Response to Reviewer #1 of our manuscript entitled

Coastal extreme sea levels in the Caribbean Sea induced by tropical cyclones submitted to *Natural Hazards and Earth System Sciences.*

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The paper uses a synthetic hurricane database to obtain a set of 1000 tropical cyclones (TC) affecting the Caribbean Sea. This information is used to assess wind speed, wave height and extreme sea levels in the region using a high-resolution coupled hydrodynamic-wave model. Results allow identifying most exposed areas to these variables depending on the origin of the TC (Caribbean or Atlantic). Besides, wave, wind and atmospheric contributions to the extreme sea levels are assessed.

I find the aim of the paper interesting and scientifically relevant, especially for the use of coupled models to simulate a large number of present storm surges and waves in the Caribbean Sea forced by TC. I believe this is important as many areas in this region, lack of observational wave and sea level data to perform TC-related risk assessments. Therefore, these results are useful to assess coastal TC risks in the entire basin, but especially at places were data is not available. Besides, return levels of wave height and sea surface elevation for the Caribbean coasts are available in a data repository.

The paper has a good presentation quality and falls into the NHESS scope. However, in my opinion some aspects need to be improved before considering its publication in the Natural Hazards and Earth System Sciences journal.

Main comment:

(1) — Buoy data from two real hurricanes (Willma and Tomas) are used to validate the modelled wave height, but authors claim that no sea level data is available to validate the sea surface elevation (SSE, L171-172). This is not accurate. In fact, Figure 7 from a referenced paper (Torres and Tsimplis, 2014) shows the nontidal storm surge produced by Hurricane David (1979) as recorded by the Magueyes tide gauge. Besides, this hurricane is mentioned later in L262. In the context of the paper, any hurricane in the region could be used for validation purposes. I recommend the authors to select two hurricanes with available sea level and wave observed records, as these variables validation is important for this research. Besides, as the paper assess hurricanes formed in the Atlantic and in the Caribbean, I think it would be better to validate the model with two real hurricanes but from different origin.

A — We thank the reviewer for the information provided. Following this and other requests, we have completely changed the validation section. Now we include all TCs for which there is information on either tide gauges or buoys after year 2000. We need to restrict ourselved to this period of time because we require information on the radius of the TC to be able to convert it to 2D fields. Please, see the new section for further explanations.

Besides, we have checked the results with hurricane David. It generated a signal in the tide gauge of Magueyes, however, the winds provided by ERA5 in that area are very underestimated (See Fig. 2a)). For both TC David and Tomas (Fig. 2 and 1 a, note that the numbering refers to the present document), winds from ERA5 are underestimated near the track, that is mainly because of the size of the TC, compared to the resolution of ERA5 [Dullaart et al., 2020]. For a tide gauge to pick up an important signal, th TC has to pass very close to the tide gauge, making it very difficult to have any good reanalyses in the area. The surge effect can be be felt at a greater distance from the center of the hurricane, where winds of ERA5 are perfectly consistent with the observations (see 1b)). That would be the reason why the validation of sse in Fig. 2 b) is underestimated. Another simulation can be made by calculating the forcing fields using the date from IBTrACS, (See Fig. 1 b and c), however, this can not be made for TC David because IBTrACS has not available data of the radius of this TC.

However, we have found some other tide gauges and we were able to remake the validation section. We have changed Sec.3.2 for this purpose.

Other specific comments:

(1) — L43. Please clarify if tropical cyclones from STORM database, include Tropical Depressions and Tropical Storms in addition to Hurricanes of all categories. If this is the case, the term "tropical cyclones" should not be replaced for "hurricanes".

A — Thank you for pointing this out. The STORM dataset is made by selecting a threshold of 18 m/s, which corresponds to a Tropical Storm classification. Therefore, we have changed all corresponding "hurricanes" with the term "Tropical cyclones" or TCs.

(2) — L56. Maximum wind speed.

A — Corrected

(3) — L57. Please clarify how the PDF was built. The dataset provide the TC track with a 3-hourly time step during its lifetime. For the PDF (and figures 1e and f) each TC was counted once at the time of its maximum wind speed or the entire track was used?

A — Each TC was counted at every time step. This is because, to compute the spatial correlation, we want to make sure that not only the genesis of the TCs is well selected but the tracks are consistent, too. Therefore, we count every time step of the track, to identify those places where there is a higher concentration of hurricanes affecting that area. We have added this explanation to the text.

