Numerical Modeling of Cyclone’s Impact on the Ocean—A Case Study of the Orissa Super Cyclone

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ABSTRACT


A three-dimensional numerical model is described to study and investigate the impact of the Orissa super cyclone on the ocean. The forcing mechanism in the model is the wind stress derived from moving cyclonic storm/satellite winds. Numerical experiments have been performed using the model in order to understand the dynamics and thermodynamics of the ocean owing to the cyclone crossing the Paradip coast. The model was used to simulate the thermal response of the ocean to study the surface cooling and the surge associated with the cyclone. A net decrease in sea-surface temperature of about 5–6°C and a peak surge of over 6 m were simulated when the storm moved over the Orissa coast. The model computations were compared with the satellite data (TMI—Tropical Rainfall Measuring Mission [TRMM] Microwave Imager) available during the storm period. In the subsequent experiments, the variation of the ocean’s response to the changes in the translation speed of the cyclone was examined. We conclude that the speed of the cyclone, which determines the resident time of the cyclone over the ocean, leaves an overwhelming influence on sea-surface cooling and surge generation.

ADDITIONAL INDEX WORDS: Numerical model, storm surge, sea-surface temperature, simulation, super cyclone.

INTRODUCTION

The importance of sea-surface temperature (SST) in the genesis and intensification of a tropical cyclone is well established. The ocean and the cyclone mutually respond to each other. The tropical cyclone–ocean system is one with both positive and negative feedbacks. During the genesis and development stages, a positive feedback exists. The ocean supplies energy to the tropical cyclone, causing the storm to keep intensifying as long as it remains over warm enough seawater. The strong winds due to the cyclone produce intense mixing and divergent flows in the upper layers of the ocean, forcing the redistribution of waters through entrainment and upwelling, resulting in cooling of the surface layer. The cooling of the sea surface near the core of the storm results in the reduction in the total heat flux (latent and sensible) and energy production into the atmosphere, dampening the storm intensity. Thus, the cyclone-induced SST drop leads to a negative feedback, because the SST is a limiting factor for the attainable strength of a cyclone. The SST anomalies forced by tropical cyclones have been observed to vary from 1 to 6°C (BLAKE, 1983; SADHURAM, 2004). The SST cooling also depends upon the translation speed of the cyclone. Observations on tropical cyclones show that events grouped as “slow, medium and fast” result in a surface cooling of “high, medium and low,” respectively (BENDER et al., 1993).

The occurrence of tropical cyclones is a regular feature in May (premonsoon) and October (postmonsoon) over the Bay of Bengal. The passage of a moving tropical storm, even though relatively short in time, is a means of intense localized surface wind stress and, hence, an epitome of strong interaction between the atmosphere and the ocean. The typical time scale for the forced stage response is of the order of half a day. The energy of the mixed layer currents is dispersed in the spreading wake of near-internal waves (GEISLER, 1970; GILL, 1984), which penetrate into the thermocline (SHAY and ELSBERRY, 1987) leaving behind a baroclinic geostrophic current along the storm track.

Prior to the super cyclone, a tropical cyclone developed over the Bay of Bengal during 16–18 October 1999 that moved west northwestward with a maximum wind strength of 60 ms⁻¹, making landfall near Gopalpur, in the Ganjam district. Subsequently, a super cyclone struck the coast of Orissa, barely 10 d after the less-intense cyclone struck the same
state. This super cyclone, during 25–31 October 1999, became the most intense and the deadliest cyclone in the last hundred years in the state of Orissa. It started as a disturbance, and, by 26 October, it assumed the dimension of a cyclone. The system had been moving northwesterly, and, by 27 October, it intensified to a severe cyclonic storm. It was further upgraded to the stage of very severe cyclonic storm by late 27 October and moved in a west-northwesterly direction. It attained peak intensity just before landfall, close to and south of Paradip on 29 October. The minimum central pressure at landfall was estimated to be 912 mbar with sustained winds of over 260 km per hour at the time landfall. It remained practically stationary over the same area for more than 24 h and weakened later (BHATIA et al., 2000). The cyclone generated high storm surge over a long stretch (100–150 km) of the coastline (maximum of over 6 m) north of the landfall point (SIMON et al., 2001). It has already been shown that an ~2 wk period is required for the revival of SST to pre-storm conditions (GOPALAKRISHNA et al., 1993). This typical "relaxation stage" response of about 10 d following a hurricane passage has also been demonstrated (GILL, 1984; PRICE, 1983). Because a storm leaves its influence on the ocean for about a couple weeks, the impact of the super cyclone on the ocean should not be visualized as an independent entity, but as a cumulative effect of both the cyclones discussed above.

