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

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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 ≈ 54m/s with the minimum pressure of 950hPa. 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 ≈ 0.25m 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 (≈6h) with net flow towards south, and thereafter reversed towards north. An increase of ≈0.2m 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 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 many on interaction between the processes. Therefore, we need to take into account different processes that impact a specific process.

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; Ardhuin 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 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 effected 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).

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, 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 modeling.

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) 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.

Presently, in storm surge modeling, 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.

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.

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; Luettich 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. 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 elevation and wave). 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%.

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 m^2/s.

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.

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. 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). 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, $C_b = 0.\ 05 m^2 s^{-3}$. ADCIRC time step was specified as 10s, and SWAN as 600s. After every time step of SWAN, two-way coupling was carried out.

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 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

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 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

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 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.

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 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 ≈0.15m 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, Longuett-Higgins and 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 ≈0.25m (≈ 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 (≈6h) with direction of flow towards south. After ≈6h of landfall, current speed reduced to ≈0.1 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 (≈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 m^2s 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≈1.3m/s just before the landfall (Fig. 6), and a an increase of ≈0.2m in the significant wave height (H_s).

4. Conclusions

A very severe super cyclone Hudhud made landfall near Visakhaptnam 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 ≈54m/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 ≈0.25m (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 (≈6h) with direction of flow towards south. After ≈6h 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.

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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.

Ardhuin, F., Rascle, 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.

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. Conf., ASCE (1978), pp. 569–587, 1978.

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.

Bennis, A.C., Ardhuin, 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.

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.

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.

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.

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.

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 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.

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.

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.

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.

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), Ergnzungsheft zur Deutschen Hydro. Zeitschrift Reihe, A(8) (Nr. 12), p.95, 1973.

Hasselmann, S., Hasselmann, K., Allender, J., Barnett, T.: Computations and parameterizations of the nonlinear energy transfer in a gravity-wave specturm. 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.

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.

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

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.

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.

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.

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

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.

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.

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.

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.

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., Shenoi, S.SC.: A coupled hydrodynamic modeling system for PHAILIN cyclone in the Bay of Bengal, Coastal Engineering. 93, 71-81, 2014.

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.

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.

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.

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/s 11069-012- 0193-6, 2012.

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.

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.

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.

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.

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.

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.

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.

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.

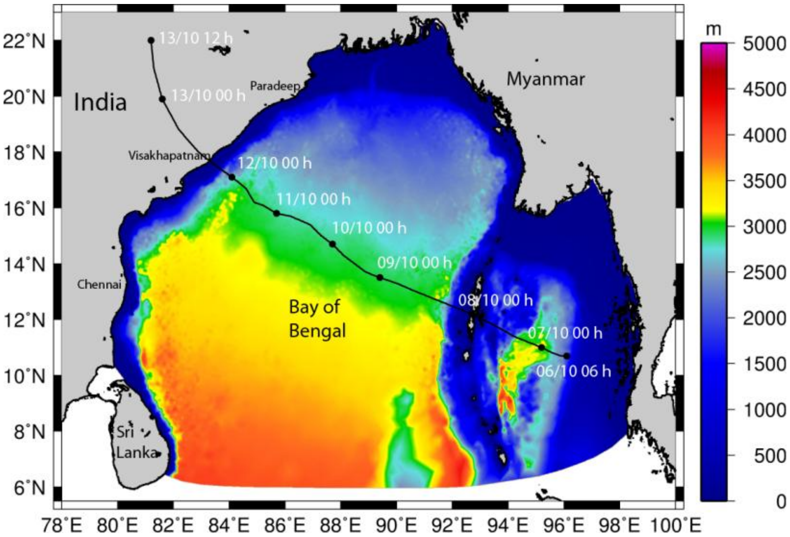
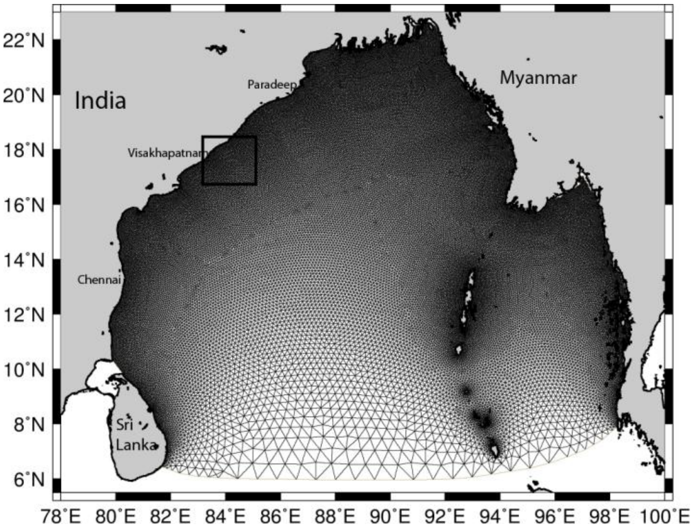