(4) — L 63. Please expand on the characteristics of the 1000 TC sub-set used. For example, indicate the % of TC with Atlantic or Caribbean origin, % or number of TC which reached the different hurricanes categories (for each origin), etc. This information might be useful to assess the results. Besides, explain how the TC were classified due to their origin, as this is discussed in the paper. E.g. in the case of TC of "Caribbean Origin", are they included if the track starts in this region (usually as a tropical depression), or depending on the place where the TC became a hurricane? (This is comment is related to comment about L43).

A — Please, note that this comment has been addressed in section 3.1. We have included the % of TCs of different origin, among those that affect the region and in the figure we added two panels to show the mean intensity and maximum wind speed reaching every coastal point (also in response to request 10 below). We do not include the categories, though, as the maximum could be reached outside the domain and would in that case be meaningless in terms of impacts.

Regarding the classification into families of TCs, it is specified that their region of origin is used, irrespective of whether they become TCs (see first paragraph Sec. 3.1, prior to percentage information)

(5) — L83. Please clarify the area where the 47 buoys were available, as the reader can understand that these buoys were available in the Caribbean Sea.

A — There are 34 buoys available inside the area of study, 27 of which are found inside the Caribbean sea, and 7 in the nearby Atlantic Ocean. This information has been added to the text (section 2.1).

(6) — L87. I suggest you clarify that "... surface wind fields for each TC were generated ...".

A — Done

(7) — L89. Clarify the term "dominant circular component". Replace it for "a circular region affected by the cyclonic wind" or a similar expression that better explain the wind field

configuration.

A — Done

(8) — L94. Include a reference or explain why a 20% is a good choice.

A — Done, we have included the reference [Willoughby and Black, 1996]. We would like to note, however, that this is not really a relevant factor, as those winds do not generate waves or storm surges, once the TC has made landfall.

(9) — L144-145. Please consider including a comment about the latitude of the southern Caribbean and its relation to the weak Coriolis Effect, which affects TC.

A — We are unsure about what the reviewer requests here.

(10) — L155. A comment about intensities from both TC's families is presented based on Figure 3. Panels c) and d) in this figure are interesting as they show the coastal areas where strong TC induced winds are expected depending on their origin. Please consider to complement this figure with a panel of intensity (median of maximum wind speed) of all the cyclones regardless of their origin, as well as a second panel but with the intensity as the 95 percentile of maximum wind speed. This information can be useful for coastal planning and risk management, as coastal infrastructure should be prepared for strong TC winds regardless of the cyclone's origin. Include in the text an assessment based on these new panels.

A — Done. See Fig. 3 panels a) and b).

(11) — L161. generated in the Caribbean; eastward; westward (check all the manuscript).

A — The answer is in the next questions

(12) — L162-163. The STORM database include 20 TC moving eastward. Although this is a very small number, they seem to be strong hurricanes when compared to other cyclones formed inside the Caribbean Sea (Fig. S1c). Is there a real hurricane that have shown this behavior? I think this is important in order to mention if this is a real possibility in an area dominated by north Trade winds or if this might be catalogued as an error in the database.

A — The reality is that there may be TCs generated in the interior of the Caribbean whose trajectory ends up affecting the Antilles. However, these are very rare. Moreover, they are not part of the Caribbean family to which we refer, whose genesis is off the coast of Honduras, but are hurricanes that are generated directly on the coasts of the Antilles and then continue northward. We have not discussed this subgroup in detail since it is not an error in the database, but a very rare family of events. In STORM they correspond to less than 0.001% of the total number of TCs generated in the Caribbean Sea

(13) — L172. To assess the hurricane effects on sea level, high frequency data is needed, which is not available from altimetry. Therefore, I recommend to delete this comment.

A — Done

(14) — L176. Replace ten for tenth if it uses Hs from the TC in the tenth position (99th percentile). If Hs is computed form the ten most intense hurricanes, which is the "measure" (¿mean, median?). Please clarify the method used in this line for Hs and in L194 for SSE. Based on this clarification, update figure 5 and 6 legends.

A — We use maximum H_s for each TC modelled at every coastal grid point to build a time series and then we keep the 99^{th} percentile. So, yes, the reviewer is right and we measure the signature of the 10 most intense TC reaching the coasts and we have modified the text as suggested.

(15) — L178. Wilma Cat 5 Hurricane recorded an 11 m Hs, while Tomas Cat 2 hurricane, recorded a 6 m Hs (Fig. 4). I think waves of almost 20 m are too high for the Caribbean Sea. I suggest you check Hs in the long time series available from the buoys used in Fig. 4, to assess

the highest wave height recorded (and peak period – L188), and compare to the ∼20 m value found with the model.

