Impact of highest maximum sustained wind speed and its duration on storm surges and hydrodynamics along Krishna-Godavari coast

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Abstract

The storm surge and hydrodynamics along the Krishna-Godavari (K-G) basin are examined based on numerical experiments designed from assessing the landfalling cyclones in Bay of Bengal (BoB) over the past 38 years with respect to its highest maximum sustained wind speed and its duration. The model is validated with the observed water levels at the tide gauge stations at Visakhapatnam during Helen (2013) and Hudhud (2014). Effect of gradual and rapid intensification of cyclones on the peak water levels and depth average currents are examined and the vulnerable locations are identified. The duration of intensification of a rapidly intensifying cyclone over the continental shelf contributed to about 10-18% increase in the peak water levels, whereas for the gradually intensifying cyclone the effect is trivial. The inclusion of the wave-setup increased the peak water levels up to 39% compared to those without wave-setup. In the deep water region, only rapidly intensifying cyclones affected the peak MWEs. Intensification over the continental slope region significantly increases the currents along the shelf region and coast. The effect on peak maximum depth averaged current extends up to 400 km from the landfall location. Thus, it is necessary to consider the effect of various combinations of the highest cyclone intensity and duration of intensification for identifying the worst scenarios for impact assessment of coastal processes and sediment transport. The study is quite useful in improving the storm surge prediction, in preparedness, risk evaluation, and vulnerability assessment of the coastal regions in the present changing climate.

Keywords: Tropical Cyclone, Rapid intensification, Gradual intensification, Duration of Intensification, Storm Surge, Hydrodynamics

Declarations

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1. Introduction

Indian ocean is warming at a rapid pace giving rise to increased tropical cyclone (TC) activities under the changing climate (Singh and Roxy 2020). Storm surge is one of the deadliest and frequently occurring extreme events associated with TCs that affect the coastal community. TC induced storm surge in the Bay of Bengal (BoB) is reported to be the most destructive in nature as it affects the socio-economics of the densely populated coastal community India, Bangladesh, Sri Lanka and Myanmar. The life of a cyclone starts as a tropical disturbance with lower wind speed that intensifies based on its favourable condition while ends with the cyclone decaying. A TC is categorised based on upper bound of the highest maximum sustained wind speed during its life cycle. The improvement in the track and the intensity prediction have resulted in improvement in the surge prediction accuracy as well. But the abrupt variation in the storm parameters such as cyclone intensity, pressure drop, duration, translation speed, cyclone track during the life of a TC make the storm surge prediction further challenging in a changing climate.

Cyclone intensity is measured in terms of the maximum sustained wind speed measured for duration of 1 or 3 or 10 minute over an unobstructed height of 10m. Table 1, shows the cyclone category based on the India Meteorological Department (IMD), with the maximum sustained wind speed measured for a duration of 3 minutes. Intensification rate of a cyclone is computed by forward differencing the maximum sustained surface wind speed in time, usually at a 6-hour interval (Mei et al. 2012). A rapidly intensifying cyclone refers to those cyclones whose wind speed escalates by 15 m/s or more within a period of 24 hours, while those intensified by less than 15 m/s are referred to as gradually intensifying cyclones. A cyclone undergoes abrupt variation in the intensity along its path of propagation leading to forecast errors that can affect the surge response at the coast. The destructive nature of the cyclone wind intensity makes it practically impossible to measure it directly. In the absences of observations from the surface ships or instrumented ocean buoys, Dvorak technique (Dvorak 1975) estimates the cyclone intensity from Infrared and/or satellite imagery based on their appearances, temperature, and apparent motion of cloud features over time and are represented as Current Intensity (C.I) or T-number, where T refers to the TC. The minimum T-number of different cyclone category is shown in Table 1.

The extreme sea level rise caused by TC storm surge pose major catastrophic damage to life and property as a result of coastal inundation, and create an imbalance to the existing coastal
ecosystem. Knapp & Kruk (2010) reported variations in the best track information provided by different agencies that include IMD and JTWC. Their study reports that there exist variations in the maximum sustained wind speed as well as the temporal scale of the maximum sustained wind speed. Recent investigations on the cyclone activities under the changing climate, (Elsner et al. 2008; Balaguru et al. 2014, 2018; Sebastian and Behera 2015; Bhatia et al. 2019; IPCC 2019; Albert and Bhaskaran 2020; Wu et al. 2020) have revealed an increase in the cyclone intensity, duration, intensifying rate, etc. especially in the Atlantic Ocean and North Indian Ocean (NIO) regions. Underestimation/overestimation of the cyclone intensity during a TC event impact the storm surge prediction accuracy. Many researchers (Mcinnes et al. 2003; Irish et al. 2009; Rego and Li 2009; Resio et al. 2013; Cyriac et al. 2018; Sahoo and Bhaskaran 2018; Sebastian et al. 2019; Thomas et al. 2019; Li et al. 2020; Poulose et al. 2020) have quantified the impact of storm surge with changing intensity, storm size, speed of the storm, approach angles but the impact of duration of the highest cyclone intensity on the storm surge has not been addressed yet. Though they are expected to result in higher storm surge, the coastal geometry can alter the storm surge characteristics (Resio and Westerink 2008; Sebastian et al. 2014, 2019). Here an attempt is made to understand the effect of the highest maximum sustained wind speed of a cyclone and its duration on the storm surge and hydrodynamics.

2. Study Area

Compared to the TCs in the world, only 7 % of them occur in NIO but consequences of one cyclone striking the Indian subcontinent is higher than elsewhere. Storm surge is one of the known threats associated with TC landfall causing a rise/fall in surface water level near the coastal area resulting in inland flooding/grounding of vessels. NIO is divided into two basins, Arabian Sea towards the west and BoB towards the east of the Indian subcontinent. Figure 1 shows the cumulative tracks of the landfalling cyclones from 1970-2019 in NIO. Therefore, storm surge related vulnerability regions are more along the east coast than the west coast.

For the present study, a low lying coast of Andhra Pradesh on the east coast of India, between Bapatla and Kakinada, holding estuaries of the two major rivers Krishna and Godavari (shown in Figure 2) is selected for the study. This region belongs to a Very High Risk Zone (VHRZ) (INCOIS, 2020; Keim et al., 2020; Rao et al., 2007) as per the storm potential vulnerability. The deltaic plain formed by the two rivers Krishna and Godavari, also widely known as Krishna-Godavari (K-G) basin is a proven petroliferous basin of continental margin located on the east coast of India. The K-G basin has a coastline of approximately 300 km and extends
offshore up to 1000m isobaths. Directorate General of Hydrocarbon (DGH) of India reports K-G Basin as an established hydrocarbon province with an oil and gas resource of about 1130 MMT (Million Metric Tons), along both onshore and offshore locations (DGH 2015). About 555 MMT are assessed for the offshore region up to 200 m isobaths.

