nature portfolio

Peer Review File

Enhanced generation of internal tides under global warming

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

The manuscript titled "Enhanced generation of internal tides under global warming" is a commendable and ambitious effort by the authors to emphasize the necessity of incorporating changes in ocean stratification into mixing parameterizations in the future CMIP projections. However, I have several concerns that need to be addressed to significantly improve the quality of the manuscript and effectively convey its importance to a broader scientific community.

Major comments:

What is the specific reason and justification for choosing a high carbon emission scenario of SSP585? Considering the worst-possible scenario may not be an ideal way to convince the scientific community to integrate stratification changes into mixing parameterizations in the future CMIP projections. I'd strongly suggest considering different CMIP6 scenarios and look at how this 8% increase varies between them for high-mode internal tides. Also, I'd encourage the authors to look at different time-periods rather than just the last decade 2091-2100, so that it'll give a better picture of how mixing is projected to change in the near-future.

Lines 74-75. This statement may not be entirely true, especially with respect to how the internal tide energy conversion is going to change based on the CMIP projections. Decarlo et al. (2015) suggested that Internal wave activity could increase in Northern South China based on CMIP5 data in different RCP scenarios. Yadidya and Rao (2022) used CMIP6 projections and internal tide energy budget from MITgcm simulations to show that increase in stratification could increase the generation and propagation of internal tides in the Andaman Sea and Bay of Bengal. Later, Guo et al. (2024) argued that increase in stratification led to decrease in internal tide activity near the Luzon Strait and South China Sea, thereby indicating caution before correlating increase in stratification with increase in internal tide activity across different regions.

Line 377: Code availability - The statement saying that MatlabR2017a is used for plotting is a bit vague. I'd encourage the authors to save the code used for analysis and plotting into a sharable repository using resources like Github.

Minor comments:

Line 327: Any specific reason for not using the latest version of TPXO (version 9)?

Reviewer #2 (Remarks to the Author):

Review of the manuscript „Enhanced generation of internal tides under global warming " by Z. Yang et al.

The manuscript analyzes future changes in the generation of baroclinic tides in the deep ocean by the linear interaction of barotropic tides and topography under global warming. By using the stratification from state-of-the-art global warming simulations, the impact of changes in near-bottom as well as depth-averaged stratification on the generation of baroclinic tides is studied. It is shown that these stratification changes differently impact low-baroclinic and high-baroclinic mode tides. Enhanced depth-averaged stratification leads to a reduction of the baroclinic tide wavenumber and results in enhanced generation of high-baroclinic mode tides and reduced low-baroclinic-mode tides. The increased energy transfer to high-baroclinic-mode tides suggest enhanced mixing over rough topography.
The manuscript is very well written, assumptions made and results are clearly presented. To my mind it represents an important step in the understanding of changing ocean dynamics under global warming worth publishing. My main concern regard, however, the somehow unclear importance of the obtained results with regard to the vertical transport of heat, fresh water and carbon globally or the meridional overturning circulation when compared to other mechanisms changing as well in a global warming scenario. How relevant is an 8% increase in the generation of high-baroclinic-mode internal tides that has to be dissipated locally? The question is what are the consequences of such an increase?

Some specific comments:
L87-90: Is it correct that the suggested consequence would be that more energy is available for deep ocean mixing, i.e. does this additional energy has to be accounted for in energetically consistent models? What would be the resulting internal wave field and particularly the depth-distribution of enhanced mixing in such a scenario? For example, I would guess that the downward increase of vertical viscosity over rough topography would likely enhance with consequences for diapycnal downwelling in the ocean interior (e.g. Ferrari et al. 2016).

L137-138 Is there an estimate of the role of internal tide generation in shallower regions (shallower than 500m) and downward propagation of tidal energy into the deep ocean to put it in perspective?

L138: I would like to see how important very high baroclinic-mode tides are (how important is it to integrate to mode 50?). I would guess that there is almost no contribution above mode 25 or so. Please include a plot of tidal energy conversion as function of mode number into the supplementary material.

