RESPONSE SHEET - REVIEW COMMENTS

Interactive comment on "Wave-current interaction during Hudhud cyclone in the Bay of Bengal" byVolvaiker Samiksha et al.

Anonymous Referee #2

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Comment – 1:

The paper at hand is interesting, and addresses an important topic, namely the influenceof wave-current interactions on water set up, current magnitude, and water waveevolution in very strong conditions. The case studied here is the Hudhud cyclone.Obviously, the topic is relevant for publication in Natural Hazards and Earth SystemSciences. Furthermore, the paper is clear and well structured. It is relatively wellwritten, and pleasant to read. For these reasons, I believe it should be published inNHESS. However, I have some concerns, which, if addressed, could help improve thepaper.

Response:

The authors thank the reviewer for thoroughly reviewing our manuscript, appreciating the work and providing the positive recommendations. Based on the valuable suggestions, the authors have improved the manuscript. The response to comments and concerns are addressed below.

Comment – 2:

The introduction states that "The present study primarily aims at quantifying the impactof wave-current interaction on waves during the Hudhud cyclone". But the paperpresents more results than this (effect of wave-current coupling in the modelling technique for predicting set-up, current, or waves). Later, the discussion clearly focuseson the modelling technique, and the influence of coupling wave and currents from bothmodels. This issue is more technical, but also really interesting. Finally, the conclusioncomes back on the topic suggested in introduction. I suggest the authors slightlymodify introduction and conclusion to mention both type of results in introduction andconclusion.

Response:

The first part of the above concern is also pointed out by reviewer-1. Accordingly, a common response has been prepared for the first part, and the same is given below:

The authors agree upon as pointed out by both the reviewers that this study focuses not only on the quantification of the impact of wave-current interaction, but also on: (i) impact of wave-current interaction on water level, (ii) impact of wave-current interaction on waves, and (iii) impact of wave-current interaction on currents. Accordingly, the last paragraph of the Introduction section is modified as follows:

From literature review, it is evident that most of the studies carried out with storm surge models for the Indian coast used standalone models (Rao et al., 2012; Bhaskaran et al., 2014; Gayathri et al., 2015; Gayathri et al., 2016, Dhana Lakshmi et al., 2017). A comprehensive review on the coastal inundation research and an overview of the processes for the Indian coast was also reported by Gayathri et al. (2017). One can find very few studies reported using a coupled model (ADCIRC with SWAN) for the Indian seas (Bhaskaran et al., 2013; Murty et al., 2014, 2016; Poulose et al., 2017) for extreme weather events. These studies examined the performance of coupled models and role of improved wind forcing on waves and hydrodynamic conditions. The present study is a comprehensive exercise that aims to study the following interaction during the Hudhud event: (i) impact of wave-current interaction on water level, (ii) impact of wave-current interaction on waves, and (iii) impact of wave-current interaction on currents. This involves simulation of winds, tides, storm surges, currents and waves in the study domain during this extreme weather event using the coupled ADCIRC and SWAN models. Only the measured wave and water level data was available for the verification of model results (which happened to be very close to the cyclone track). Both these data sets were utilized in this study. Unfortunately, no measured current data was available for verification of the model-computed currents. The coupled model (ADCIRC+SWAN) has demonstrated its efficacy in predicting storm surge and water level elevation as compared to the standalone ADCIRC model. For example, considering the 2013 Phailin cyclone event (Murty et al., 2014), the difference in residual water level between standalone and coupled versions at Paradeep in Odisha coast were about 0.3m, and the coupled model performed relatively better than standalone model. In addition, for the 2011 Thane cyclone, good performance of coupled parallel ADCIRC-SWAN model was reported by Bhaskaran et al. (2013). The overall performance of waves and currents during Thane event validated against HF Radar observations and with satellite tracks of ENVISAT, JASON-1, JASON-2 and wave rider buoy observations very clearly show that coupled model performed reasonably well. During extreme weather events like cyclones, the interaction between waves and currents is a highly non-linear process, and the transfer and exchange of energy between them is a very complex process. Along the nearshore regions, the non-linear interaction process is highly complex and to a larger extent, it is controlled by the local water depth and coastal geomorphological features. There can be instance wherein the computed results using a coupled model may be under-estimated considering the influence of currents. However, in this case the role of bottom characteristics and water level needs a separate detailed study. Also, including fine resolution bathymetry and cyclonic winds will further enhance the accuracy of the model.

References

Dhana Lakshmi, D., Murty, P.L.N., Bhaskaran, P.K., Sahoo, B., Srinivasa Kumar, T., Shenoi, S.S.C., Srikanth, A.S.: Performance of WRF-ARW winds on computed storm surge using hydrodynamic model for Phailin and Hudhud cyclones. Ocean Engineering, 131, 135-148, 2017.