The Cyclone eAtlas-IMD (2020), reports 24 CS or more intense storms along the Andhra Pradesh coast from 1982-2020 out of which 8 made landfall along the coast of K-G basin. The coastal region of K-G basin consists of complex geomorphologic units like upland plains, coastal plains, recent flood and delta plains that are low lying and with gentle slope (DGH 2015) making storm surge prediction challenging in this region. For offshore platform constructions, the American Petroleum Institute (API 2003) recommends design criteria based on a 100 year return period storm event. The design water level is a combination of tide, storm surge and wave set up due to a 100-year return period storm event. But before designing the water level, it is necessary to define worst-case scenarios during risk evaluation or impact assessment studies. Previous studies carried out along the K-G basin includes, the impact of rising sea level along the low lying region of the K-G basin (Rao et al., 2008), storm surge inundation studies resulting from 1989 Kavali Cyclone and 1996 Andhra Cyclone (Rao et al., 2013), shoreline changes due to change in climate over the K-G basin (Kallepalli et al. 2017). Previous studies (Jain et al., 2010; Sindhu & Unnikrishnan, 2012) that computed the expected total water level with a return period of 50 years along the east coast of India found the low-lying area of the Krishna River prone to expected total water level of 6.0 ± 0.4 m. The K-G basin is a micro-tidal region with a tidal range less than 1.5 m and significant wave height less than 2 m (Rao et al., 2008). Sebastian & Behera (2018) studied the storm surge and current response along the K-G basin due to SCS events Laila (2010) and Helen (2013), approaching at two different angles making landfall closer to each other, reportedly generating a maximum storm surge height of 1m and maximum currents of 1.2 m/s along the coast.

3. Data and Methodology

Based on the IMD and JTWC best track archives of TC, a preliminary assessment of concerning highest cyclone intensity, duration sustained and their distance to the landfall of BoB cyclones is carried out. The JTWC provides the best track of cyclones in NIO from 1945 to 2018 (JTWC 2020), whereas the best tracks of cyclone from IMD are available only from 1982. Thus, on comparing the frequency cyclone events in BoB from 1982-2018, it could be identified that JTWC reported 6 cyclones less when compared to the IMD. On investigating
further, it could be found that two of them belong to ESCS, and originated in the Gulf of Thailand and belonged to the JTWC best track archives of Western North Pacific Ocean. The highest cyclone intensity and its durations of the landfalling cyclones, formed in BoB from IMD and JTWC best track archives are shown in Figure 3. Variation in the intensity and duration of the maximum sustained wind speed from the two different agencies can be explicitly observed from Figure 3. This instigates a need to understand the effect of highest cyclone intensity and duration on the storm surge behavior.

Figure 4(a) represents the highest cyclone intensity, duration sustained and its closeness to the landfall time of TCs from 1982-2020 obtained from IMD best tracks. It is observed that 34 (~38%) TC events made landfall with their highest cyclone intensity, 46 (~52%) TCs dissipated within 24 hours to landfall. Similar to the sustained duration, the distance travelled by highest cyclone intensity and their closeness to the landfall location estimated from the best tracks of IMD from 1982-2020 (up to May) is shown in Figure 4(b). On examining Figure 4(b), it could be found that about 80% of cyclones’ highest intensity decays within 200 km to landfall location. In Figure 4(a) the circles represent the cyclones with their highest intensity only at a given time (22 such events reported from 1982-2020). Similarly, the circles in Figure 4(b) represent the cyclone highest intensity at a given time (22 TCs) as well as those intensified over a duration but remained stationary (5 TCs) for some duration but reduced their intensity as they move towards the land.

In the present study, we have only considered the impact of cyclones with maximum sustained wind speed higher than 33 m/s during its lifetime. On inspecting the historical cyclone tracks we come to an understanding that about 90% of the cyclones intensify and dissipate within 24 hours to the landfall time. Hence, for the numerical experiments the cyclone intensities are increased at 24 hours or lesser duration to the landfall time. To quantify the effect of cyclone intensity and its duration a single cyclone track is only considered for the present study. For understanding the impact caused by the change in the cyclone intensity and duration, a cyclone track from the best tracks is selected and the maximum sustained wind speed of the cyclone are increased by 2.57 m/s (5 knots), 5.14 m/s (10 knots), 7.71 m/s (15 knots), 15.4 m/s (30 knots) and 30.86 m/s (60 knots) for 10 different test scenarios for which the cyclone intensities are increased for varying durations as shown in Figure 5. The central pressure values were also updated corresponding to the increased maximum sustained wind speed according to the information available from the best tracks. The experiments were conducted using Laila Cyclone that made landfall as a SCS at Bapatla, on May 20th, 2010, 1200 UTC. The increased
cyclone intensity resulted in changes in the maximum sustained wind speed, minimum central pressure and the radius of the maximum winds. Table 2 shows the total numerical experiments conducted for the analysis.

3.2 Numerical Model

3.2.1 ADCIRC

ADCIRC solves the shallow water equations (SWE) on unstructured meshes using continuous-Galerkin finite element method with linear C₀ triangular elements, allowing localized refinement in the region where the solution gradients are largest. The time derivative for the continuity equation is discretised over three levels such that the future water level requires information on the present and past water levels. In the case of momentum equation, the temporal discretization is explicit for all terms except the Coriolis, which uses an average of present and future velocities. ADCIRC solves for the water level and two components of currents at every mesh node at each time step over the simulation duration.

ADCIRC computes the water level from the solution of Generalized Wave Continuity Equation (GWCE) that is a combined form of the continuity and momentum equations, whereas the currents are computed from the solution of the vertically integrated momentum equations.