L174-175: correlation: How is it calculated? On a grid-point base? Is this correlation just based on the topography?

L351-353: What is the contribution of baroclinic tides generated at the continental slope and shelf breaks in areas with water depth shallower than 500m but propagating along beams into the deep ocean. Is there a possibility that this contribution changes significantly as well?

Ferrari, R., Mashayek, A., McDougall, T., Nikurashin, M., & Champin, J.-M. (2016). Turning ocean mixing upside down. Journal of Physical Oceanography, 46(7), 2239–2261. https://doi.org/10.1175/jpo-d-15-0244.1

Reply to the first reviewer

We are very grateful to you for your time in carefully reading our manuscript and providing helpful comments that make our manuscript better. We have carefully considered each of your comments (in black) and revised the manuscript accordingly. Please find our response (in blue) to your comments below.

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Thanks for your question. The temporal changes of stratification and further tidal energy conversion rate can be caused by both natural internal variabilities (noises) and anthropogenic forcings (signals). We choose the SSP585, a high carbon emission scenario, to enhance the signal-to-noise ratio, providing a qualitatively more reliable projection of anthropogenic changes of tidal energy conversion.

We fully agree with you that the quantitative responses of tidal energy conversion to greenhouse gas warming depend on the carbon emission scenarios. To address your question, we have calculated the projected future changes of tidal energy conversion under SSP245, a medium carbon emission scenario which may be acceptable for most countries pursuing sustainable growth (Fig. R1). The change of total tidal energy conversion E^{1-50} under SSP245 is qualitatively similar to but quantitively smaller in magnitude than that under SSP585 (Fig. R1). Furthermore, both the projected results under SSP245 and SSP585 show that the change of E^{1-50} is dominated by that of high-mode tidal energy conversion $E^{4\text{-}50}$ (Fig. R1). The values of $E^{4\text{-}50}$ increase by about 5% and 8% under SSP245 and SSP585, respectively. Therefore, conclusions derived under SSP585 also qualitatively hold under SSP245.

Following your advice, we have plotted the time series of globally integrated tidal energy conversion changes under SSP585 (Fig. R2). The values of E^{1-50}, $E^{1\text{-}3}$ and $E^{4\text{-}50}$ increase with the time. The increase of E^{1-50} is primarily attributed to $E^{4\text{-}50}$ at all the times. Therefore, the deep-ocean mixing over rough topography is likely to be enhanced in the near future and the enhancement would become larger in magnitude as the time increases.

We have added Fig. R1 and R2 to the Supplementary Materials and briefly discussed the above results in the revised manuscript. Please see line 202-208.

