Response to Reviewers

We would like to thank all the reviewers for your careful reading and constructive comments on this manuscript. We believe our manuscript is now improved after addressing these concerns. The reviewers' comments are listed below, point by point, with the reviewers' original comments in italics and our responses in bulleted blue Roman text.

Anonymous Referee #1

This manuscript presents a well-executed study on regional wave simulations along the Australian coast using the WAVEWATCH III (WW3) model, with particular emphasis on improving model performance over the Great Barrier Reef (GBR) through a two-step subgrid parameterization approach. The study is timely and relevant, demonstrating both technical rigor and practical applicability in modeling ocean waves in complex coastal environments.

I believe this manuscript is suitable for publication after minor revisions. I recommend the authors consider the following suggestions to further enhance the clarity and completeness of the work:

Thank you very much for your positive comments. We will revise our manuscript by following all of your suggestions. Please see our point-by-point reply below.

1. Brief description of the prevailing wave conditions along the northeastern Australian coast would help contextualize the results. Based on the manuscript, the region appears to be predominantly swell-influenced. It would be helpful to comment on model performance under wind-sea–dominated conditions.

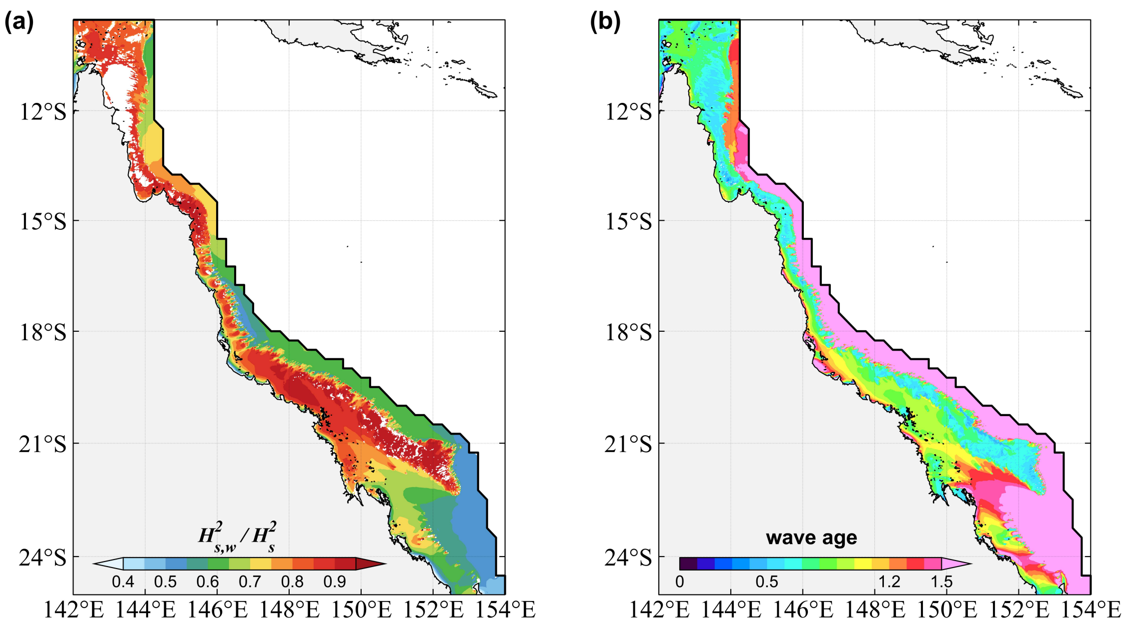

Figure R1. Spatial distribution of the (a) wind sea fraction and (b) wave age in the Great Barrier Reef region, based on the Run 7 simulation for 2011.

- Thank you for this comment.

