

RESPONSE SHEET - REVIEW COMMENTS

Interactive comment on “Wave-current interaction during Hudhud cyclone in the Bay of Bengal” by Volvaiker Samiksha et al.

Anonymous Referee #1

Received and published: 30 May 2017

Comment – 1:

The manuscript has a subject that is appropriate to the NHSS publication and should be of interest to readers of the journal. The paper is reasonably well written, logically organised, structured and illustrated. The authors present an interesting set of simulations to assess the mutual effects of waves and currents during the passage of the Very Severe Cyclonic Storm Hudhud. The principal results are: (1) Waves contributed 0.25 m to the total water level during the event, which agrees with measurements at Visakhapatnam; (2) Current speed increased from 0.5 to 1.8 m/s for a short time during the event; (3) the two-way coupling increased the current magnitude by 0.25 m/s along the track; (4) The use of wave-ocean coupling increases H_s in 2 m compared to wave model only; (5) waves decrease due to currents when they travel normal to the coast after crossing the shelf area (right side of track) and increased on the left side of track when currents oppose wave direction. Cyclonic systems currently pose one of the most challenging and important meteo-oceanographic phenomena for the earth science community and the study is a valuable contribution. However I have fundamental objections that I believe should be addressed before final publication.

Response:

The authors thank the reviewer for thoroughly reviewing our manuscript, appreciating the work and providing valuable suggestions to improve the manuscript. The fundamental objections raised by the reviewer have been addressed in the following paragraphs.

Comment – 2:

My main concern is related to the overall content and discussions. In the end of introduction, the authors state that “The present study primarily aims at quantifying the impact of wave-current interaction on waves during the Hudhud cyclone”. The analysis however seems to be equally focused on the effects of waves on currents and water level. I presume they do so because the only data source available is of a Wave Rider buoy. No current data is available. However,

there is no clear discussion on whether the inclusion of current improves wave simulation at the buoy location. The authors just mention the differences in model results show the plots of comparison of model and measurement and let the readers draw their own conclusion. The coupling system increase wave height (0.2 m) at the wave height peak moment. But wave height is decreased before this moment and model actually agrees better with data without the inclusion of currents. Wave period is also slightly better represented in the simulation without currents. If the main goal of the paper is “quantifying” the effect of wave-current interactions on waves, this must be discussed also in terms of improvement and/or deterioration of simulations compared to measurements. At least an attempt should be made. It is an interesting opportunity to address some limitations of these models and if currents are actually beneficial to wave modelling (and vice-versa).

Response:

The authors appreciate the reviewer comments and agree that this study focus not only on the quantification pertaining to 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 in the Introduction section has been modified, and relevant references were added as follows:

From the literature review, it is evident that most of the storm surge studies carried out 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 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; Poullose 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 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, the difference in residual water level at Paradeep obtained by standalone and coupled models at Paradeep in Odisha coast during 2013 Phailin cyclone were about 0.3m, and the coupled model performed relatively better than the standalone model (Murty et al., 2014). For the 2011 Thane cyclone also good performance of coupled parallel ADCIRC-SWAN model was reported by Bhaskaran et al. (2013). The model values of waves and currents obtained

during Thane cyclone validated against HF Radar observations, satellite data 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 region, 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 instances, wherein the computed results using a coupled model may be under-estimated, when the influence of currents is considered. However, in this case the role of bottom characteristics and water level needs a separate detailed study.

The present study is a comprehensive exercise that aims at studying the following interactions 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 wave and water level measured data were available for the verification of model results. Unfortunately, no measured current data was available for verification of the model-computed currents.

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.

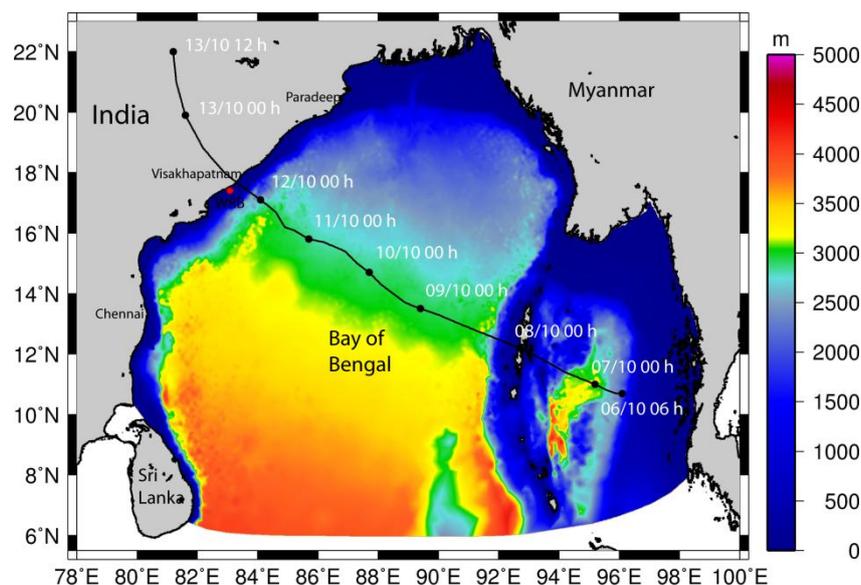
Poulose, J., Rao, A.D., Bhaskaran, P.K.: Role of continental shelf on non-linear interaction of storm surges, tides and wind waves: An idealized study representing the west coast of India. *Estuarine, Coastal and Shelf Science*, <http://dx.doi.org/10.1016/j.ecss.2017.06.007>

Comment – 3:

The exact location of the wave rider buoy must be plotted, possibly on the map of figure 1a, so that the reader can know where the validation of the wave model was performed for.

Response:

The authors appreciate the reviewer comments. Accordingly as suggested, the buoy location is marked in Figure 1a.



Comment – 4:

Very little detail is given about wave measurements. Although section 2 is entitled “Data and Methodology” it is basically about the modelling configuration. What is the sampling time of wave information, how is it obtained (spectral method, record length)?

This information together with the aforementioned plot of the buoy location may be of interest to readers.

Response:

The authors appreciate the reviewer comments. The wave data used in this study was obtained from the National Institute of Ocean Technology, Chennai. As suggested by the reviewer, the details of wave measurements and data analysis are now added in the revised manuscript as follows:

Wave data was obtained from the directional wave rider buoy deployed off Visakhapatnam (17.63°N; 83.26°E) at 15 m water depth. The measurement range is -20 m to 20 m, with an accuracy of 3%. 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).

Reference:

Kuik, A.J., Vledder, G., Holthuijsen, L.H., A method for the routine analysis of pitch and roll buoy wave data, *Journal of Physical Oceanography* 18, 1020–1034, 1988.

Comment – 5:

Why do the authors decide for the set of physics of growth and dissipation from Cavaleri and Malanotte-Rizzoli (1981) and Komen et al. (1984)? These old parameterisations and especially the Komen et al. dissipation form are proven to not be adequate in non-standard conditions, as in opposing currents, for example (see Ardhuin et al JPO(2012) and Rapizo et al (JGR 2017)). The dissipation form in Westhuysen et al (2007) shows better performance than the Komen et al. term in adverse currents (Rapizo et al, 2017). The newly implemented in SWAN and recently released 'ST6' physics (Rogers et al, 2012) performs best in conditions of effective currents Rapizo et al (JGR2017), which is the subject of investigation here. If the old physics are used instead, a justification must be given.

Response:

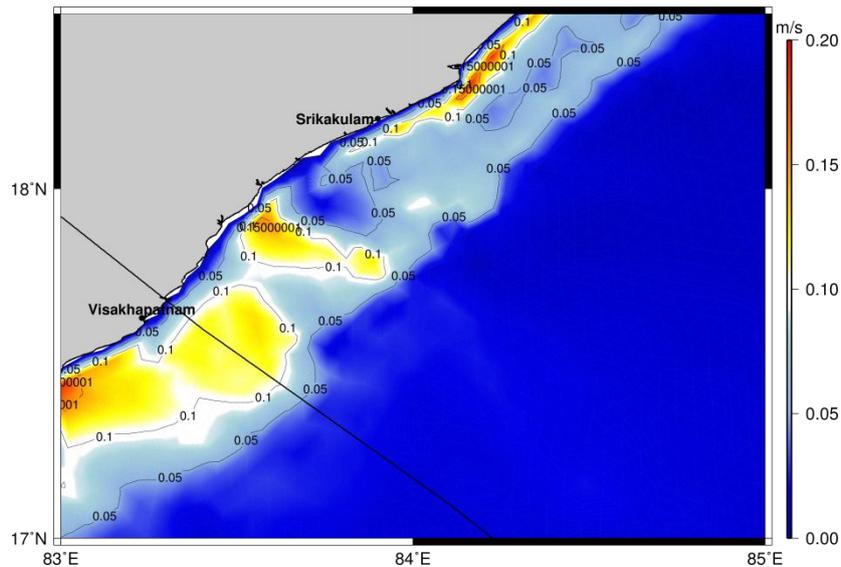
The authors appreciate the reviewer comments. The authors have conducted this study in 2015 using the unstructured version of SWAN (version 40.85) implementing an analog to the four-direction Gauss-Seidel iteration technique with unconditional stability (Zijlema, 2010). However, Rapizo et al (2017) reported the good performance of SWAN in tidal current regime (ebb and flood flows) very recently (2017) only. It may kindly be noted that, the co-author of this work, Bhaskaran and his team has carried out a few studies (Bhaskaran et al., 2014; Gayathri et al., 2015; Gayathri et al., 2016, Dhana Lakshmi et al., 2017; Bhaskaran et al., 2013; Murty et al., 2014, 2016; Poullose et al., 2017) using the same formulation of Komen et al. (1984) for cyclones that occurred in the Indian Ocean region, and found that SWAN with this scheme performed well for extreme weather events also. Keeping this in view, in the present study the authors have gone ahead with using the same formulation of Komen et al to study the wave-current interaction during the Hudhud event. However, the authors appreciate the reviewer comments and shall use the scheme of Roger et al (2012) in SWAN and study the wave-current interaction in tidal as well in cyclonic conditions as a separate study in future.

Comment – 6:

I find it hard to analyse the differences in current speed shown in Fig. 5 (especially for figure (b)). Although it is interesting to see the pattern produced by the cyclone landfall, all figures show similar patterns. I suggest here to plot (b) and (c) as current speed differences (similar to Fig. 10 bottom panels).

Response:

The authors appreciate the reviewer comments. As suggested one more Figure (5d) is added to show the difference in current speed similar to Fig. 10 in the revised manuscript.



Comment – 7:

Other minor points: Line 22: “Studies show that waves contribute to local currents, water level and mixing.” By mentioning “Studies” I feel at least one reference is needed here.

Response:

The authors appreciate the reviewer comments. As suggested the following three references are added to this statement in the revised manuscript:

Kudryavtsev et al., 1999; Davies and Lawrence, 1995; McWilliams et al., 2004. These studies show that waves contribute to local currents, water level and mixing.