The generalized wave continuity equation is

\[
\frac{\partial^2 \zeta}{\partial t^2} + \tau_0 \frac{\partial \zeta}{\partial t} + S_p \frac{\partial J_\lambda}{\partial \lambda} + \frac{\partial f_\phi}{\partial \phi} + S_p U \frac{\partial \tau_0}{\partial \lambda} - V \frac{\partial \tau_0}{\partial \phi} = 0
\]

(1)

where,

\[
J_\lambda = S_p Q_\lambda \frac{\partial U}{\partial \lambda} - Q_\phi \frac{\partial U}{\partial \phi} + f Q_\phi - \frac{g}{2} S_p \frac{\partial \zeta^2}{\partial \lambda} - g S_p H \frac{\partial}{\partial \lambda} \left[ \frac{P_s}{g \rho_0} - \alpha \eta \right] + \tau_{s\lambda,\text{winds}} + \tau_{s\lambda,\text{waves}} - \tau_{b\lambda} \frac{\rho_0}{\rho_0}
\]

\[
+ (M_\lambda - D_\lambda) + U \frac{\partial \zeta}{\partial t} + \tau_0 Q_\lambda - g S_p H \frac{\partial \zeta}{\partial \lambda}
\]

\[
J_\phi = S_p Q_\lambda \frac{\partial V}{\partial \lambda} - Q_\phi \frac{\partial V}{\partial \phi} + f Q_\phi - \frac{g}{2} S_p \frac{\partial \zeta^2}{\partial \phi} - g H \frac{\partial}{\partial \phi} \left[ \frac{P_s}{g \rho_0} - \alpha \eta \right] + \tau_{s\phi,\text{winds}} + \tau_{s\phi,\text{waves}} - \tau_{b\phi} \frac{\rho_0}{\rho_0}
\]

\[
+ (M_\phi - D_\phi) + V \frac{\partial \zeta}{\partial t} + \tau_0 Q_\phi - g H \frac{\partial \zeta}{\partial \phi}
\]

The vertically integrated momentum equations are
\[
\frac{\partial U}{\partial t} + S_p U \frac{\partial U}{\partial \lambda} + V \frac{\partial U}{\partial \phi} - fV = -gS_p \frac{\partial}{\partial \lambda} \left[ \frac{p_s}{\rho_0} + \frac{\zeta}{\rho_0} \right] + \frac{\tau_{\lambda,\text{winds}} + \tau_{\lambda,\text{waves}} - \tau_{b\lambda}}{\rho_0 H} + \frac{M_{\lambda} - D_{\lambda}}{H} (2)
\]

\[
\frac{\partial V}{\partial t} + S_p U \frac{\partial V}{\partial \lambda} + V \frac{\partial V}{\partial \phi} - fU = -g \frac{\partial}{\partial \phi} \left[ \frac{p_s}{\rho_0} + \frac{\zeta}{\rho_0} \right] + \frac{\tau_{\phi,\text{winds}} + \tau_{\phi,\text{waves}} - \tau_{b\phi}}{\rho_0 H} + \frac{M_{\phi} - D_{\phi}}{H} (3)
\]

where, \( t = \) time,

\( H = \zeta + h = \) the total water depth,

\( \zeta = \) the deviation of the water surface from the mean water level,

\( h = \) bathymetric depth;

\( \lambda = \) degrees longitude (east of Greenwich is positive) and

\( \phi = \) degrees latitude (north of equator is positive)

\( S_p = \cos \phi_0 / \phi, \) is a spherical co-ordinate conversion factor and \( \phi_0 = \) a reference latitude.

\( U, V = \) the depth-averaged horizontal velocities in x- and y-directions, respectively,

\( Q_\lambda = UH, \) and \( Q_\phi = VH, \) are fluxes per unit width in x- and y-directions, respectively,

\( f = 2\Omega \sin \phi = \) the Coriolis parameter,

\( \Omega = \) the angular speed of the earth,

\( P_s = \) the atmospheric pressure at free surface,

\( g = \) acceleration due to gravity,

\( \eta = \) the Newtonian equilibrium tidal potential,

\( \alpha = \) the effective earth elasticity factor,
\[ \rho_0 = \text{the reference density of water}, \]
\[ \tau_{s,\text{wind}}, \tau_{s,\text{waves}} = \text{the applied free surface stress due to winds and waves, respectively}, \]
\[ \tau_b = \text{bottom stress}, \]
\[ M_\lambda, M_\phi = \text{are lateral stress gradients}, \]
\[ D_\lambda, D_\phi = \text{are momentum dispersion terms} \]
\[ \tau_0 \text{ is a numerical parameter that optimizes the phase propagation properties (Kolar et al. 1994; Atkinson et al. 2004)} \]

ADCIRC utilizes the mass conservation in the depth-integrated form of Generalized Wave-Continuity Equation (GWCE) and the momentum conservation subjected to incompressibility. Additionally, equations of motion in the ADCIRC model are formulated based on the traditional hydrostatic pressure, Boussinesq approximations. The GWCE formulation developed by Lynch & Gray (1979) eliminate the spurious node-node oscillations associated with a primitive Galerkin finite element formulation of the vertically-integrated continuity equation. The model utilizes FEM for spatial discretisation and FDM for temporal discretisation. ADCIRC uses a linear Lagrange interpolation to solve for the water levels \((\zeta)\) and velocities \((U, V)\) at every node point of the unstructured triangular mesh. The GWCE can use explicit or implicit time stepping scheme. The momentum equation uses a consistent or lumped mass matrix. The 2DDI form uses the explicit time stepping scheme and in order to avoid the instability in the computation a suitable time step was selected to satisfy the Courant–Friedrichs–Lewy (CFL) (Courant et al. 1928) stability criteria.

**3.2.2 SWAN**

SWAN is a third generation wave model that simulates the nearshore waves (Booij et al. 1999) that represents the wave field as phase averaged spectrum. The wave action density, \(N(t, \lambda, \phi, \sigma, \theta)\) is allowed to evolve in time \((t)\), geographic space \((\lambda, \phi)\) and spectral space (relative frequencies \(\sigma\) and directions \(\theta\)). The governing action balance equation is

\[
\frac{\partial N}{\partial t} + \frac{\partial}{\partial \lambda} [(c_\lambda + U)N] + \cos^{-1} \phi \frac{\partial}{\partial \phi} [(c_\phi + V)N \cos \phi] + \frac{\partial}{\partial \theta} [c_\theta N] = 0
\]  
\(4\)
\[
+ \frac{\partial}{\partial \sigma} [c_a N] = \frac{S_{tot}}{\sigma}
\]

where, \(c_A, c_\phi\) are the group velocities; \(U, V\) are the ambient current; \(c_\theta, c_\sigma\) are the propagation velocities in \(\theta\)- and \(\sigma\)-spaces; \(S_{tot}\) is wave growth by wind action lost due to white capping, surf breaking and bottom friction and action exchanged between spectral components due to nonlinear effects in deep and shallow water.

The radiation stress gradients are computed by

\[
\tau_{sx,\text{waves}} = -\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}
\]

(5)

\[
\tau_{sy,\text{waves}} = -\frac{\partial S_{xy}}{\partial x} + \frac{\partial S_{yy}}{\partial y}
\]

(6)

where, \(S_{xx}, S_{xy}, S_{yy}\) are the wave radiation stresses (Longuet-Higgins and Stewart 1964; Battjes 1972) and are given as:

\[
S_{xx} = \rho_o g \int \left( (n \cos^2 \theta + n - \frac{1}{2}) \sigma N \right) d\sigma d\theta
\]

(7)

\[
S_{xy} = \rho_o g \int (n \sin \theta \cos \theta \sigma N) d\sigma d\theta
\]

(8)

\[
S_{yy} = \rho_o g \int \left( (n \sin^2 \theta + n - \frac{1}{2}) \sigma N \right) d\sigma d\theta
\]

(9)

where, \(n\) is the ratio of group velocity to phase velocity.