- Figure R1 presents the spatial distribution of the wind sea fraction, calculated as $(H_{s,w}/H_s)^2$, where $H_{s,w}$ and H_s are the significant wave heights of wind sea and the total spectrum, respectively, and wave age ($c_p/U_{10}\Delta\theta$, where c_p is the phase velocity for the peak wave frequency, U_{10} is 10 m wind speed and $\Delta\theta$ denotes the angle between the wind direction and peak wave direction) in the Great Barrier Reef (GBR) region based on our Run 7 simulation for 2011. The results show that the seaward side of the GBR and its southern region are primarily dominated by swell originating from the Coral Sea (e.g., Smith et al., 2023). Due to the dissipation of long-period wave energy by the coral reefs, the wave field over the reef matrix is largely composed of wind sea, with relatively low wave age values (ranging from 0.5 to 1). The inter-reef areas, however, remain significantly influenced by offshore swell. In the lee of the reef, the wave field is primarily governed by locally generated waves (e.g., Gallop et al., 2014).
- Based on the results shown in Fig. R1, it can be indicated that the outer edge of the GBR is dominated by swell conditions. As the low-frequency energy is dissipated, wind sea conditions become dominant within the reef matrix. This suggests that our model does indeed represent both wave regimes, and the overall reasonable performance demonstrates the robustness of our approach.
- Moreover, in our modelling framework, the UOST energy dissipation is applied separately across wave directions and frequencies. A correction factor, ψ (Eq. 14), is included in the UOST scheme to adjust the level of dissipation based on wave age (Mentaschi et al., 2015). As indicated by the equation, full dissipation is applied only when the wave age exceeds 1.5, corresponding to swell-dominated conditions. When the wave age lies between 0.5 and 1.5, representing mixed sea states, the dissipation is gradually scaled. For wave age below 0.5—indicating wind-sea-dominated conditions—the UOST source term does not contribute to energy dissipation.
- In summary, wind sea conditions are reasonably accounted for in our model. We clarified this point in the revised manuscript. Please see the track changes version of our manuscript, in which several lines on the description of wave age (the beginning of Section 2.3) and a new panel in Fig. 2 (i.e., Fig. 2c) are added.

Smith, C., Vila-Concejo, A. and Salles, T: Offshore wave climate of the Great Barrier Reef. *Coral Reefs*, 42, 661–676, https://doi.org/10.1007/s00338-023-02377-5, 2023.

Gallop, S. L., Young, I. R., Ranasinghe, R., Durrant, T. H., and Haigh, I. D: The large-scale influence of the Great Barrier Reef matrix on wave attenuation. *Coral Reefs*, 33, 1167–1178, https://doi.org/10.1007/s00338-014-1205-7, 2014.

Mentaschi, L., Pérez, J., Besio, G., Mendez, F. J., and Menendez, M.: Parameterization of unresolved obstacles in wave modelling: A source term approach, *Ocean Modelling*, 96, 93–102, https://doi.org/10.1016/j.ocemod.2015.05.004, 2015.

2. The authors have carefully included several important coastal processes, such as tidal variations and wave–current interactions. However, the representation of wind stress could be further improved. The drag coefficient used in ST6 is originally developed for open-ocean conditions; a brief discussion of its applicability and limitations in reef-dense or shallow water environments would be valuable.

- Thank you for the comment.
- As the reviewer pointed out, the drag coefficient used in ST6, based on the work of Hwang (2011) was originally developed based on open-ocean observations. Please note that, this empirical drag coefficient is used by ST6 for two purposes: 1) converting the usually used U_{10} to friction velocity u_*, 2) acting as an upper limiter for the wave-induced stress which can be calculated from the wind input term (e.g., Zieger et al. 2015). Our present results suggest that nearshore wave simulations using this configuration perform reasonably well, indicating that this drag coefficient might be reasonably applied to shallow coastal environments. In this regard, I would like to note that a drag coefficient law of the similar form to the one used by ST6 has been implemented by SWAN (Zijlema et al. 2012) and were extensively used for coastal wave modelling. The reviewer is referred to Liu et al. (2017, their Fig. 9) for the comparison of C_d between the studies of Hwang (2011) and Zijlema et al. (2012).
- That said, we agree that the representation of wind stress could be further improved. For example, Chen et al. (2020) investigated the impact of shoaling wind waves on C_d in coastal waters.
- Following your and reviewer #2' suggestions, we now included a new subsection 5.3 in the revised manuscript to discuss other possible uncertainties in our simulations. Please see the second paragraph in Section 5.3, which is specifically related to the discussion here.

Hwang, P. A.: A note on the ocean surface roughness spectrum. *Journal of Atmospheric and Oceanic Technology*, 28(3), 436-443, https://doi.org/10.1175/2010JTECHO812.1, 2011.