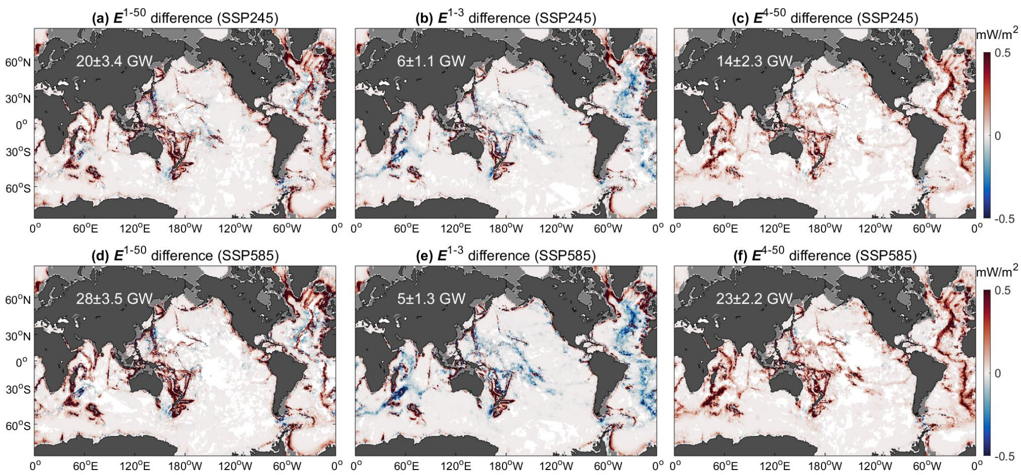

Fig. R1. Response of tidal energy conversion and its modal partition to global warming under the SSP245 and SSP585. a-c, Geographical distribution of projected changes (2091-2100 minus 1995-2004) of total tidal energy conversion E^{1-50} (a), and its partition into low modes $E^{1\text{-}3}$ (b) and high modes $E^{4\text{-}50}$ under the SSP245 (c). **d-f,** Same as **a-c,** but under the SSP585. Changes insignificant at a 95% confidence level are filled in white. Numbers in white represent the globally integrated values as well as their 95% confidence intervals.

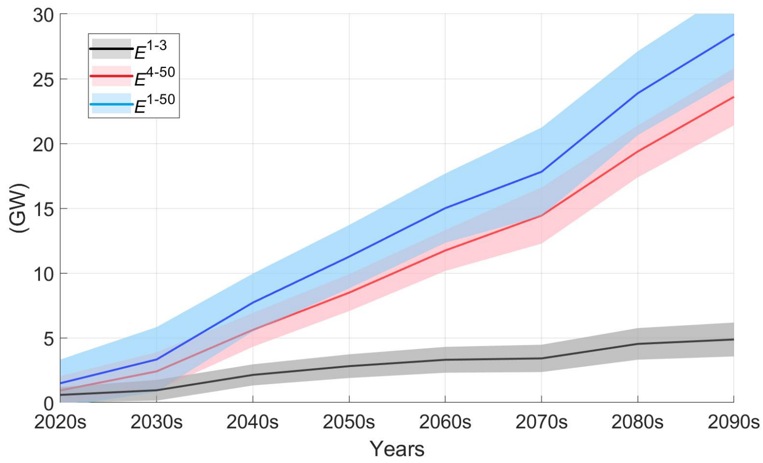

Fig. R2. Projected changes of globally integrated tidal energy conversion under the SSP585. Changes of the total tidal energy conversion E^{1-50} (blue) and its partition into low modes E^{1-3} (black) and high modes E^{4-50} (red), relative to the time-mean values during 1995-2004. The color shadings represent their 95% confidence intervals.

Lines 74-75. This statement may not be entirely true, especially with respect to how the internal tide energy conversion is going to change based on the CMIP projections. Decarlo et al. (2015) suggested that Internal wave activity could increase in Northern South China based on CMIP5 data in different RCP scenarios. Yadidya and Rao (2022) used CMIP6 projections and internal tide energy budget from MITgcm simulations to show that increase in stratification could increase the generation and propagation of internal tides in the Andaman Sea and Bay of Bengal. Later, Guo et al. (2024) argued that increase in stratification led to decrease in internal tide activity near the Luzon Strait and South China Sea, thereby indicating caution before correlating increase in stratification with increase in internal tide activity across different regions.

We are grateful to you for listing these useful references. We have revised this sentence as follows.

"There have been some regional studies showing that the enhanced stratification could cause complicated changes in the tidal energy conversion (Decarlo et al. 2015; Yadidya and Rao 2022; Guo et al. 2024). Yet it remains unclear how the tidal energy conversion and its modal partition respond to global warming on a **global scale**."

Please see Line 75-78.

Line 377: Code availability - The statement saying that MatlabR2017a is used for plotting is a bit vague. I'd encourage the authors to save the code used for analysis and plotting into a sharable repository using resources like Github.

We have added a code link to reproduce the results (https://doi.org/10.7910/DVN/BF5CSO).

Minor comments:

Line 327: Any specific reason for not using the latest version of TPXO (version 9)?

We also calculated the tidal energy conversion with TPXO 9 (Fig. R3). The globally integrated tidal energy conversion is slightly smaller than that of TPXO 8. However, they have similar geographical distributions, and the energy conversion to high-mode internal tides $E^{4\text{-}50}$ is also projected to rise by about 8% by the end of the 21st century. Therefore, we believe that using the latest version of TPXO will not change our conclusions.