Figure 1a



435 **Figure 1b**

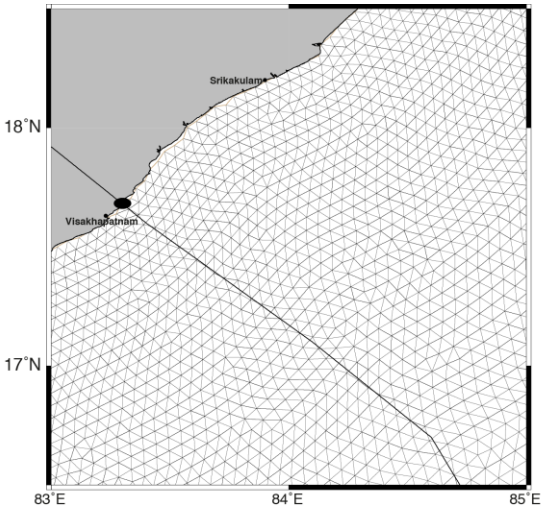


Figure 1c

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.

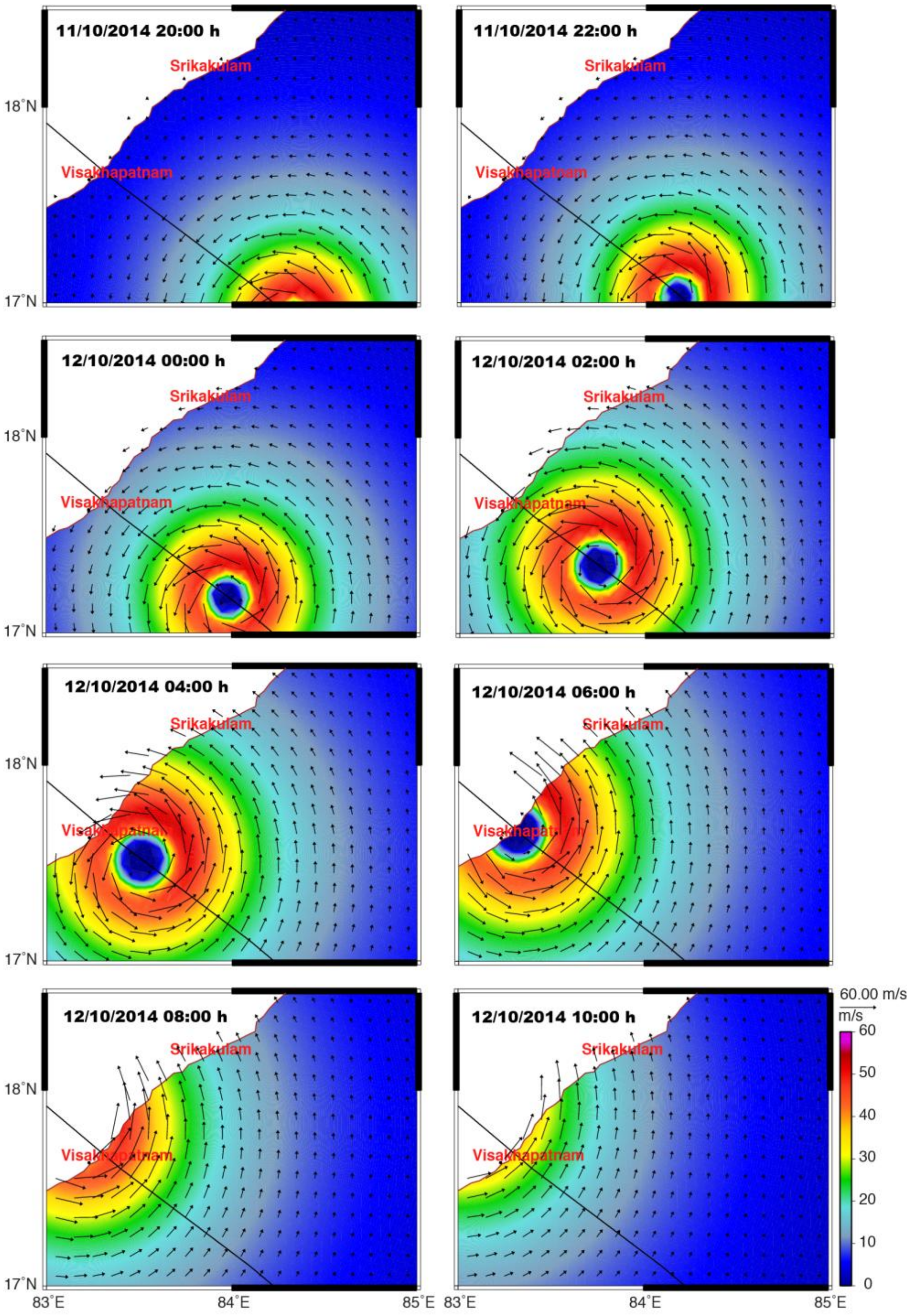


Fig. 2. Typical winds (speed and direction) generated using Holland symmetrical model along the track of Hudhud cyclone.

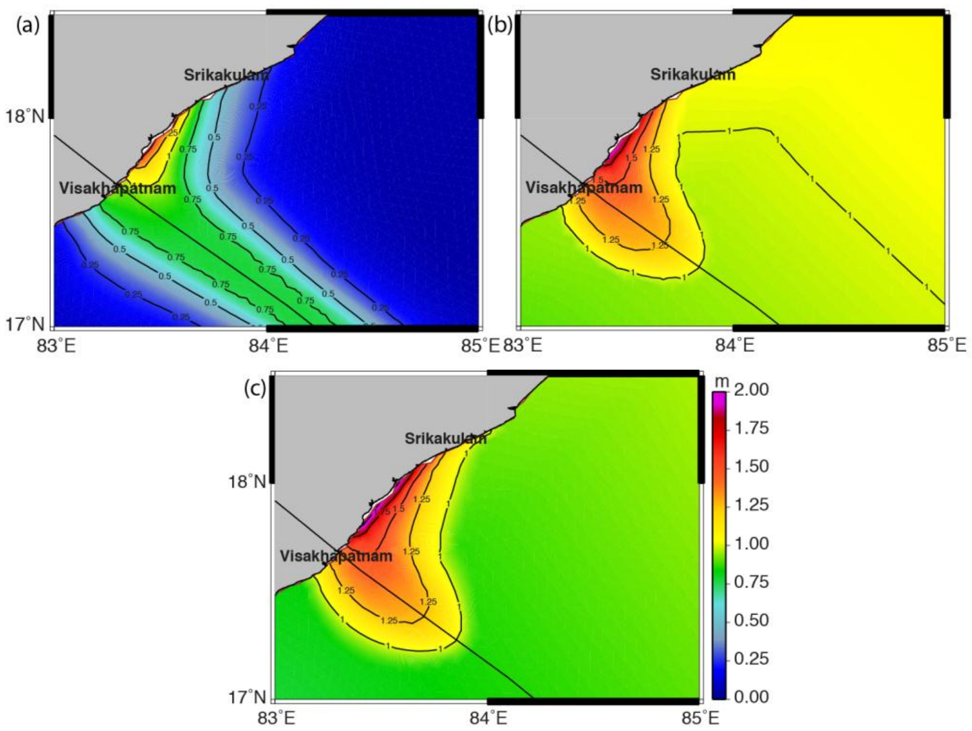


