was calculated by comparing the 2005–2014 monthly climatology from the CMIP6 historical simulations with ERA5 over the Ross Sea and Amundsen Sea region. Results are shown for 7 atmospheric variables used to force the RAISE simulations: u10 (10-m zonal wind component), v10 (10-m meridional wind component), tcc (total cloud cover), tpr (total precipitation rate), slp (sea level pressure),

t2m (2-m air temperature), and hum (relative humidity). The best-performing models are dominated by blue squares.

The analysis shows that CMIP6-MME10 has lower RE than most individual models across the forcing variables, indicating that the multi-model mean reduces individual model biases in the present-day atmospheric mean state. This improved representation of the historical atmospheric forcing provides greater confidence that CMIP6-MME10 offers a robust basis for characterizing future atmospheric forcing, while we acknowledge that it does not remove the uncertainty associated with inter-model spread and nonlinear coupled responses. In the revised manuscript, we have added this analysis to Section 2.2, which includes the rationale for using the CMIP6-MME10 forcing and a description of the historical-period RMSE evaluation (Lines 233–252). The RE heatmap has also been added as Fig. 3.

#### References:

- Gleckler, P. J., Taylor, K. E., and Doutriaux, C.: Performance metrics for climate models, *J. Geophys. Res.-Atmos.*, 113, D06104, 2008.
- Naughten, K. A., Meissner, K. J., Galton-Fenzi, B. K., England, M. H., Timmermann, R., Hellmer, H. H., Hattermann, T., and Debernard, J. B.: Future projections of Antarctic ice shelf melting based on CMIP5 scenarios, *J. Climate*, 31, 5243–5261, 2018.
- O’Connor, G. K., Nakayama, Y., Steig, E. J., Armour, K. C., Thompson, L., Hyogo, S., Berdahl, M., and Shimada, T.: Enhanced West Antarctic ice loss triggered by polynya response to meridional winds, *Nat. Geosci.*, 18, 840–847, 2025.

#### *3. Wind perturbation experiments and wind-stress curl*

*The manuscript uses sensitivity experiments in which wind perturbations are applied only to selected regions, but it is unclear to me how the authors address the resulting wind-stress curl patterns. Localized modifications to the wind field can generate unrealistic curl fields and associated circulation anomalies. The authors must demonstrate that the imposed perturbations do not introduce unphysical conditions, either by showing the resulting curl fields or by explaining how these artifacts are mitigated.*

We agree that regional wind perturbations may generate artificial wind-stress curl anomalies, particularly near the boundaries of the perturbation regions where the imposed wind changes transition to zero. In our experiments, the wind perturbations were linearly smoothed over a 1° transition zone near the boundaries to avoid abrupt discontinuities. Because the boundary zones

remain the most likely locations for artificial curl anomalies, we performed an additional quantitative check along the four boundaries of each perturbation region.

For each boundary grid point, we calculated the daily wind-stress curl fields. The wind-stress curl anomaly was defined as the difference between the future perturbation experiment and the present:

$$\Delta C_i(t) = C_i^{\text{future}}(t) - C_i^{\text{present}}(t), \quad (3)$$

where  $i$  denotes a boundary grid point and  $t$  denotes a daily time step. To quantify the magnitude of the induced curl anomaly, the RMSE was calculated at each boundary grid point:

$$\text{RMSE}_i = \sqrt{\frac{1}{T} \sum_{t=1}^T [\Delta C_i(t)]^2}, \quad (4)$$

where  $T$  is the total number of daily time steps used in the calculation. We then normalized this value by the standard deviation of the present wind-stress curl at the same boundary grid point:

$$\sigma_i = \sqrt{\frac{1}{T-1} \sum_{t=1}^T C_i^{\text{present}}(t) - \overline{C_i^{\text{present}}}}^2. \quad (5)$$

The normalized RMSE anomaly was defined as the ratio between RMSE and standard deviation:

$$R_i = \frac{\text{RMSE}_i}{\sigma_i}. \quad (6)$$

We used the normalized RMSE of the anomaly to assess the magnitude of the induced boundary wind-stress curl anomalies relative to the intrinsic daily variability of the present-day wind-stress curl. The boundary-averaged normalized RMSE values range from 0.04 to 0.19 in the Ross Sea region (RS), 0.03 to 0.05 in the western Amundsen Sea region (WAS), and 0.28 to 0.34 in the eastern Amundsen Sea shelf and slope region (EASS) under 2050F. Under 2100F, the corresponding ranges are 0.124 to 0.49, 0.120 to 0.201, and 0.491 to 0.573, respectively. Since all values are below 0.6, the induced boundary wind-stress curl anomalies remain within the range of present-day daily variability and are unlikely to dominate the simulated ocean response. In the revised manuscript, we added texts justifying the way we make regional wind perturbations (Lines 343–345).