A — Please, see the answer in the next question.

(16) — L178. Results indicate waves of nearly 20 m height in the West Indies eastern side induced by TC's. These results call my attention as major hurricanes, which can produce such large waves, are uncommon in the West Indies (e.g., `https://www.nhc.noaa.gov/climo/images/1851_2017_allstorms.jpg`**). Therefore, validating the model with a large hurricane from Atlantic origin is recommended (see main comment).**

A — Waves of more than 15 m correspond to return periods greater than 100 years (see Fig. 7a). Other comparisons with observations and other studies are included in the discussion (see Sec.4 from L: 252-274). We would like to note that all are in agreement with our study.

(17) — L185. The small fetch area inside the Caribbean Sea is proposed as the reason for smaller TC's induced waves in the western Caribbean. ¿How does the wave model forced by the hurricane wind field account for the fetch? I think wave height produced by a hurricane is related to the wind intensity, radius of maximum wind speed and the period this wind is transferring momentum to the sea surface, all of these variables forcing the model. Please consider which of the forcing variables of the wave model can be responsible for the smaller wave height seen in the western Caribbean.

A — The idea we are trying to transmit is that, considering two identical TCs originated inside and outside the Caribbean Sea, the one generated outside has a larger area of development and intensify. That would be the reason why more intense hurricanes generated in front the coasts of Honduras generate lower waves when arrive to the south coasts of Cuba, however, they can still intensify in their way to the coasts of Mexico and Florida. Then, there is another effect of the Lesser Antilles in the already develop TCs from the Atlantic, as they act as a barrier that protect the inside of the Caribbean coasts.

(18) — L188. I think waves of 14 to 18 s period are too long to occur inside the Caribbean Sea. I suggest comparing these values with Tp recorded by the buoys and/or make a comment about the period in the validation section.

A — We have compared the outputs of the model, also the period, and it seems to show good results in the validation. Therefore, despite the large values for the periods we see no reason to believe that the results provided are incorrect. We show you the validation of this T_p for the same buoys and TCs used for the validation of H_s in Fig. 3 here in the review.

(19) — L199-200. I expected such behavior in the coast of Nicaragua, due to the large continental platform, but Belize bathymetry is not particularly shallow (Fig 2). In the case of Nicaragua I think this research is very useful, as to my knowledge there are no observed wave or sea level data in this region, what makes validation impossible. Can you think of a reason why wind setup does not cause higher SSE in Nicaragua when compared to e.g., Belize?

A — There is a very small percentage of TCs affecting the southern coast of Nicaragua. It also has a continental shelf smaller than the norther part, which as we know makes it difficult to generate SSE due to its less local effects (wind and wave-setup). The case of Belize if special due to the morphology of the its coasts full of very narrow and shallow cays.

(20) — L204. Wave-setup is underestimated in your results. Through a numerical experiment (running a case with better spatial resolution in the model) can it be estimated the SSE underestimation? Besides, SSE validation can give an idea of the underestimation value (main comment).

A — Thank you for the comment but it is beyond of the scope of the present manuscript. We are doing this computation in the Mediterranean Sea and requires a lot of computational effort.

(21) — L237. Summary and Discussion. I suggest rearranging this section as follows: 1) summary of the study. 2) Assessment of TC intensity and Hs results. 3) Assessment of SSE results. 4)

Comparison of results with historical hurricanes as impacts are due to wind speed, Hs and SSE interaction. 5) Global warming probable effects in the Caribbean future hurricanes. 6) Closing paragraph.

A — Our section is structured as follow: 1) Brief explanation of the study and characteristic of the TCs affecting our area of study 2) Discussion of the H_s 3) Discussion of the SSE along with their components, all accompanied by comparisons with other studies and possible future changes due to climate change. Finally ends with a paragraph of limitations. We believe this structure is easy to follow and understand, therefore no change have been made. However, if the reviewer thinks otherwise we can arrange some changes.

(22) — L242. Hurricanes from Caribbean origin were only formed off the coast of Honduras? See comment of L63.

A — See response in reviewer's comment on line 63.

(23) — L266. Montoya et al., (2018).

A — Done.