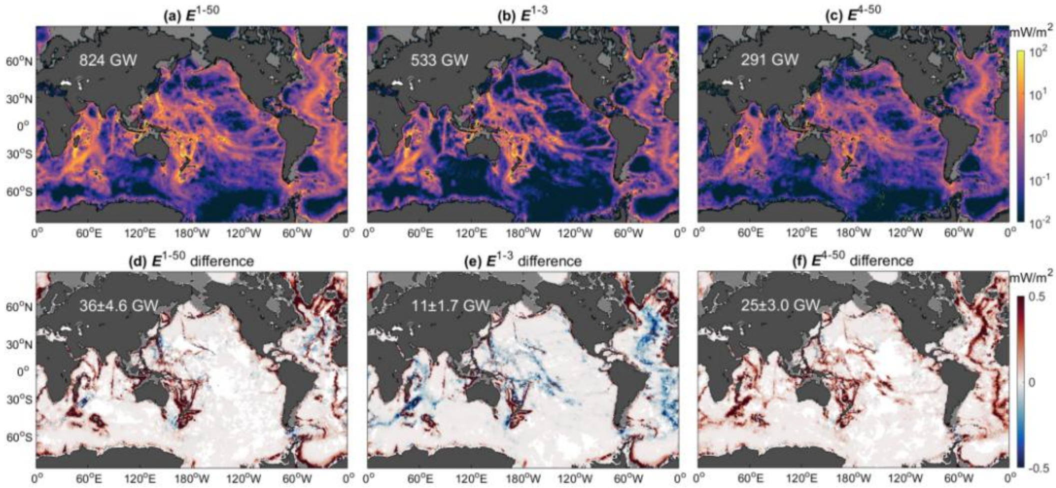

Fig. R3. Same as Fig. 2 but calculated based on TPXO 9.

Reference:

1. Decarlo, T. M., Karnauskas, K. B., Davis, K. A. & Wong, G. T. F. Climate modulates internal wave activity in the Northern South China Sea. Geophysical Research Letters 42, 831 – 838 (2015).

2. Guo, Z. et al. Variability of the M2 internal tides in the Luzon Strait under climate change. Climate Dynamics (2024).

3. Yadidya, B. & Rao, A. D. Projected climate variability of internal waves in the Andaman Sea. Communications Earth and Environment 3, (2022).

Reply to the second reviewer

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We thank you for your helpful comments. We have performed analysis to show that the Atlantic meridional overturning circulation (AMOC) and the dianeutral upwelling change significantly in response to the 8% increase of high-mode tidal energy conversion. These significant changes suggest the importance of our results in predicting and understanding future climate changes. Please see detailed descriptions in our response to your specific comments.

Some specific comments:

L87-90: Is it correct that the suggested consequence would be that more energy is available for deep ocean mixing, i.e. does this additional energy has to be accounted for in energetically consistent models? What would be the resulting internal wave field and particularly the depth-distribution of enhanced mixing in such a scenario? For example, I would guess that the downward increase of vertical viscosity over rough topography would likely enhance with consequences for diapycnal downwelling in the ocean interior (e.g. Ferrari et al. 2016).

Yes, our results suggest more energy would be dissipated over rough topography due the increase of high-mode tidal energy conversion, leading to enhanced deep-ocean diapycnal mixing there. This is shown in Fig. 6 by using a tidal mixing parameterization for high-mode internal tides.

