20.12.2022

<u>Answer RC1:</u>

The authors wish to thank the anonymous reviewer for his/her thorough assessment and constructive comments which greatly helped us to improve the quality of the paper. We are pleased to address the point-by-point answers to your review in blue in the supplement to this comment.

Best regards,

The authors.

Main comments:

1. Methodology:

- As stated by the authors (L60-61), "wave characteristics used to estimate wave setup are sensitive to water level changes in shallow waters, where waves interact with the ocean bottom." From section 2.2.4 I understand that the wave model considers water-level variations only for the wave propagation (i.e., group velocity and wave number) while "coastal (depth-induced) breaking is not included" in the model (L92-95). My concern is that by not including the depth-induced wave-breaking the authors are missing a fundamental depth-dependent process, which can have a first order effect on the wave statistics in shallow water and hence on the wave setup. In addition, as the authors also explain in the introduction (L35-36), the wave setup is in fact due to the depth-induced wave breaking. So what I cannot understand is how the authors can assess the impact of water-level variations on the wave setup if the leading order physical mechanism driving the wave setup is not included in the model. I think the authors should carefully address this point in their manuscript.

The Introduction, Sect. 2.1 (Description of the wave model) and Discussion have been revised to clarify this point by (1) highlighting more clearly the processes taken into account in the model that are likely to be impacted by non-linear interactions and those that are not activated (2) modifying the introduction which focused too much on the coastal wave breaking compared to the model's capabilities and the purpose of the study.

To explain the choice not to activate the depth-induced wave breaking in the model, the two following sections have been added in the Discussion:

"5.3 Limitations associated with the applicability of the parametrization to coastal points

To calculate the wave setup for the coastal points of our regional domain, we chose to use the simple parameterization of Stockdon et al., 2006 based on deep water parameters. However, the coastal points are theoretically not purely deep water as shown in Figure 2a (yellow dotted lines). Yet, this approach, used in other climate studies (Melet et al., 2018, 2020a; Lambert et al., 2020), appears pragmatic given the model resolution limitations (Sect. 5.1) and the processes accounted for in the wave model (Sect. 2.1).

5.4 Impact of the absence of depth-induced wave breaking

Very close to the coast, the depth-induced wave breaking is a fundamental depth-dependent process that can have a first-order effect on the shallow water wave statistics and thus on the wave setup. As explained in Sect. 2.1, the physics associated with the explicit representation of coastal breaking waves is not activated. Such an approach is justified because our primary interest is to calculate the wave setup contribution to include it in further analyses on extreme water levels and the parameterization used to compute this contribution is based on deep water parameters (Sect. 2.5) that are not supposed to be affected by coastal wave breaking.

With the coastal wave breaking included, the significant wave heights should be substantially impacted in shallow waters. The impact of the inclusion of the water level variations in the wave model would also probably differ. A perspective for this study would be to take into account coastal wave breaking and to apply new specific wave setup formulations which would not require deep water characteristics or to use a wave model that directly resolve the wave setup."

Some tests have been performed with the coastal wave breaking activated (Battjes and Janssen, 1978) in the regional wave model for the significant wave extreme event of the year 1993 in the Bay of Mont Saint Michel (Fig. RC1). These tests suggest that the conclusions of larger extreme significant wave heights due to the inclusion of the water level variations occurring at high tide are still qualitatively valid. Nevertheless, the impact is larger with the coastal wave breaking activated, which is expected to be even more significant at the end of the century with the mean sea level rise.