Fig. 3. Spatial distribution of maximum surface elevation (m) due to (a) cyclonic winds, (b) cyclonic winds and tides and (c) cyclonic winds, tides and waves.

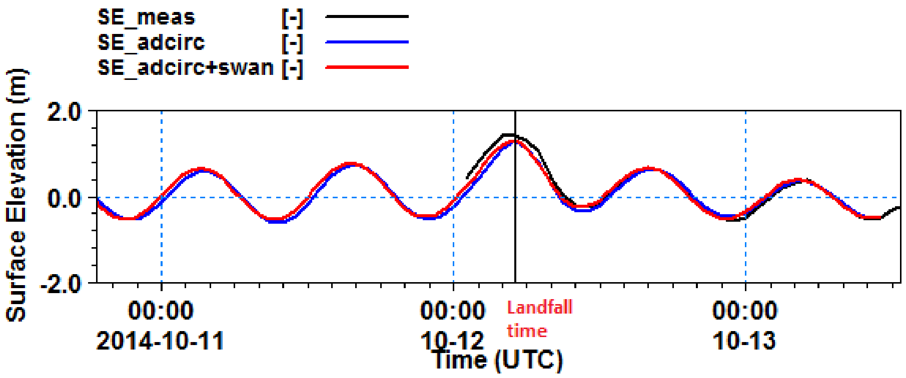


Fig. 4. Time series of surface elevation (m) at Visakhapatnam coast (17.63°E; 83.26°N) during 10-13 October 2014.