(24) — L269. Consider to mention that, due to SST increase, the hurricane season will be probably extended. Doi: 10.1007/s10236-021-01462-z

A — Done. (Lines 254-255)

(25) — L278. Make a comment about the differences between observed sea level extremes and SSE found in this work. The former will include the contribution from the tide, eddies and seasonal cycle, while the later only accounts for the TC forcing.

A — Done.

(26) — L295. Mean sea-level rise might cause a decrease in the contribution of wind setup, but it is responsible for positive trends observed in sea level extremes (Torres and Tsimplis, 2014).

A — Added

(27) — L313. Include all available DOI to the references.

A — Done

Comments to figures:

(28) — Figure 1. The last panels are e) and f) no f) and g). Update the legend based on comment about L57.

A — Done

(29) — Figure 2. Include in the legend "The spatial resolution varies as a function of the depth". Name first Wilma (a,b) and then Tomas (c,d).

A — Done

(30) — Figure 3. (i) I do not understand why some segments of the coast appear with no color, as the colorbar starts from zero (e.g., Darien Gulf). Besides, it is curious that in some coastal segments no color appear, while neighbor coasts show that are regularly affected by hurricanes. E.g., a segment of the southern coast of Dominican Republic. This seems to be a technical fault, as information about this segment is available in other figures. (ii) In panel b) I understand that a 20% of Caribbean origin (light yellow) will indicate that of 10 TC, 2 more (20%) TC were originated in the Caribbean; therefore 7 TC are of Caribbean origin while 3 TC are of Atlantic origin. I think this color scale is confusing for only two possible outputs. I recommend reporting only the % of Caribbean origin TC using a colorbar from 0 (blue) to 100% (red). Therefore, 70% will indicate the percentage of Caribbean origin, what easily indicates that 30% are from

Atlantic origin. Besides, no color will indicate areas where TC do not affect the coastline. (iii) See comment about L155.

A — Now the panels have changed as you request in question 10. Regarding the doubts of each panel: (i) Uncoloured places indicate that there are no TCs affecting those areas. As can be seen later (see Fig.5 and 6), these same areas will be areas of null H_s. (ii) We have tried to represent as much information as possible condensed in a single panel so as not to have to duplicate the figures, especially now that we have added 2 extra panels to the figure. If we only put the total % of one of the families, then the areas without colour could indicate that they are affected by the other family, or not affected by any of them. (iii) Done.

(31) — Figure 4. Consider including some marks in the dates to indicate the category of these hurricanes in this time span, as this would help to see the wave height relation to the hurricane category.

A — We have changed the way we represent the validation in order to add more events to the validation. This figure is no longer in the manuscript.

(32) — Figure 5. (i) Remove titles at the right side of the figure. (ii) Clarify the legend accordingly to comment about L176 (note that in the legend, both reported Dp and Tp are the median from a range of data). (iii) Inverse the order in the legend as panel c) is Dp. (iv) The color code of Dp is confusing. E.g. the coast of Nicaragua is blue (relative 180° shown at the left of the color circle); as wave direction is from where the wave comes, I assume that it indicates that the waves comes from the east (the opposite side of the circle). I recommend eliminating the relative degrees in the color circle, and flipping the circle, showing light blue colors at the left and yellow colors down. An explanation about the color code should be included in the figure's legend.

A — We have clarified the legend to make it consistent with the text and the comment above. We have also corrected the order. As for the circular colourbar, it shows the D_p in nautical convention, so we have added this information on the caption.

(33) — Figure 6. Clarify the legend accordingly to comment about L176.

A — The caption has been changed in the same way as in the previous figure.

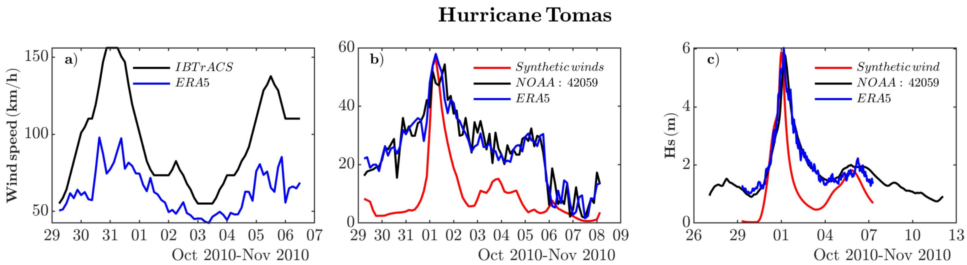

Figure 1: Panel a) representes the along track winds extracted from IBTrACS and the nearest point of ERA5 to the tracks, for Hurricane Tomas. Panel b) representes the winds near one the buoys select for the validation during the pass of Hurricane Tomas, for both ERA5 reanalsys and the winds for the buoy also with the synthetic winds created from the IBTrACS dataset. For panel c) a validation fo Hs using all winds from panel b) is shown.

