Reply to Referee #1

We are grateful to Referee #1 for the constructive comments on the observational data description, the organization of the Results and Discussion, and the clarity of the figures and text. We have followed each of the comments, presented in black font below, to carefully revise our manuscript. Our replies to the comments are given in blue, and the line numbers indicated are those of the revised manuscript with track changes enabled.

General comment:

This manuscript presents a high-resolution model study of tidal dynamics in the Ross Sea. The results show that steep topography strongly modifies the tidal flow, producing localized eddy-like structures and bottom-trapped waves. These features are associated with enhanced near-bottom energy and vertical shear, highlighting the importance of seabed geometry in redistribution of tidal energy. The study suggests that tides may play an important role in cross-slope exchange and shelfward heat transport.

Model validation is carried out against observational datasets and provides confidence in the model results. Overall, the manuscript is well written and presents interesting results; however, several aspects of the interpretation and presentation could be improved.

We sincerely thank the referee for the encouraging and constructive feedback. Following the general suggestion on improving interpretation and presentation, we have thoroughly revised the manuscript: we added mechanistic clarifications on cross-slope heat transport and why confinement of energy to the bottom boundary is expected to enhance mixing, improved the figures for greater visual clarity, and expanded the discussion section. We hope these revisions adequately address the concerns, and we remain open to further specific suggestions.

Main comments:

The manuscript would benefit from a dedicated data section describing the observational datasets used for model validation, including the mooring instrumentation, deployment period, and data processing.

We thank the referee for this constructive suggestion. In the revision, we have added Section 2.2.1 (Observational data and processing) to include a dedicated description of the observational datasets used for model validation.

The separation between Results and Discussion is not always clear. The Results section contains interpretive material, while the "Summary and Discussion" section is relatively brief and does not fully explore the physical implications of the results. The manuscript would benefit from either expanding the Discussion or combining the Results and Discussion into a single integrated section. Several important processes are described, but the underlying mechanisms and broader dynamical implications are not always clearly articulated.

We thank the referee for this perceptive comment. To address the referee's concern about insufficient exploration of physical implications, we have added explicit mechanistic clarifications at lines 334–343 (cross-slope heat transport) and lines 455–459 (explanation of why the confinement of energy to the bottom boundary is expected to enhance turbulent mixing) and expanded Section 4 to place these findings in a broader regional context (Lines 546-554). We believe these changes make the logical flow clearer and ensure that each result is followed by a well-supported physical interpretation. We hope the revised version meets the referee's expectations.

Minor comments:

The Southern Ocean State Estimate version should be specified.

The version of the Southern Ocean State Estimate is the 2005-2010 solution (iteration 100). We have clarified this in the revised manuscript (Line 90).

Please specify which version of the CATS tidal model was used (e.g. CATS2008_v2023).

We have specified the version of the CATS tidal model (CATS2008) in the revised manuscript (Lines 91 and 92).

Please specify which ERA5 atmospheric variables were used to force the model.

The ERA5 variables used include 10 m wind speed, 2 m temperature, 2 m dewpoint temperature, total precipitation, and mean surface downward radiation flux. We have specified them in the revised manuscript (Lines 94 and 95).

For figures showing along-isobath structure, please clarify orientation (east/west).

The orientation (east/west) has been clarified for all along-isobath figures.

Please clarify what happens to the eddy-like structures during the transition between flood and ebb tides; do they persist, dissipate, or reverse with the changing flow?

We thank the referee for this insightful suggestion. During the flood-ebb transition, tidal flows reverse, and eddy-like structures are no longer sustained as SSH anomalies diminish, as shown in the supplementary Fig. S18 (also attached below). They re-emerge only when the next tidal phase re-establishes the SSH gradient. We have clarified this in the revised manuscript (Lines 313–315).

