Review #2

Internal tides vertical structure and steric sea surface height signature south of New Caledonia revealed by glider observations

Arne Bendinger[1,a], Sophie Cravatte[1,2], Lionel Gourdeau[1], Luc Rainville[3], Clément Vic[4], Guillaume Sérazin[4,a], Fabien Durand[1], Frédéric Marin[1], and Jean-Luc Fuda[5]

[1]Université de Toulouse, LEGOS (CNES/CNRS/IRD/UT3), Toulouse, France
[2]IRD, Centre IRD de Nouméa, New Caledonia
[3]Applied Physics Laboratory, University of Washington, Seattle, WA, USA
[4]Laboratoire d'Océanographie Physique et Spatiale, Univ. Brest, CNRS, Ifremer, IRD, IUEM, Brest, France
[5]Aix Marseille Univ., Université de Toulon, CNRS, IRD, MIO UM 110, Marseille, France
[a]now at: Laboratoire d'Océanographie Physique et Spatiale, Univ. Brest, CNRS, Ifremer, IRD, IUEM, Brest, France
[b]now at: Institut de Recherche de l'Ecole Navale (IRENav), EA 3634 - Ecole Navale, 29240, Brest, France

Correspondence: Arne Bendinger (arne.bendinger@univ-brest.fr)

Summary

This paper describes an effort to investigate internal tide structure using glider observations. I found this paper to be interesting and not hard to follow.

We thank the reviewer for her/his review. In the following, we would like to address the reviewer's minor comments. The reviewer stated that she/he had additional thoughts which were enumerated by reviewer #1. We therefore refer to review #1 for additional information.

Minor comments

Line 8-9 – eddy-internal tide interactions are certainly one source of discrepancy. I don't discount this mechanism, but there are other potential sources of error as well (such as topography and stratification). What about those?

We agree with the reviewer that other mechanisms and sources of errors exist (e.g. topography and stratification). Eddy-internal tide interactions as a major driver for the discrepancies relies on the findings deduced from the ray tracing. In contrast to the current's impacts, we find that the impact of topography and stratification is of less importance on the spatial scales that we consider here in internal tide propagation direction (compare \wo currents with \w currents scenario in Fig. 9). For the sake of simplicity, we applied the ray tracing on bathymetry from ETOPO2v2 (Smith and Sandwell, 1997) and climatological stratification from the World Ocean Atlas (Locarnini et al., 2018; Zweng et al., 2019). For evident reasons, the latter does not take into account eddy-induced stratification changes in internal tide propagation direction - a potential source for tidal incoherence. Though, it has recently been shown in a more realistic ray tracing approach that the eddy-associated currents make a greater contribution to internal tide refraction than eddy-associated stratification (Guo et al., 2023). We made modifications by replacing *primarily* by *in large part* in lines 8-9.

Line 14 – "glider observations' predominating coherent nature". Why would this be the case? I assume there isn't something intrinsic about the glider observations that would make them have a coherent nature. Is the observation record too short to observe much incoherence, was this a time period of low variability or some other reason?

We agree with the reviewer that the phrase *glider observations' predominating coherent nature* may be confusing. We changed it in lines 12-14: *Notably, the steric SSH from glider observations aligns closely with empirical estimates derived from satellite altimetry, highlighting the internal tide's predominant coherent nature during the glider's sampling*.

Lines 44-46 – problems separating high and low frequency signals. Can these be separated enough to get insight into the coherent/incoherent question?