DATA

A realistic representation of the overall bathymetry is obtained with the help of hydrographic charts. Ocean-surface wind data were derived from QuickSCAT/NCEP, blended from Colorado Research Associates with spatial blending of high-resolution satellite data (Seawinds instrument on the QuickSCAT satellite [QSCAT]) and global weather center analyses (NCEP), resulting in high temporal and spatial resolution data sets (once every 6 hours) of winds vector components. The global coverage data sets began in July 1999 and are updated periodically. The data has a 0.5° × 0.5° resolution composed of 720 × 353 grid points, starting at 0.5°E, 88°S and ending at 360°E, 88°N. The blended wind product has been designed to provide valid wind values over the ocean. The source of the data and the associated documentation may be obtained from http://dss.ucar.edu/datasets/ds744.4/.

Cubic spline interpolation was used to bring the initial data fields to the required model resolution. To validate the model results, a 3 d mean of the TMI (Tropical Rainfall Measuring Mission [TRMM] Microwave Imager) SST images was examined (http://www.remss.com).

MODEL DESCRIPTION

In the present study, the model used is the same as that of Rao and CHAMARTHI (1997). Hence, the model formulation is not discussed in detail here. The model uses a system of rectangular Cartesian coordinates, with x and y increasing offshore and alongshore, respectively, and z is positive vertically upward. The origin is taken at the mean sea level at the coast of the southern open-sea boundary. The geographical location of the analysis region is shown in Figure 1. The

![Figure 1. Analysis region with 1999 Orissa super cyclone track.](image)

northern and southern open-sea boundaries are situated at y = L_y and y = 0. The western coastal boundary (the east coast of India) is situated at x = b_1(y), and an eastern open-sea boundary is set at x = b_2(y). The alongshore extent of the analysis zone is about 1000 km in the y direction, extending from south of Kakinada to north of Paradip. The breadth, which is the distance from the coastline to the eastern open-sea boundary, is constant and is approximately 400 km. Along the open boundaries, radiation conditions are used to permit disturbances generated from the interior to travel outward as progressive waves. The horizontal domain comprises 40 × 41 grid points with 36 computational levels through the depth. Accordingly, the model incorporates high-resolution data points near the surface and the bottom using the suitable transformation in the vertical direction. The grid increment in the x direction is about 10 km. The grid distance in the y direction is about 27 km. A conditionally stable semi-explicit finite difference scheme with staggered grid is used for the numerical solution of the model equations. The staggered grid consists of three distinct types of computational points on which the prognostic variables are computed. The computational stability is achieved by satisfying the CFL (Courant-Friedrich-Lewy) criterion (SIELECKI, 1968). In the present model, this condition is achieved by limiting the time step of integration to 90 seconds.

NUMERICAL EXPERIMENTS

Numerical experiments were performed to investigate the response of the ocean to the super cyclone off Orissa coast in October 1999. The response is seen in terms of change in the
SST. To begin with, the model ocean is initially quiescent and all the dynamical variables are set to zero. All isotherms and isohalines in the model are considered to be horizontal before the onset of the wind stress forcing with density stratification representative of October (postmonsoon), with a maximum SST of 28.5 °C and mixed layer depth of 30 m.