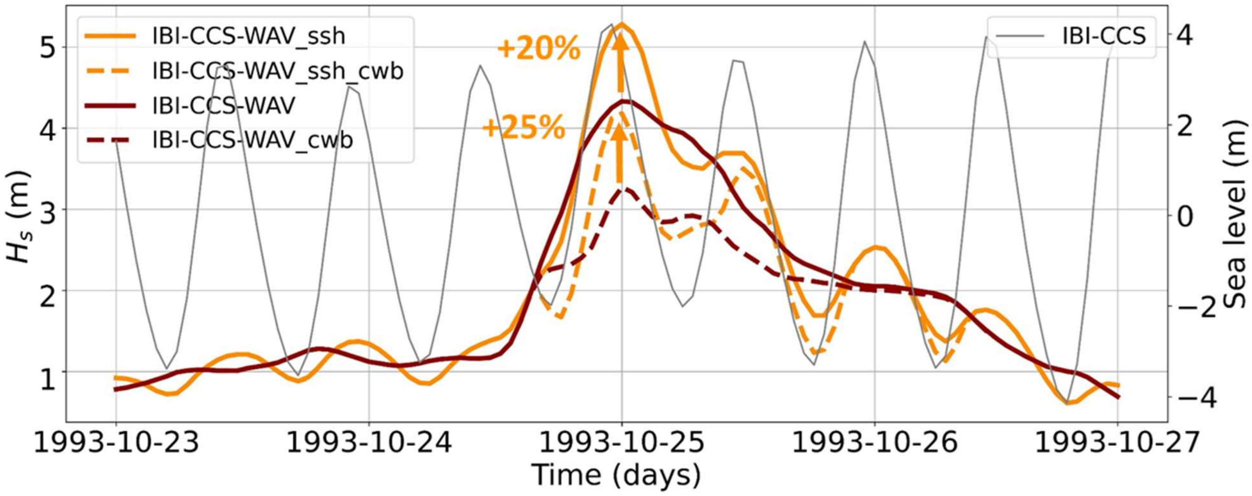

Figure RC1: Same as Fig. 12a of the paper but with new simulations that include the depth-induced coastal wave breaking: IBI-CCS-WAV_ssh_cwb and IBI-CCS-WAV_cwb.

- When assessing the impact of water-level forcing on the wave setup at a domain level the authors report an impact in few coastal locations. My doubt is: how much can we trust these results given the 6m minimum depth approximation?

Sect. 5.1 has been revised:

"5.1 Model resolution limitations

In our study, the impact of including the hourly water level variations in the wave model is limited by several resolution aspects. The first limitation is the horizontal resolution of the wave model. The model resolution of 1/10 ° (~10 km) is conditioned by the computational cost due to the length of the simulations needed to address the question of extremes in a climate scale. It does not allow a very fine representation of the coastline and of the bathymetry in the coastal zones. For instance, to maintain a realistic balance between the 10 km horizontal resolution and the water depth, the minimum bathymetry is set to 6 m (i.e. time-mean minimum of 6 m) because it would have been unrealistic to have a bathymetry of 1 m within a 10 km grid point. In consequence, the wave model has fewer intermediate and shallow water areas than a higher resolution model and thus less non-linear interactions. […] Therefore, the results are not representative of the real situation at the coast but rather give a regional information."

- Also, could it be that the authors found a generally small (very few locations) impact because the depth-induced breaking is neglected and the minimum depth approximation is applied?

Our work highlights that wave-water level non-linear interactions exist and should be considered for applications on extreme wave events for large tidal range areas and especially for climate applications due to future sea level rise. However, as stated by the reviewer, due to the resolution of the model and therefore the limit on the minimal bathymetry, the estimates provided represent only a part of the processes responsible for the wave-water level non-linear interactions.

A sentence has been added in Sect. 5.4:

"As the regional wave model does not have a very fine representation of the bathymetry or the coastline (Sect. 5.1) and does not resolve the wave transformations in the coastal zones, the estimates provided in this study only partially represent the processes responsible for the wave-water level non-linear interactions."

2. Validation:

- The title of section 3 is "Validation and projections of IBI-CCS-WAV, without wave-water level interactions" and in fact the figures of this section report data only for IBI-CCS-WAV. However, at L259-261 the authors state that "The ability of IBI-CCS-WAV and IBI-CCS-WAV_ssh to reproduce observed distributions is assessed for the mean state and the 99th percentile of the significant wave height and peak period since these variables are then used to compute the wave setup scaling". Is the IBI-CCS-WAV_ssh validated as well? If not (as I believe is the case), then I think the authors should also include the validation for the experiment using water-level forcing since, apart from the impact on the wave setup, it is also interesting and useful to know for the wave modelling community whether including this forcing can help to improve the accuracy of the model.

The validation of the IBI-CCS-WAV_ssh simulation has been added only on the two scatter plots of Figure 4 and 5 which are the comparisons to tide gauge data.

A paragraph has been added in Sect. 3.1.1 : "The comparison of IBI-CCS-WAV_ssh with the reanalysis is not relevant since the latter does not consider the forcing with hourly sea level variations. The IBI-CCS-WAV_ssh simulation is compared to the buoy data in Figure 4d,h and Figure 5,d,h. However, it is difficult to get useful information from these comparisons with buoys since they are not located at the coast. Actually, they are in areas where there is no impact of the wave-water level non-linear interactions (Sect. 4) so the performances of IBI-CCS-WAV_ssh are similar to those of IBI-CCS-WAV."

For the same reasons and also because we found that the inclusion of the water level variations on the wave model has no impact on the mean wave direction over the 1993-2014 period, we chose to not include the wave rose of IBI-CCS-WAV_ssh. A sentence is added Sect. 3.1.2 : "In Figure 6, the focus is only on the IBI-CCS-WAV simulation as we found that the impact of the water level variations on the mean wave direction was negligible over the 1993-2014 period."

