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A coupled hydrodynamic modeling system for PHAILIN cyclone in the Bay of Bengal

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ABSTRACT

East coast of India is characterized by low to medium topography and an extensive network of major estuaries, bays, mangrove creeks, rivers and tidal inlets that permit inland flooding during tropical cyclones. A coupled wave + surge hydrodynamic modeling system (ADCIRC + SWAN) is implemented to simulate storm surge, still water level elevation and wave induced setup associated with '*Phailin*', a very severe cyclonic storm that made landfall in the Odisha State, east coast of India, during October, 2013. The coupled model provides a realistic description on the dynamic interaction of tides, wind, waves and currents, which is critical for operational needs. The study assesses the role of wave-induced setup on the net water level elevation using time varying wave radiation stress that is dynamically updated in the coupled model run. Numerical experiments are carried out for both storm surge alone and coupled mode versions. Dependent upon complex bathymetry and coastal geometry, inclusion of wave-induced setup in coupled runs results in an additional 23–36% increase of peak surge relative to an uncoupled, surge-tide simulation. The significant wave height from coupled model also shows an excellent match with observed wave heights from a wave-rider buoy located off the Odisha coast. The comparison of surge residuals between model and observation also exhibits a good match. The study highlights the importance of having a coupled wave-hydrodynamic model for operational needs in the north Indian Ocean.

1. Introduction

Cyclone '*Phailin*' in Thai language meaning "sapphire" was one of the strongest tropical cyclones ever recorded over the northern Indian Ocean basin (Bernhard et al., 2013). Next only to the 1999 Odisha super cyclone, in terms of maximum wind speed and central pressure, *Phailin* made landfall at Odisha coast, along the east coast of India on October 2013. This cyclone originated as a tropical depression in the Gulf of Thailand on October 4. Later it crossed over Malay Peninsula and entered into Andaman Sea (eastern Indian Ocean) on the 6th of October, 2013. It continued its journey through Indian Ocean in a west–northwest direction. On October 10, '*Phailin*' intensified rapidly and became a cyclone equivalent to a category 1 hurricane. On the next day, still moving over warm tropical Indian Ocean, it exploded into a super cyclone, equivalent to a category 5 hurricane. During a period of 24 h, wind speed increased from 83 km h^{-1} to 213 km h^{-1}. The system started to weaken as it approached Odisha coast of India and made landfall at Gopalpur (see cyclone track details in Fig. 1) around 17 UTC on October 12, 2013. The maximum sustained wind speed during landfall was about 215 km h^{-1} with central pressure of 940 mb. Further details on the intensification and movement of '*Phailin*' are available in the IMD (2013). The severe cyclonic storm left behind a wide swath of damaged infrastructure, flooding of agricultural farmlands, widespread death of livestock and a few instances of human loss along coastal Odisha and parts of northeastern Andhra Pradesh. Timely warnings and alertness by the national disaster management authorities and massive evacuation efforts were very effective in minimizing human loss, as compared to the death toll during 1999 Odisha Super Cyclone.

East coast of India encompasses a network of highly productive estuaries and mangrove creeks. Many larger cities are located along this coast, viz; Chennai, Vijayawada, Visakhapatnam, Gopalpur, Paradeep, Puri, and Kolkata. The low to medium elevation open coast is highly vulnerable to storm surges resulting from the landfall of tropical cyclones that are originating in the Bay of Bengal. Along the east coast of India, between Paradeep and Balasore in Odisha state, and between Bapatla and Kakinada in the Andhra Pradesh, coastal zone adjoining the Bay of Bengal is classified as a very high-risk zone, in terms of coastal vulnerability from natural calamities. Several case studies were reported

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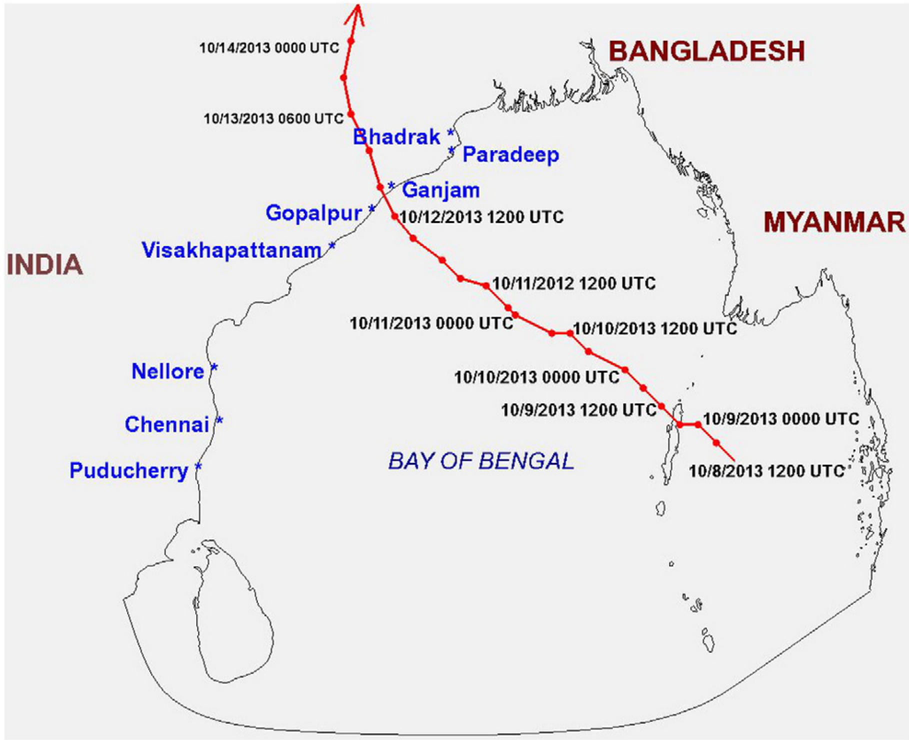