Gayathri, R., Bhaskaran, P.K., Sen, D.: Numerical study on Storm Surge and associated Coastal Inundation for 2009 AILA Cyclone in the head Bay of Bengal. Int. Conf. on Water Resources, Coastal and Ocean Engineering (ICWRCOE 2015), Aquatic Procedia, 4, 404-411, 2015.

Gayathri, R., Murty, P.L.N., Bhaskaran, P.K., Srinivasa Kumar, T.: A numerical study of hypothetical storm surge and coastal inundation for AILA cyclone in the Bay of Bengal. Environmental Fluid Mechanics, 16(2), 429-452, 2016.

Gayathri, R., Bhaskaran, P.K., Jose, F.: Coastal inundation research: an overview of the process. Current Science, 112(2), 267-278, 2017.

Murty, P.L.N., Bhaskaran, P.K., Gayathri, R., Sahoo, B., Srinivasa Kumar, T., SubbaReddy, B.: Numerical study of coastal hydrodynamics using a coupled model for Hudhud cyclone in the Bay of Bengal. Estuarine, Coastal and Shelf Science, 183, 13-27, 2016.

Poulose, J., Rao, A.D., Bhaskaran, P.K.: Role of continental shelf on non-linear interaction of storm surges, tides and wind waves: An idealized study representing the west coast of India. Estuarine, Coastal and Shelf Science, http://dx.doi.org/10.1016/j.ecss.2017.06.007

The Conclusion section is modified in the revised manuscript as follows:

A coupled ADCIRC+SWAN modelling system has been used to simulate the changes that occurred in the ocean surface dynamics during the passage of Very Severe Cyclonic Storm Hudhud that made landfall near Visakhapatnam located on the East Coast of India. At the time of peak intensity, the Holland parametric model reproduced maximum wind speed of ≈54 m/s with a minimum central pressure drop of 950 hPa. The landfall of Hudhud event occurred during the spring high tide, and the tide gauge observation off Visakhapatnam recorded a maximum surge of 1.4 m, that matched reasonably well with the modelled surge (1.2 m). The two-way coupling with SWAN showed an increment of ≈0.25 m (20%) in the total water level elevation during this cyclone, which was contributed by waves to the total rise in water level. During the time of landfall near Visakhapatnam, the current speed increased from 0.5 m/s to 1.8 m/s for a short duration (≈6 h) with the direction of flow towards south, and thereafter ≈ 6 h the current speed reduced to ≈ 0.1 m/s with a reversal in direction (towards north). The study signifies that an increase of ≈ 0.2 m in significant wave height (H_s) was noted by including the effect of currents on the wave field. The inclusion of currents in the modelling system does have influence on the wave field, especially on wave length (in the present case, a change of about 2 s in wave period) and wave height. Increase in wave height was observed on the left side of the cyclone track, when waves and currents opposed each other (waves were propagating from southwest and currents flowing towards southwest). As wave-current interaction is a complex problem, and the expected changes in wave parameters are very small, further refinement is required in the two-way coupling of ADCIRC+SWAN (with fine resolution bathymetry and improved cyclonic winds).

Comment – 3:

The modelling procedure for SWAN could be detailed a little bit more. The conditionsused here are really not usual conditions, and a commentary on how accurate theapproximations are in hurricane conditions would be welcomed.

Response:

The authors appreciate the reviewer comments. The details of SWAN modelling are briefly given below:

SWAN (Simulating WAves Nearshore) is a third-generation wave model developed at the Delft University of Technology, Netherlands. It computes random, short-crested wind-generated waves in coastal regions and inland waters. The current version of SWAN is 40.85. The model is based on the wave action balance equation, with various source and sink mechanisms, that governs the redistribution of energy balance in the wave system. SWAN can be used on any scale relevant for wind generated surface gravity waves. However, the SWAN model is specifically designed for coastal applications that should actually not require such flexibility in scale. The input parameters that can be provided to SWAN includes bathymetry, current, water level, bottom friction and wind. The governing equation of SWAN is the wave action balance equation expressed in the form:

$$\frac{\partial N}{\partial t} + \frac{\partial C_{g,x} N}{\partial x} + \frac{\partial C_{g,y} N}{\partial y} + \frac{\partial C_{g,\sigma} N}{\partial \sigma} + \frac{\partial C_{g,\theta} N}{\partial \theta} = \frac{S}{\sigma}$$

where, N is the wave action density; σ is the relative frequency; θ is the wave direction; Cg is the propagation speed in (x,y,σ,θ) space; and S is the total of source/sink terms expressed as the wave energy density. In SWAN model the source terms are expressed in the form:

$$S = S_{in} + S_{ds,w} + S_{ds,b} + S_{nl4} + S_{nl3}$$

The terms in the R.H.S of the equation represents the wind input, white-capping, bottom friction, quadruplet wave-wave interactions and triad wave-wave interactions, respectively. The terms like bottom friction and triad wave-wave interaction can be neglected in deep water calculations. The model coupling is based on the work by Bunya et al. (2010) and Dietrich et al. (2011) conducted for the Gulf of Mexico region. The SWAN model employs an implicit sweeping method to update the wave field at each computational vertex, which allows SWAN to apply longer time steps than ADCIRC. Thus, the SWAN time step usually defines the coupling interval between SWAN and ADCIRC models (Dietrich, 2010; Dietrich et al., 2011a,b).

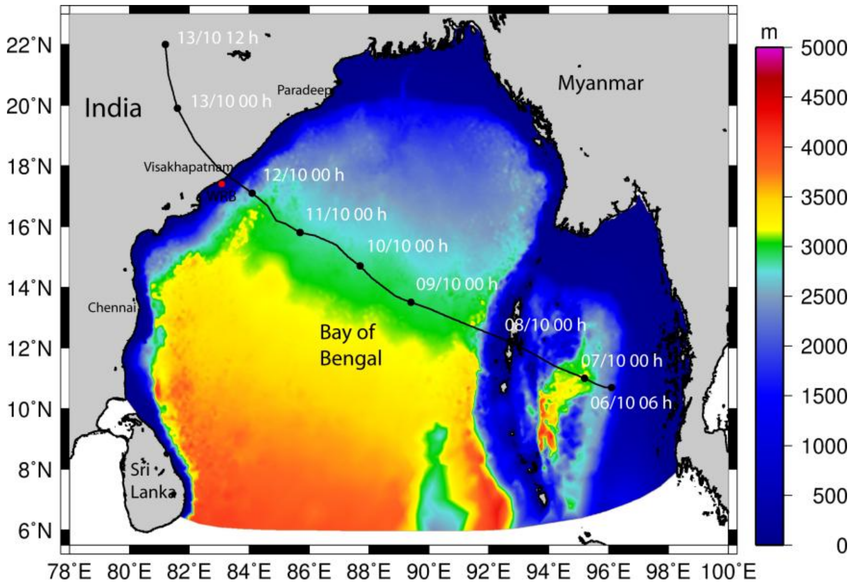
The wind field provided as input to SWAN model during Hudhud cyclone was generated using the Holland parametric model, which is specifically meant for simulating winds during cyclones.

Comment – 4:

Except for the wave buoy data (I would appreciate to see the location of the buoy ona map, by the way), the paper suffers a lack of data for validation. Could the authorsaccess some other data, such as surface velocity from satellite, or water elevation fromPSMSL, for instance? It would help validating the numerical results.

Response:

The authors appreciate the reviewer comments. The wave rider buoy location is plotted in Figure 1a. This was also pointed out by reviewer-1. It may kindly be noted that the water level elevation data off Visakhapatnam used in this study for validation of model results (Figure 4) is from PSMSL data only. However, no data is available for validation of currents, including satellite data during the passage of Hudhud cyclone at this location.



Comment – 5:

In section 3.4, I had difficulties to understand if the "SWAN alone" simulations werereferring to SWAN with absolutely no current, or SWAN with input current from ADCIRC,but no coupling. This clarification is obviously important for interpreting theresults.

Response:

The authors appreciate the reviewer comments. Two cases were run, viz, SWAN in standalone mode, and SWAN coupled with ADCIRC to assess the impact of currents on cyclone generated waves. SWAN alone simulations are referred to as simulation with no currents.

Comment – 6:

Minor points:

- section 2.1, line 94. There is a misprint on the location of the wave rider buoy. Furthermore,I could not understand what the +20m -20m measurement range refers to. WaveHeight? It seems huge, and is probably not true regardless to the waves frequency.

Response:

The authors appreciate the comments and thank the reviewer for pointing out this mistake. Also, as suggested by the other reviewer-1, the authors have modified the Section 2.1 with more detailed information of wave rider buoy as given below:
The wave rider buoy location is corrected as: 17.63°N and 83.26°E. The measurement range +20m to -20m refers to the wave height with an accuracy of 3%. There were occasions when wave heights were in excess of 30 m, especially during very severe hurricanes.