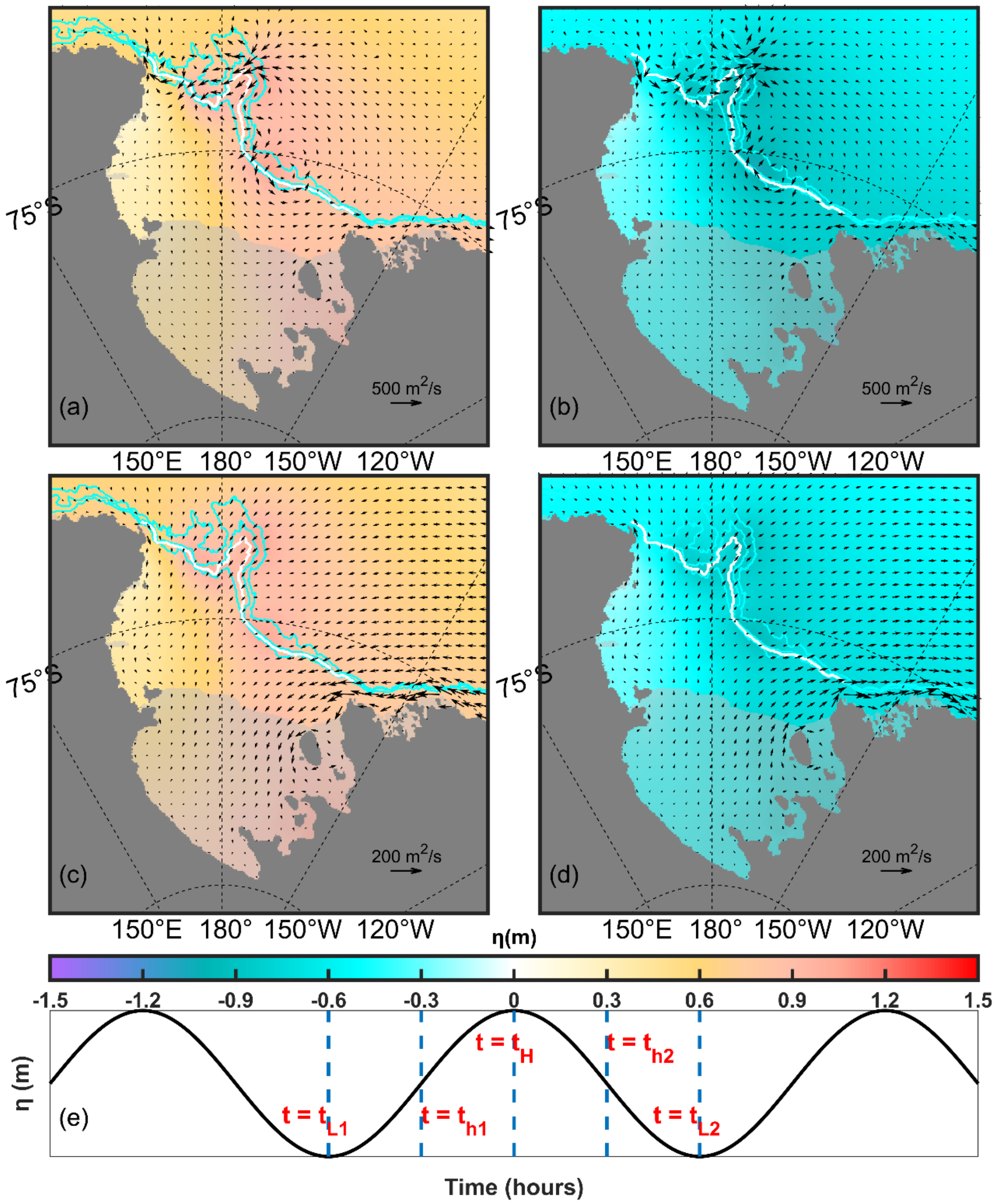

Figure S18. (a) Tide-induced sea level change (color shading) during half flood period (from t_{L_1} to t_{h1}), overlain by volume transport vectors of the topographic mode at t_{h1}. (b) Tide-induced sea level change (color shading) during half ebb period (from t_{H} to t_{h2}), overlain by volume transport vectors of the topographic mode at t_{h2}. (c, d) Corresponding volume divergence due to the surface mode (color shading) during flood and ebb periods, overlain by volume transport vectors of the surface mode at t_{h1} and t_{h2}, respectively. The 500, 1000, and 2000-m isobaths (cyan) and the 700-m isobath (white) are shown along the continental slope. (e) Schematic for illustrating the flood and ebb periods for integration.