Comment – 8:

Line 24-26: “Several studies have been carried out relating to individual processes, but not many on interaction between the processes. Therefore, we need to take into account different processes that impact a specific process.” Very confusing, many repetitions of word “process”. Rephrase.

Response:

The sentence is rephrased as follows in the revised manuscript: ‘Several studies have been carried out relating to individual processes, but not on interactions between them’.

Comment – 9:

Line 34: “effected” => “affected”

Response:

The correction made accordingly in the revised manuscript.

Comment – 10:

Line 37: “The wave processes that impact the coastal environment are:” There are many other wave-related processes that impact the coastal environment other than the ones listed (wave set-up, wave-current interactions and breaking-induced mixing). The first phrase should be rephrased to something like: “Some of the relevant wave processes that impact the coastal environment are as follows:”

Response:

The sentence is modified as follows in the revised manuscript:

"Some of the wave processes that impact the coastal environment are as follows:"

Comment – 11:

Line 55: SWAN stands for Simulating Waves Nearshore, not "in Nearshore".

Response:

The correction is made accordingly in the revised manuscript.

Comment – 12:

Line 93: Buoy coordinates are wrong. (same for legend in Fig. 4, 6 and 8)

Response:

The authors appreciate the reviewer comments. As suggested, the corrections are made (17.63°N; 83.26°E) in the revised manuscript.

Anonymous Referee #2

Received and published: 6 June 2017

Comment – 1:

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

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 impact of wave-current interaction on waves during the Hudhud cyclone”. But the paper presents more results than this (effect of wave-current coupling in the modelling technique for predicting set-up, current, or waves). Later, the discussion clearly focuses on the modelling technique, and the influence of coupling wave and currents from both models. This issue is more technical, but also really interesting. Finally, the conclusion comes back on the topic suggested in introduction. I suggest the authors slightly modify introduction and conclusion to mention both type of results in introduction and conclusion.

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 the literature review, it is evident that most of the storm surge studies carried out 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 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; Poulouse 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 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, the difference in residual water level at Paradeep obtained by standalone and coupled models at Paradeep in Odisha coast during 2013 Phailin cyclone were about 0.3m, and the coupled model performed relatively better than the standalone model (Murty et al., 2014). For the 2011 Thane cyclone also good performance of coupled parallel ADCIRC-SWAN model was reported by Bhaskaran et al. (2013). The model values of waves and currents obtained during Thane cyclone validated against HF Radar observations, satellite data 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 region, 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 instances, wherein the computed results using a coupled model may be under-estimated, when the influence of currents is considered. However, in this case the role of bottom characteristics and water level needs a separate detailed study.

The present study is a comprehensive exercise that aims at studying the following interactions 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 wave and water level measured data were available for the verification of model results. Unfortunately, no measured current data was available for verification of the model-computed currents.

References

Dhana Lakshmi, D., Murty, P.L.N., Bhaskaran, P.K., Sahoo, B., Srinivasa Kumar, T., Sheno, 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, 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 when the effect of currents was included 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 conditions used here are really not usual conditions, and a commentary on how accurate the approximations 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 provided to SWAN includes bathymetry, current, water level, bottom friction and wind. The governing equation of SWAN is the wave action balance equation is expressed in the following 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; C_g 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 following form:

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

The terms in the R.H.S of the equation represent 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 of 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).

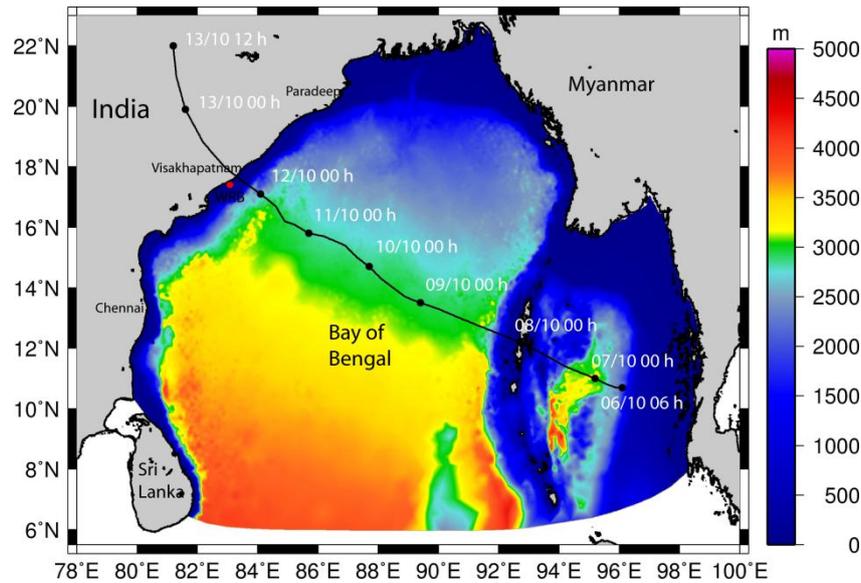
The wind field provided as input to SWAN model during Hudhud cyclone was generated using the Holland parametric model, which is specifically meant for simulating winds during cyclones.

Comment – 4:

Except for the wave buoy data (I would appreciate to see the location of the buoy on a map, by the way), the paper suffers a lack of data for validation. Could the authors access some other data, such as surface velocity from satellite, or water elevation from PSMSL, 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 the results.

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 s a total number of 256 wave 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 s 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)) was estimated from the wave spectrum. The wave direction (D_p) and directional width corresponding to the spectral peak were estimated based on the circular moments (Kuik et al., 1988).

Reference:

Kuik, A.J., Vledder, G., Holthuijsen, L.H., A method for the routine analysis of pitch and roll buoy wave data, *Journal of Physical Oceanography* 18, 1020–1034, 1988.

Comment – 7:

- Section 3.1: Do we have estimation on how accurate Holland's numerical results were? 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.

Wave-current interaction during Hudhud cyclone in the Bay of Bengal

Samiksha Volvaiker¹, Ponnumony Vethamony¹, Charls Antony¹, Prasad Bhaskaran², Balakrishnan Nair³

¹Physical Oceanography Division, CSIR-National Institute of Oceanography, Dona Paula, 403004, Goa - India

²Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology Kharagpur, Kharagpur - 721 302, India

³Indian National Centre for Ocean Information Services, Hyderabad - 500 090, India

Correspondence to: Samiksha S. V. (vsamiksha@nio.org)

Abstract. The present work describes the interaction between waves and currents utilizing a coupled ADCIRC+SWAN model for the very severe cyclonic storm 'Hudhud' which made landfall at Visakhapatnam on the east coast of India in October 2014. Model computed wave and surge heights were validated with measurements near the landfall point. The Holland model reproduced the maximum wind speed of ≈ 54 m/s with the minimum pressure of 950 hPa. The modelled maximum surge of 1.2 m matches with the maximum surge of 1.4 m measured off Visakhapatnam. The two-way coupling with SWAN showed that waves contributed ≈ 0.25 m to the total water level during the Hudhud event. At the landfall point near Visakhapatnam, the East India Coastal Current speed increased from 0.5 to 1.8 m/s for a short duration (≈ 6 h) with net flow towards south, and thereafter reversed towards north. An increase of ≈ 0.2 m in H_s was observed with the inclusion of model currents. It was also observed that when waves travelled normal to the coast after crossing the shelf area, with current towards southwest, wave heights were reduced due to wave-current interaction; however, an increase in wave height was observed on the left side of the track, when waves and currents opposed each other.

1 Introduction

In coastal and shelf regions, winds and waves interact with the prevailing current system and several mutual non-linear interactions occur. Studies (Kudryavtsev et al., 1999; Davies and Lawrence, 1995; McWilliams et al., 2004) show that waves contribute to local currents, water level and mixing. Wind and wave induced currents can reinforce or interfere with tidal currents, depending on the phase of the tide. The impact of surface waves on currents or currents on waves is an important aspect in coastal hydrodynamics. Several studies have been carried out relating to individual processes, but not on the interactions between them. Several studies have been carried out relating to individual processes, but not many on interaction between the processes. Therefore, we need to take into account different processes that impact a specific process.

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

30 In the last few decades, there have been several efforts to develop theories and models on wave-current interactions*
(Davies and Lawrence, 1995; McWilliams et al., 2004; Arduin et al., 2008; Mellor, 2008; Warner et al., 2008; Uchiyama et
al., 2010; Bennis et al., 2011). Holthuijsen and Tolman (1991) and Komen et al. (1994) studied interaction between current
and wave fields in the regions of the Gulf Stream, the Kuroshio and the Agulhas currents. The refraction theory of waves on
35 current has advanced well, and this concept has been already introduced into the wave-action conservation equation. Linear
wave theory on vertically sheared weak current is also discussed using both perturbation and numerical methods (Kirby and
Chen, 1989; Dong, 2012). When waves propagate through strong currents, their characteristics change with refraction,
bottom friction and blocking (Kudryavtsev et al., 1999; Ris et al., 1999). Also, the mean flow will be affected by the
addition of momentum and mass fluxes. With variation in water level, the depth felt by the waves also changes in the coastal
region, thereby modifying the shallow water effects on the waves (Pleskachevsky et al., 2009).

Formatted: Line spacing: 1.5 lines,
Adjust space between Latin and Asian
text, Adjust space between Asian text
and numbers

40 ~~Some of the wave processes that impact the coastal environment are as follows: wave set-up, wave-current
interactions and breaking induced mixing. The wave processes that impact the coastal environment are:~~ (i) wave set-up
during cyclones, which contributes significantly to storm surge and inundation; for example, when waves were included in
the model, Beardsley et al., 2013 found that more areas were influenced by flooding in the Massachusetts Bay, (ii) wave-
current interaction increases the bottom friction, and thereby increasing the bottom stress. For example, Xie et al. (2001,
45 2003) introduced wave-induced surface and bottom stresses in the dynamic coupling between waves and currents, (iii)
Carniel et al. (2009) and Zhang et al. (2011) included mixing due to wave breaking in their respective models and found
improvements in the accuracy of surface drifter tracks in the Adriatic Sea and surface boundary layer thickness in the
Yellow Sea, and (iv) Mellor (2003) and Xia et al. (2004) incorporated radiation stress in the coupling between wave, ocean
circulation and storm surge modelling.

Formatted: Font: 10 pt, Font color:
Auto

50 Several numerical coupling experiments linking waves, currents and storm surges have been conducted in coastal
areas in the past. For example, Tolman (1991) demonstrated the effect of water level and storm surges on wind waves for
storms generated in the North Sea, and indicated that storm surges are essential factors to be considered for assessing the
wave-current interactions. Mastenbroek et al. (1993) and Zhang and Li (1996) modelled the impact of waves on storm surges
and showed that wind stress with wave-dependant parameterization amplified the storm surge by 10–20%. Moon (2005)
55 developed a wave-tide-circulation coupled system by including the influence of wave-current interaction, wave breaking and
depth changes due to water level and found that the wave-dependent stress is strongly dependent on wave age and relative
position from the storm center. However, it may be noted that storm surge, tides or oceanic currents will have a significant
effect on wave field only if their strengths are sufficient to interact.