Following your advice, we evaluate the effects of 8% increase of high-mode tidal energy conversion on the climate. We first analyze the change of the Atlantic meridional overturning circulation (AMOC) in response to the 8% increase of high-mode tidal energy conversion. This is done by running a pair of numerical simulations based on a global OGCM with a tidal mixing parameterization for high-mode internal tides (St Laurent et al. 2002). The OGCM has a nominal horizontal resolution of 1° and 60 layers vertically and is driven by the climatological atmospheric forcing constructed from the NCEP–NCAR reanalysis (Kalnay et al. 1996), GXGXS precipitation dataset (Large and Yeager 2004) and GISS radiation model (Zhang et al. 2004). The OGCM is initialized from rest and spun up for 600 years to reach a quasi-equilibrium state. The high-mode tidal energy conversion in the tidal mixing parameterization is obtained from the empirical formula proposed by St Laurent et al. (2002). Then two experiments (Exp-Historical and Exp-Future) are branched off and run for another 1000 years. They share the same setting except that the high-mode tidal energy conversions in the Exp-Historical and Exp-Future are replaced by the historical (1995-2014) and future (2091-2100) mean values estimated in this study (Fig. 2c and f). In other words, the globally integrated high-mode tidal energy conversion in the Exp-Future is 8% higher than that in the Exp-Historical.

Fig. R1b shows the difference of time-mean AMOC during the last 100 years between Exp-Historical and Exp-Future. The enhanced tidal mixing accelerates the lower limb of the AMOC by about 10%. Such an increase is comparable in magnitude to the projected decrease (~10%) of the lower limb of the AMOC under a high carbon emission scenario caused by the intrusion of the Antarctic Bottom Water (Heuzé et al. 2015), suggesting the important effects of the 8% increase of high-mode tidal energy conversion on climate changes.

In addition to the AMOC, we analyze the effects of 8% increase of high-mode tidal energy conversion on the dianeutral upwelling that is important for the formation of deep water (Munk and Wunsch 1998). The dianeutral upwelling transport is calculated following the method of de Lavergne et al. (2016):

$$T\left(\gamma^n\right) = \iint_{A\left(\gamma^n\right)} \frac{\partial F}{\partial \gamma^n} dA \quad (1)$$

where γ^n is the neutral density, F is the neutral density flux, and the integral is computed over the isosurface of γ^n (denoted as $A(\gamma^n)$). The F is defined as:

$$F = -\int_{-H}^{z_{A(\gamma^n)}} \left[b \frac{\partial \rho}{\partial \Theta} \frac{\partial}{\partial z}\left(\kappa_\rho \frac{\partial \Theta}{\partial z}\right) + b \frac{\partial \rho}{\partial S_{\mathrm{A}}} \frac{\partial}{\partial z}\left(\kappa_\rho \frac{\partial S_{\mathrm{A}}}{\partial z}\right) \right] dz \quad (2)$$

where H is the sea water depth, $z_{A(\gamma^n)}$ is the vertical coordinate of $A(\gamma^n)$, the factor $b = \partial_\perp \gamma^n / \partial_\perp \rho$ with $\partial_\perp$ is the gradient along the diapycnal direction, ρ is the potential density, Θ is the conservative temperature, S_{A} is the absolute salinity, and κ_ρ is the parameterized turbulent diffusivity induced by breaking of high-mode internal tides (St Laurent et al. 2002).

To analyze the effects of 8% increase of high-mode tidal energy conversion on $T\left(\gamma^n\right)$, we fix the γ^n, Θ and S_{A} as their climatological mean values derived from the WOCE hydrographic atlas (Gouretski and Koltermann 2004) and vary the high-mode tidal energy conversions in the tidal mixing parameterization. There is a significant increase in $T(\gamma^n)$ due to the enhanced tidal mixing (Fig. R2). The peak of the globally integrated $T(\gamma^n)$ increases by about 10%, from 8.8 to 9.7 Sv.

We have added Fig. R1 and Fig. R2 to the Supplementary Materials and briefly discussed the above results in the revised manuscript. Please see line 235-246.