Please ensure consistent capitalization of axis labels across figures.

The axis labels in all figures have been checked and made consistent in capitalization.

Section 3.3 is rather long and would benefit from subheadings. There are also several repeated statements that could be streamlined.

Many thanks for this constructive criticism. We have now divided Section 3.3 into two subsections (3.3.1 Characteristics of Bottom-Trapped Waves and 3.3.2 Energetics). The repeated statements (lines 401–415) have been removed and streamlined into lines 424–445 in the revised manuscript.

Line by line comments:

Line 58: Should it be “previous works”?

Sorry for the typo. The wording has been revised to “previous works” (Line 58).

Line 81: Please specify the SOSE version used.

The version of the Southern Ocean State Estimate (2005-2010 solution, iteration 100) has been specified in the revised manuscript (Line 90).

Line 90: Please confirm the version of the CATS model used.

The version of the CATS tidal model (CATS2008) has been specified in the revised manuscript (Line 91 and 92).

Line 93: Please specify which ERA5 variables were used for atmospheric forcing.

The ERA5 variables (10 m wind speed, 2 m temperature, 2 m dewpoint temperature, total precipitation, and mean surface downward radiation flux) used to force the model have been specified in the revised manuscript (Lines 94 and 95).

Line 96: Please clarify why the 2003–2004 period was selected, as it appears to coincide with mooring deployment timing.

Yes, this period coincides with available mooring observations and enables direct model–observation comparison. We have clarified this in the manuscript (Lines 99 and 100).

Figure 1: Please consider reducing ice shelf transparency to improve readability, particularly for smaller features.

The transparency of ice shelves has been reduced to improve readability.

Please clarify the relevance of the 74.5°S reference (critical latitude) in the figure caption.

We have clarified that 74.5°S is the critical latitude for semi-diurnal tide in the caption of Fig. 1.

Line 122: Please justify the use of the deepest observational data point.

Thanks for the suggestion. Mooring motion can contaminate velocity measurements. During the AnSlope project, strong currents exerted considerable drag on the mooring lines, causing significant blow-down and compromising some of the collected data. To mitigate this, we only use data measured by the deepest ADCP or RCM at each station, as such instrument is closest to the anchor, where line tension is greatest, and thus experiences the least vertical and horizontal displacement. We have clarified this in Lines 116-140 in the revised manuscript.

Line 129: Please clarify how the time series was filtered.

We use the t_tide toolbox for time-series filtering. We have clarified this in the revised manuscript (Lines 128-130).

Figure 3: Please ensure consistent capitalization of axis titles.

The capitalization of axis titles has been made consistent for all figures.

Line 173: Please consider moving this material to the Results section.

We thank the referee for this constructive suggestion. Following this advice, we have removed the detailed description of the specific phenomena (namely, the three eddy-like structures, their quasi-stationary nature, and their tidal reversal of rotation). However, to maintain a logical bridge, we have retained a brief sentence (lines 224 and 225): "In our model, the decomposition does yield a topographic mode, but it does not behave as a propagating Rossby wave (further discussed in Sect. 3)."

Line 214: Is this behaviour expected? If so, please add a brief reasoning.

Yes, this behaviour is expected given that their wavelengths differ substantially relative to the Ross Sea basin scale. We have clarified this in the manuscript at lines 265 and 266.

Line 216: Please refer to a figure.

A reference to Fig. 5a and 5b has been added at line 267 in the manuscript to show the K1 and M2 amplitude distributions.

Line 224-225: Please refer to a figure.

A reference to Figs. 6a and 6b has been added at line 276 in the manuscript to show the pronounced differences between diurnal and semi-diurnal tides in the barotropic tidal current fields.

Line 233: Should it be Fig. 5c?

Thanks for catching this. The figure reference has been corrected to Fig. 6c at line 284 in the manuscript (as a new figure has been added, renumbering the original Fig. 5c to Fig. 6c).

Figure 4: As above, consider capitalizing the first letter of axis titles.