Zieger, S., Babanin, A. V., Rogers, W. E., and Young, I. R: Observation-based source terms in the third-generation wave model WAVEWATCH III. *Ocean modelling*, 96, 2-25, http://dx.doi.org/10.1016/j.ocemod.2015.07.014, 2015.

Zijlema, M., Van Vledder, G. P., and Holthuijsen, L. H: Bottom friction and wind drag for wave models. *Coastal Engineering*, 65, 19-26, https://doi.org/10.1016/j.coastaleng.2012.03.002, 2012.

Liu, Q., Babanin, A., Fan, Y., Zieger, S., Guan, C., and Moon, I. J: Numerical simulations of ocean surface waves under hurricane conditions: Assessment of existing model performance. *Ocean Modelling*, 118, 73-93, https://doi.org/10.1016/j.ocemod.2017.08.005, 2017.

Chen, X., Hara, T., & Ginis, I. (2020). Impact of shoaling ocean surface waves on wind stress and drag coefficient in coastal waters: 1. Uniform wind. *Journal of Geophysical Research: Oceans*, 125(7), e2020JC016222, https://doi.org/10.1029/2020JC016222, 2020.

3. While the manuscript addresses the challenges of wave modeling over complex reef geometries, it would strengthen the discussion to acknowledge potential limitations in applying the UOST scheme to other reef-rich coastal systems globally.

- Thank you a lot for the suggestion.
- As discussed in the Introduction and Section 2.3, the Great Barrier Reef (GBR) is the largest coral reef system in the world, consisting of nearly 3,000 individual reefs arranged in a complex and irregular pattern (e.g., Fig. 4). In such areas, the use of the UOST scheme helps correct the excessive overestimation of wave energy. As shown in Fig. 8, the improvements achieved by applying the UOST scheme are more evident in

regions with higher reef density. This suggests that the structural complexity of the reef matrix s likely a key factor influencing wave energy dissipation.

- In addition to offshore reefs such as the GBR, coral reef systems also include fringing or land-backed reefs that are directly attached to coastlines or islands, such as those found in the Philippines. In these cases, because the reefs are closely connected to land, their additional capacity to dissipate wave energy may be limited. As a result, the improvements achieved by applying the UOST scheme may not be as significant in such areas, where the role of the reef in energy dissipation is less pronounced compared to offshore, structurally complex reef systems like the GBR. This may represent a potential limitation of the current approach.
- We included a discussion of this point in a newly added subsection (Section 5.3). Please see the third paragraph of our new Section 5.3 for more details.

Anonymous Referee #2

The authors present a numerical simulation study of ocean waves in the Great Barrier Reef (GBR) region of Australia. This research incorporates state-of-the-art physics and numerical schemes, with principal methodologies comprising: implementation of an unstructured mesh to accurately resolve Australia's extensive coastline, and development of a two-step modeling strategy to address unresolved individual coral reefs and their dissipative effects. This two-step strategy treats discrete reefs as unresolved obstacles that act as complete barriers to wave energy, and parameterizes subgrid-scale reef-induced dissipation through a novel source term to represent the effects of unresolved obstacles. Critically, the experimental design features comprehensive controls: appropriate specification of open boundary conditions; isolation of interference from wind forcing errors, tidal currents, and surface circulation on GBR wavefield simulations. Validation against satellite altimetry and buoy observations demonstrates reduction of wave height bias from >100% to <20%, providing compelling evidence of substantially enhanced model performance following strategy implementation.

This methodology offers valuable insights for simulating wave fields in archipelago-fringed marginal and regional seas where dense reef systems exist. I recommend acceptance of this work for publication in your esteemed journal. However, I think a minor revision is necessary before the acceptance. Below are a few comments and suggestions for the authors' consideration.

Thank you very much for your thoughtful comments and suggestions. We will address all of these points in the revised manuscript. Please find our point-by-point reply below.

1. The coral reef location data used in this study were extracted from the global dataset provided by UNEP-WCMC et al. (2010), which defines the outer polygons of reef structures. These polygons may represent reef platforms rather than the actual outlines of reef canopies, and such discrepancies could introduce uncertainties into the model results. A comment on the possible effect of the accuracy of the reef outline on the model performance is desired in the discussion or conclusion section.

