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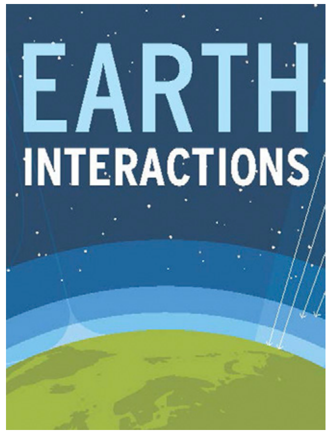

A Great Escape from the Bay of Bengal ''Super Sapphire–Phailin'' Tropical Cyclone: A Case of Improved Weather Forecast and Societal Response for Disaster Mitigation

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ABSTRACT: The very severe cyclonic storm (VSCS) "Phailin (2013)" was the strongest cyclone that hit the eastern coast of the India Odisha state since the supercyclone of 1999. But the same story of casualties was not repeated as that of 1999 where approximately 10 000 fatalities were reported. In the case of Phailin, a record 1 million people were evacuated across 18 000 villages in both the Odisha and Andhra Pradesh states to coastal shelters following the improved operational forecast guidance that benefited from highly skillful and accurate numerical model guidance for the movement, intensity, rainfall, and storm surge. Thus, the property damage and death toll were minimized through the proactive involvement of three-tier disaster management agencies at central, state, and district levels.

KEYWORDS: Tropical cyclones; Mesoscale models; Numerical weather prediction/forecasting

1. Introduction

The north Indian Ocean (NIO) comprising the Bay of Bengal (BoB) and the Arabian Sea (AS) is impacted by five to six tropical cyclones (TCs; wind speed > 17 m s^{-1} or 33 kt[1]) each year [Cyclone Warning and Research Centre 2011]. The typical duration of a TC over NIO is 5–6 days, and very severe cyclonic storm intensity [>33 m s^{-1} or 64 knots (kt; 1 kt = 0.51 m s^{-1})] persists for only 2–3 days as compared to 6 days for the global average. The NIO region experiences two seasons of TC formation: premonsoon (April–May) and postmonsoon (October–December). Nevertheless, this subcontinent accounts for the highest number of cyclone-related fatalities globally [World Meteorological Organization (WMO) 2011]. Of the 23 recorded deadly storms (>10 000 fatalities over the last 300 years), 20 cyclones were formed over the BoB (WMO 2011).

Phailin (a Thai word for "sapphire," a yellow flower) was the strongest named cyclone in the BoB that hit the Odisha, India, coast since the devastating 1999 Orissa supercyclone. A well-marked low pressure was seen over the Andaman Sea on 7 October 2013 from a remnant of unnamed cyclonic circulation over the South China Sea [Regional Specialized Meteorological Centre (RSMC) 2013]. It intensified into a depression (8.7–13.9 m s^{-1} or 17–27 kt) and then a deep depression (14–17 m s^{-1} or 28–33 kt) on 8 October and further intensified into cyclonic storm Phailin (17–24 m s^{-1} or 34–47 kt) on 9 October. Moving in the northwestward direction, it intensified into a very severe cyclonic storm (VSCS) and crossed the Odisha, India, coast around 1700 UTC 12 October 2013 with winds in excess of 59 m s^{-1} (115 kt), taking a similar course as the 1999 Orissa supercyclone that made landfall with 69 m s^{-1} (134 kt) peak winds. The damage due to the 1999 Orissa supercyclone was approximately $4.5 billion U.S. dollars and resulted in approximately 10 000 fatalities (Kalsi 2006). In the case of Phailin, the reported death toll was 22, and property loss was considerably minimized.

Thus, despite the similarity in the two storms in terms of track, intensity, and lead time, the story of devastation and casualties was fortunately not repeated. There was an obvious scientific- and policy-relevant curiosity and strategic interest in the possible reasons for this success story that leads to this assessment.

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[1] All peak winds are defined as by the India Meteorological Department and represent sustained 3-min maximum winds.