The in situ data was recorded continuously at 1.28 Hz and the recording interval for every 30 min was processed as one record. At every 200 seconds a total number of 256 heave samples were collected and a Fast Fourier Transform (FFT) was applied to obtain a spectrum in the frequency range 0 to 0.58 Hz having a resolution of 0.005 Hz. Eight consecutive spectra covering 1600 seconds were averaged and used to compute the half-hourly wave spectrum. Significant wave height (H_{m0}) or $4\sqrt{m_0}$ was obtained from the wave spectrum. The n^{th} order spectral moment (m_n) is given by: $m_n = \int_0^\infty f^n S(f) df$, where $S(f)$ is the spectral energy density at frequency f. The period corresponding to the maximum spectral energy (i.e., spectral peak period (T_p) is estimated from the wave spectrum. The wave direction (D_p) and directional width corresponding to the spectral peak is estimated based on the circular moments (Kuik et al.,1988).

Comment – 7:

- Section 3.1: Do we have estimation on how accurate Holland's numerical resultswere? Could the authors mention it with a sentence?

Response:

The authors appreciate the reviewer comments. Hudhud cyclone reached the maximum intensity in the early morning of 12th October 2014 with a sustained wind speed of 180 km/h off Andhra coast. It crossed Visakhapatnam between 1200 and 1300 h IST on 12th October with the same wind speed (IMD Report, 2014). Figure 2 shows the passage of Hudhud cyclone, and the Holland model reproduced the maximum wind speed of ≈186 km/h with a minimum central pressure drop of 950 hPa when it transformed into a Very Severe Cyclonic storm (Figure 2).

Comment – 8:

- For every figure, the captions are not detailed enough. Most of the time, it is unclearwhat symbol corresponds to what line. The date and time used for various maps arenot mentioned.

Response:

The authors appreciate the reviewer comments. Most of the suggested corrections are incorporated in the revised figures.

Fig. 1a. Bathymetry of the model domain chosen for wave-current interaction during Hudhud cyclone; cyclone track details are also shown; red dot represents wave rider buoy location. Fig. 1b. Fine resolution unstructured mesh generated for the domain to run the coupled ADCIRC+SWAN model; rectangular box represents the region where measured data are available for model validation (details of the box is shown in Fig. 1c). Fig. 1c. Fine-resolution mesh of the box shown in Fig. 1b; black circle is the landfall point of the Hudhud cyclone; cyclone track is also shown.

Fig. 2. Typical winds (speed and direction) generated using Holland symmetrical model along the track of Hudhud cyclone (colour code represents wind speed in m/s; vectors represent wind direction).

Fig. 3. Spatial distribution of maximum surface elevation (m) due to (a) cyclonic winds, (b) cyclonic winds and tides and (c) cyclonic winds, tides and waves (colour code represents surface elevation in m).

Fig. 4. Time series of surface elevation (m) representing measured surface elevation (red line), SE from ADCIRC alone (blue line) and SE from ADCIRC+SWAN (black line) at Visakhapatnam coast (17.63°N; 83.26°E) during 10-13 October 2014.

Fig. 5. Spatial distribution of maximum surface currents (m/s) due to (a) winds, (b) winds and tides and (c) winds, tides and waves, during cyclone, (d) difference in current speeds from (b) and (c), illustrating change in current speeds due to wave-current interaction (colour code represents current speeds in m/s).

Fig. 6. Time series of currents (m/s) representing current speeds and direction obtained from ADCIRC alone ('x' and blue rectangle) and coupled ADCIRC+SWAN ('+' and red rectangle) off Visakhapatnam coast (17.63°N; 83.26°E) during 10-13 October 2014.

Fig. 7. Current speed and direction simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (colour code represents current speed in m/s; vectors represent current direction).

Fig. 8. Comparison of measured (black) and modelled (a) significant wave heights (H_s), (b) mean wave periods, (c) peak wave periods and (d) peak wave directions obtained from SWAN (red) and coupled ADCIRC+SWAN (blue) during Hudhud cyclone with measured data off Visakhapatnam (17.63°N; 83.26°E).

Fig. 9. Significant wave heights (H_s) simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (colour contours represent H_s in m).

Fig.10. Spatial distribution of maximum significant wave heights (H_s) simulated along the track of Hudhud cyclone using (a) SWAN model (no wave-current interaction), (b) coupled ADCIRC+SWAN model (with wave-current interaction); colour code and contours represent H_s; (c) change in H_s from (a) and (b), illustrating change in wave energy due to wave-current interaction.

Fig. 11. Spatial distribution of (a) mean wave period (T_m) and (b) peak wave period (T_p) simulated along the track of Hudhud cyclone using coupled ADCIRC+SWAN model (with wave-current interaction).

Fig. 12. (a). Maximum radiation stress gradient values calculated from SWAN and (b) spatial distribution of mean wave direction (Dir) simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (with wave-current interaction); colour code and contours represent wave direction.