- Thank you for this insightful comment.
- The multi-source global coral reef dataset v4.0, compiled by UNEP-WCMC et al. (2010), is widely used as a standard reference in reef-related modeling studies (e.g., Lowe and Falter, 2015; Lyons et al., 2024), and was among the highest-quality publicly available datasets at the time of our study. This dataset was compiled from a global collection of Landsat 7 ETM+ satellite imagery, along with various other sources and nautical charts at different scales, with a maximum achievable spatial resolution of approximately 30 meters.
- In this study, we extracted the reef outlines of the GBR from the UNEP-WCMC v4.0 dataset. Based on these outlines (shown as grey squares in Fig. 3), two transparency parameters, α and β, were calculated.
- As the reviewer pointed out, the accuracy of the reef outline could influence model performance and, more specifically, could affect the calculation of the α and β coefficients in our scheme. If higher-resolution or more accurate datasets become

available in the future (e.g., Lyons et al., 2024), this issue could be further investigated using higher-resolution models.

- Following your and reviewer #1' suggestions, we now included a new subsection 5.3 in the revised manuscript to discuss other possible uncertainties in our simulations. In the regard, please see the first paragraph of our Section 5.3.

UNEP-WCMC, WorldFish Centre, WRI, and TNC: Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project, Version 4.0. Includes contributions from IMaRS-USF and IRD (2005), IMaRS-USF (2005), and Spalding et al. (2001). Cambridge (UK): UNEP World Conservation Monitoring Centre. http://data.unep-wcmc.org/datasets/1, 2010.

Lowe, R. J. and Falter, J. L.: Oceanic Forcing of Coral Reefs, *Annual Review of Marine Science*, 7, 43–66, https://doi.org/10.1146/annurev-marine-010814-015834, 2015.

Lyons, M.B., Murray, N.J., Kennedy, E.V., Kovacs, E.M., Castro-Sanguino, C., Phinn, S.R., Acevedo, R.B., Alvarez, A.O., Say, C., Tudman, P., and et al.: New global area estimates for coral reefs from high-resolution mapping. *Cell Reports Sustainability*, 1(2), https://doi.org/10.1016/j.crsus.2024.100015, 2024.

2. The application of UOST has clearly improved the model's performance in simulating significant wave height and peak period in the Great Barrier Reef region. However, the simulated values of T02 are underestimated. This may be related to the choice of the empirical coefficient ψ in Eq. (14). I would appreciate if the authors could stress the limitation of this engineering scaling on the model results.

- Thank you for your valuable comment.
- We appreciate this comment and consider it as a valid point—the underestimation of T02 may be related to the use of the empirical coefficient ψ in Eq. (14). This coefficient was introduced into the UOST scheme based on previous theoretical arguments and modelling experiences (Mentaschi et al. 2015, Mentaschi et al. 2018). When the shadow effect term S_{se} (Eq. 13) was derived, an important assumption is that for the cell in question, its upstream energy F_{Ad} equals to its cell-averaged energy F_B, provided that the local wave growth and other physical processes changing wave energy are neglected. If, however, there is local wind wave growth, an assumption $F_{Ad} \sim F_B$ may cause overestimation of the dissipation owing to the shadow effect. Therefore, an empirical (engineering) scaling function ψ was proposed to reduce the shadow effect for relatively young wave components. Thus far, the validity of this empirical scaling function has not been checked seriously. For doing so, dedicated spectral observations in the proximity of both the upstream and downstream of islands and reefs are desired, which are unfortunately unavailable to us at present.
- Following the suggestion of the reviewer, we included the discussion above in the revised manuscript to further stress the uncertainty and the possibility for further improvement of the current approach. Please see the second paragraph of the updated Section 5.3.

Mentaschi, L., Pérez, J., Besio, G., Mendez, F. J., and Menendez, M.: Parameterization of unresolved obstacles in wave modelling: A source term approach, *Ocean Modelling*, 96, 93–102, https://doi.org/10.1016/j.ocemod.2015.05.004, 2015.