60 Presently, in storm surge modelling, circulation and wave models are coupled in the same mesh, so that
mesh resolution is fit to capture both circulation and wave physics. ADCIRC+SWAN (ADvanced CIRCulation + Simulating
WAVes-in Nearshore) is a coupled model that works on an unstructured mesh, and allows for interaction between storm

surges, waves and currents. This modelling system has been applied to hindcast hurricanes such as Katrina, Rita, Gustav and Ike (Westerink et al., 2008; Dietrich et al., 2011a, 2011b, 2012; Hope et al., 2013; Longley, 2013; Sebastian et al., 2014).

Several studies (Rao et al., 1982; Murty et al., 1986; Dube et al., 1997, 2000; Rao et al., 2013) reported storm surge along the east coast of India. Rao et al. (2012) simulated surge and inundation using ADCIRC for the following cyclones: Kavali (1989), Andhra (1996) and Cuddalore (2000). Three super cyclones, viz, 1999 Odisha cyclone, 2013 Phailin and 2014 Hudhud created significant impact along the east coast of India. Phailin cyclone generated waves with significant wave heights of the order of 7m (Balakrishnan et al., 2014). Hudhud was the first cyclone which effected urban areas and it is the second severe cyclone which crossed the Visakhapatnam coast (Amarendra et al., 2015). Also, the beach erosion was very severe on the Ramkrishna beach, with a net sand volume of about 1457 cu.m lost over a stretch of 14 km (Hani et al., 2015).

Balakrishnan et al. (2014) reported wave heights in the Bay of Bengal during Phailin cyclone using MIKE21 SW model in a standalone mode, but various non-linear interactions between surge, tide and current were not accounted for. Bhaskaran et al. (2013, 2014) used coupled ADCIRC+SWAN model for the Thane cyclone in the Bay of Bengal and studied inundation along the Tamil Nadu coast. The same modelling system was used by Murty et al. (2014) to estimate wave induced setup for the cyclone Phailin.

From the literature review, it is evident that most of the storm surge 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; Poulouse 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 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 at Paradeep obtained by between standalone and coupled models at Paradeep in Odisha coast during 2013 Phailin cyclone were about 0.3m, and the coupled model performed relatively better than the standalone model (Murty et al., 2014). In addition, for the 2011 Thane cyclone also, good performance of coupled parallel ADCIRC-SWAN model was reported by Bhaskaran et al. (2013). The model values overall performance of waves and currents obtained during Thane cyclone event validated against HF Radar observations, and with satellite data 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 instances, wherein the computed results using a coupled model may be under-estimated, when considering the influence of currents is considered. However,

Formatted: Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font color: Auto

95 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.

100 The present study is a comprehensive exercise that aims at studying the following interactions 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 measured data were 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.

105 The review shows that most of the studies on storm surge modelling were carried out for the coast of India with models, which are standalone. Coupled models were used only in a very few cases, but focussed on studying the storm surges rather than changes in waves and currents due to those extreme weather events. The present study primarily aims at quantifying the impact of wave-current interaction on waves during the Hudhud cyclone. This involves simulation of winds, tides, storm surges, currents and waves in the domain during this extreme event using the coupled models ADCIRC and SWAN.

110 2. Data and methodology

2.1 Modelling system

ADCIRC and SWAN models were run in standalone and coupled modes on the same computational grid system. The cyclonic wind data were derived from the Holland formulation (Holland, 1980) using the best track estimate of Hudhud obtained from the JTWC (Joint Typhoon Warning Center) database. The hydrodynamic depth-averaged model ADCIRC applies the continuous Galerkin finite-element method to solve shallow water equations for water levels and vertically integrated momentum equations for velocity (Kolar et al., 1994; Atkinson et al., 2004; Luetlich and Westerink, 2004; Dawson et al., 2006; Westerink et al., 2008; Kubatko et al., 2009; Tanaka et al., 2011). The model utilizes an unstructured mesh, and allows for refinement in areas where the solution gradients are the highest. It has an option for wetting and drying that activates and deactivates the entire grid elements during inundation and recession.

120 SWAN is a third-generation wave model based on the wave action balance equation and was developed at the Delft University of Technology. It computes random, short crested wind generated waves in coastal and inland waters (Booij et al., 1999). The latest version of SWAN (41.01) (Zijlema, 2010) has been used in the present study. Wind, water depth, current, water level and bottom friction are the major input parameters required for SWAN. In the present work, the performance of the coupled model during Hudhud cyclone was evaluated based on available measured data (surface

Formatted: Font: 10 pt, Font color: Auto

Formatted: Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font color: Auto

Formatted: Font: 10 pt

Formatted: Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted: Normal, Space After: 0 pt, Line spacing: 1.5 lines

elevation and wave). 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 (Booij et al., 1999). The current version of SWAN is 40.85 (Zijlema, 2010). 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 is expressed in the following 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 following 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 of 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). In the present work, the performance of the coupled model during Hudhud cyclone was evaluated based on available measured data (surface elevation and wave). 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.

The tide data were taken from the Permanent Service for Mean Sea Level (PSMSL) (www.psmsl.org). The wave data was obtained from the Directional Wave Rider buoy deployed off Visakapatnam (17.63°E; 83.26°N) at 15 m water depth; measurement range is -20 m to 20 m with an accuracy of 3%. Wave data was obtained from the directional wave rider buoy deployed off Visakhapatnam (17.63°N; 83.26°E) at 15 m water depth. The measurement range is -20 m to 20 m, with an accuracy of 3%. 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.

Formatted

Formatted

Formatted: Justified, Line spacing: 1.5 lines

Formatted: Line spacing: 1.5 lines

Formatted

Formatted

Formatted

Formatted: Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Formatted

155 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)) was estimated from the wave spectrum. The wave direction (D_p)
and directional width corresponding to the spectral peak were estimated based on the circular moments (Kuik et al., 1988).

160 2.2 Model domain and set-up

The model domain, chosen for the generation of winds, waves, currents and storm surges, covers the entire Bay of Bengal from 80-98°E and 6-21°N (Fig. 1a). The modified Etopo2 datasets by Sindhu et al. (2007) were used to generate the bathymetry grid. The data include improved shelf bathymetry for the Indian Ocean derived from sounding depths less than 200 m from the NHO (Naval Hydrographic Office, India) charts. The triangulated irregular mesh was prepared using SMS (Surface water Modeling System, <http://www.aquaveo.com/>) package for the selected domain (Fig. 1b). The unstructured mesh resolves sharp gradients in bathymetry, particularly in nearshore regions (Dietrich et al., 2011b), and it minimizes the computational cost relative to a structured mesh. For better results, tides and surges are resolved using a coarse grid in deep water, and higher resolution in the nearshore (Blain et al., 1994; Luettich and Westerink, 1995). Accordingly, in the present study, the mesh was generated with 82,253 elements and 41,795 nodes (Fig. 1b). A zoomed-in view of the landfall region with fine resolution of the mesh is shown in Fig. 1c. The mesh resolution varies from 1km in the nearshore region to a maximum of 80km in the deep water. The model has been run in a two-dimensional depth-averaged mode. The specifications of the model set-up are: (i) spherical coordinate system for the domain, (ii) cyclone duration (6.75 days), (iii) constant bottom friction (0.0025), (iv) minimum depth of 0.5 m for wet and dry elements and (v) horizontal eddy viscosity coefficient of $2 \text{ m}^2/\text{s}$.

170 The dynamic Holland wind field model (Holland, 1980) calculates the wind field, sea-level pressure distribution and gradient wind within the tropical cyclone. The wind stress was specified to ADCIRC model using the relation proposed by Garrett (1977). Fig. 2 shows the relative position of cyclone eye and associated wind field of the Hudhud cyclone computed from the wind model at different intervals as the cyclone approached the coast, before making the landfall at Visakhapatnam coast. Fig. 2 shows the relative position of cyclone eye and associated wind field of the Hudhud cyclone computed from the wind model at different intervals as the cyclone approached the coast, before making the landfall at Visakhapatnam coast. Holland model reproduced the maximum wind speed of $\approx 186 \text{ km/h}$ with a minimum central pressure drop of 950 hPa when it transformed into a Very Severe Cyclonic storm.

Formatted: Font: 11 pt, Font color: Auto

Formatted: Font: 11 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 11 pt, Font color: Auto

Formatted: Font: 11 pt, Font color: Auto

Formatted ...

185 2.3 Model setup for water level, current and wave generation

ADCIRC was tightly coupled to the unstructured wave model SWAN (Zijlema, 2010). The ADCIRC model was cold started with 13 tidal harmonic constituents (K1, N2, O1, P1, S2, K2, L2, M2, 2N2, MU2, NU2, Q1 and T2) taken from the LeProvost tidal database, and specified along the open boundary to reproduce tidal response in the Bay of Bengal.

190 In the present study, the unstructured version of SWAN (version 40.85) has been used which implements the four-direction Gauss-Seidel iteration technique with unconditional stability (Zijlema, 2010). SWAN was discretized into 31 frequency bins ranging from 0.05 to 1.00 Hz on a logarithmic scale and 36 direction bins having an angular resolution of 10°. SWAN was setup with Cavaleri and Malanotte-Rizzoli (1981) wave growth physics; the shallow water triad non-linear interaction was computed using the lumped triad approximation of Eldeberky (1996). Earlier studies (Bhaskaran et al., 2014; Gayathri et al., 2015; Gayathri et al., 2016; Dhana Lakshmi et al., 2017; Bhaskaran et al., 2013; Murty et al., 2014, 2016; Poulouse et al., 2017), carried out using the formulation of Komen et al. (1984) for cyclones which occurred in the Indian Ocean region, showed found that SWAN with this scheme performed well for extreme weather events. Keeping this in view, in the present study, we have used the authors have gone ahead with using the same formulation of Komen et al. (1984) to study the wave-current interaction during the Hudhud event. The model was initiated with modified white-capping dissipation (Komen et al., 1984); quadruplet non-linear wave-wave interaction was computed using Discrete Interaction Approximation (Hasselmann et al., 1985); depth induced breaking was computed using spectral version of the model with breaking index of $\gamma = 0.73$ (Battjes and Janssen, 1978); bottom friction was calculated based on JONSWAP physics (Hasselmann et al., 1973) with a friction coefficient, $C_b = 0.05\text{m}^2\text{s}^{-3}$. ADCIRC time step was specified as 10s, and SWAN as 600s. After every time step of SWAN, two-way coupling was carried out.