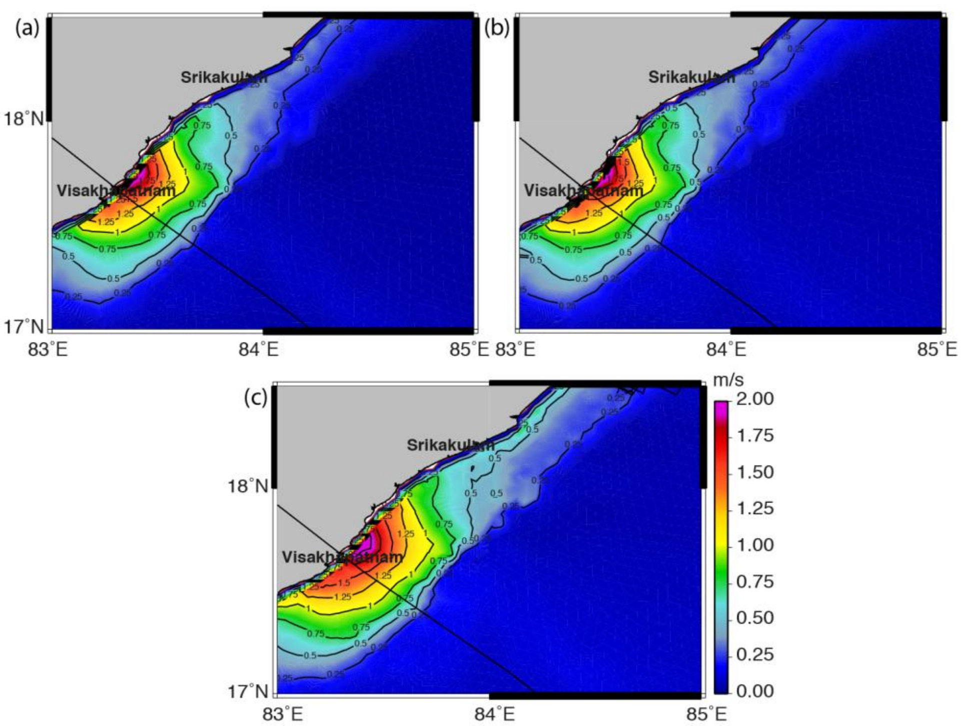


Fig. 5. Spatial distribution of maximum surface currents (m/s) due to (a) winds, (b) winds and tides and (c) winds, tides and waves, during cyclone.

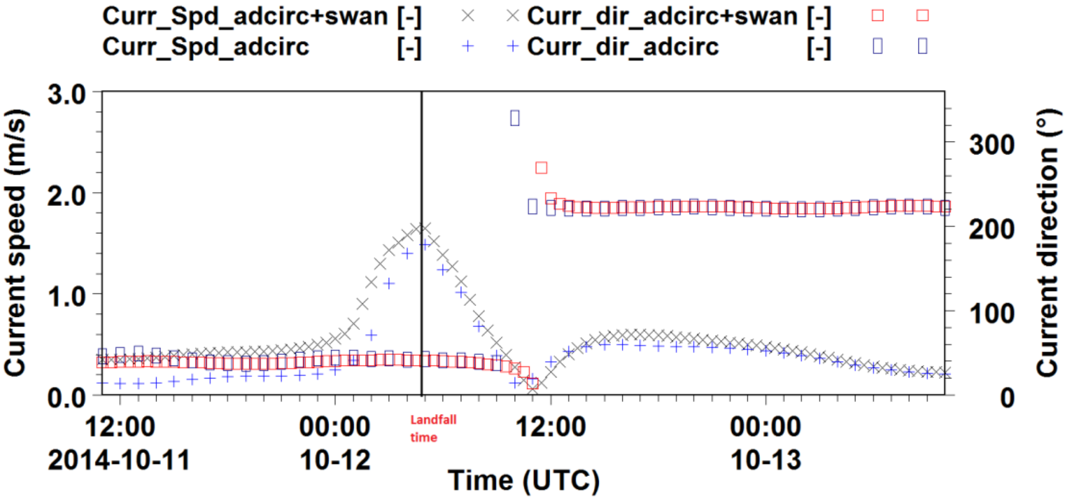


Fig. 6. Time series of currents (m/s) off Visakhapatnam coast (17.63°E; 83.26°N) during 10-13 October 2014.