2. Performance of operational TC forecasts at IMD in the last decade

We conclude that the success story seen for Phailin is not due to any one singular event, rather it is the culmination of a sustained investment in research and development of numerical models, observations, and data assimilation techniques for providing improved initial states in those models and, above all, multiple media sources for forecast dissemination across the region. Until 2003 forecast methods were subjective at the India Meteorological Department (IMD), with the exception of the aging, coarse-resolution quasi-Lagrangian model (QLM) providing track guidance for 24 h (Kalsi 2006; Mohapatra et al. 2013b). Largely as a result of a modernization program and support for high performance computing at IMD, several in-house models were introduced for predictions such as the IMD Global Forecast System (GFS), the National Center for Atmospheric Research (NCAR) version of Weather Research and Forecasting (WRF) Model, and the National Oceanic Atmospheric Administration (NOAA) Hurricane WRF (HWRF) Model system. The IMD launched a national program, Forecast Demonstration Project of landfalling TCs (FDP-TC) over BoB, under which various operational, research, and academic institutes in India are providing real-time forecast of TCs in short and extended range scales to IMD for its operational use. In addition, several products from models such as National Centers for Environmental Prediction (NCEP) GFS, European Centre for Medium-Range Weather Forecast (ECMWF), the Met Office (UKMO), Japan Meteorological Agency (JMA) GFS, and the cloud-resolving version of NOAA HWRF are now readily available to forecasters. A single model ensemble prediction system (EPS) from various global models and multimodel ensembles (MME) was also introduced. The ECMWF Variable Ensemble Prediction System (VarEPS) provides skillful TC forecasting parameters for genesis, pregenesis, and postgenesis track and intensity through a climate forecast applications network (Belanger et al. 2012). The system demonstrated better skill for individual storms and a monthly outlook of TC genesis and tracks with a lead of 7–10 days over the NIO basin (Belanger et al. 2012; Rajasekhar et al. 2014). Based on the reliability of the suite of products, the official forecast was extended up to 72 h in 2009 (RSMC 2011) and to 120 h in 2013 (Mohapatra et al. 2015).

Application of high-resolution numerical models in the Atlantic basin improved track errors by about 8%–24% (Gopalakrishnan et al. 2012). In recent years, similar reductions were observed over the NIO as well (Osuri et al. 2013). The authors also reported significant gains in predicting the recurvature of eastward-moving (recurving) storms using the Advanced Research version of WRF Model (ARW) with improved data assimilation procedures including that from the Doppler weather radars (DWR) (Osuri et al. 2015). The HWRF model became an additional operational asset in 2010 at IMD for TC forecasts, particularly for structure and intensity. The HWRF model was adapted from NOAA thanks to sustained interactions between NOAA, the Ministry of Earth Sciences (MoES), and partnering research institutions in India and the United States. With support from NOAA Hurricane Forecast Improvement Project (HFIP) (Gall et al. 2013), the hurricane modeling team at NCEP is providing skillful operational forecast guidance for all TCs in the Northern Hemisphere including the BoB and AS using the high-resolution triple-nested HWRF model operating at cloud-permitting 3-km resolution near the storm region (Tallapragada et al. 2015). The operational track forecast error [skill over climatology and persistence; CLIPER model (Aberson 1998; Neumann 1972)] decreased (increased) at the rate of about 7.3 km (3%) yr^{-1} during 2003–11 for 24-h forecasts over the NIO (Mohapatra et al. 2013b). Similarly, the skill of the 12- and 24-h operational intensity forecasts significantly increased by about 6% and 9% yr^{-1}, respectively, as compared to the persistence method (Mohapatra et al. 2013a). A recent study by Ramarao et al. (2015) comparing short-range forecasts of NIO TCs for the period 2010–14 by global operational centers demonstrated that the ensemble mean of 72-h mean track forecast errors of NCEP, ECMWF, and UKMO are 252, 322, and 374 km, respectively.

3. Advanced model forecast guidance for TC Phailin

The operational centers all over the globe started forecasting TC Phailin beginning 7 October 2013, as it formed over the Andaman Sea. In spite of the large spread in movement of the system in 4–5 days lead-time forecast by different operational agencies, the IMD produced a precise landfall forecast between Kalingapatnam (north Andhra Pradesh) and Paradip, close to Gopalpur (south Odisha) 84 h in advance of landfall based on guidance from the reliable models as described above.