205 The model coupling is based on the work of Bunya et al. (2010) and Dietrich et al. (2011) in the Gulf of Mexico. SWAN employs an implicit sweeping method to update the wave details 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). SWAN computed radiation stress was passed on to ADCIRC to calculate wave set-up and nearshore currents. Similarly, water levels and currents computed by ADCIRC were passed on to SWAN in the prescribed time step. SWAN accesses these inputs and wind speeds at each node 210 and time, corresponding to the beginning and end of present interval. The radiation stress gradients used by ADCIRC were extrapolated forward in time, while the wind speeds, water levels and currents used by SWAN were averaged over each time step.

3. Results and Discussion

3.1. Cyclone track and wind generation

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

Formatted: Font: 10 pt, Font color: Auto

215 Hudhud cyclone is the second strongest tropical cyclone that crossed Visakhapatnam after 1985 (Amarendra et al.,
2015) and caused extensive damage to the property. Hudhud crossed the Andaman Islands on 08 October 2014 at 0930h
(IST). It moved west-northwest and intensified into a Very Severe Cyclonic Storm on 10 October 2014 (AN). It intensified
further on 12 October and crossed the Visakhapatnam coast around 1300h (IST) with a maximum wind speed of 180 km/h
(IMD Report, 2014). Figs. 1a and 2 show the track and passage of Hudhud. The maximum wind speed reproduced by the
220 Holland model is ≈ 54 m/s (Fig. 2) with maximum pressure drop to 950 hPa.

3.2. Role of waves in surface elevation during Hudhud cyclone

225 Tidal phase plays a major role in affecting the surface elevation during cyclones. If a cyclone makes its landfall
during high tide, the effective water level would be higher than during low tide. In this case, the landfall of Hudhud cyclone
occurred during spring high tide. We have conducted three numerical experiments to assess the impact of waves, currents
and tides on the total water surface elevation along the track during the passage of Hudhud cyclone. In the first experiment,
the ADCIRC model was set-up with only the cyclonic winds and atmospheric pressure generated by the Holland
Asymmetrical model (Fig. 2), and tides were switched-off. The model produced the maximum surge, which was due to
230 cyclonic winds and pressure alone. In the second experiment, ADCIRC model was run with tides, cyclonic winds and
atmospheric pressure, and the model provided the maximum water elevation generated by these contributing factors. The
third experiment was a two-way coupling of ADCIRC and SWAN, that is, the model run was executed by combining winds,
pressure fields, tides and wave forcing.

235 The resultant surface elevations from all these three numerical experiments were inter-compared and also validated
with tide gauge data off Visakhapatnam. The tide data from the Permanent Service for Mean Sea Level (PSMSL) was
adjusted to a Mean Sea Level (MSL) reference to match with ADCIRC generated surface elevation. Fig. 3 represents the
spatial distribution of maximum water surface elevation (in the whole domain) produced by the cyclone from the above three
experiments. The India Meteorological Department (IMD Report, 2014) reports a maximum water level of 1.6 m. However,
the tide gauge at Visakhapatnam recorded a maximum water level of 1.4 m. The simulation with winds, tides and waves
240 predicted a water level of 1.2 m (Fig. 4), which matches reasonably well with the measured data as well as other model
predictions (with a difference of 0.2 m during peak surge).

The two-way coupling with SWAN showed an increment of ≈ 0.15 m in total water level near Visakhapatnam during
the cyclone, which was contributed by waves to the total rise in water level. Wave set-up along the coast was caused as a
result of waves generated by the storm that subsequently released momentum (radiation stress, Longuet-Higgins and
245 Stewart, 1964) to the water column due to dissipation. Therefore, during storm events, water level rises not only by winds,

but by waves also, though the magnitude is much less compared to the water level contributed by the winds and pressure. Model results from both the runs were analysed to observe the change in storm surge height due to wave setup along the storm affected coastal regions, and the maximum change in the modelled surge height was $\approx 0.25\text{m}$ ($\approx 20\%$ of total surge height) between Visakhapatnam and Srikakulam (Fig. 3 b&c). Overall, the model prediction showed that during Hudhud cyclone wave induced setup had a significant impact on the total surge height, which provides an example of the importance of coupling wave and circulation model in predicting the total storm surge height accurately, especially during extreme tropical cyclones.

3.3 Effect of wave-current interaction on currents

Currents in the study region generated during the Hudhud cyclone period were analyzed to study the impact of wave-current interaction on the local current system. The maximum current speed obtained from the three numerical experiments (model runs) are shown in Fig. 5. As current measurements were not available for the cyclone period, the model produced velocity fields were analyzed and compared with earlier studies. In general, the East India Coastal Current (EICC) flows towards north along the east coast of India (ECI) during southwest monsoon. During northeast monsoon, the current reverses, and flows southward (Schott et al., 1994; Schott and McCreary, 2001; Shankar et al., 2002). On average, the maximum current speed along the ECI varies from 0.2 to 0.5 m/s (Mishra, 2010; Mishra, 2011; Panigrahi et al., 2010). Misra et al. (2013) observed through model simulations that tidal currents near the coast (water depth=20m) increases gradually from south to north.

The present simulations predicted current speeds upto 0.5 m/s, and this range is consistent with the earlier studies. However, during the cyclone period, the two-way coupling (ADCIRC+SWAN) increased the current magnitude by 0.25 m/s (due to waves) along the cyclone track and near the landfall region. When the cyclone made its landfall near Visakhapatnam, the current speed increased from 0.5 to 1.8 m/s for a short duration ($\approx 6\text{h}$) with direction of flow towards south. After $\approx 6\text{h}$ of landfall, current speed reduced to $\approx 0.1\text{ m/s}$, with reversal of current (towards north) (Figs. 6 & 7). The current pattern shows semi-diurnal variation associated with tidal currents. The spatial distribution of current speed and direction during the cyclone period driven by winds, tides and waves is given in Fig. 7, and it is very evident how the flow pattern changed with the passage of cyclone.

3.4 Effect of wave-current interaction on waves

Waves were modelled using SWAN alone and SWAN coupled with the ADCIRC to assess the impact of currents on the cyclone generated waves. Measured wave data were available only at one location, off Visakhapatnam (83.26°E , 17.63°N), which was on the track of Hudhud cyclone. Fig. 8 presents the comparison between the simulated and measured wave heights, wave periods and wave directions for the model runs of SWAN alone and coupled ADCIRC+SWAN. In the

early stages of Hudhud, the wave heights were of the order of 3 -5m near the Andaman and Nicobar islands (Fig. 9). But, when Hudhud intensified further while progressing towards ECI, it generated waves with heights of the order of 9-11 m, before making the landfall near Visakhapatnam on 12 October 2014 (1200h). Fig. 9 shows a swath of large waves (wave heights exceeding 10 m) propagating towards the coast with the passage of the storm. When the system was examined just before the landfall on 11 October 2014 at 2000 h (Fig. 9), it was found that the waves followed the pattern of cyclone winds. As waves experienced depth-limited breaking during its course onto the continental shelf, they propagated towards the right side of the track. Near Visakhapatnam, the buoy recorded a peak wave height of 7.8 m (Fig. 8), whereas, the model peak value is 6.2m. The spatial distribution of maximum significant wave heights (H_s) simulated along the track of Hudhud cyclone using SWAN (no wave-current interaction) and coupled ADCIRC+ SWAN (with wave-current interaction) is given in Fig. 10 (a & b). Fig. 10(c) illustrates change in wave energy due to wave-current interaction.

The spatial distribution of mean wave period (T_m) and peak wave period (T_p) simulated along the track of Hudhud cyclone using coupled ADCIRC+SWAN model (with wave-current interaction) is presented in Fig. 11 (a & b). Fig. 11a shows large mean wave periods ($\approx 13s$) in the nearshore region off Visakhapatnam during the cyclone (otherwise, during normal condition, wave periods will be of the order of 6s). Fig. 11b shows small pockets (at a few locations) of waves with large peak periods, of the order of 20s, moving towards the coast, south of Visakhapatnam. It was found that despite these large peak periods, the coupled wave-surge modelling system reproduced reasonably good wave-induced water level changes at these locations. Bender et al. (2012) reported similar large peak period scenarios, and reasoned that the ADCIRC model applies the SWAN radiation stress gradients based on individual spectral components only, and not the peak or mean parameters. This feature is also supported by the results of another coupled model, STWAVE, applied to the Louisiana Storm Surge (Atkinson et al, 2008), where isolated regions exhibited peak wave periods, greatly different from the surrounding values. Dietrich et al. (2013) presented a method that greatly removed the high peak period values with little degradation of model results. These isolated high peak wave periods point to the difficulty in simulating waves in inundating inland areas with shallow water depths and significant wind forcing.

Fig. 12a presents the maximum radiation stress gradient values calculated from SWAN, and passed on to the ADCIRC component of the coupled model. In the nearshore, the breaking waves exert stress on water column, causing changes in total water level and underlying currents. Fig. 12a shows the expected features for radiation stress gradient of $0.009 \text{ m}^2\text{s}^{-1}$ in the main wave breaking zone along the coastline when Hudhud made landfall between Visakhapatnam and Srikakulam.

We find from Fig. 10c that wave heights reduced by 0.5 m on the right side of the cyclone. Fig. 12b shows that waves travelled normal to the coast after crossing the shelf area, and currents flowed in the southwest direction (Fig. 7), and due to wave-current interaction wave heights have reduced. Subsequently, increase in wave height is noticed on the left side of the cyclone track when waves and currents opposed each other (waves propagated from southwest and currents flowed towards southwest direction, Fig. 7). In general, wave-current interaction is prominent, when currents are strong. The effect

of currents on the wave field is examined by comparing the wave parameters collected off Visakhapatnam and the model results obtained from SWAN alone and ADCIRC+SWAN just before the landfall of the cyclone (Fig. 8). As discussed earlier, we observed an increase in current speed of ≈ 1.3 m/s just before the landfall (Fig. 6), and an increase of ≈ 0.2 m in the significant wave height (H_s).

4. Conclusions

A very severe super cyclone Hudhud made landfall near Visakhapatnam causing extensive damage to coastal infrastructure. A coupled ADCIRC-SWAN modelling system was used to simulate the changes in the ocean surface dynamics during this event. The Holland model reproduced maximum wind speed of ≈ 54 m/s with minimum central pressure drop of 950 hPa when the Hudhud cyclone attained its peak intensity. As the landfall of Hudhud occurred during the high tide of spring phase, the estimated surge was correspondingly higher. The tide gauge off Visakhapatnam recorded a maximum surge of 1.4 m, and it matches 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 during the cyclone, which was contributed by waves to the total rise in water level. When the cyclone made its landfall near Visakhapatnam, the current speed increased from 0.5 m/s to 1.8 m/s for a short duration (≈ 6 h) with direction of flow towards south. After ≈ 6 h of landfall, current speed again reduced to ≈ 0.1 m/s, with reversal in current direction (towards north).