Zijlema (2010) introduced a numerical procedure to compute the wind-wave spectra using SWAN on unstructured-grid. A vertex based, fully implicit, finite difference method accommodated the unstructured meshes with high variability associated with bathymetry in the nearshore region and irregular shoreline. A point to point multi-directional Gauss-Seidel iteration method requiring a number of sweeps through the grid was adopted for the numerical solution method. The implicit time scheme permitted stability in the computation even in case of local refinement in the area of interest.

3.2.3 Coupled ADCIRC+SWAN

A coupled wave and circulation model can define shelf, nearshore and inland hydrodynamics better during a cyclone event. The wave effects are incorporated in the circulation model by
parallely coupling the third generation wave model, SWAN with ADCIRC (Dietrich et al. 2012). The unstructured-mesh SWAN spectral wave model and the ADCIRC shallow-water circulation model have been integrated into a tightly-coupled ADCIRC + SWAN model.

The tight coupling of the unstructured SWAN model and ADCIRC allows physical interaction between the wave-circulation to be resolved correctly in both models. ADCIRC passes wind velocities, water levels, and currents through local memory to SWAN, which is utilized for its computation. SWAN computes wave radiation stresses and their gradients and passes radiation stress gradients as a forcing function to ADCIRC at the end of each its time steps. ADCIRC time step is relatively small in order to satisfy the Courant number criteria of its explicit features as well as to limit the propagation speed of wetting front during a time step. Whereas, SWAN is unconditionally stable and allows large time steps. Thus, the coupling interval is the same as the SWAN time step. The models are run sequentially to ensure that either ADCIRC or SWAN runs alternatively passing information to each other (Dietrich et al. 2011, 2012).

At the beginning of the coupling interval ADCIRC can access the radiation stress gradient computed by SWAN at times corresponding to the beginning and end of the previous interval. At the end of the coupling time interval, ADCIRC passes the wind velocities, water levels, currents and roughness lengths to SWAN. SWAN recalculates the water depth and related wave process (wave propagation, depth-induced breaking, etc.) at the coupling time. SWAN is run for the same time step to bring the same moment in time as ADCIRC. The radiation stresses are computed at each mesh node and are interpolated into the space of continuous, piecewise linear functions and differentiated to obtain the radiation stress gradient that is constant on each element. The area-weighted average of the radiation stress gradient on the element is projected onto the mesh nodes. The radiation stress gradients used by ADCIRC are always extrapolated forward in time, while the wind speed, water levels and currents used by SWAN are always averaged over each of its time step (Dietrich et al. 2011).

ADCIRC and SWAN are run in parallel mode for the present study. ADCIRC and SWAN have a one-to-one correspondence between geographic locations of the mesh vertices as they use the same local sub-mesh. Information such as water level, currents, wind velocities and radiation stress gradients are passed directly through the local cache or memory, without any need for interpolation.
3.3 Generating the Wind field and Pressure Field

Holland et al. (2010) proposed a revision to the parametric Holland (1980) model to represent the surface wind profile more accurately. The earlier model utilized the central and environmental surface pressure, maximum winds and radius of maximum wind, while the revised model is capable of incorporating the wind observations at some radius within the hurricane circulation. The revised model is considerably less sensitive to data errors. The surface pressure $P_s$ is given by

$$P_s = P_{cs} + (P_{ns} - P_{cs}) e^{-\left(\frac{R_m r}{R_m r - R_m r}ight)^b}$$  \hspace{1cm} (10)

where, $P_s$ is surface pressure at radius $r$, $P_{cs}$ is central pressure, $P_{ns}$ is the external pressure to the centre of the cyclone, $R_m$ is the radius of maximum winds. $b$ is the scaling parameter that defines the proportion of pressure gradient near the maximum wind, $e$ is the exponential function.

$$V_s = V_{ms} \left\{ \frac{r_{rms}}{r} \right\}^{b_s} \left[ 1 - \left( \frac{r_{rms}}{r} \right)^{b_s} \right] \right\}^x$$  \hspace{1cm} (11)

where, $V_s$ = surface wind (wind at any level), $V_{ms}$ = maximum surface wind, $r_{rms}$ is the radius of maximum wind, $b_s$ = $bg_x$, where, $g_s$ is the reduction factor for gradient to surface winds, $e$ is the base of natural logarithm. Based on the central pressure value, $b_s$ is obtained as follows;

$$b_s = -4.4 \times 10^{-5} \Delta P_s^2 + 0.01 \Delta P_s + 0.03 \frac{\partial P_{cs}}{\partial t} - 0.014 \phi + 0.15 V_t^x + 1.0$$  \hspace{1cm} (12)

$$x = 0.5 \left( 1 - \frac{\Delta P_s}{215} \right)$$  \hspace{1cm} (13)

$$V_{ms} = \left( \frac{100 b_s}{\rho_{ms} e} \right)^{0.5}$$  \hspace{1cm} (14)

where, $\Delta P_s$ is in hPa, $\partial P_{cs}/\partial t$ intensity change in hPa/h, $\phi$ is the absolute value of latitude in degree, $V_t$ is the cyclone translate speed in m/s.

The surface air density can be derived as

$$\rho_s = \frac{100 P_s}{RT_{vs}}$$  \hspace{1cm} (15)

$$T_{vs} = (T_s + 273.15)(1 + 0.61 q_s)$$
\[ q_s = RH_s \left( \frac{3.802}{100 P_s} \right) e^{\frac{17.6 T_s}{243.5 + T_s}} \]

\[ T_s = SST - 1 \]

where, \( R = 286.9 \) J kg\(^{-1}\)K\(^{-1}\) is the gas constant for dry air, \( T_{vs} \) is the virtual surface temperature (in K), \( q_s \) is the surface moisture (in g kg\(^{-1}\)), \( T_s \) is the surface temperature, SST is the sea surface temperature (both in °C), \( RH_s \) is the surface relative humidity.

The radius of maximum wind is computed using Willoughby & Rahn (2004) equation given by

\[ R_m = 46.4 e^{-0.0515 V_m + 0.0169 \phi} \]  (16)

The storm parameters (track positions, maximum sustained wind speeds and estimated pressures) obtained from the JTWC best track for cyclones Hudhud, Helen and Laila to compute their respective wind and pressure fields from this modified Holland Model (MHM). The radius of the maximum winds are computed using the Willoughby & Rahn (2004) equation. For the numerical experiments the radius of maximum winds varies based on the wind speed and is as shown in Figure 6. Further, for the numerical experiments, adopting the track positions of Laila Cyclone maximum sustained wind speeds and the minimum central pressures are varied at selected time instances as shown in Figure 7. These wind and pressure information are interpolated in space onto the ADCIRC grid and in time to match the wind and pressure information with the model time step. The wind drag coefficients are adopted from Garratt(1977) for all the simulations.