3. Manuscript structure:

Thank you very much for this comment which has significantly improved the structure of the manuscript.

- In general, I think the structure of the paper should be substantially improved before being suitable for publication. Below, a list of possible changes:
- Section 2: this section is quite confused and not logically structured in my opinion. I would first move L101-112 as in intro of Sec. 2, improving the text and Fig 2 (the colours are to weak). Then, I think the authors could

a) describe the numerical wave model (sec 2.1), avoiding the references to global and regional simulations (e.g. L85), since I think can confuse the reader. Done.

b) describe the regional wave configuration IBI-CCS-WAV (sec 2.2): this is the real focus of this paper, all the other models are used to force this model in my opinion. Done. In addition, I would move L185-190 at the beginning of this section just to state at the beginning what is the aim of this model.

The authors finally decided to first describe the zone, the processes involved, and then to explain the downscaling methodology.

c) describe the external forcings (sec 2.3) with three subsections:

*) Atmospheric forcing (sec. 2.3.1), describing and validating (L138-152) CNRM-CM6-1-HR model and the fields used to force IBI-CCS-WAV. Also, please avoid the acronym GCM which is typically used for General Circulation Model instead.

Done. The acronym GCM has been removed.

*) Hydrodynamic forcing (sec 2.3.2), describing IBI-CCS and the fields used to force IBI-CCS-WAV. Done.

*) Wave forcing (sec 2.3.3), describing CNRM-HR-WAV and the fields used to force IBI-CCS-WAV. Done.

d) Inclusion of water level variations in the regional wave model: IBI-CCS-WAV_ssh (sec 2.4). Done.

e) Wave setup calculation (sec. 2.5): Please check the definition of the wave setup scaling – there is a delta in the definition (L243) that I think should not be there.

The delta has been removed.

- Section 4: I would first describe the impact on the entire coastal domain and after on the specific locations. Also, I think the authors should clarify better what is the rational behind the choice of those two specific locations. Why not for example the Bristol channel? The tidal range there is almost as large as in Mont-Saint Michel. Also, I would rewrite Sec. 4.2 and 4.1 (which are the most important sections in my opinion), trying to discuss more in depth what is the impact and to contextualise it, maybe moderating a bit the wording (e.g., "highly impacted") which I think it is not fully reflecting the results of the authors.

The impact on the entire domain is provided before the specific locations. The two specific locations are chosen in France as it is our country of interest here but in terms of processes, indeed, the Bristol Channel would also have been relevant for the effects of the large tidal range. The wording has been moderated in Sect. 4.1 and 4.2.

A paragraph has been added in Sect. 4.2

"However, it can be pointed out that the most significant increase in wave height occurs in both cases at high tide. These results are in agreement with Lewis et al., 2019 and Calvino et al., 2022 who both showed a significant increase in wave height at high tide at a finer scale. In Calvino et al., 2022, this impact seems to be explained mainly by the effect of bottom friction, which is less important at high tide as there is more water. In our case, additional analyses would be needed to understand which is the primary process included in the model (Sect. 2.1) responsible for the non-linear interactions."

Also, another section has been added in the Discussion to discuss more deeply the results:

"**5.6 Implications of the results on extreme wave projections**

Marine flooding hazards cannot be quantified based on wave setup alone but wave setup can locally partially balance or enhance water levels at the coast (Melet et al., 2020). Depending on the location (wave regimes, local ocean processes involved, sign of the extreme wave projected changes, amplitude of the projected changes in ocean processes), the inclusion of the non-linear interactions could thus enhance or balance the future wave extremes and may be important to consider for future flooding hazard calculations. The results presented in this study highlight that wave-water level non-linear interactions can be substantial for extreme wave height and wave setup, but are region dependent. For instance, the extreme wave projections are directly dependent on the water level variations forcing. In our case, the future water level variations and therefore a large part of the non-linear interactions are mainly associated with the mean sea level rise of about +80 cm and less so to changes in tides or storm surges. In other regions, large projected changes in tides or storm surges could impact the future waves conditions. For instance, Pickering et al., 2017 and Haigh et al., 2019 showed changes up to + 20 cm in the M2 component in the China Sea and in the Gulf of Saint Lawrence. Then, the future wave extremes could also be substantially more impacted in areas subject to larger mean sea level rise such as along the eastern coasts of the United States, in the Gulf of Mexico and in the Caribbean Sea where a rise of +1.4 m is expected at the end of the century under scenario SSP5-8.5 (Fox-Kemper et al., 2021)."