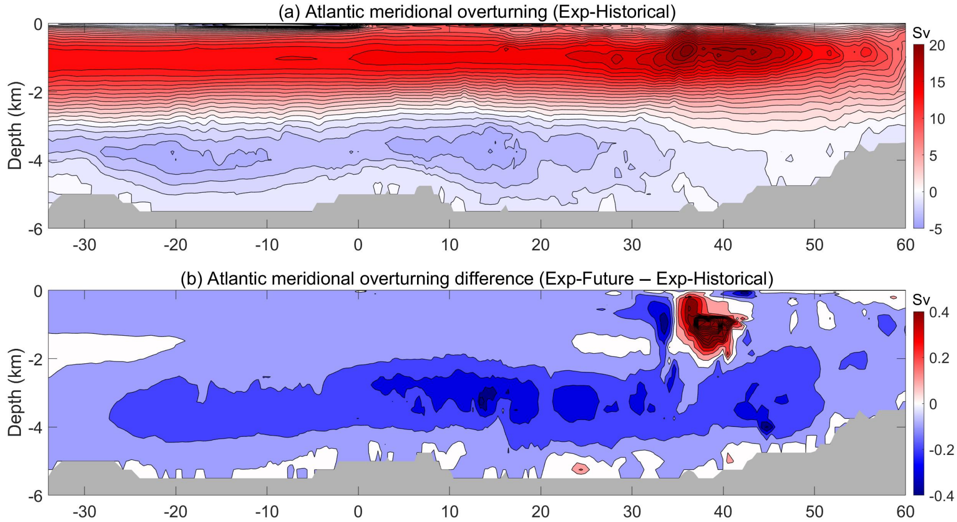

Fig. R1. Response of the Atlantic meridional overturning circulation (AMOC) to the increase of energy conversion into high-mode internal tides. a, Time-mean AMOC in the Exp-Historical. **b,** Difference of AMOC between Exp-Historical and Exp-Future (the latter minus the former).

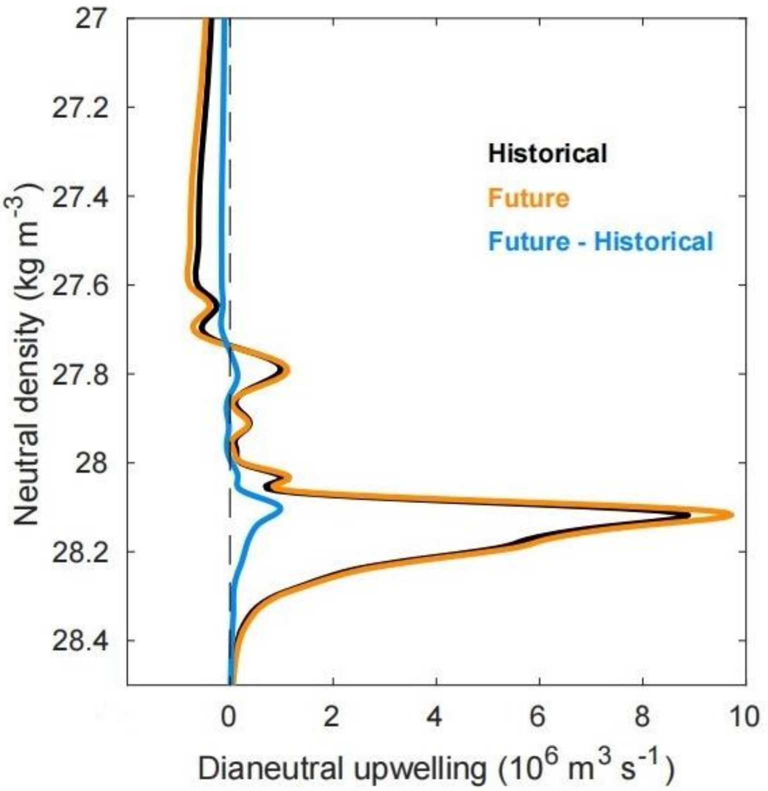

Fig. R2. Response of dianeutral upwelling to the increase of energy conversion into high-mode internal tides. Black and yellow lines represent the globally integrated $T\left(\gamma^n\right)$ calculated using the historical (1995-2014) and future (2091-2100) high-mode tidal energy conversions in the tidal mixing parameterization, with the blue line representing their difference (future minus historical).