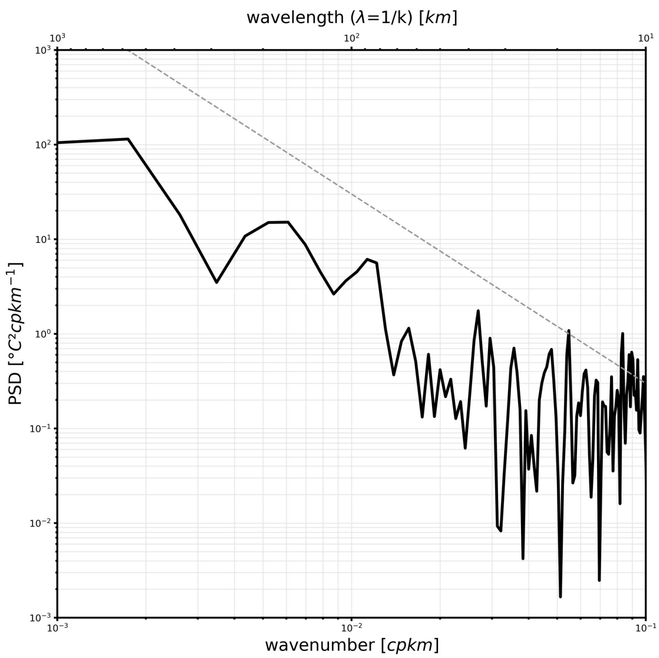

Figure R1. Power spectrum density of conservative temperature at 300 m depth. The dashed gray line indicates a k^{-2} slope for reference.

This is clearly a fair question to ask. Despite the limitations that are associated with the glider sampling, we believe that we were able to show that the glider observations were successfully exploited to extract the high-frequency internal-tide signal. The coherent semidiurnal signal from the model (analysed on the model grid and not using the pseudo-glider sampled data) gives us confidence in this regard (compare Fig. 8a and Fig. 8c). Further, the conclusions made on tidal incoherence are supported by the ray tracing to show that the potential departure from tidal coherence (compare Fig. 8b and Fig.8c) can be indeed attributed to eddy-internal tide interactions through tidal beam refraction (Fig. 9-10).

In the new manuscript we refer to Rudnick and Cole (2011) and Rainville et al. (2013) who address this question with regard to the glider sampling (lines 55-57). According to Rudnick and Cole (2011), the glider observations underlie Doppler smearing (due to glider's finite speed and aliasing due to discrete sampling), which in turn is responsible for the projection from higher wavenumbers onto lower wavenumbers. A break in slope would indicate the minimum resolved wavenumber. Similarly to Rudnick and Cole (2011), we find the break of slope around 30 km wavelength (see Fig. R1)

Line 121 - the numerical model used, has it been compared against other models and/or observations to show it is sufficiently accurate/realistic to aid in this study?

We kindly refer to Bendinger et al. (2023) in which the numerical model has been introduced and largely validated. Further, it contains an assessment on the model's capability to realistically reproduce motion from the large-scale circulation down to high-frequency motion while justifying the model's eligibility to simulate internal-tide dynamics. Here, we will recall the main conclusions.

The mean circulation was assessed using the Argo-CARS merged velocity product from Kessler and Cravatte (2013) revealing a good representation of the regional circulation. The model accurately depicts the westward zonal jets with well-located positions and reasonable amplitudes (see Fig. 2 in Bendinger et al., 2023. Mesoscale eddy variability was validated against satellite altimetry. Overall, the spatial pattern of simulated EKE is in good agreement (see Fig. 3 in Bendinger et al., 2023). Maximum levels of EKE are elevated in the model south of New Caledonia. Though, this can be inter alia attributed to the conventional two-dimensional gridded satellite altimetry products, which do not resolve wavelengths smaller than 150-200 km in our region and may miss the contribution of smaller-scale dynamics.

Kinetic energy levels were validated against moored in-situ observations revealing that model energy levels are very close to observations from seasonal to inertial timescales (180 d to 36 h), i.e., for mesoscale and submesoscale processes. Inertial and tidal energy peaks are also in good agreement (Fig. R2. Furthermore, for higher frequencies ($> f$), the simulation with tidal forcing (red line) introduces a major improvement to the simulation without tidal forcing (blue line). This validation, even if only performed at one location, gives us confidence in the ability of the numerical simulation to correctly represent the tides and their interaction with mesoscale processes.

The realism of the governing M2 internal tide was investigated by the internal tide's expression in SSH while being compared to the satellite-altimetry-derived empirical estimates from the HRET model (Zaron, 2019). The M2 SSH amplitude for modes 1-2 is shown in Fig. R3. It is in good agreement with the HRET model concerning the spatial representation of the M2 SSH for both mode 1 and mode 2. Overall, mode 1 seems to be enhanced in our model, whereas mode 2 is underestimated in some regions. Note that the given differences may be associated with the different time periods the datasets are referenced to as well as the length of the time series for the model (1 year) and altimetry (25 years).