I would describe a bit better in the Conclusions and Abstract the limitations of your study.

A sentence has been added at the end of the Abstract: "However, as the wave setup is computed with a parameterization based on offshore characteristics, the depth-induced wave breaking is not activated in the model. The estimates provided in this study therefore only partially represent the processes responsible for the wave-water level non-linear interactions."

The end of the Conclusion has been revised: "However, as the regional wave model does not have a very fine representation of the bathymetry or the coastline and does not resolve the depth-induced wave breaking in the shallow areas, the estimates provided in this study only partially represent the processes responsible for the wave-water level non-linear interactions. Moreover, the results found might be dependent on the parametrization used to compute the wave setup and therefore on the beach slopes.

Specific comments

- L13: you don't need the acronym EWL here, since you don't use it anymore in the abstract.

Done.

- The authors may want to add some references at L170 – 173. Here I am suggesting some possible references for the North Atlantic (which is the area I am more familiar with): the Atlantic coasts are subject to very energetic events in terms of significant wave heights, wave periods and energy flows (e.g., Masselink et al. 2016, Bruciaferri et al. 2021) whereas the Mediterranean Sea and North Sea are more sheltered areas. In addition, the zone also contains very different tidal regimes with both macro and micro tidal regimes respectively in the English Channel/Celtic Sea (Valiente et al. 2018, Stokes et al. 2021) and in the Mediterranean Sea.

Some references have been added : "the Atlantic coasts are subject to very energetic events in terms of significant wave heights, wave periods and energy flows (Masselink et al., 2016; Bruciaferri et al., 2021) whereas the Mediterranean Sea and North Sea are more sheltered areas dominated by wind waves (Chen et al., 2002; Bergsma et al., 2022). In addition, the zone also contains very different tidal regimes with both macro and micro tidal regimes respectively in the English Channel/Celtic Sea (Valiente et al., 2019; Stokes et al., 2021) and in the Mediterranean Sea."

- L219-220: "Limitations related to the use of parameterizations have been extensively discussed in Melet et al., 2020" -> can the authors do a summary of those limitations here so that the reader is aware?

The limitations associated with the use of parameterizations (L229-237) have been moved to the Discussion section and completed by:

"**5.2 Limitations associated with the use of parametrizations for the wave setup**

Limitations in the use of parametrizations to estimate wave setup are thoroughly discussed in Melet et al., 2020; Lambert et al., 2020, including sensitivity analyses of the wave setup and runup contributions to different empirical parametrizations. The generic parametrization of Stockdon et al., 2006 used to compute the wave setup in our study is indeed subject to intrinsic limitations. A major limitation is that the formulation is only representative of sandy beaches. Other parameterizations (Guza and Thornton, 1981; Holman, 1986; dissipative case of Stockdon et al., 2006 or for a review Dodet et al. 2019) exist but they are often limited to specific coastal environments (e.g. dissipative sandy beaches, rocky cliffs) and have been calibrated with relatively few field data. The calibration therefore does not cover all the spectra of the environmental conditions.

For our large-scale study, another major limitation is that the parameterization relies on the specification of a beach slope. [L229-237]".

- L224: please define "foreshore".

The sentence has been modified: "where β is the foreshore beach slope (i.e. the slope in the swash zone)".

- L355: Figure 7 illustrates "projected **changes"** -> changes respect to what? Please clarify

"Projected changes in incoming waves conditions from 1986-2005 to 2081-2100" has been replaced by "Projected changes in incoming waves conditions for the 2081–2100 period (relative to 1986–2005)." Same for Figures 8 and 9.

- L422-425: please rephrase it.

L422-425 have been rephrased: "In Sect. 3.2, as reported in other studies, we observed a general decrease in mean and extreme significant wave height and peak period over the domain and a clockwise mean wave direction change along the French Atlantic coasts. As IBI-CCS-WAV seems to be representative of other studies, we can used it to assess methodological modelling questions such as the impact of considering the hourly water level variations on the wave model."

- L453: the most significant impact -> quite strong wording, you have an impact (not so strong) only in one location out of two in Fig. 10.

"the most significant impact" has been replaced by "the larger impact".

- L461: however small -> to me seems nihil

"is however small" has been replaced by "is however almost zero".

- L484-485: I would be careful here. If what the authors are saying is true, then why it is not valid everywhere, e.g. Mont-Saint Michel? Please clarify.

The sentence has been removed and we need to further investigate the impact on the mean state, maybe with a high tide/low tide analysis to assess if there is an asymmetry of the impact of the water level variations on waves.