### 3.4 Model Set up and Initialization

The numerical simulations are carried out using standalone model ADCIRC and coupled model ADCIRC+SWAN on the domain consisting of the BoB basin of NIO. The model domain is discretised into highly flexible unstructured mesh as shown Figure 8. The model domain consists of 85,371 triangular elements and 459,419 nodes, with a resolution of 100 m along the east coast of India. However, the coastal belt of this region is low lying with gentle slopes and is categorized as highly vulnerable to storm surge (Kallepalli et al. 2017). Figure 9(a) shows BoB model domain with interpolated bathymetry from GEBCO. Figure 9(b) shows the enlarged view of the K-G basin. Before conducting the numerical experiment, the model is validated with the water levels obtained at Visakhapatnam and Krishnapatnam during Helen
(2013), which made landfall as a SCS as well as the water levels obtained at Visakhapatnam during Hudhud (2014) that made landfall as an ESCS. In Figure 9, in addition to the bathymetry, the cyclone tracks of Laila, Helen and Hudhud are also incorporated. The landfall locations as well as the tide gauge stations are shown in the enlarged view of the study area (Figure 9(b)).

Boundary conditions used in the present simulations include mainland boundary and islands with no normal flow condition and free tangential slip and open ocean boundary with specified tidal constituents for harmonic forcing. The meteorological forces comprising the wind and pressure field during cyclone events of Hudhud, Helen and Laila are computed from the MHM. In addition to the boundary conditions, an elemental wetting-drying scheme with minimum water depth 0.05 m and a minimum velocity of 0.05 m/s is adopted. A constant bottom friction coefficient of 0.0028 that uses the quadratic friction formulation is used for bottom friction parameterisation. The time step of 6 s satisfied the Courant number criteria.

The model is initially run for 60 days in cold start with tidal forcing and potential constituents obtained from Le Provost database allowing 20 days for the model to spin up. The numerical simulation is forced with all 13 forcing and potential tidal constituents (2N₂, K₁, K₂, L₂, M₂, MU₂, N₂, NU₂, O₁, P₁, Q₁, S₂, T₂) at the open ocean boundary. The simulation is initialised with tidal potential forcing. Further, simulations are carried out hot starting the computational domain with meteorological forcing for another 5 days (life of Laila Cyclone).

4. Results and Discussion

The simulations carried out using the ADCIRC model considers the effect of atmospheric forcing of a cyclone along with tide are referred to as storm tide (ST) conditions. Similarly, simulations carried out using ADCIRC+SWAN model consider the effect of wave setup along with the storm tide and are referred to as storm-tide-wave (STW) conditions in the following sections.

4.1 Validation of water level

The water levels simulated during Helen cyclone is compared with the tide gauge observations at Visakhapatnam and Krishnapatnam obtained from INCOIS and is shown in Figure 10. It is seen the numerical model slightly under predicts the amplitude of the water levels but the phase is in good agreement with each other. The observed water levels are recorded by the tide gauge
station located inside the Visakhapatnam port, whereas, the numerical model point lies in the open coast without considering the port enclosure. Also, the numerical model used GEBCO bathymetry only. The results might further improve by considering more refined bathymetry information from hydrographic charts for the K-G basin region. Further, the water levels simulated during an ESCS Hudhud Cyclone are compared with the tide gauge observations at Visakhapatnam, where the cyclone made its landfall and are shown in Figure 11. The model could capture the amplitude as well as phase of the total water level using the coupled ADCIRC+SWAN model with a CC value of 0.98 and RMSE of 0.02 m.

4.2 Maximum Wind Speed and Minimum Pressure

In the present study, to investigate the impact of intensification on the coastal storm surge, cyclones are intensified gradually by increasing the maximum sustained wind speed by 2.57 m/s (5 knots), 5.14 m/s (10 knots) and 7.71 m/s (15 knots) as well as rapidly by 15.4 m/s (30 knots) and 30.86 m/s (60 knots) for 10 hypothetical different durations. The maximum sustained wind speed and pressure variation during the life of the cyclone are presented in Figure 7, which are used for generating the wind fields in the numerical simulations. With respect to the change in the wind speed there will be change in the radius of maximum winds as well. The radius of maximum winds corresponding to the maximum sustained wind speed is shown in Figure 6. When the cyclones are intensified, changes occur in wind speed, pressure as well as in the radius of maximum wind of the cyclone. The spatial distribution of the maximum wind speed during Laila Cyclone and for increased intensities of test scenario A (where the cyclone intensity was increased 24 hours prior to landfall and 6 hours after landfall as shown in Figure 5) is shown in Figure 12. Since the highest maximum sustained wind speeds are increased by 5, 10, 15, 30 and 60 knots, they are designated as A5, A10, A15, A30 and A60, respectively. Similarly, the spatial distributions of minimum pressure experienced during Laila Cyclone and for increased intensities of test scenario A are shown in Figure 13.

From Figure 12, we can see that with an increase in wind speed by 2.57 m/s (5 knots), the highest wind speed of A5 (Figure 12(b)) increases by 0.5 m/s of Laila Cyclone (Figure 12(a)). The increased wind speed between 24-32 m/s, closer to the landfall, belongs to SCS. While with an increase of 5.14(10), 7.71(15) m/s(knots), as seen in Figure 12(c) and (d), the maximum wind speed near the landfall changed to VSCS category. Similarly, an increase in the wind speed by 15.4 (30) and 30.86(60) m/s(knots), seen in Figure 12(e) and (f), resulted in ESCS and SuCS (62.4 m/s).
Spatial plots of maximum wind speed with 30.86 m/s (60 knots) increase for different test scenarios (A – J) representing varying durations are shown in Figure 14(a-j). Similarly, the corresponding minimum pressures are shown in Figure 15(a-j). The highest wind speed for Cyclone Laila is 34 m/s whereas the lowest pressure value is 9.94 m of water. The highest maximum wind speeds and the lowest central pressures for all the test scenarios considered for the study are provided in Table 3.

From Table 3, it could be seen that the highest maximum wind speed and lowest minimum pressure values are same for A, B, C, D, E scenarios because the highest intensification of Laila Cyclone occurred 24 hours prior to landfall that is captured by all these scenarios. For other scenarios, the highest maximum wind speed and lowest minimum pressure values vary depending on the specific time instance considered. Sensitivity of the duration and intensity on the maximum water levels and significant wave heights are investigated using the wind and pressure fields of different scenarios.