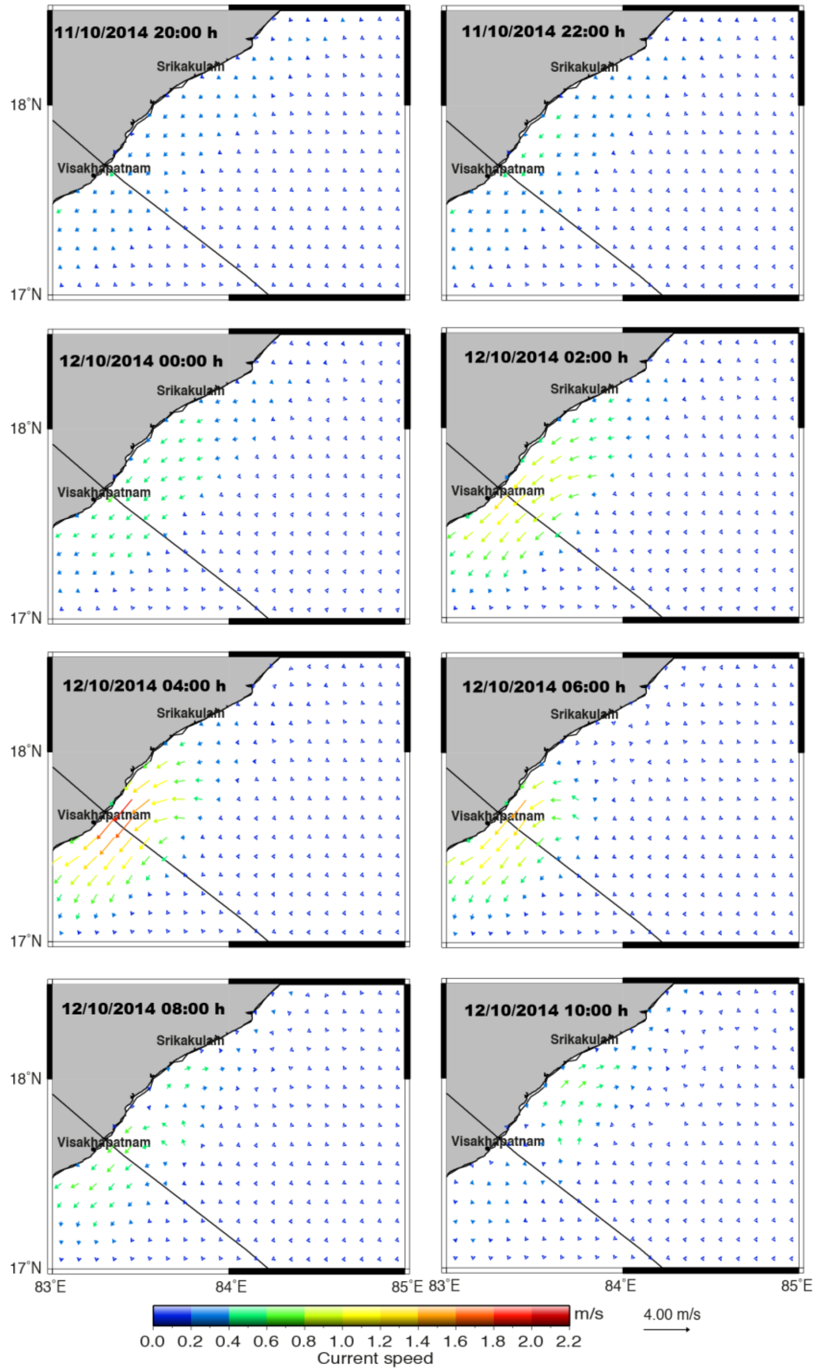


Fig. 7. Current speed and direction simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (colour code represents current speed; vectors represent current direction).