IMD issued the first genesis forecast for Phailin on 1 October 2013 using the guidance available from statistical–dynamical model (RSMC 2013). Details of the statistical–dynamical model can be obtained from Kotal et al. (2009). The ECMWF VarEPS indicated the genesis of Phailin on 7 October 2013 over the Andaman Sea 7 days in advance of landfall based on 1 October 2013 forecast cycle with a confidence level of 30% that subsequently increased to about 60% a day later. The NCEP–HWRF model also detected genesis of TC Phailin on 7 October 2013, as noted from the model-simulated microwave satellite imagery at the top of the atmosphere and minimum sea level pressure (hPa) in the 48-h forecast of 0000 UTC 5 October and subsequently the cycle for Typhoon Fitow (22W) in the western Pacific basin. Figure 1a depicts the genesis of Phailin at 0600 UTC 7 October 2013 from a forecast cycle initialized at 0600 UTC 6 October 2013. Then, 5-day TC forecasts from operational NCEP–HWRF were made available at every 6-h interval to operational forecasters at the U.S. Navy's Joint Typhoon Warning Center (JTWC) and IMD. More detailed NCEP–HWRF model products for all cycles of TC Phailin were made available to IMD forecasters through a dedicated website (accessible at http://www.emc.ncep.noaa.gov/HWRF/WestPacific/RT_WPAC_FY13/PHAILIN02B/). Figure 1 shows the complete life cycle of TC Phailin as predicted by NCEP–HWRF in a sequence of real-time forecasts starting with the genesis of TC Phailin (on 7 October 2013), concentrating into a depression on 8 October 2013, intensification into a VSCS in the central BoB, and subsequent weakening during landfall along the Odisha coast near Gopalpur.

The real-time track forecast obtained from different global and high-resolution mesoscale models was verified against the IMD observed track and showed in Figure 2a. IMD GFS, JMA, and IMD–HWRF had relatively large errors (km) as compared to other models. The track prediction from NCEP–GFS and HWRF, IMD–MME, and the ARW Model run at the Indian Institute of Technology (IIT), Bhubaneswar (IITBBS), had smaller errors when compared with other models up to the 96-h forecast. The deterministic track forecast from ECMWF VarEPS

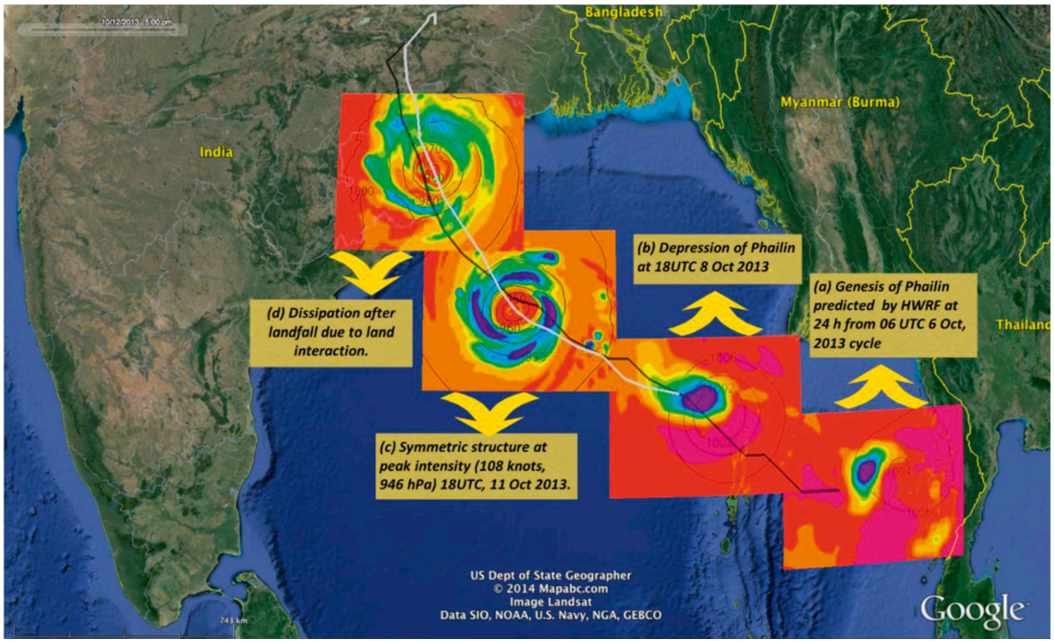

Figure 1. HWRF forecast of the life cycle of TC Phailin starting from (a) genesis at 0600 UTC 7 Oct 2013, (b) formation of depression on 8 Oct 2013, (c) intensification, and (d) dissipation. Shading depicts the model-simulated microwave satellite imagery at the top of the atmosphere, and contours represent minimum sea level pressure (hPa). The black line represents the best track from JTWC, and the white line is the HWRF predicted track from 0000 UTC 10 Oct 2013.

indicated that the landfall would be over the Andhra Pradesh coast starting from the forecast cycles 6–10 October 2013. Thereafter, the track forecast improved showing landfall over south Odisha coast near at Gopalpur [deterministic track forecast from ECMWF Variable Ensemble Prediction System (VarEPS), M. Rajasekar 2013, e-mail communication to Forecast Demonstration Project of Landfalling TCs (FDP-TC) program group]. IMD implemented the 2010 version of the HWRF model run at a reduced resolution (9 km near the storm region) for operational TC forecast guidance over the NIO region. Evaluation of IMD–HWRF compared to NCEP–HWRF indicated superior performance from the latter due to higher (cloud resolving) resolution, advanced data assimilation techniques, and advanced model physics (Tallapragada et al. 2013).