We added a small paragraph on the model's validation in Sect. 2.2, lines 148-154.

Line 127 – tidal forcing along boundary. It appears you're forcing with FES along the boundary. This is barotropic forcing only. Mazloff et al (2020-JGR) talk about the importance of remote forcing for regional modeling of internal waves. Can you comment on the results of this paper and either it's relevance or lack of relevance to this work?

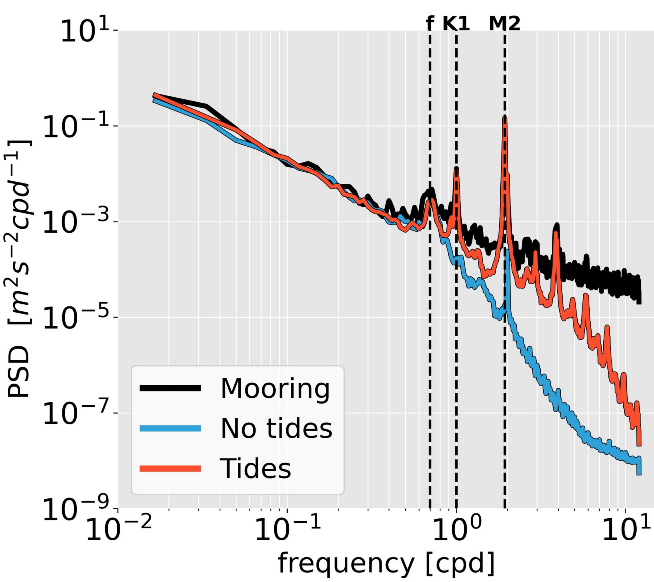

Figure R2. Power spectral density of near surface (20-100 m) horizontal kinetic energy for CALEDO60 without (blue) and with (red) tidal forcing for the full model time series near 167.25° E, 20.43° S in the New Caledonian eastern boundary current (see Fig. 2 in Bendinger et al., 2023). The energy spectra are compared to a mooring time series that was deployed between November 2010 and October 2011 (Durand et al., 2017). The vertical dashed black lines are representative of the inertial frequency f, the peak frequency of the K1 diurnal tide, and the peak frequency of the M2 semidiurnal tide.

We appreciate the reviewer's comments. It is indeed relevant for this study. We are aware of the importance of remote forcing for regional modeling of internal waves (e.g. Nelson et al., 2020; Mazloff et al., 2020; Siyanbola et al., 2023). In our model configuration, we account for high-frequency oceanic variability from remote regions by employing a sufficiently large host-grid domain (TROPICO12). Within this domain, barotropic tide forcing is applied at the open lateral boundaries, and a two-way lateral boundary coupling is maintained between the host (TROPICO12) and nesting grid (CALEDO60) throughout the simulation. The latter ensures the free internal wave propagation from remote regions into the regional domain. The model's domain configuration is shown in Fig. R4. For more information, we kindly refer to Sect. 2.1 in Bendinger et al. (2023).

Figure 7 – I find this gray scale plot hard to interpret. The other plots in the paper are color, was there a reason why gray scale was used? I may be missing something that this color bar choice was intended to help convey.

We thank the reviewer for this remark. This was also noted by reviewer #1. We changed the colormap in Fig. 7.