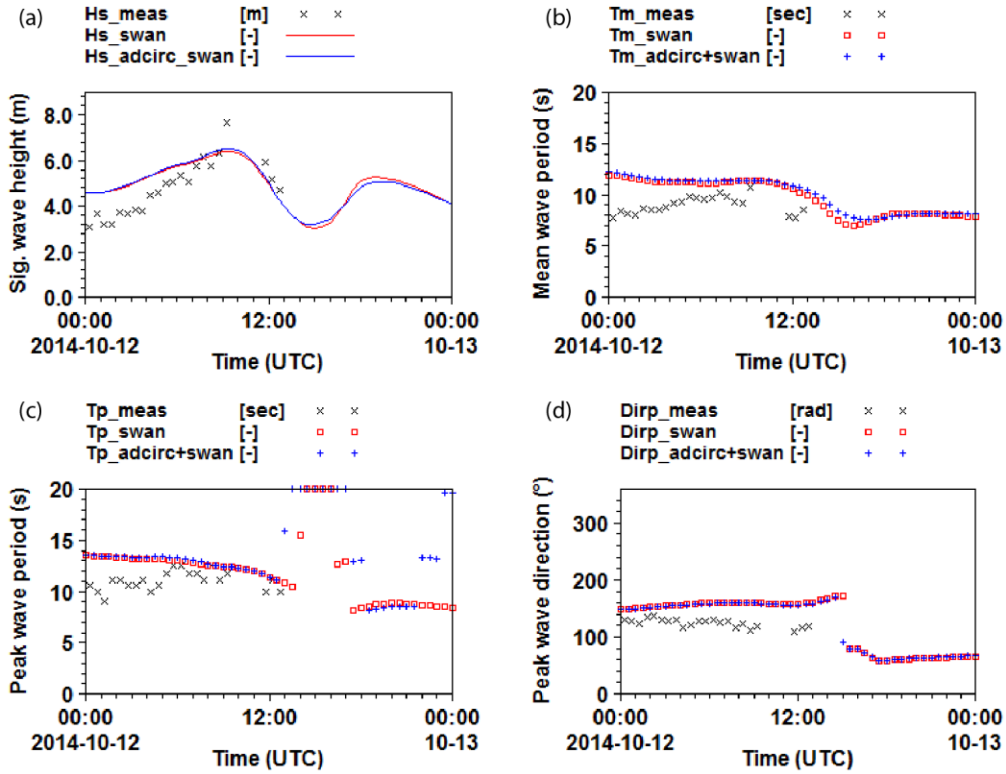


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Fig. 8. Comparison of modelled significant wave heights (H_s), mean wave periods, peak wave periods and peak wave directions obtained from SWAN and coupled ADCIRC+SWAN during Hudhud cyclone with measured data off Visakhapatnam (17.63°E; 83.26°N).