The model track of the super cyclone is shown as an arrow across the coast in Figure 1. There is a limitation on the strength of the maximum value to represent the super cyclone from the data set in question. However, it may be emphasized that the wind stress is computed not from wind data sets but from the idealized symmetric cyclone winds of varying wind stress in space and time on the ocean to simulate and represent a true moving super cyclone. Although the alongshore extent of the model domain is about 1000 km, only the zone between Paradip (20°30’ N, and 86°55’ E) and Gopalpur (19°16’ N, and 84°57’ E) is of interest to us. There is a wide range of wind speeds, and the region where the results are focused is mostly a zone of cyclone wind stress and distant points that are not expected to influence the active region, and, consequently, a suitable uniform wind stress has been assumed. In the super cyclone experiments, the radius of maximum winds is taken as 40 km with an associated maximum wind speed of 85 ms⁻¹. The average speed of translation of the cyclone is about 14 km/h. The computed cyclonic wind stress is the driving force in the ocean model. The surface wind stress \( \tau \) is calculated from the aerodynamic bulk transfer formula

\[
\tau = \rho_c u_w |u|
\]

where \( \rho_c \) is the density of the air; \( u \) the wind speed; and \( c_w \) the drag coefficient, which is taken as 2.8 \times 10⁻³ (JOHNS et al., 1985). The idealized cyclone incorporated in the model picks up strength as it moves towards landfall. A snapshot of the wind stress generated by the cyclone before the landfall is shown in Figure 2.

### RESULTS AND DISCUSSION

In discussing the results, it may be reiterated that the model simulations are shown in a limited zone in which significant effects of the cyclone are perceived. Hence, the diagrams elucidate the model results of about 200 km on either side of the cyclone track. The model is integrated from the state of rest as an initial condition with the forcing of the super cyclone. Figure 3 depicts the snapshot picture of SST drop derived from the model simulations at the time of landfall of the cyclone. The dotted line with an arrowhead in the figure shows the path of the super cyclone. A maximum SST drop of about 5.5 °C in a narrow elongated zone of about 100 to 150 km is seen to the right of the storm track. This result of a cyclone leaving a cold wake directly to the right is in consensus with earlier studies (MONALDO and SRORKA, 1997; NELSON, 1998). Figure 4 shows a 3 d mean TMI satellite SST image ending with 29 October. The monochrome image in Figure 4 may not be good for assessing the SST field and its drop because of the lack of color (and the appropriate color bar). (For a better appreciation of the same, one may refer to the site: http://www.remss.com.) This imagery also indicates the same order of cooling due to the passage of the cyclone. However, the location of the maximum surface cooling occurs to the left of the cyclone track in the satellite imagery, in contrast to the model simulations. The reason for this discrepancy could be nonincorporation of prestorm ocean conditions in the model. As mentioned earlier, prior to the super cyclone, there had been a less-intense cyclone in the Bay of Bengal that crossed the coast near Gopalpur, about 250 km...
south of Paradip. Therefore, in the numerical study, to assume a near realistic initial condition, the effect of this cyclone on the ocean was incorporated by integrating the model with the forcing of the Gopalpur cyclone. Figure 5 depicts the ensuing SST drop obtained from the model simulations owing to the cyclone at the time of landfall on 18 October. It may be noticed that the sea-surface cooling due to this cyclone is about 4 to 4.5 °C to right of the track, off Puri and well south of Paradip. After the Gopalpur cyclone crossed the coast, there was a gap of over a week before the super cyclone developed. Therefore, the model is further integrated with the wind stress forcing by using the prevailing wind of October 25 from QSCAT/NCEP, before the emergence of the super cyclone. This simulated prestorm condition is used as the initial state in the model for further integration with the forcing of the super cyclone to study the near-realistic response of the ocean due to the super cyclone. The resulting model simulation of the ocean response reflects the combined and cumulative effect of the atmospheric forcing events that had taken place since the Gopalpur cyclone. The simulated SST cooling is portrayed in Figure 6 at the time of landfall of the super cyclone on 29 October. It may be noticed that the maximum SST drop of about 6.0 °C in a narrow elongated zone of about 150 km is seen to the left of the storm track. It is important to note the conspicuous differences in the simulations shown in Figure 3 and Figure 6. The comparison shows that the location of the maximum cooling has shifted to the left of the storm track in Figure 6, though the surface cooling is almost the same in magnitude. This simulation of ocean cooling on the left side of the track is now in fairly good agreement with the TMI imagery (Figure 4). This suggests that appropriate initial conditions of the ocean state need to be incorporated in the model to study tangible response due to any synoptic extreme atmospheric disturbances.