An increase of ≈ 0.2 m was noted in H_s after including currents from the circulation model at a location off Visakhapatnam. It was found that when waves travelled normal to the coast after crossing the shelf area and current flowed in the southwest direction, wave heights reduced due to wave-current interaction. Subsequently, 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 and bathymetry of the inundated coastal regions, where depth-limited breaking dominates.

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

Formatted: Font: 10 pt, Font color: Auto

Formatted: Line spacing: 1.5 lines

Formatted: Font: 10 pt, Font color: Auto

340 (towards north). The study signifies that an increase of ≈ 0.2 m in significant wave height (H_s) was noted when by including
the effect of currents was included on the wave field. The inclusion of currents in the modelling system, thus has, 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
345 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).

Acknowledgements

We thank Director, CSIR-NIO, Goa for his support and interest in this study. The first author acknowledges the
350 Dept. of Sci & Tech, Govt. of India for supporting the research work through WOS-A(SR/WOS-A/ES-17/2012). The
fieldwork data sharing is bounded with our institute data sharing policy. The ERA-Interim wind and wave data were freely
downloaded from ECMWF (<http://apps.ecmwf.int/datasets/>). We are thankful to INCOIS, Hyderabad for providing the wave
data. We acknowledge CSIR-NIO for providing high performance computing domain, HPC-Pravah for running the model.
We are thankful to Dr. V.S.N Murty for giving input on impact of Hudhud on the coast. We are thankful to model developers
355 for providing the source code for the model used in this study, ADCIRC+SWAN. We are also thankful to Chaitanya for
assisting in preparation of the figures. The NIO contribution number is xxx.

References

- Amarendra, P.G., Bharathi, P., Bhanumurthy, K., Gopala Reddy, Balakrishnan Nair, T.M.: An observational study on wave
characteristics during HUDHUD cyclone off Gangavaram, OSICON, CSIR,NIO, Goa 2015.
- 360 Ardhuin, F., Rasle, N., Belibassakis, K. A.: Explicit wave-averaged primitive equations using a generalized Lagrangian
mean, Ocean Modeling, 32, 35–60, 2008.
- Atkinson, J.H., Westerink, J.J., Hervouet, J .M.: Similarities between the Wave Equation and the Quasi-Bubble
Solutions to the Shallow Water Equations, International Journal for Numerical Methods in Fluids, 45, 689-714,
2004.
- 365 Atkinson J. H., Westerink J. J, Wamsley T., Cialone M. A., Dietrich J. C., Dresback K. M., Kolar R. L., Resio D. T., Bender
C., Blanton B. O., Bunya S., De Jong W., Ebersole B. A., Grzegorzewski A., Jensen R. E., Pourtaheri H., Ratcliff J., Roberts
H. J., Smith J. M., Szpilka C. M.: Hurricane Storm Surge and Wave Modeling in Southern Louisiana: A Brief Overview,
Proceedings of the Tenth International Conference on Estuarine and Coastal Modeling, 467-506, 2008.
- Battjes, J.A., Janssen, J.P.F.M.: Energy loss and setup due to breaking of random waves, Proc. 16th Coastal Eng.
370 Conf., ASCE (1978), pp. 569–587, 1978.

Formatted: Font: 10 pt, Font color: Auto

Formatted: Space Before: 0 pt, After: 0 pt

Beardsley, R.C., Chen, C., Xu, Q.: Coastal flooding in Scituate (MA): A FVCOM study of the 27 December 2010 nor'easter, *Journ Geophys. Res.* 118, 6030–6045, doi:10.1002/2013JC008862, 2013.

Bender, F.A.M., Ramanathan, V., Tselioudis, G.: Changes in extratropical storm track cloudiness 1983-2008: Observational support for a poleward shift, *Clim. Dyn.* 38, 2037-2053, doi:10.1007/s00382-011-1065-6, 2012.

375 Bennis, A.C., Arduin, F., Dumas, F.: On the coupling of wave and three-dimensional circulation models: Choice of theoretical framework, practical implementation and adiabatic tests, *Ocean Modelling.* 40(3), 260-272, 2011.

Bhaskaran, P.K., Nayak, S., Bonthu, S.R., Murty, P.N., Sen, D.: Performance and validation of a coupled parallel ADCIRC–SWAN model for THANE cyclone in the Bay of Bengal, *Environmental Fluid Mechanics.* 13(6), 601-623, 2013.

380 Bhaskaran, P.K., Gayathri, R., Murty, P.L.N., Subba Reddy, B., Sen, D.: A numerical study of coastal inundation and its validation for Thane cyclone in the Bay of Bengal, *Coastal Engineering.* 83, 108–118, 2014.

Blain, C.A., Westerink, J.J., Luettich, R.A.: The influence of domain size on the response characteristics of a hurricane storm surge model, *Journal of Geophysical Research.* 99, doi: 10.1029/94JC01348. Issn: 0148-0227, 1994.

385 Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third generation wave model for coastal regions, Part I: Model description and validation, *Journal of Geophysical Research.* 104, 7649-7666.

Carniel, S.J., Chiggiato, W.J., Sclavo, M.: Investigating the impact of surface wave breaking on modeling the trajectories of drifters in the northern Adriatic Sea during a wind-storm event, *Ocean Modelling* 30(2), 225-239, 2009.

Cavaleri, L., Malanotte-Rizzoli, P.: Wind wave prediction in shallow water: Theory and applications, *Journal of Geophysical Research* 86, 961- 973, 1981.

390 Davies, A.M., John Lawrence.: Modeling the effect of wave-current interaction on the three-dimensional wind-driven circulation of the eastern Irish Sea, *Journal of Physical Oceanography.* 25(1), 29-45, 2005.

Dawson, C.N., Westerink, J.J., Feyen, J.C., Pothina, D.: Continuous, Discontinuous and Coupled Discontinuous-Continuous Galerkin Finite Element Methods for the Shallow Water Equations, *International Journal for Numerical Methods in Fluids.* 52(1), 63-88, 2006.

395 [Dhana Lakshmi, D., Murty, P.L.N., Bhaskaran, P.K., Sahoo, B., Srinivasa Kumar, T., Shenoj, 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.](#)

Dietrich, J.C., Tanaka, S., Westerink, J.J., Dawson, C.N., Luettich, R.A.Jr., Marcel Zijlema, Holthuijsen, L.H., Smith, J.M., Westerink, L.G., Westerink, H.J.: Performance of the unstructured-mesh, SWAN+ ADCIRC model in computing hurricane waves and surge, *Journal of Scientific Computing* 52(2), 468-497, 2012.

400 Dietrich, J.C., Dawson, C.N., Proft, J.M., Howard, M.T., Wells, G., Fleming, J.G., Luettich, R.A.Jr., Westerink, J.J., Cobell, Z., Vitse, M., Lander, H., Blanton, B.O., Szpilka, C.M., Atkinson, J.H.: Real-Time Forecasting and Visualization of

Formatted: List Paragraph, Line spacing: 1.5 lines, Tab stops: 0.5 cm, Left

Formatted: Font: 10 pt, Font color: Auto

Hurricane Waves and Storm Surge Using SWAN+ADCIRC and FigureGen, Computational Challenges in the Geosciences, The IMA Volumes in Mathematics and its Applications, 156, 49-70, DOI: 10.1007/978-1-4614-7434-0_3, 2013.

405 Dietrich, J.C., Bunya, S., Westerink, J.J., Ebersole, B.A., Smith, J.M., Atkinson, J.H., Jensen, R.: A high-resolution coupled riverine flow, tide, wind, wind wave, and storm surge model for southern Louisiana and Mississippi. Part II: Synoptic description and analysis of Hurricanes Katrina and Rita, Monthly Weather Review 138(2), 378-404, 2010.

Dietrich, J.C., Westerink, J.J., Kennedy, A.B., Smith, J.M., Jensen, R.E., Zijlema, M., Holthuijsen, L.H.: Hurricane Gustav (2008) waves and storm surge: Hindcast, synoptic analysis, and validation in southern Louisiana, Monthly Weather Review. 139(8), 2488-2522, 2011a.

410 Dietrich, J.C., Zijlema, M., Westerink, J.J., Holthuijsen, L.H., Dawson, C., Luettich, R.A., Jensen, R.E., Smith, J.M., Stelling, G.S., Stone, G.W.: Modeling hurricane waves and storm surge using integrally-coupled, scalable computations, Coastal Engineering. 58(1), 45-65, 2011b.

Dong, Z., Kirby, T.: Theoretical and numerical study of wave-current interaction in strongly-sheared flows, Coast Engg., 2012.

415 Dube, S.K., Rao, A.D., Sinha, P.C., Murty, T.S., Bahulayan, N.: Storm surge in the Bay of Bengal and Arabian Sea: the problem and its prediction, Mausam. 48, 283-230, 1997.

Eldeberky, Y., Polnikov, V., Battjes, J.A.: A statistical approach for modeling triad interactions in dispersive waves, Proc. 25th Int. Conf. Coastal Eng., pp. 1088-1101, 1996.

420 Hani, T., Ganesan, P., Murty, V.S.N.: Impact of the very severe cyclonic storms - The Phailin and Hudhud - on the beach processes along the Visakhapatnam coast, OSICON, CSIR,NIO, Goa, 2015.

Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Kruseman, P., Meerburg, A., Mller, P., Olbers, D.J., Richter, K., Sell, W., and Walden, H.: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP), Ergänzungsheft zur Deutschen Hydro. Zeitschrift Reihe, A(8) (Nr. 12), p.95, 1973.

425 Hasselmann, S., Hasselmann, K., Allender, J., Barnett, T.: Computations and parameterizations of the nonlinear energy transfer in a gravity-wave spectrum. Part II: Parameterizations of the nonlinear energy transfer for application in wave models, Journal of Physical Oceanography. 15, 1378-1391, 1985.

Holland, G.J.: An analytic model of the wind and pressure profiles in hurricanes, Monthly Weather Review. 108, 1212-1218, 1980.

430 Holthuijsen, L.H., Tolman, H.L.: Effects of the Gulf Stream on ocean waves, Journal of Geophysical Research. 96, 12-755, 1991.

Hope, M.E., Westerink, J.J., Kennedy, A.B., Kerr, P.C., Dietrich, J.C., Dawson, C., Bender, C.J.: Hindcast and validation of Hurricane Ike (2008) waves, forerunner, and storm surge, Journal of Geophysical Research. 118, 4424-4460, 2013.

Formatted: List Paragraph, Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers, Tab stops: 0.5 cm, Left

435 [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.](#)

Formatted: Font: 10 pt, Font color: Auto

[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.](#)

Formatted: Font: 10 pt, Font color: Auto

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

Formatted: Font: 10 pt, Font color: Auto

IMD Report: Very Severe Cyclonic Storm, HUDHUD over the Bay of Bengal (07-14 October 2014), A Report, 2014.

445 Kirby, J.T., Tsung-Muh, Chen.: Surface waves on vertically sheared flows: approximate dispersion relations, Journal of Geophysical Research: Oceans. 94, 1013-1027, 1989.