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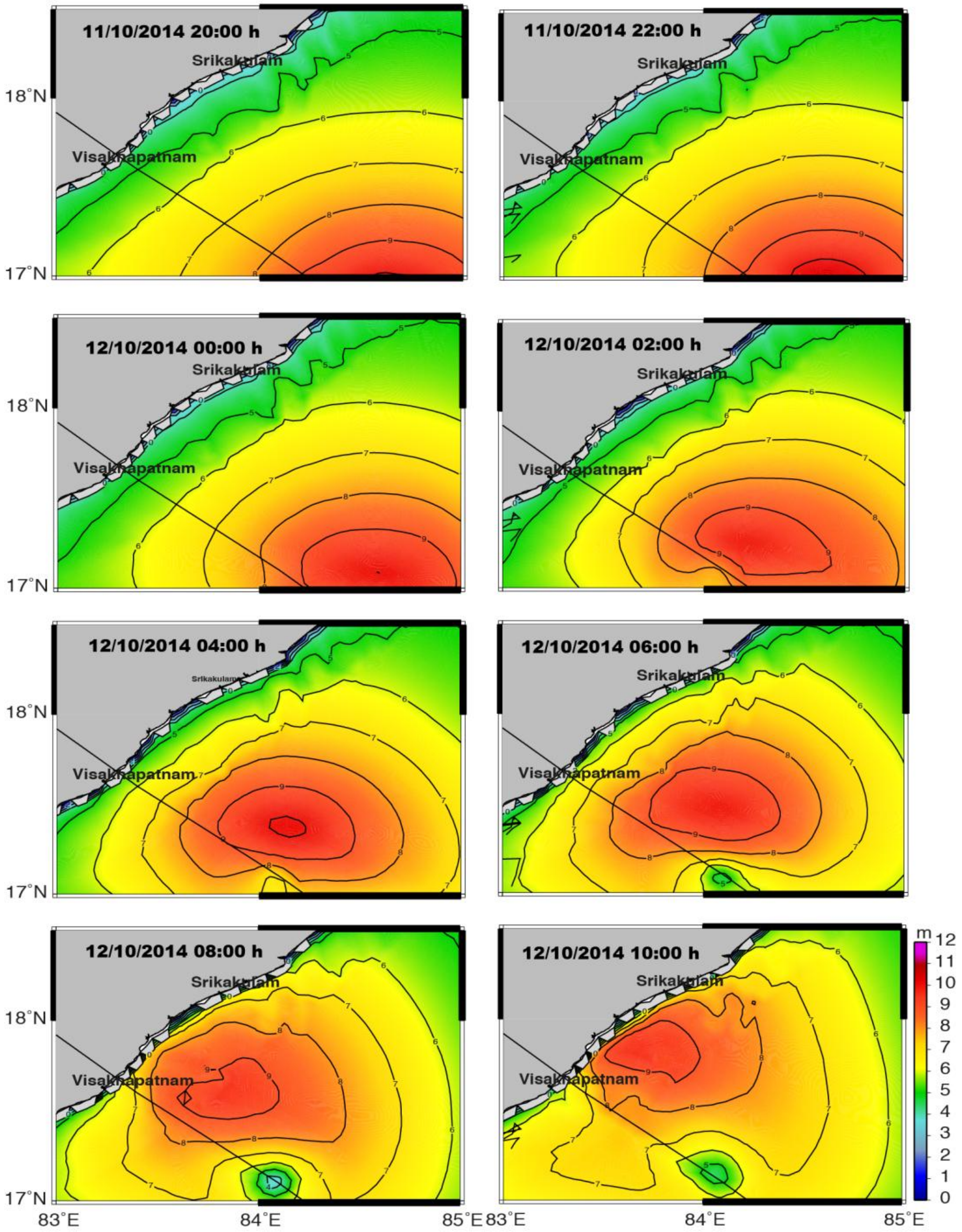

Fig. 9. Significant wave heights (H_s) simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (colour contours represent H_s).

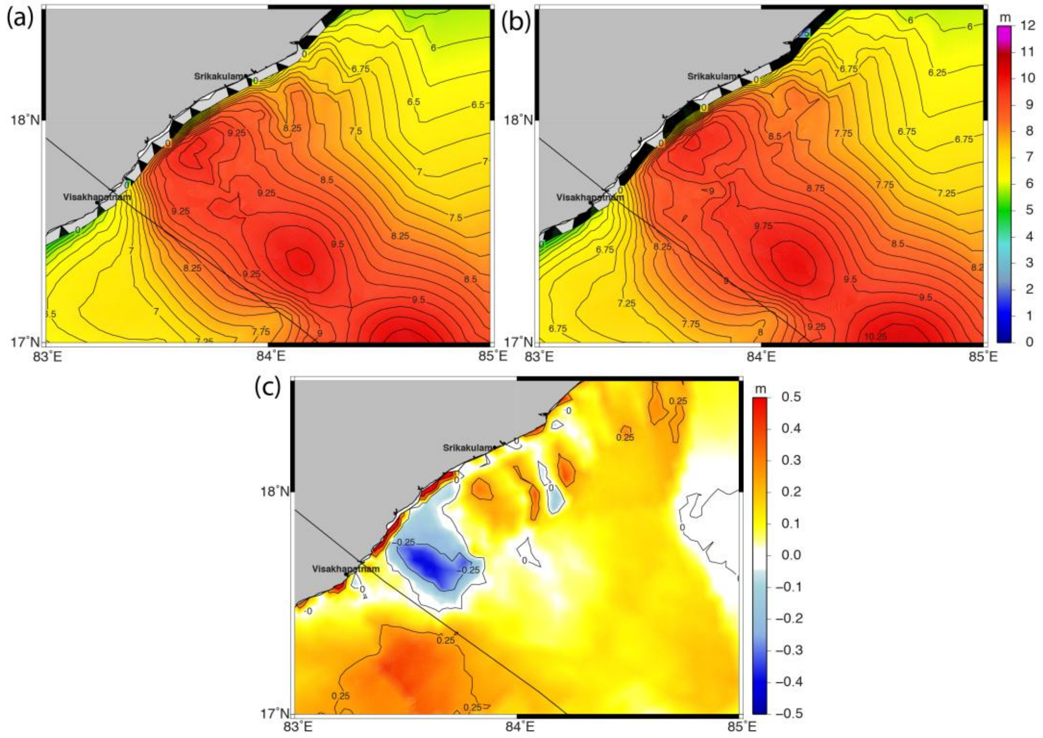

Fig. 10. Spatial distribution of maximum significant wave heights (H_s) simulated along the track of Hudhud cyclone using (a) SWAN model (no wave-current interaction), (b) coupled ADCIRC+SWAN model (with wave-current interaction); colour code and contours represent H_s; (c) change in H_s from (a) and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