Further study was also carried out to better understand the ocean's response to different speeds of translation of the super cyclone. The model uses the initial state of ocean at rest. In the first experiment, the model was integrated with the forcing of the super cyclone by doubling the actual speed of translation. The corresponding SST drop at the time of landfall is shown in Figure 7a. Notice that the maximum sea-surface cooling is only 2.0°C, which is significantly lower compared to the cyclone traversing with the observed speed of
The given speed of translation of the super cyclone in which maximum induced cooling was about 5.5°C. The region of maximum SST perturbations was simulated at an average of 1.4 to 2 times the radius of maximum winds in all the numerical experiments. From the foregoing analysis, it may be inferred that the speed of translation has a profound bearing on the underlying sea surface over which it travels—the faster the speed of the cyclone, the smaller its influence on SST drop. Further, we may infer from the results that the inverse relationship between the SST drop and the cyclone speed is not exactly linear. However, for a specific strength of a storm, the speed of translation has a definite heightened influence on the ocean over most other important parameters, such as the depth of the oceanic mixed layer and the position of the underlying water with respect to the storm track, etc. This inference is of immense use, because the drop of temperature of the sea surface beneath the cyclone will in turn have an overwhelming effect on the dissipation/intensification and motion of the cyclone.

In order to understand the ocean’s response more clearly, it is worthwhile to study the temporal variation of SST as the cyclone approaches the coast with different translation speeds. Figure 8 shows the variation of temperature with time at Paradip before and after the landfall of the cyclone with different speeds. Note that the cooling continues even after landfall (up to 6 h), and it may take about 10 d of typical revival time for SSTs to get back to the normal state. The reason for this longer revival time may be due to the current induced by the predominant northerly component of the wind after the landfall, which is conducive to upwelling along the east coast. It may also be noted that the ocean shows an early response in the case of slow-translation speed of the cyclone. This may be due to the fact that slow-moving storms will have more resident time to exert strong stress on the ocean’s surface, allowing mixing and intrusion of colder water from below.

The temporal variation of the sea-surface elevation and peak surge generated by the super cyclone at Paradip is shown in Figure 9. The maximum sea-surface elevation of 6 m is simulated at the time of landfall. Soon after the landfall of the cyclone, the elevation at Paradip drops exponentially compared to the case of the actual motion of the super cyclone.

Figure 7. (a) Computed SST drop with fast moving cyclone. (b) Computed SST drop with slow-moving cyclone.
to near normal state. The maximum peak surge of about 6.2 m is simulated at Paradip about 30 km north of the landfall. The poststorm survey report of India Meteorological Department (IMD) also agrees with the model simulation of the maximum surge at Paradip. It is important to note that the simulated peak surge is extended to a long stretch of the Orissa coastline near to and north of the landfall point.

**CONCLUSIONS**

The performance of the model is found to be very satisfactory in simulating the ocean state due to the passage of the super cyclone. The model computes a maximum SST drop of about 6.0°C to the left of the cyclone track. This anomalous result of the occurrence of maximum sea-surface cooling to the left of the cyclone track has been validated using satellite imagery. This was achieved in the present modeling study by specifying prestorm ocean conditions in the model. The SST drop and the peak surge are found to be dependent on the speed of translation of the cyclone. The faster the speed of the cyclone, the less would be its influence on the SST drop and the associated peak surge. This inference is of immense use, as the ocean cooling beneath the cyclone will in turn have a profound influence on the dissipation/ intensification and motion of the cyclone. A significant temporal variation of SST and sea-surface elevation is simulated at the coastal station, Paradip. This implies that the cyclone has clearly left its signature on the coastal zone. The anomalous temperatures induced by the cyclone together with the associated local circulation likely encourage the development of eddies. Information on oceanic eddies is important in many studies, such as acoustic propagation, heat transport, and identification of potential fishery zones, etc.

**LITERATURE CITED**