The axis labels in all figures have been checked and made consistent in capitalization.

Figure 5: Consider removing tidal ellipses, if they are not discussed in the text.

We appreciate the suggestion, but we believe the tidal ellipses are worth keeping because they indicate variability of tidal current directions. We have mentioned this in the revised manuscript (line 277).

Line 248: Consider referring to a figure: where we can see that is reverses between flood and ebb tides (Fig. 6 a and b, respectively).

A reference to Figs. 7a and 7b has been added at line 301 to show the reversal between flood and ebb tides in the manuscript.

Line 267: Please correct the notation for specific heat capacity units (avoid dot product form).

The notation for specific heat capacity units has been corrected at lines 323 in the manuscript.

Line 275-279: Consider elaborating on the mechanisms responsible for this behaviour and discuss its potential implications.

The mechanism for this tidal heat flux is preconditioned by a mean cross-slope thermal gradient (Fig. S19, also attached below), set up by warmer open-ocean waters abutting colder shelf waters. During flood tide, warmer water is advected across the slope onto the shelf, where it undergoes irreversible mixing with the ambient colder water. During ebb tide, the returning mixed water is colder than that advected onshore during flood tide, resulting in a flood-ebb difference in heat content on the slope. Although this difference varies spatially along the slope and even reverses locally, the regions with higher flood-tide heat content coincide with the strongest cross-slope velocities, primarily over the 100–200 km along-slope section. Since cross-slope heat transport scales with the product of velocity and thermal anomaly, the transport within the 100–200 km along-slope band overwhelms counter-gradient transport elsewhere, yielding a net onshore heat flux of 12 TW. Overall, these results highlight topographic-mode tides as a critical driver of cross-slope heat transport onto the Ross Ice Shelf, which potentially affects Antarctic ice-shelf melt and global sea-level rise. We have clarified this mechanism and its implications in Lines 334-343.

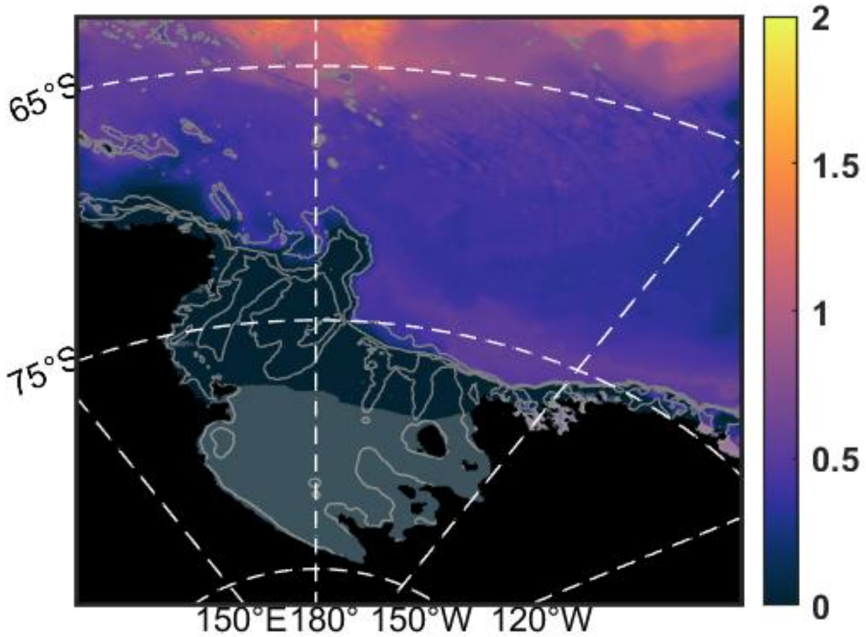

Figure S19. Spatial distribution of depth-averaged, period-averaged sea water temperature (℃). Bathymetry contours are spaced at 500, 1000, and 2000 m.

Figure 8: Consider consistently capitalizing axis labels.

The axis labels in all figures have been checked and made consistent in capitalization.

Line 301: Please clarify that the Ross Sea also lies poleward of the diurnal critical latitude.

The clarification that the Ross Sea also lies poleward of the diurnal critical latitude has been added at line 365 in the manuscript.