Mentaschi, L., Kakoulaki, G., Vousdoukas, M., Voukouvalas, E., Feyen, L., and Besio, G.: Parameterizing unresolved obstacles with source terms in wave modeling: A real-world application, *Ocean Modelling*, 126, 77–84, https://doi.org/10.1016/j.ocemod.2018.04.003, 2018.

3. In line 551 of the Appendix, the authors mention a comparison between model results and satellite altimeter data before and after accounting for tidal effects (Run5 vs. Run8). However, the results of this comparison are not presented. It is recommended that the authors include these results, as they could provide useful reference for future research.

- Thanks for your suggestion.
- We appreciate your careful reading of the Appendix. The comparison between Run5 and Run8 was not originally included because the differences in statistical metrics (e.g., bias and RMSE) were relatively minor. However, we agree that presenting these results could still provide useful context for future applications. Figure R2 presents the comparison results between Run5 and Run8, and we included this figure in the Supplements of the revised manuscript (i.e., Fig. S9).

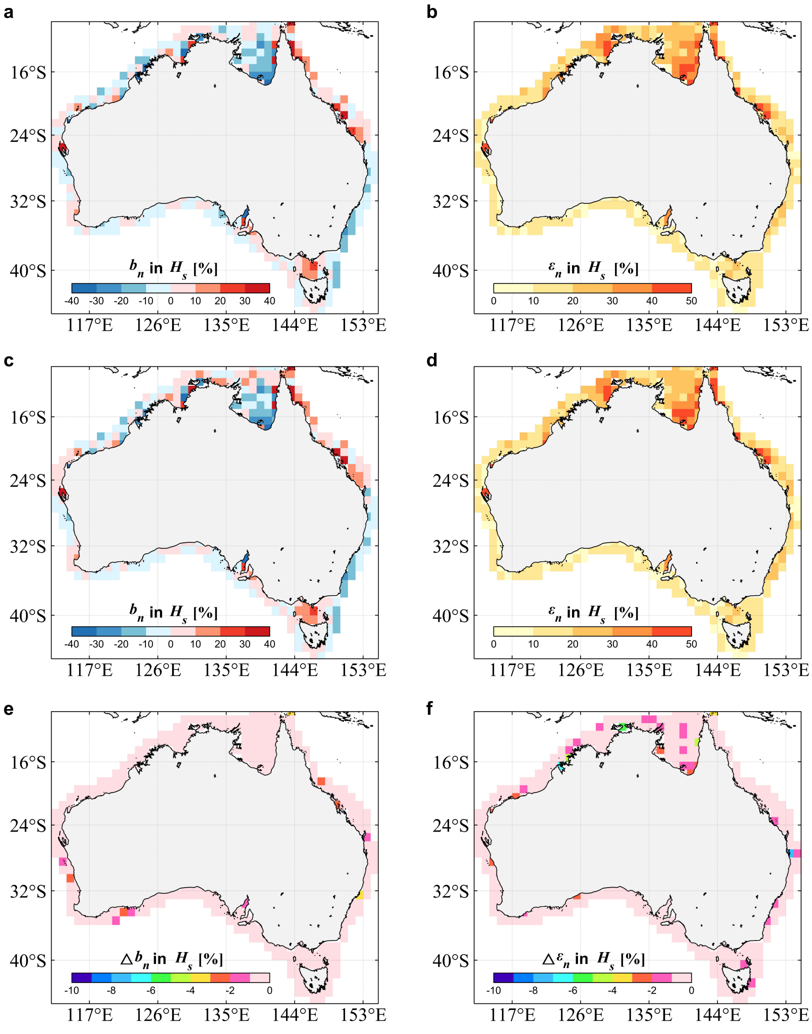

Figure R2. Error statistics of the significant wave height H_s gridded in 1°×1° bins for the WW3 for a two-month period (October – November 2011). (a, b) Run 5 (without FES2014) and (c, d) Run 8 (with FES2014) relative to the altimeter wave records: (a, c) the normalized bias b_n, (b, d) normalized RMSE ε_n. (e, f) Differences in H_s errors between the two WW3 runs: (e) $\Delta b_n = b_{n,8} - b_{n,5}$, (f) $\Delta\varepsilon_n = \varepsilon_{n,8} - \varepsilon_{n,5}$.