References

Job Dullaart, Sanne Muis, Nadia Bloemendaal, and Jeroen CJH Aerts. Advancing global storm surge modelling using the new era5 climate reanalysis. *Climate Dynamics*, 54(1):1007–1021, 2020. doi: https://doi.org/10.1007/s00382-019-05044-0.

HE Willoughby and PG Black. Hurricane andrew in florida: Dynamics of a disaster. *Bulletin of the American Meteorological Society*, 77(3):543–550, 1996. doi: https://doi.org/10.1175/1520-0477(1996)077⟨0543:HAIFDO⟩2.0.CO;2.

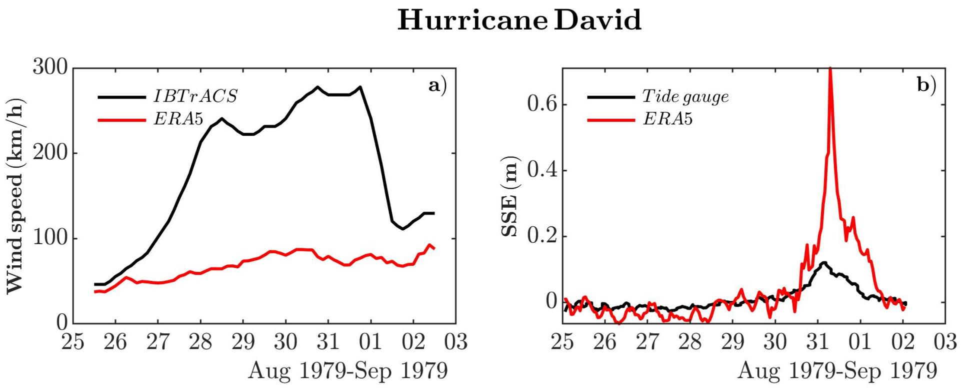

Figure 2: Panel a) representes the along track winds extracted from IBTrACS and the nearest point of ERA5 to the tracks, for Hurricane David. Panel b) shows the sse from the Magueyes tide gauge, and sse simulated using ERA5 to force the model.

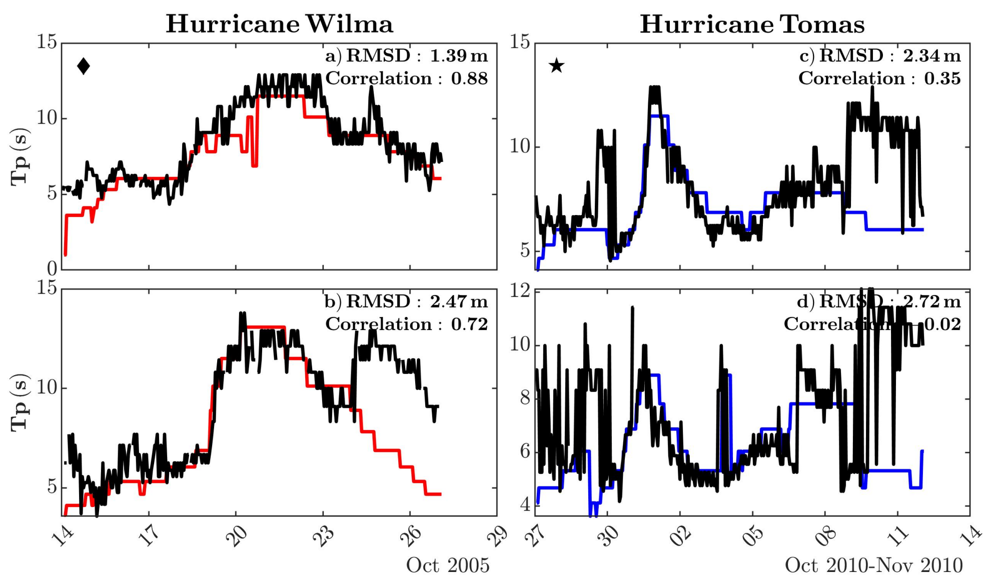

Figure 3: Each column represents the validation for the T_p using the same buoys used for the validation of H_s in Fig.4, for both Hurricanes Wilma and Tomas respectively.