Fig. 1. Track of *Phailin* cyclone and observational locations for waves (Gopalpur) and water level (Paradeep).

(Rao et al., 1994; Murty et al., 1986; Dube et al., 1997, 2000) on cyclone-induced storm surge for the Bay of Bengal coast. In the recent literature it is highlighted that coupling of waves, surge and tide is essential for improving the accuracy of predicting storm surge in coastal areas (Brown and Wolf, 2009; Roland et al., 2009; Wolf, 2009). Therefore, a coupled model that takes into account the combined effects of wind, waves, currents, surge and tides is imperative for developing an operational cyclone forecasting system. The Earth System Science Organization (ESSO)-Indian National Centre for Ocean Information Services (INCOIS) at Hyderabad has a mandate for providing operational marine weather forecasting services that envisages integration and coupling state-of-the-art weather models for operational oceanographic needs. The ESSO-INCOIS plays an important role in this task by providing ocean observing data, information and advisory services to the public through sustained ocean observing programs and modeling studies. Balakrishnan Nair et al. (2014) recently reported on wave monitoring and forecasting during '*Phailin*' cyclone in the Bay of Bengal, using the MIKE21-SW model. This study was limited in using the wave model on a standalone mode, and various environmental forcing resulting from the non-linear interaction between surge, tides and currents was not accounted in their study.

The time varying water depths and current fields remarkably influence the wave field in coastal waters. In this context, accurate wave prediction in coastal waters is only possible through a two-way coupling of wave model with a hydrodynamic model; the latter could provide feedback on water level back to the wave model. Xing et al. (2011) mentioned that simulation of storm surges and physical processes that affect coastal areas requires numerical models having high spatial and temporal resolutions, with appropriate downscaling techniques capable of reproducing the mass conveyance between open sea and coastal waters. In the application of coupled model for the first time in the Indian seas, Bhaskaran et al. (2013), reported on the performance and validation of coupled (ADCIRC + SWAN) model for the *Thane* cyclone in the Bay of Bengal. In a recent study and extension of the previous work, Bhaskaran et al. (2014) performed a comprehensive analysis on the coastal inundation potential for the Tamil Nadu coast. The application of coupled wave-hydrodynamic models for the global oceans is quite recent. And some of the few studies include the MAST III PROMISE Project (Ozer et al., 2000); modeling energetic events like hurricane Katrina and Rita in 2005, Gustav and Ike in 2008 in the Atlantic Ocean (Dietrich, 2010); Mediterranean Sea with focus on Italian coast (Ferrarin et al., 2013); and coupled modeling system for typhoon Maemi in Korean seas (Bung et al., 2013).

The present study is an application of coupled (ADCIRC + SWAN) model to understand the wave and hydrodynamic characteristics associated with '*Phailin*' cyclone along the eastern Indian coast. The performance and assessment of coupled model was evaluated with all available observations.

1.1. The modeling system

The modeling system used for the present study is a coupled wave, current and astronomical tide model that uses the same computational grid for all the physical processes. In other words, the 'tight-coupling' mode is used for the computation of both waves and hydrodynamic conditions. The wind data are derived using the Jelesnianski formulation (Jelesnianski and Taylor, 1973), using the best track estimate of '*Phailin*' obtained from the IMD records and more details on the implementation are described in Section 1.1.4.

A flexible triangular unstructured mesh is used for both wave and hydrodynamic models, that has the advantage of accurately representing complicated bathymetry and complex coastal geometry. The following dynamic interaction between waves, surge and tide components is considered in the present study. (1) The contribution of waves to the total water level elevation through wave induced set-up and wave set-down; (2) the influence of tides and storm surge on wave propagation that affects the refraction, shoaling and wave-breaking process; and (3) the effect of water level variation and currents on propagation, generation and decay of wind waves. The spatial variation of wave action-density spectra causes a net momentum flux, also known by the radiation stress tensor. The onshore component of this momentum flux is balanced by pressure gradient in the opposite direction. In other words, the physical manifestation of this pressure gradient causes the rise and fall of mean sea level, also known as the wave set-up