Kolar, R.L., Westerink, J.J., Cantekin, M.E., Blain, C.A.: Aspects of nonlinear simulations using shallow water models based on the wave continuity equation, Computers and Fluids. 23, 523-538, 1994.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen P.A.E.M.: Dynamics and Modelling of Ocean Waves, 532 pp., Cambridge Univ. Press, New York, 1994.

450 Komen, G., Hasselmann, K., Hasselmann, S.: On the existence of a fully developed wind-sea spectrum, Jour. of Phy. Oceanography. 14, 1271-1285, 1984.

Kubatko, E.J., Bunya, S., Dawson, C., Westerink, J.J.: Dynamic p-adaptive Runge-Kutta Discontinuous Galerkin Methods for the Shallow Water Equations, Computer Methods in Applied Mechanics and Engineering. 198, 1766-1774, 2009.

455 Kudryavtsev, V.N., Makin, V.K., Chapron, B.: Coupled Sea Surface-Atmosphere Model 2. Spectrum of Short Wind Waves, J. Geophys. Res. 104, 7625-7639, 1999.

[Kuik, A.J., Vliedder, G., Holthuijsen, L.H.: A method for the routine analysis of pitch and roll buoy wave data, Journal of Physical Oceanography 18, 1020-1034, 1988.](#)

Formatted: Font: (Default) Times New Roman, 10 pt

Longuet-higgins, M.S., Stewart, R.W.: Radiation stresses in water waves; a physical discussion, with application, Deep-Sea Res. 11, 529-562, 1964.

Formatted: Font: (Default) Times New Roman, 10 pt

460 Luettich, R.A., Westerink, J.J.: Continental shelf scale convergence studies with a barotropic tidal model, Quantitative skill assessment for coastal ocean models. 349-371, 1995.

Luettich, R.A., Westerink, J.J.: Formulation and numerical implementation of the 2D/3D ADCIRC finite element model version 44, Tech Rep., 2004.

465 Mastenbroek, C., Burgers, G., Janssen, P.A.E.M.: The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer, Journal of Physical Oceanography. 23, 1856-1866, 1993.

McWilliams, J.C., Restrepo, J.M., Lane, E.M.: An asymptotic theory for the interaction of waves and currents in coastal waters, *Journal of Fluid Mechanics*. 511, 135–78, 2004.

Mellor, G.L.: The three-dimensional current and surface wave equations, *Journal of Physical Oceanography*. 33, 1978–1989, 2003.

470 Mellor, G.L.: The depth-dependent current and wave interaction equations: a revision, *Journal of Physical Oceanography*. 38, 2587–96, 2008.

Mishra, P., Patra, S.K., Bramha, S., Mohanty, P.K., Panda, U.S., Rao, V.R., Ramanamurthy, M.V.: Wave characteristic and tidal regime off Gopalpur, east coast of India and its implication in coastal erosion, In: *Proceedings of the joint Indo-Brazil workshop on coastal process and modeling relevant to understanding shoreline changes*, Chennai, India, pp 22-32 4, 2010.

475 Misra, S.K.: Studies on nearshore currents along the southern part of the East Coast of India, Ph.D. thesis, Awarded by Berhampur University, 2011.

Misra, S.K., Chandramohan, P., Satyanarayana, M.A., Panigrahi, J.K., Mahadevan, R.: Nature of the tide induced flow field along the East Coast of India, *International Journal of Oceans and Oceanography*. 7, 57-71, 2013.

480 Moon, Il-Ju.: Impact of a coupled ocean wave–tide–circulation system on coastal modeling. *Ocean modelling*. 8, 203-236, 2005.

Murty, P.L.N., Sandhya, K.G., Bhaskaran, P.K., Felix, J., Gayathri, R., Balakrishnan, N.T.M., SrinivasaKumar, T., Sheno, S.S.C.: A coupled hydrodynamic modeling system for PHAILIN cyclone in the Bay of Bengal, *Coastal Engineering*. 93, 71-81, 2014.

485 [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.](#)

Murty, T.S., Flather, R.A., Henry, R.F.: The storm surge problem in the Bay of Bengal, *Progress in Oceanography*. 16, 195-233, 1986.

490 Nair, Balakrishnan, Remya, P.G., Harikumar, R., Sandhya, K.G., Sirisha, P., Srinivas, K., Nagaraju, C.: Wave forecasting and monitoring during very severe cyclone Phailin in the Bay of Bengal, *Current Science*. 106, 1121-1125, 2014.

Panigrahi, J.K., Swain, J.: Numerical Simulation and Validation of Deepwater Spectral Wind-Waves, *Marine Geodesy*. 33, 39-52, 2010.

495 Pleskachevsky, A., Eppel, D.P., Kapitza, H.: Interaction of waves, currents and tides, and wave-energy impact on the beach area of Sylt Island, *Ocean Dynamics*. 59, 451-461, 2009.

[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>.](http://dx.doi.org/10.1016/j.ecss.2017.06.007)

Formatted: List Paragraph, Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers, Tab stops: 0.5 cm, Left

Formatted: Font: 10 pt, Font color: Auto

Formatted: List Paragraph, Line spacing: 1.5 lines, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers, Tab stops: 0.5 cm, Left

Formatted: Font: 10 pt

Formatted: Font: 10 pt, Font color: Auto

500 Rao, A.D.: Numerical storm surge prediction in India, Ph.D. thesis, IIT Delhi, New Delhi, 211 pp, 1982.

Rao, A.D., Murty, P.L.N., Jain, I., Kankara, R.S., Dube, S.K., Murty, T.S.: Simulation of water levels and extent of coastal inundation due to a cyclonic storm along the east coast of India, *Nat. Hazards*. <http://dx.doi.org/10.1007/s11069-012-0193-6>, 2012.

505 Rao, V.R., Subramanian, B.R., Mohan, R., Kannan, R., Mageswaran, T., Arumugam, T., Rajan, B.: Storm surge vulnerability along Chennai–Cuddalore coast due to severe cyclone THANE, *Nat. Hazards*. <http://dx.doi.org/10.1007/s11069-013-0630-1>, 2013.

Ris, R., Holthuijsen, L.H., Booij, N.: A third-generation wave model for coastal regions: 2. Verification, *Journal of geophysical research*. 104, 7667-7681, 1999.

Schott, F., McCreary, J.P.: The monsoon circulation in the Indian Ocean, *Progress Oceanogr.* 51, 1–123, 2001.

510 Schott, F., Reppin, J., Fischer, J., Quadfasel, D.: Currents and transports of the Monsoon Current south of Sri Lanka, *Journal of Geophysical Research*. 99, doi: 10.1029/94JC02216. Issn: 0148-0227, 1994.

Sebastian, A., Bedient, P., Proft, J., Dietrich, J., Dawson, C.: Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC Model, *Coastal Engineering*. 88, 171-181, DOI: 10.1016/j.coastaleng.2014.03.002, 2014.

515 Shankar, D., Vinayachandran, P.N., Unnikrishnan, A.S.: The monsoon currents in the north Indian Ocean, *Progr. Oceanography* 52, 63–120, 2002.

Sindhu, B., Suresh, I., Unnikrishnan, A.S., Bhatkar, N.V., Neetu, S., Michael, G.S.: Improved bathymetric datasets for the shallow water regions in the Indian Ocean, *Journal of Earth System Science*. 166(3), 261-274, 2007.

Tanaka, S., Bunya, S., Westerink, J.J., Dawson, C., Luettich, R.A.: Scalability of an Unstructured Grid Continuous Galerkin Based Hurricane Storm Surge Model, *Journal of Scientific Computing*. 46, 329-358, 2011.

520 Thompson, E.F., Cardone, V.J.: Practical modeling of hurricane surface wind fields, *ASCE, J. of Waterway, Port, Coastal and Ocean Engg.* 122, 195-205, 1996.

Tolman, H.L.: A third-generation model for wind waves on slowly varying, unsteady, and inhomogeneous depths and currents, *Journal of Physical Oceanography*. 21, 782-797, 1991.

Uchiyama, Y., McWilliams, J.C., Shchepetkin, A.F.: Wave-current interaction in an oceanic circulation model with a vortex-force formalism: application to the surf zone, *Ocean Modelling*. 34, 16–35, 2010.

525 Warner, J.C., Sherwood, C.R., Signell, R.P., Harris, C.K., Arango, H.G.: Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, *Computers & Geosciences*. 34, 1284-1306, 2008.

Westerink, J.J., Luettich, R.A., Feyen, J.C., Atkinson, J.H., Dawson, C., Hugh, J.R., Powell, M.D., Dunion, J.P., Kubatko, E.J., Pourtaheri, H.: A basin-to channel-scale unstructured grid hurricane storm surge model applied to southern Louisiana, *Monthly Weather Review*. 136, 833-864, 2008.

530

Xia, Y., Yang, Z., Jackson, C., Stoffa, P.L., Sen, M.K.: Impacts of data length on optimal parameter and uncertainty estimation of a land surface model, *Journal of Geophysical Research*. 109, doi: 10.1029/2003JD004419, 2004.

Xie, L., Wu, K., Pietrafesa, L., Zhang, C.: A numerical study of wave-current interaction through surface and bottom stresses: Wind-driven circulation in the South Atlantic Bight under uniform winds, *Journal of Geophysical Research*. 106, 16841-16855, 2001.

535

Xie, L., Pietrafesa, L.J., Wu, K.: A numerical study of wave-current interaction through surface and bottom stresses: Coastal ocean response to Hurricane Fran of 1996. *Journal of Geophysical Research*. 108, 3049, doi:10.1029/2001JC001078, 2003.

Zhang, M.Y., Li, Y.S.: The synchronous coupling of a third-generation wave model and a two-dimensional storm surge model, *Ocean Engg*. 23, 533-543, 1996.

540

Zhang, M., Zhao, Y.W., Chen, H., Jiang, W.Q.: SAR imaging simulation for composite model of ship on dynamic ocean scene, *Progress In Electromagnetics Research*. 113, 395-412, 2011.

Zijlema, M.: Computation of wind-wave spectra in coastal waters with SWAN on unstructured grids, *Coastal Engineering*. 57, 267-277, 2010.