Line 304-305: The observed intensification is consistent with the presence of bottom-trapped waves, but it is not uniquely indicative of them. Consider softening this interpretation or discussing alternative explanations.

We thank the referee for the suggestion. We have revised the interpretation to state that the intensification is "consistent with" trapped internal tides, and we have added a discussion of alternative mechanisms (frictional boundary layer dynamics, nonlinear tidal rectification over rough topography, and topographic scattering or critical reflection) at lines 373–375.

Line 314-315 Please provide reasoning for why these thresholds are chosen.

We thank the referee for the request. We have replaced the relative depth (RD) with a new a non-dimensional parameter, R_{KE}, defined as the ratio of the near-bottom-averaged kinetic energy to the column-averaged kinetic energy. This parameter effectively highlights the distribution of bottom-intensified energy while requiring fewer thresholds than RD. We retain the 5 cm s^{-1} threshold and now explicitly state that it identifies the top 10% of energetic regions (Lines 384–389).

Line 325-326: Please refer to a figure.

We have added a reference to Fig. 7 at line 429 to show that the conversion rate varies in sign along the slope due to the alternating alignment of eddy velocities with the surface mode.

Line 328: Consider providing quantitative examples when comparing values.

Quantitative examples have been added at lines 432–434, comparing our values to ~0.1 W/m^2 in Monterey Bay and ~1 W/m^2 over the Luzon Ridge.

Figure 9: Please consider capitalizing the first letter of axis titles.

The axis labels in all figures have been checked and made consistent in capitalization.

Line 341-351: Please note that this paragraph repeats Lines 321–335 and should be revised/removed.

We have removed the duplicated text regarding the conversion rates (surface-to-topographic and barotropic-to-baroclinic), and the consolidated discussion is now at lines 424–445.

Line 353: Could the authors provide an example of how much lower the conversion rate is compared with other ocean regions?

Quantitative examples have been added at lines 432–434, comparing our values to ~0.1 W/m^2 in Monterey Bay and ~1 W/m^2 over the Luzon Ridge.

Line 369: Please explain why confinement of energy to the bottom boundary is expected to enhance mixing, and discuss the underlying physical mechanism.

We have addressed this at lines 455–459 by explaining that bottom-trapped sub-inertial waves confine energy to the boundary layer, intensifying near-bottom shear, which promotes shear instabilities and turbulent dissipation, thereby enhancing diapycnal mixing (with references to D'Asaro and Morison, 1992; Falahat and Nycander, 2015; Musgrave et al., 2017).

Reference:

Falahat, S., and Nycander, J.: On the Generation of Bottom - Trapped Internal Tides. J. Phys. Oceanogr., 45, 526-545, https://doi.org/10.1175/JPO-D-14-0081.1, 2015.

D'Asaro, E. A.; Morison, J. H.: Internal waves and mixing in the Arctic Ocean. Deep-Sea Res. Pt. A, 39, S459–S484, https://doi.org/10.1016/S0198-0149(06)80016-6, 1992.

Musgrave, R. C., MacKinnon, J. A., Pinkel, R., Waterhouse, A. F., Nash, J., and Kelly, S. M.: The Influence of Subinertial Internal Tides on Near-Topographic Turbulence at the Mendocino Ridge: Observations and Modeling. J. Phys. Oceanogr., 47, 2139–2154, https://doi.org/10.1175/JPO-D-16-0278.1, 2017.

Line 402-403: Please elaborate on the implications of the reported "significant numerical uncertainty" for the interpretation of the results.

We thank the reviewer for this important question. At lines 498–512 we discuss the implications of the numerical uncertainty: the C-grid staggering over the slope can omit one velocity component in bottom cells, which affects energy flux estimates more severely than energy density (uncertainty <20%). Since the integrated flux is dominated by the near-bottom layer, the missing component distorts its magnitude and direction, so we do not report dissipation as a residual. However, because the barotropic-to-baroclinic conversion is an order of magnitude smaller than the total dissipation shown in Fig. 14, the conclusion that barotropic tides dominate the regional energy budget remains unchanged.