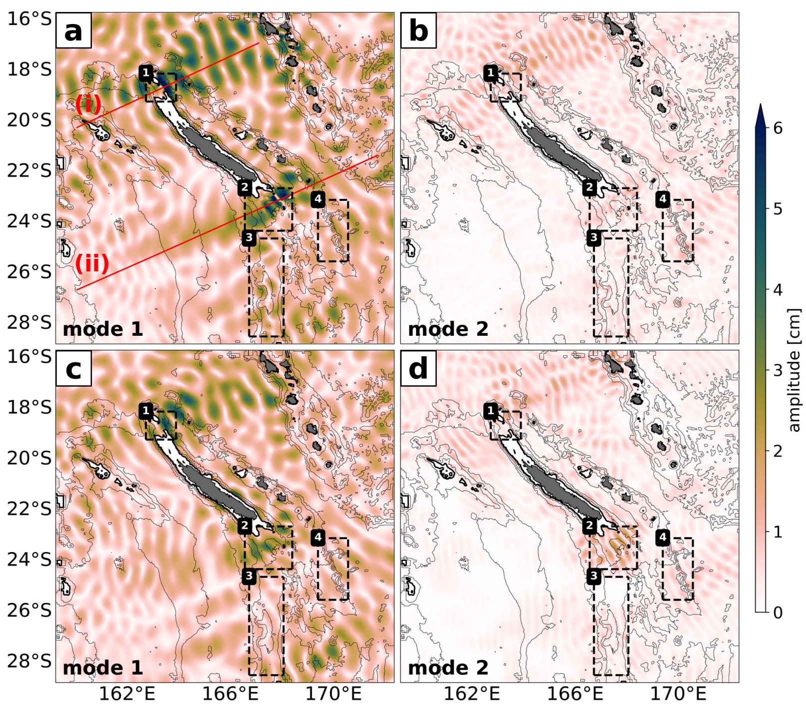

Figure R3. CALEDO60 M2 SSH amplitude for **(a)** mode 1 and **(b)** mode 2 in comparison with the empirical estimates of the High Resolution Empirical Tide (HRET) model for **(c)** mode 1 and **(d)** mode 2.

Line 255 – "have never been used the SSH signature" doesn't read right. Did you intend to convey "have never been used to derive the SSH signature"?

We thank the reviewer for spotting this little mistake. Indeed, we meant *have never been used to derive the SSH signature*.

Line 344 – There are other sources of potential disagreement as well, such as forcing, topography and stratification errors and unconstrained variability. Have you explored or considered those?

We acknowledge the sources of potential disagreement stated by the reviewer. The stratification has been validated against climatology in Bendinger et al. (2023) revealing a good agreement of the normalized modal structures for the four lowest modes and for both the displacement and vertical velocity (see their Fig. 6). The topography has also received very careful attention. The bathymetry is composed of the GEBCO_2019 grid and a compilation of multibeam echosounder data acquired over the years in the New Caledonia economic zone (see Sect. 2.1 in Bendinger et al., 2023). In this way, we ensure the accurate representation of fine-scale bathymetric features, including ridges and seamounts around New Caledonia. Figure 8a-c together with the ray tracing results in Fig. 9-10 strongly suggest that the main source of discrepancy is tidal incoherence. Nonetheless, other error sources certainly exist. We replaced the paragraph in lines 340-344 to the following: *Given that both glider observations and the full-model pseudo glider feature identical sampling, variations linked to the spring-neap tide cycle are not valid hypotheses. Potential sources for the discrepancies may lie in the erroneous representation of the model's*

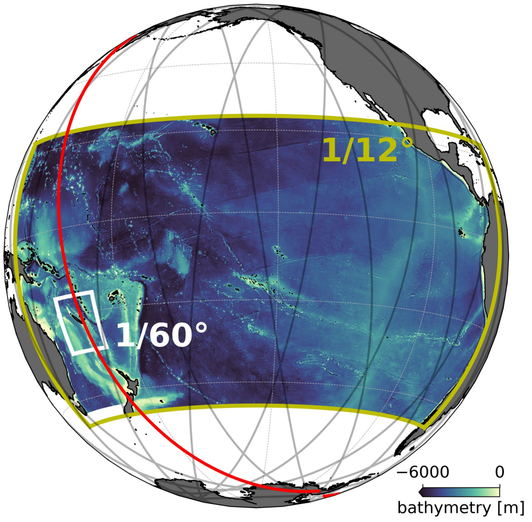

Figure R4. Model setup showing the host grid domain (TROPICO12, yellow box) and the nesting grid (CALEDO60, white box) including the bathymetry (shading) and the SWOT CalVal orbit (black transparent lines) with the highlighted ground track (red line) that crosses the CALEDO60 domain.

bathymetry and/or stratification leading to inaccuracies in simulating the precise beam location or the model's vertical mode structure. Though, the used bathymetry product has received careful attention in the model configuration and is believed to accurately represent fine-scale bathymetric features while stratification was validated against climatology (Bendinger et al., 2023) (lines 375-380 in the new manuscript).