545

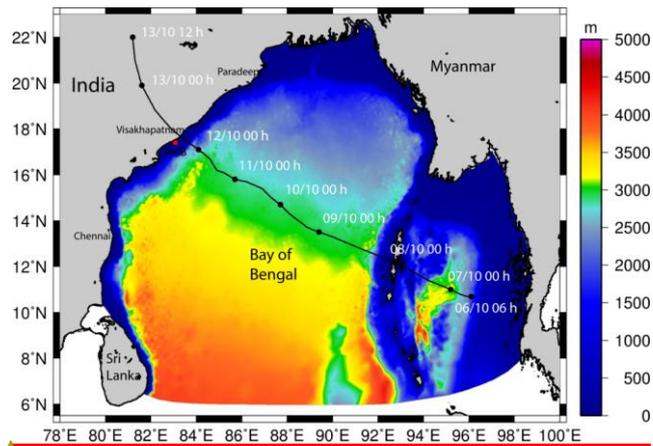


Figure 1a

Formatted: Font: (Default) Times New Roman, 12 pt, Bold

Formatted: Tab stops: 13.83 cm, Left

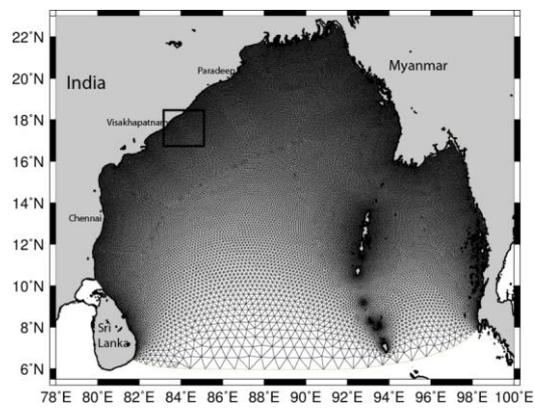


Figure 1b

550

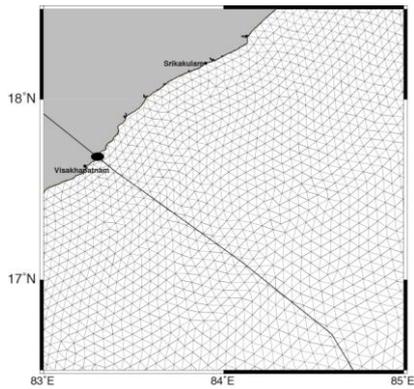


Figure 1c

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.

555

Fig. 1a. Bathymetry of the model domain chosen for wave-current interaction during Hudhud cyclone; cyclone track details are also shown. Fig. 1b. Fine resolution unstructured mesh generated for the domain to run the coupled ADCIRC+SWAN model; 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.

560

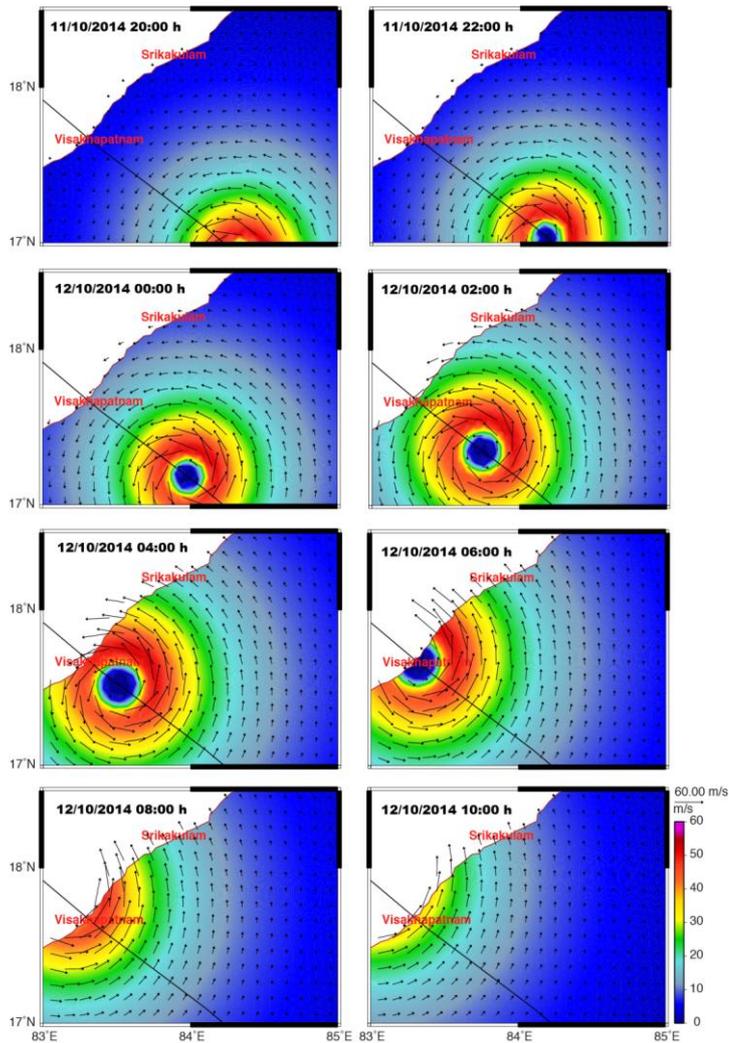
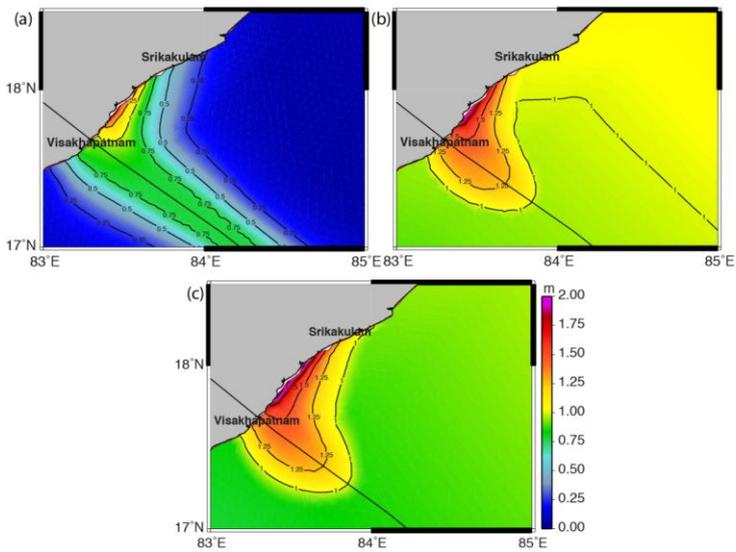


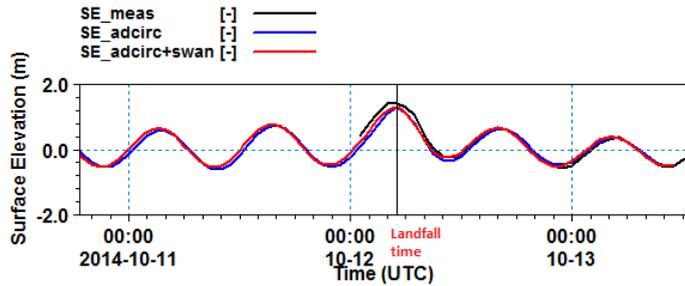
Fig. 2. Typical winds (speed and direction) generated using Holland symmetrical model along the track of Hudhud cyclone (colour code represents wind speed in m/s; vectors represent wind direction).

565 | **Fig. 2. Typical winds (speed and direction) generated using Holland symmetrical model along the track of Hudhud cyclone.**



570 | **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).**

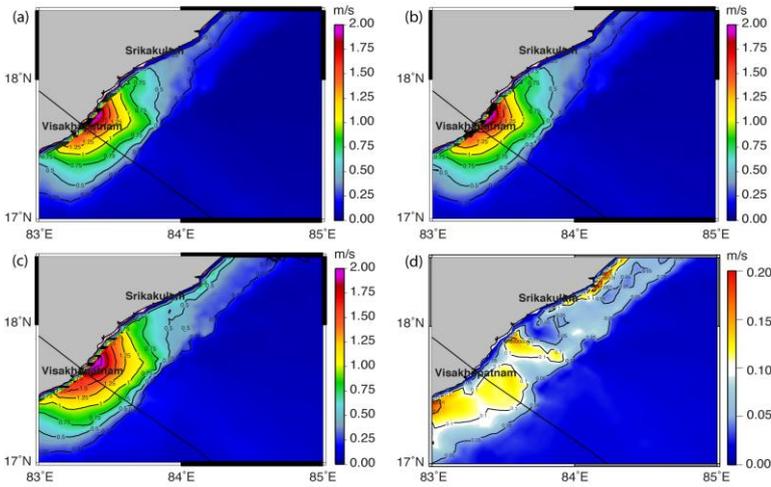
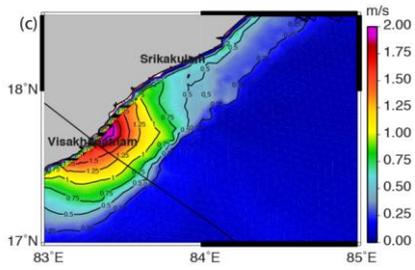
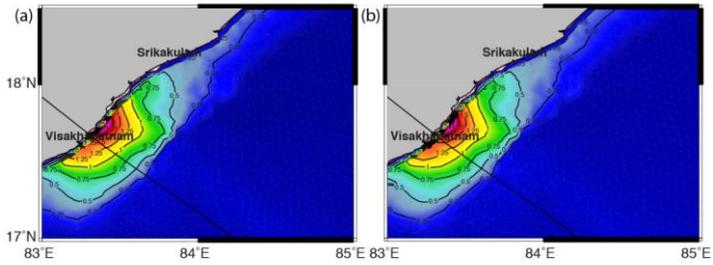
Fig. 3. Spatial distribution of maximum surface elevation (m) due to (a) cyclonic winds, (b) cyclonic winds and tides and (c) cyclonic winds, tides and waves.



575

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.

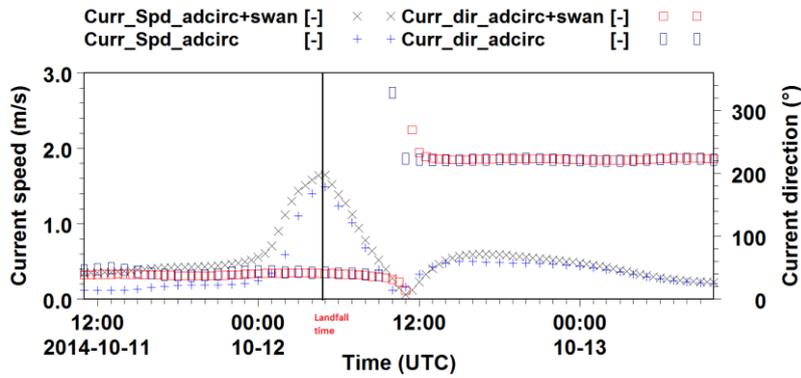
Fig. 4. Time series of surface elevation (m) at Visakhapatnam coast (17.63°E; 83.26°N) during 10-13 October 2014.



580

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).