References

Battjes, J. A. and Janssen, J. P. F. M.: Energy loss and set-up due to breaking random waves, Proceedings of 16th Conference on Coastal Engineering, Hamburg, Germany, 1978, 1978.

Bergsma, E. W. J., Almar, R., Anthony, E. J., Garlan, T., and Kestenare, E.: Wave variability along the world's continental shelves and coasts: Monitoring opportunities from satellite Earth observation, Advances in Space Research, 69, 3236–3244, https://doi.org/10.1016/j.asr.2022.02.047, 2022.

Bruciaferri, D., Tonani, M., Lewis, H. W., Siddorn, J. R., Saulter, A., Castillo Sanchez, J. M., Valiente, N. G., Conley, D., Sykes, P., Ascione, I., and McConnell, N.: The Impact of Ocean-Wave Coupling on the Upper Ocean Circulation During Storm Events, Journal of Geophysical Research: Oceans, 126, e2021JC017343, https://doi.org/10.1029/2021JC017343, 2021.

Calvino, C., Dabrowski, T., and Dias, F.: A study of the wave effects on the current circulation in Galway Bay, using the numerical model COAWST, Coastal Engineering, 180, 104251, https://doi.org/10.1016/j.coastaleng.2022.104251, 2022.

Chen, G., Chapron, B., Ezraty, R., and Vandemark, D.: A Global View of Swell and Wind Sea Climate in the Ocean by Satellite Altimeter and Scatterometer, Journal of Atmospheric and Oceanic Technology, 19, 1849–1859, https://doi.org/10.1175/1520-0426(2002)019<1849:AGVOSA>2.0.CO;2, 2002.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A., and Yu, Y.: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [MassonDelmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B. (eds.)]. Cambridge University Press. In Press. 2021

Guza, R. T. and Thornton, E. B.: Wave set-up on a natural beach, Journal of Geophysical Research: Oceans, 86, 4133–4137, https://doi.org/10.1029/JC086iC05p04133, 1981.

Holman, R. A.: Extreme value statistics for wave run-up on a natural beach, Coastal Engineering, 9, 527–544, https://doi.org/10.1016/0378-3839(86)90002-5, 1986.

Lambert, E., Rohmer, J., Cozannet, G. L., and Wal, R. S. W. van de: Adaptation time to magnified flood hazards underestimated when derived from tide gauge records, Environ. Res. Lett., 15, 074015, https://doi.org/10.1088/1748-9326/ab8336, 2020.

Lewis, M. J., Palmer, T., Hashemi, R., Robins, P., Saulter, A., Brown, J., Lewis, H., and Neill, S.: Wave-tide interaction modulates nearshore wave height, Ocean Dynamics, 69, 367–384, https://doi.org/10.1007/s10236-018-01245-z, 2019.

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., and Floc'h, F.: Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe, Geophysical Research Letters, 43, 2135–2143, https://doi.org/10.1002/2015GL067492, 2016.

Melet, A., Meyssignac, B., Almar, R., and Le Cozannet, G.: Under-estimated wave contribution to coastal sea-level rise, Nature Clim Change, 8, 234–239, https://doi.org/10.1038/s41558-018-0088-y, 2018.

Melet, A., Almar, R., Hemer, M., Cozannet, G. L., Meyssignac, B., and Ruggiero, P.: Contribution of Wave Setup to Projected Coastal Sea Level Changes, Journal of Geophysical Research: Oceans, 125, e2020JC016078, https://doi.org/10.1029/2020JC016078, 2020.

Pickering, M. D., Horsburgh, K. J., Blundell, J. R., Hirschi, J. J.-M., Nicholls, R. J., Verlaan, M., and Wells, N. C.: The impact of future sea-level rise on the global tides, Continental Shelf Research, 142, 50–68, https://doi.org/10.1016/j.csr.2017.02.004, 2017.

Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H.: Empirical parameterization of setup, swash, and runup, Coastal Engineering, 53, 573–588, https://doi.org/10.1016/j.coastaleng.2005.12.005, 2006.

Stokes, K., Poate, T., Masselink, G., King, E., Saulter, A., and Ely, N.: Forecasting coastal overtopping at engineered and naturally defended coastlines, Coastal Engineering, 164, 103827, https://doi.org/10.1016/j.coastaleng.2020.103827, 2021.

Valiente, N. G., Masselink, G., Scott, T., Conley, D., and McCarroll, R. J.: Role of waves and tides on depth of closure and potential for headland bypassing, Marine Geology, 407, 60–75, https://doi.org/10.1016/j.margeo.2018.10.009, 2019.