L137-138 Is there an estimate of the role of internal tide generation in shallower regions (shallower than 500m) and downward propagation of tidal energy into the deep ocean to put it in perspective?

We didn't estimate the tidal energy conversion in shallower regions (shallower than 500 m) as the calculation may become unreliable due to violation of the assumptions of small tidal excursion and subcritical topography. However, the downward propagation of tidal energy generated in the shallow regions is suggested to have little impact on the deep ocean mixing, since most of their energy ultimately dissipates in the top kilometer of the ocean (de Lavergne et al. 2020).

We have cautioned readers about the limitation of our calculations in the revised manuscript. Please see Line 402-404 in the revised manuscript.

L138: I would like to see how important very high baroclinic-mode tides are (how important is it to integrate to mode 50?). I would guess that there is almost no contribution above mode 25 or so. Please include a plot of tidal energy conversion as function of mode number into the supplementary material.

Thanks for your question. Fig. R3 shows the modal partition of tidal energy conversion under global warming. We have added Fig. R3 to the Supplementary Materials.

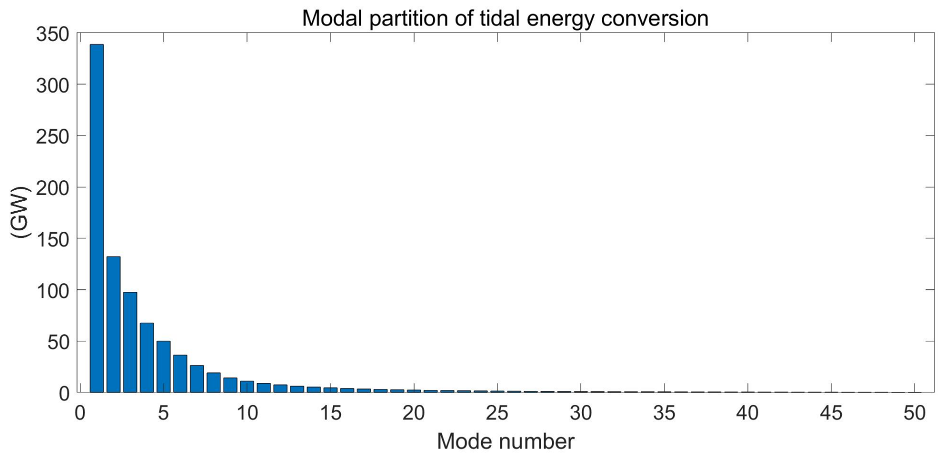

Fig. R3. Energy conversion into internal tides of different modes. Globally integrated tidal energy conversion into different modes during 1995-2004.

L174-175: correlation: How is it calculated? On a grid-point base? Is this correlation just based on the topography?

The correlation is computed as the correlation between the geographical maps of E^{1-50} and $E^{1-50}_{M_2}$. Specifically, we treat E^{1-50} and $E^{1-50}_{M_2}$ at each grid point as one pair of samples.

L351-353: What is the contribution of baroclinic tides generated at the continental slope and shelf breaks in areas with water depth shallower than 500m but propagating along beams into the deep ocean. Is there a possibility that this contribution changes significantly as well?

Yes, high resolution numerical model (Opel et al. 2024) and satellite observations (Zhao 2023) have suggested the tidal energy conversion at the continental slope and shelf breaks could also change significantly. However, as the downward propagation of tidal energy generated in the shallow regions is suggested to have little impact on the deep ocean mixing (de Lavergne et al. 2020), it is unlikely that taking into account the anthropogenic change of internal tide generation in the shallow regions could qualitatively change the major conclusions of our study.

Reference:

1. de Lavergne, C., Madec, G., Le Sommer, J., Nurser, A. J. G. & Naveira Garabato, A. C. On the consumption of Antarctic Bottom Water in the abyssal ocean. J. Phys. Oceanogr. 46, 635–661 (2016).