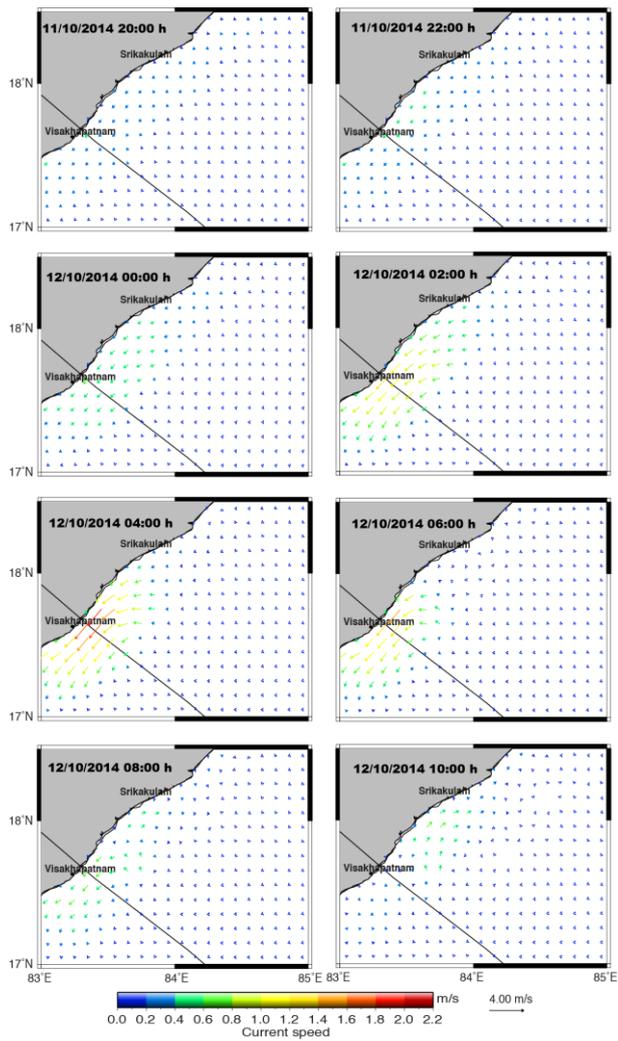
Fig. 5. Spatial distribution of maximum surface currents (m/s) due to (a) winds, (b) winds and tides and (c) winds, tides and waves, during cyclone.



585

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. 6. Time series of currents (m/s) off Visakhapatnam coast (17.63°E; 83.26°N) during 10-13 October 2014.



590 | **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. 7. Current speed and direction simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (colour code represents current speed; vectors represent current direction).

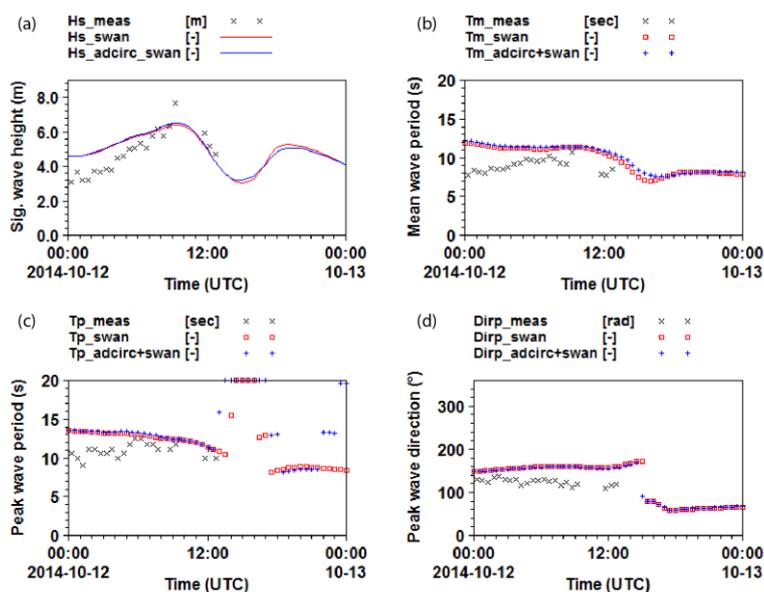
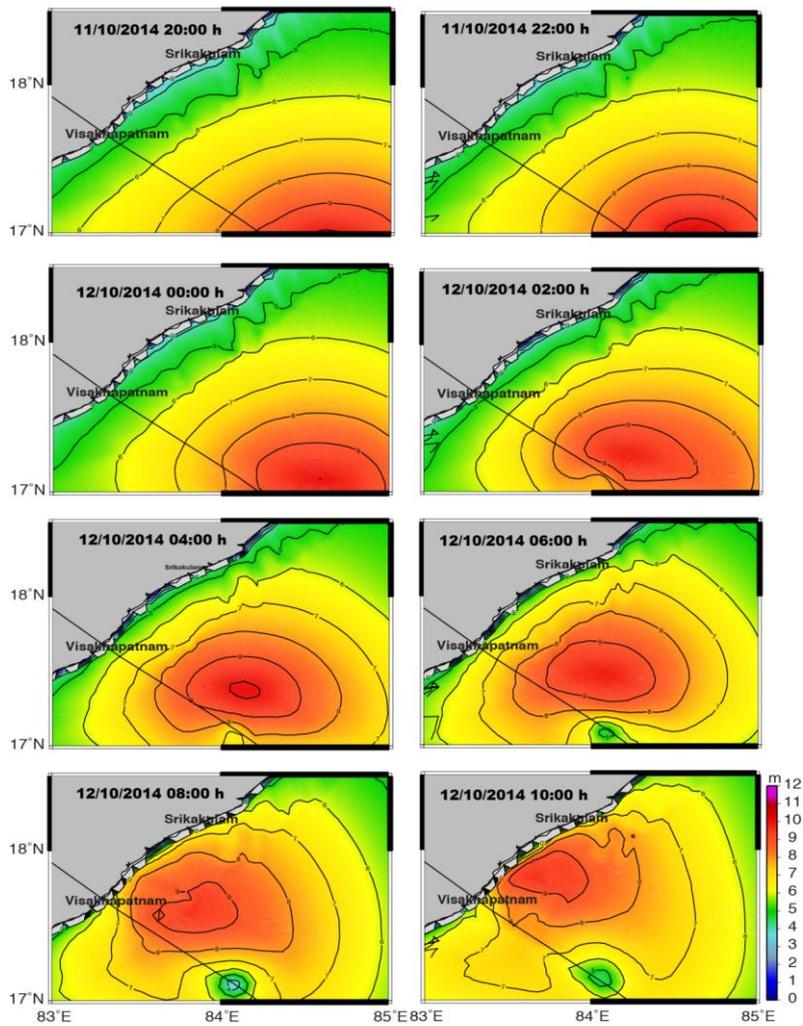


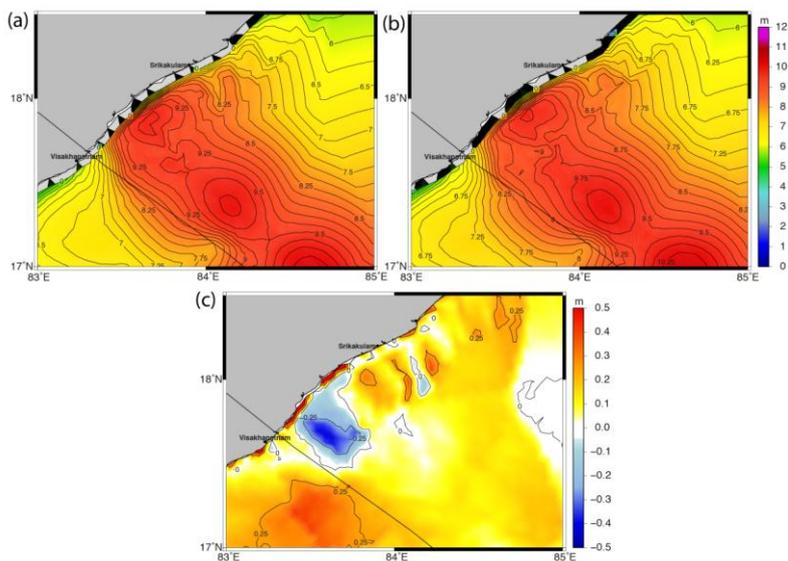
Fig. 8. Comparison of measured (black) and modelled (a) significant wave heights (H_s), (b) mean wave periods, (c) peak wave periods and (d) peak wave directions obtained from SWAN (red) and coupled ADCIRC+SWAN (blue) during Hudhud cyclone with measured data off Visakhapatnam (17.63°N; 83.26°E).

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



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



Formatted: Space After: 0 pt

Fig.10. Spatial distribution of maximum significant wave heights (H_m) 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_m ; (c) change in H_m from (a) and (b), illustrating change in wave energy due to wave-current interaction.
Fig. 10. Spatial distribution of maximum significant wave heights (H_m) 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_m ; (c) change in H_m from (a) and (b), illustrating change in wave energy due to wave-current interaction.

610

615

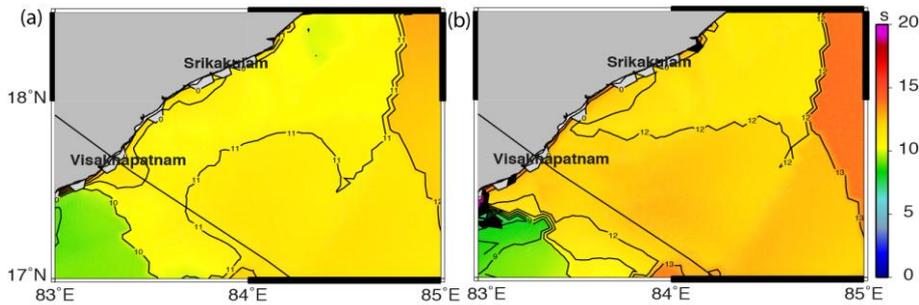


Fig. 11. Spatial distribution of (a) mean wave period (T_m) and (b) peak wave period (T_p) simulated along the track of Hudhud cyclone using coupled ADCIRC+SWAN model (with wave-current interaction).

620

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).

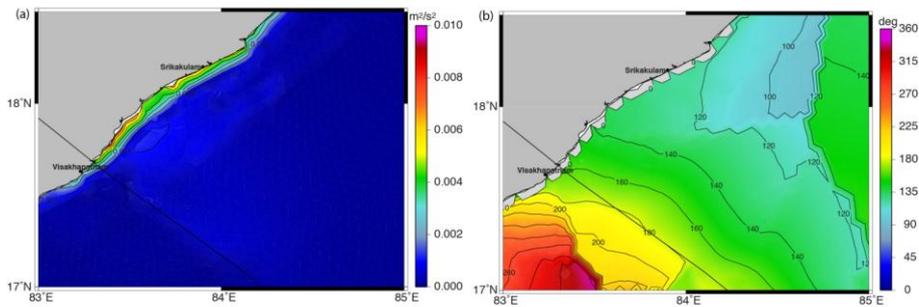


Fig. 12. (a) Maximum radiation stress gradient values calculated from SWAN and (b) spatial distribution of mean wave direction (Dir) simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (with wave-current interaction); colour code and contours represent wave direction.

625

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.

630