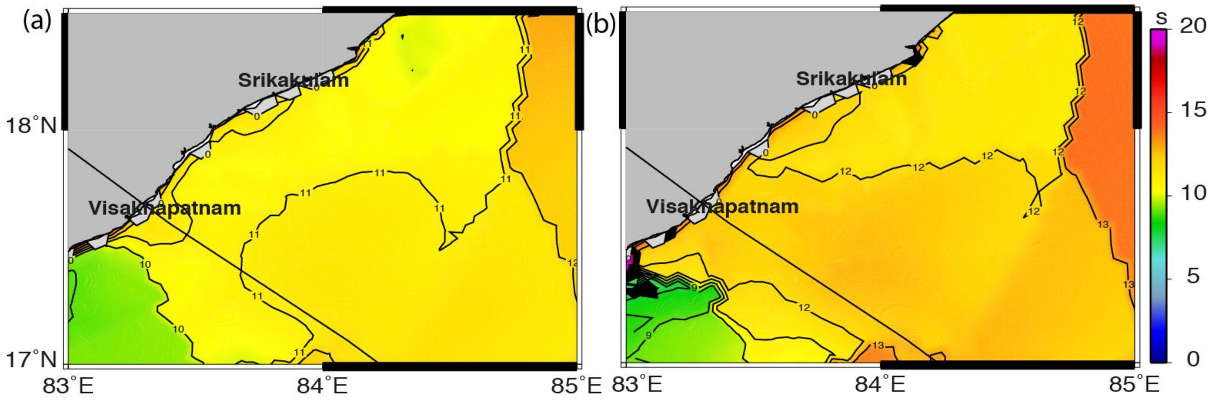

Fig. 11. Spatial distribution of (a) mean wave period (T_m) and (b) peak wave period (T_p) simulated along the track of Hudhud cyclone using coupled ADCIRC+SWAN model (with wave-current interaction).

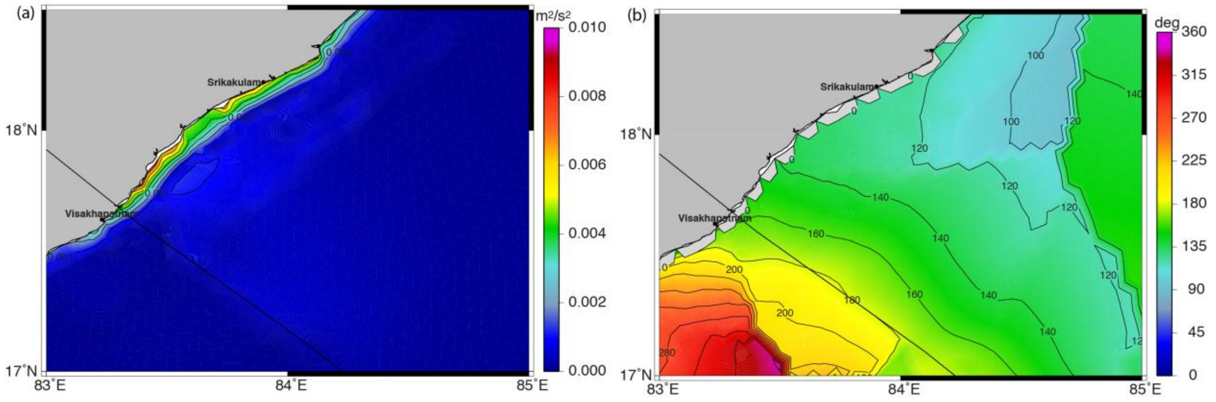

Fig. 12. (a) Maximum radiation stress gradient values calculated from SWAN and (b) spatial distribution of mean wave direction (Dir) simulated along the track of Hudhud cyclone using the coupled ADCIRC+SWAN model (with wave-current interaction); colour code and contours represent wave direction.