### 4.3 Maximum Water Elevation (MWE)

The MWE refers to the peak values of water levels obtained throughout the computational domain for the total period of simulation considered for the study. The MWEs are computed for ST conditions using ADCIRC model, where cyclonic surge is simulated along with tide. Similarly, MWEs are also computed for STW conditions using ADCIRC+SWAN model to consider the effect of wave setup along with storm tide.

The peak MWE of ST and STW are computed for all the test scenarios and are shown in Figure 16. The peak MWEs of STW increase up to 39 % of peak MWEs of ST for varying cyclone intensity and duration of intensification considered here. The peak MWEs are recorded at different locations for different scenarios and selected locations of peak MWEs are shown in Figure 17 along with the bathymetric depth. The farthest peak MWE is observed north of Machilipatnam (~90 km from landfall). As seen in Figure 5, the intensifications are considered over a duration (A-E) and at specific time instances (F-J). The scenarios B-F, C-G, D-H and E-I are paired together as their intensification ends at the same time. The comparison of the peak MWEs among these paired scenarios is done to understand the impact of duration of intensification. The MWE obtained for Laila Cyclone (highest maximum sustained wind...
intensity of 34 m/s occurred 30 hours prior to the landfall) is also plotted along with the scenarios to compare and understand the effect of intensification and duration.

From Figure 16 it could be concluded that the duration of intensification is trivial. The peak MWE of STW in the K-G basin with 30.86 m/s (60 knots) increase in intensity shows 10.8%, 17.8%, 1.4% and 14.7% higher MWEs for B, C, D and E scenarios compared to F, G, H and I scenarios, respectively. In order to understand the impact of the intensification, percentage increase in the peak water levels of STW with respect to that of Laila is estimated and is provided in Table 4. As explained earlier, an increase in wind speed by 2.57, 5.14, and 7.71 m/s results in gradual intensification and an increase in wind speed by 15.4, 30.86 m/s results in rapid intensification (>15 m/s change within 24 hours) of the cyclone. The scenario A where the intensification continued even after landfall shows substantial increase in the MWEs with increasing intensities. Similarly, scenarios B, C, F, and G show significant increase in MWEs for increasing intensities. However, scenarios D and H show considerable increase for rapid intensification only. Scenarios E and I show an increase in MWEs for an increase of 30.86 m/s only below which the effect is negligible.

In the above discussion, it should be noted that the intensification in these scenarios ends at different positions of cyclones where the water depths are also varying. As we observe, the scenarios B, C, F, and G intensification continued over the shallow continental shelf region, where the bathymetry is less than 200m (seen in Figure 9(b)). Whereas, the scenarios D and H intensifications happened up to the continental slope (500-2000 m) and scenarios E and I intensifications were limited to deeper water regions beyond the continental slope (~3000 m). Now referring to Table 4, it can be concluded that intensification over shallow continental shelf regions has significant effect on the MWEs. Similarly, intensification in deeper water regions beyond continental slope has minimal effect on MWEs for gradual intensification but considerable effect for rapid intensification. The scenario J where the intensification takes place in deep water (> 3000 m) 24 hours prior to landfall shows insignificant effect on the MWEs along the coast. Overall, we could conclude that an intensification on shallower regions results in higher MWEs along the coast for both gradual and rapid intensification. On the contrary, a rapid intensification in deep water regions can affect the MWEs along the coast but not a gradual intensification.

Although the analysis of peak MWEs has been discussed, it is prudent to investigate the spatial variation of MWEs along the coast. The spatial contours of MWEs for the extreme case with 30.86 m/s (60 knots) intensification are presented in Figure 18 along with the base case of Laila Cyclone. The scenarios B and F with the same intensity have different duration of
intensification. For scenario B, where the intensification happens over duration, the extent of MWEs along the coast is larger compared to that of scenario F with specific time intensification. This difference in the extent of influence is mainly due to the locations of intensification. As in scenario B the intensification happened even farther away from the coast, the generated surge could reach a wider stretch of the coast. While in scenario F, the effect of intensification is restricted to a smaller stretch of the coast. Similarly, the location of intensification also influences the location of MWE along the coast. The spatial MWEs for scenario J60 and Laila are similar without much variation as seen in Figure 18(j) and (k), respectively. Therefore, the intensification before 24 hours of landfall does not affect the overall surge characteristics along the coast.

It was also observed that the locations of peak MWEs for ST and STW cases do not occur at the same locations for all scenarios (as seen in Figure 18). The MWEs of ST are subtracted from STW simulation to obtain the contribution of wave setup and are shown in Figure 19. Figure 19(a) shows the peak MWEs due to storm tide and wave setup contribution at locations where the peaks were recorded during STW simulations. Similarly, Figure 19(b) shows the values from coupled STW simulations but at locations where the peaks were recorded during ST simulations. This helps to understand the wave setup contribution and its effect at various locations along the coast. Figure 19(a) shows locations where the storm tide component is zero signifying that these locations were not inundated when only storm tide simulations were carried out. However, Figure 19(b) shows less wave setup contribution and more storm tide contribution at locations where peak MWEs were observed during ST simulations. Hence, coupled STW modelling is necessary to accurately assess the vulnerability of coastal regions due to cyclones.

The results for scenario A60 show a substantial increase in the ST and STW values. The tidal range at this location is 0.4 – 0.6 m, which means the surge and wave setup contribution is highest. To understand the local process and STW amplification, the wind field around the region and maximum water elevations are shown in Figure 20. It can be seen that this location has a coastal profile with high curvature and can trap the flow without much escape of flux. This could lead to piling of water resulting in very high MWE, emphasizing the importance of coastal geometry on the resultant flooding and inundation.
The depth averaged velocities ($V_{av}$) are obtained from the coupled model, and the $V_{avg\_max}$ refers to the highest $V_{avg}$ in the computational domain during the considered simulation period. The peak $V_{avg\_max}$ for *Laila* cyclone is 5.4 m/s, while for different test scenarios the peak $V_{avg\_max}$ is given in Table 5. On the first hand observation, it can be seen that the peak $V_{avg\_max}$ has increased for all scenarios with rapid intensification. However, the same is not seen in case of gradual intensification and with 2.54 (5) and 5.14 (10) m/s (knots) increase, most scenarios show reduced peak $V_{avg\_max}$. In case of 7.71 m/s (15 knots) increase, scenarios A, B, C, D, H, and I show increased peak $V_{avg\_max}$. A closer look suggests that an increase in average velocity magnitude is observed where the gradual intensification takes place over the continental slope region (where bathymetric gradient is very high). For gradually intensifying cyclones, a variation in the peak $V_{avg\_max}$ up to 11% is observed compared to *Laila*. In order to understand the spatial variation of average velocities, the $V_{avg\_max}$ with the extreme case (30.86 m/s intensification) of all scenarios are plotted in Figure 21 along with results of *Laila* cyclone. A strong velocity field is observed in the shelf region for scenarios A, B, C, and G, whereas, the magnitude reduces for the scenarios D, E, F, H, I, and J. It is important to note that scenario G shows similar current magnitudes as of the scenarios A, B, and C, those intensify over duration. This clearly states that the intensification along the continental slope results in higher currents along the cyclone path in the shelf region.