2. de Lavergne, C. et al. A Parameterization of Local and Remote Tidal Mixing. J. Adv. Model. Earth Syst. 12, (2020).

3. Ganachaud, A. & Wunsch, C. Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. Nature 408, 453 – 457 (2000).

4. Heuzé, C., Heywood, K. J., Stevens, D. P. & Ridley, J. K. Changes in global ocean bottom properties and volume transports in CMIP5 models under climate change scenarios. J. Clim. 28, 2917–2944 (2015).

5. Kalnay, E. et al. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437 – 471 (1996).

6. Large, W. G. & Yeager, S. G. Diurnal to Decadal Global Forcing For Ocean And Sea-ice Models: The Data Sets And Flux Climatologies (National Center for Atmospheric Research, Boulder, 2004).

7. Munk, W. & Wunsch, C. Abyssal recipes II: energetics of tidal and wind mixing. Deep-Sea Res. I 45, 1977–2010 (1998).

8. Opel, L., Schindelegger, M. & Ray, R. D. A likely role for stratification in long-term changes of the global ocean tides. Communications Earth and Environment 5, (2024).

9. St Laurent, L., Simmons, H. & Jayne, S. Estimating tidally driven mixing in the deep ocean. Geophys. Res. Lett. 29, 21-1–21-4 (2002).

10. Zhao, Z. Satellite Evidence for Strengthened M2 Internal Tides in the Past 30 Years. Geophysical Research Letters 50, (2023).

11. Zhang, Y-C., Rossow, W. B., Lacis, A. A., Oinas, V. & Mishchenko, M. I. Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP

and other global data sets: Refinements of the radiative transfer model and the input data. J. Geophys. Res. 109, D19105 (2004).

REVIEWERS' COMMENTS

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I'm happy with the revisions made by the authors. I recommend the publication of this article in Nature Communications.

Reviewer #2 (Remarks to the Author):

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The authors have revised the manuscript very well, and I am happy to accept it. Congratulations on an excellent paper. I still have some very minor comments that might be taken into account by the authors.

L27: I would prefer “freshwater”
L76: I think “complicated” is not appropriate. I would suggest “… could result in locally enhanced or reduced tidal energy conversion …”
L313: include N_b and bar{N} in the caption to link it with the Figure titles
Fig. 6: Title is somehow misleading and not consistent with previous figure titles. Here, diapycnal diffusivity, k_rho is shown. Title could be k_rho and k_rho difference
L362: “counterpart” of N change is unclear. Just state how it is estimated as difference between two periods? Which one?
L381: Do not use the same sign “PSI” for the integrated and non-integrated variable.
L431: Link cannot be opened here.

Supplementary material
Suppl. Fig. 1: Would be more consistent with the caption if N_b would be plotted at the y-axis and Depth/Roughness on the x-axis.
Suppl. Fig. 2: Would be nice to see the cumulative sum of the energy conversion (right axis).
L110: mode 2, mode 3 and mode 4
L199, L217: Please see …

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We thank you for your positive and helpful comments that led to a much improved manuscript.

L27: I would prefer “freshwater”

Changed.

L76: I think “complicated” is not appropriate. I would suggest “… could result in locally enhanced or reduced tidal energy conversion …”

Thanks. We have changed this sentence following your suggestion.

L313: include N_b and bar{N} in the caption to link it with the Figure titles

They have been added in the caption now.

Fig. 6: Title is somehow misleading and not consistent with previous figure titles. Here, diapycnal diffusivity, k_rho is shown. Title could be k_rho and k_rho difference

Thanks. The title has been revised.

L362: “counterpart” of N change is unclear. Just state how it is estimated as difference between two periods? Which one?

Thanks. We have now added a statement in Line 363-364.

L381: Do not use the same sign “PSI” for the integrated and non-integrated variable.

We use a new sign ψ for the integrated variable now.

L431: Link cannot be opened here.

Thanks. We have added a new link (https://doi.org/10.5281/zenodo.13346979).

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