References

Bendinger, A., Cravatte, S., Gourdeau, L., Brodeau, L., Albert, A., Tchilibou, M., Lyard, F., and Vic, C.: Regional modeling of internal-tide dynamics around New Caledonia – Part 1: Coherent internal-tide characteristics and sea surface height signature, Ocean Science, 19, 1315–1338, https://doi.org/10.5194/os-19-1315-2023, 2023.

Durand, F., Marin, F., Fuda, J.-L., and Terre, T.: The east caledonian current: a case example for the intercomparison between altika and in situ measurements in a boundary current, Marine Geodesy, 40, 1–22, https://doi.org/10.1080/01490419.2016.1258375, 2017.

Guo, Z., Wang, S., Cao, A., Xie, J., Song, J., and Guo, X.: Refraction of the M2 internal tides by mesoscale eddies in the South China Sea, Deep Sea Research Part I: Oceanographic Research Papers, 192, 103 946, https://doi.org/10.1016/j.dsr.2022.103946, 2023.

Kessler, W. S. and Cravatte, S.: Mean circulation of the Coral Sea, Journal of Geophysical Research: Oceans, 118, 6385–6410, https://doi.org/10.1002/2013JC009117, 2013.

Locarnini, M., Mishonov, A., Baranova, O., Boyer, T., Zweng, M., Garcia, H., Seidov, D., Weathers, K., Paver, C., and Smolyar, I.: World ocean atlas 2018, volume 1: Temperature, NOAA Atlas NESDIS 81, p. 52pp, https://archimer.ifremer.fr/doc/00651/76338/, 2018.

Mazloff, M. R., Cornuelle, B., Gille, S. T., and Wang, J.: The importance of remote forcing for regional modeling of internal waves, Journal of Geophysical Research: Oceans, 125, e2019JC015 623, https://doi.org/10.1029/2019JC015623, 2020.

Nelson, A., Arbic, B., Menemenlis, D., Peltier, W., Alford, M., Grisouard, N., and Klymak, J.: Improved internal wave spectral continuum in a regional ocean model, Journal of Geophysical Research: Oceans, 125, e2019JC015 974, https://doi.org/10.1029/2019JC015974, 2020.

Rainville, L., Lee, C. M., Rudnick, D. L., and Yang, K.-C.: Propagation of internal tides generated near Luzon Strait: Observations from autonomous gliders, Journal of Geophysical Research: Oceans, 118, 4125–4138, https://doi.org/10.1002/jgrc.20293, 2013.

Rudnick, D. L. and Cole, S. T.: On sampling the ocean using underwater gliders, Journal of Geophysical Research: Oceans, 116, https://doi.org/10.1029/2010JC006849, 2011.

Siyanbola, O. Q., Buijsman, M. C., Delpech, A., Renault, L., Barkan, R., Shriver, J. F., Arbic, B. K., and McWilliams, J. C.: Remote internal wave forcing of regional ocean simulations near the US West Coast, Ocean Modelling, 181, 102 154, https://doi.org/10.1016/j.ocemod.2022.102154, 2023.

Smith, W. H. and Sandwell, D. T.: Global sea floor topography from satellite altimetry and ship depth soundings, Science, 277, 1956–1962, https://doi.org/10.1126/science.277.5334.1956, 1997.

Zaron, E. D.: Baroclinic tidal sea level from exact-repeat mission altimetry, Journal of Physical Oceanography, 49, 193–210, https://doi.org/10.1175/JPO-D-18-0127.1, 2019.

Zweng, M., Seidov, D., Boyer, T., Locarnini, M., Garcia, H., Mishonov, A., Baranova, O., Weathers, K., Paver, C., Smolyar, I., et al.: World ocean atlas 2018, volume 2: Salinity, NOAA Atlas NESDIS 82, p. 50pp, https://archimer.ifremer.fr/doc/00651/76339/, 2019.