Although, the increase in current magnitude is less for many scenarios shown in Figure 21(a-j), it is higher compared to the current magnitudes generated due to *Laila* cyclone (Figure 21(k)). It can be concluded that a rapid intensification of cyclones in deep and shallow water can result in increased current magnitudes in the shelf region.

It is also important to identify the locations of peak $V_{avg\_max}$ in addition to the increased magnitude. The locations and bathymetry of the peak $V_{avg\_max}$ for all the scenarios are shown in Figure 22. It can be seen that for all simulations, the peak $V_{avg\_max}$ are recorded along the coast, which could affect the coastal dynamics and processes during the event. Unlike the peak MWEs that were influenced up to a distance of ~90 km from the landfall point, the effect on peak $V_{avg\_max}$ is wider extending up to ~400 km, mostly on the right side of the landfall point (seen in Figure 22). Overall, a rapid intensification of cyclones increases the current magnitudes in the shelf region as well as along the coast. Intensification over the continental slope region significantly increases the currents along the coast. Thus, it is necessary to consider such
intensifying cyclones while assessing the cyclone impact on coastal processes and sediment transport during such extreme events.

5. Conclusions

The present study shows the sensitivity of coastal water levels with respect to increased cyclonic intensity with different intensification periods. The studies conclude that duration of intensification is trivial for gradually intensifying cyclones. The duration of intensification contributes to about 10-18 % change in the water levels when rapidly intensified over the continental shelf region. Intensification on shallower regions results in higher MWEs along the coast for both gradual and rapid intensification. On the contrary, in deep water region, only rapid intensification can affect the peak MWEs and the effect of gradual intensification in deep water is insignificant on peak MWEs. A rapid intensification before 24 hours to the landfall does not affect the overall surge characteristics along the coast. Coupled storm-tide-wave (STW) simulations result up to 39 % increase in peak MWEs compared to storm tide (ST) simulations. Therefore, a coupled storm surge-tide-wave (STW) modelling should be carried out to obtain accurate MWEs and its location for identifying vulnerable coastal regions due to cyclones. Coastal geometry plays an important role in localized amplification of surge characteristics.

A gradually intensifying cyclone over the continental slope region, resulted in a variation in the peak $V_{avg,max}$ is up to 11%. While a rapidly intensifying cyclone in deep and shallow water regions can increase the current magnitudes in the shelf region as well as along the coast. The effect on peak $V_{avg,max}$ can extend up to ~400 km mostly on the right side of the landfall point. Thus, it is necessary to consider such intensifying cyclones while assessing the cyclone impact on coastal processes and sediment transport under extreme events.

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Figure Captions

Figure 1 Cumulative tracks of landfalling TCs in NIO region from 1970-2019 (Source: Cyclone eAtlas-IMD 2020)

Figure 2 (a) Cyclone tracks from year 1982-2019 landfalling in Andhra Pradesh Coast, and (b) Enlarged view along the coast of K-G Basin
Figure 3 Scatterplot representing the highest associated cyclone intensity and its duration from IMD and JTWC for cyclones landfalling in BoB from 1982-2018.

Figure 4 Landfalling TCs in BoB from 1982-2020 (up to May) with their highest maximum sustained wind speed and (a) duration by highest wind speed with respect to landfall time (represented by 0 in the X axis) (b) distance travelled by highest wind speed estimated from the landfall location (represented by 0 in the X axis).
Figure 5 Hypothetical test scenarios showing the cyclone path on temporal scale 24 hours prior to landfall and 6 hours after landfall where the cyclone intensities are altered.

Figure 6 Radius of Maximum Winds corresponding to Maximum Sustained Wind Speed.
Figure 7 Temporal Variation of (a) Maximum sustained wind intensity of Laila and increased by 2.57 (5), 5.14 (10), 7.71 (15), 15.4 (15) and 30.86 (60) m/s (knots) for different durations (A to J), and (b) Central Pressure for Laila and the corresponding changes in the pressure for different durations (A to J) considered for the study.
Figure 8 Discretised BoB Domain

Figure 9(a) Study domain with interpolated bathymetry and the tracks of *Laila*, *Helen*, and *Hudhud* cyclones, and (b) Enlarged View showing the tide gauge stations and location along the *Laila* track where the intensities are varied for the present study.
Figure 10: Comparison of observed and computed Water Levels at Visakhapatnam and Krishnapatnam during Helen 2013.

Figure 11: Comparison of observed and computed Water Levels at Visakhapatnam during an ESCS Hudhud 2014.
Figure 12 Spatial plot of Maximum Wind Speed during (a) *Laila* Cyclone and for Test A Scenario where the wind speed increased by (b) 2.57 m/s (5 knots), (c) 5.14 m/s (10 knots), (d) 7.71 m/s (15 knots), (e) 15.4 m/s (30 knots), and (f) 30.86 m/s (60 knots).

Figure 13 Spatial extent of Minimum Pressure during (a) *Laila* Cyclone, and for Test Scenario A where the wind speed increased by (b) 2.57 m/s (5 knots), (c) 5.14 m/s (10 knots), (d) 7.71 m/s (15 knots), (e) 15.4 m/s (30 knots), and (f) 30.86 m/s (60 knots).
Figure 14: Spatial plot of Maximum Wind Speed with 30 m/s (60 knots) increase for different test scenarios (A - J).

Figure 15: Spatial extent of Minimum Pressure for different Test Scenarios with an increasing wind speed by 30.86 m/s (60 knots) considered for the study.
Figure 16 Peak Maximum Water Levels recorded by ST and STW along the K-G basin of Laila along with those of cyclone intensities increase by (a) 2.57 m/s (5 knots), (b) 5.14 m/s (10 knots), (c) 7.71 m/s (15 knots), (d) 15.4 m/s (30 knots), and (e) 30.86 m/s (60 knots) for 10 test scenarios.

Figure 17 Location showing the Peak MWEs of STW and ST.
Figure 18 Spatial plot showing MWE of STW along the K-G basin for cyclone with increasing wind speed by 30.86 m/s (60 knots) for different durations (a-j), and (k) Laila.

Figure 19 Wave contributions of all the numerical simulations at (a) location of peak MWE of STW (b) location of peak MWE of ST.
Figure 20 Wind field of Test A60 during the peak MWE for STW and the enlarged MWE showing the peak MWE (top right corner).

Figure 21 Spatial extent of $V_{avg\_max}$ with increasing wind speed by 30.86 m/s (60 knots) for different durations considered for the study.
Table Captions

Table 1 IMD classification of low-pressure system over the Indian Ocean

| T- Number/ C.I. Number | System                        | Maximum Sustained Wind Speed (m/s) | Pressure Drop (hPa) |
|------------------------|-------------------------------|-----------------------------------|--------------------|
| T1.5                   | Depression (D)                | 8-14                              | 1.0 - 3.0          |
| T2.0                   | Deep Depression (DD)          | 14.5–17                           | 3.0 - 4.5          |
| T2.5                   | Cyclonic Storm (CS)           | 17.5 -24                          | 6.1 - 10           |
| T3.5                   | Severe Cyclonic Storm (SCS)   | 24.5-32.5                         | 15                 |
| T4.0                   | Very Severe Cyclonic Storm (VSCS) | 33-45.5                        | 20.9-29.4          |
| T5.0                   | Extremely Severe Cyclonic Storm (ESCS) | 46-61                            | 40.2-63.6          |
| T6.5                   | Super Cyclonic Storm (SuCS)   | ≥62                               | ≥80                |

Table 2 Details of the numerical simulations conducted

| Model                 | Increased Maximum sustained wind speed m/s (knots) | Intensification durations | Experiments        |
|-----------------------|---------------------------------------------------|---------------------------|-------------------|
| ADCIRC                | 2.57(5), 5.14 (10), 7.71 (15), 15.4 (30) &30.86 (60) | A, B, C,D, E,F,G, H, I, J | 5x10=50 + Laila   |
| ADCIRC+SWAN           | 2.57(5), 5.14 (10), 7.71 (15), 15.4 (30) &30.86 (60) | A, B, C,D, E,F,G, H, I, J | 5x10=50 + Laila   |

Total Experiments 102
Table 3 Highest of the Maximum Wind Speeds (m/s) & Lowest of the Minimum Central Pressures (m of water) for all the considered test cases

| Test Scenarios | 2.57 m/s (5 knots) | 5.14 m/s (10 knots) | 7.71 m/s (15 knots) | 15.4 m/s (30 knots) | 30.86 m/s (60 knots) |
|----------------|--------------------|---------------------|---------------------|---------------------|---------------------|
|                | Wind Speed | Central Pressure | Wind Speed | Central Pressure | Wind Speed | Central Pressure | Wind Speed | Central Pressure | Wind Speed | Central Pressure |
| A              | 34.5       | 9.93             | 36.9        | 9.89             | 39.1        | 9.86             | 47         | 9.75             | 62.4      | 9.54             |
| B              | 34.5       | 9.93             | 36.9        | 9.89             | 39.1        | 9.86             | 47         | 9.75             | 62.4      | 9.54             |
| C              | 34.5       | 9.93             | 36.9        | 9.89             | 39.1        | 9.86             | 47         | 9.75             | 62.4      | 9.54             |
| D              | 34.5       | 9.93             | 36.9        | 9.89             | 39.1        | 9.86             | 47         | 9.75             | 62.4      | 9.54             |
| E              | 34.5       | 9.93             | 36.9        | 9.89             | 39.1        | 9.86             | 47         | 9.75             | 62.4      | 9.54             |
| F              | 34         | 9.94             | 34.1        | 9.93             | 36.8        | 9.89             | 44.6       | 9.79             | 59.5      | 9.56             |
| G              | 34         | 9.94             | 34.1        | 9.93             | 36.7        | 9.89             | 44.2       | 9.79             | 58.9      | 9.57             |
| H              | 34         | 9.94             | 34.3        | 9.93             | 36.7        | 9.89             | 44.1       | 9.79             | 59.1      | 9.57             |
| I              | 34         | 9.94             | 34.5        | 9.94             | 37          | 9.90             | 44.4       | 9.80             | 59.0      | 9.59             |
| J              | 34.5       | 9.93             | 36.9        | 9.89             | 39.2        | 9.87             | 47.1       | 9.75             | 62.5      | 9.55             |

Table 4 Percentage change in the peak MWE(STW) for all the test cases with respect to the peak MWE of *Laila* (STW)

| Test Scenarios | 2.57 m/s (5 knots) | 5.14 m/s (10 knots) | 7.71 m/s (15 knots) | 15.4 m/s (30 knots) | 30.86 m/s (60 knots) |
|----------------|--------------------|---------------------|---------------------|---------------------|---------------------|
|                | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> |
| A              | 11.5               | 32.0               | 60.1               | 128.3              | 487.4              |
| B              | 8.1                | 18.3               | 32.2               | 67.7               | 159.7              |
| C              | 4.9                | 15.1               | 28.0               | 66.7               | 175.5              |
| D              | 2.8                | 0.6                | 0.6                | 31.2               | 135.5              |
| E              | 0.2                | 2.9                | 0.6                | 0.1                | 54.5               |
| F              | 8.4                | 12.1               | 30.5               | 64.3               | 134.5              |
| G              | 4.4                | 13.4               | 26.7               | 60.6               | 133.5              |
| H              | 0.6                | 0.6                | -0.1               | 27.2               | 132.0              |
| I              | 0.5                | 3.0                | 0.3                | 0.3                | 34.5               |
| J              | 1.1                | 0.2                | 3.4                | 3.6                | 3.6                |

Table 5 Peak V<sub>avg</sub> (m/s) for different scenarios and intensifications

| Test Scenarios | 2.57 m/s (5 knots) | 5.14 m/s (10 knots) | 7.71 m/s (15 knots) | 15.4 m/s (30 knots) | 30.86 m/s (60 knots) |
|----------------|--------------------|---------------------|---------------------|---------------------|---------------------|
|                | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> | V<sub>avg</sub> |
| A              | 5.2                | 5.1                | 6.3                | 7.9                | 10.3               |
| B              | 5.2                | 5.1                | 6.0                | 7.9                | 10.1               |
| C              | 5.2                | 5.5                | 6.0                | 8.5                | 12.2               |
| D              | 5.2                | 4.9                | 6.0                | 6.4                | 10.6               |
| E              | 5.6                | 5.6                | 5.3                | 5.5                | 6.1                |
| F              | 5.4                | 5.4                | 5.4                | 5.4                | 6.1                |
| G              | 5.0                | 5.0                | 5.0                | 5.6                | 10.4               |
| H              | 5.3                | 5.6                | 5.9                | 6.4                | 7.9                |
| I              | 4.9                | 5.6                | 5.5                | 5.5                | 7.8                |
| J              | 5.3                | 5.2                | 5.3                | 6.0                | 7.9                |