The intensity forecasts by IMD result from a manual forecasting process, utilizing synoptic and an in-house statistical cyclone intensity prediction (SCIP) model (Kotal et al. 2008) guidance along with several numerical model's guidance as mentioned in section 2 and Mohapatra et al. (2013a). The global models are not skillful in providing intensity guidance, particularly, the rapid intensification (http://www.emc.ncep.noaa.gov/HWRF/IWTC_VIII/intensity_guidance_NCEP_HWRF.docx). IMD issued forecasts for rapid intensification of Phailin during 10–11 October 2013 as observed, based on available guidance from SCIP, NCEP–HWRF, and IMD–HWRF models with 0000 UTC 10 October 2013 initial condition. The NCEP–HWRF

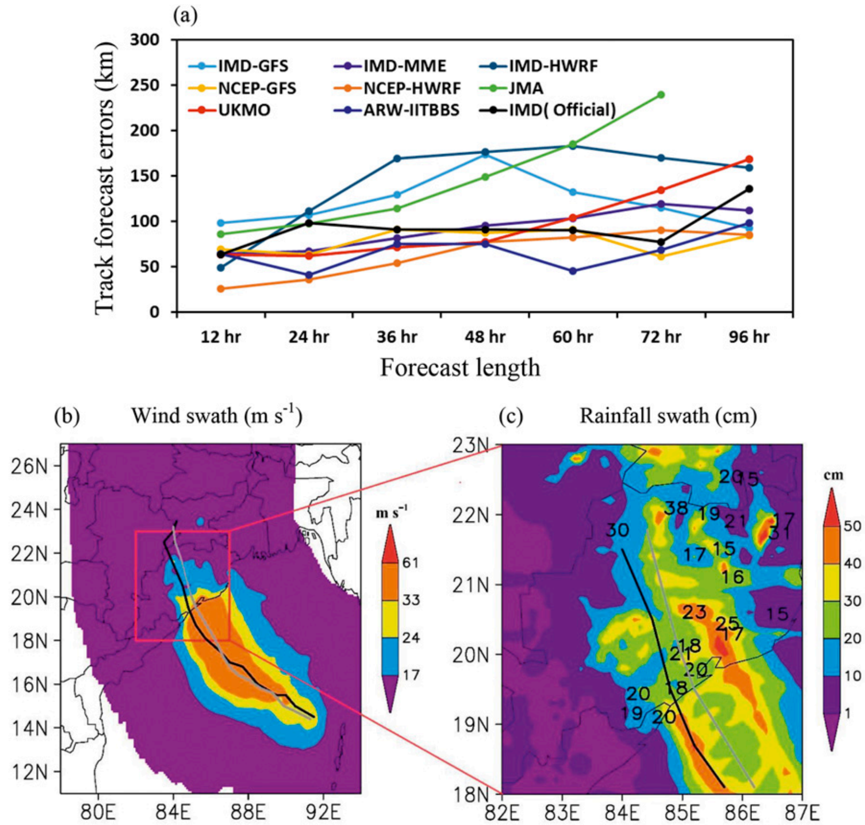

Figure 2. The top shows real-time track forecast errors in km (verified against the IMD observed track) obtained from different global and high-resolution mesoscale models. HWRF forecast of (a) 10-m maximum wind speed in $m\,s^{-1}$ and (b) rainfall swath in cm during the life cycle of TC Phailin from 0000 UTC 10 Oct 2013. The black and gray lines represent the JTWC best and HWRF model track, respectively. Rainfall swath accumulated over 126 h of forecast is zoomed over the rectangular region highlighted in (a) and the numbers in (b) represent the IMD station-observed accumulated rainfall for the landfall day (0300 UTC 12–13 Oct 2013) period.

showed rapid intensification starting from 1200 UTC 9 October 2013 for the period 10–11 October 2013. The 24-h change in 10-m 1-min sustained maximum wind was 18–21 $m\,s^{-1}$ from the forecast cycles of 1200 UTC 9 October to 0000 UTC 10 October 2013. ECMWF deterministic intensity forecast is obtained from The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) site for all cycles between 0000 UTC 9 October and 0000 UTC 12 October 2013. ECMWF suggested the rapid intensification during 11–12 October 2013 based on the initial condition of 0000 UTC 10 October 2013 onward.

The NCEP–HWRF model was able to accurately capture size, structure, and rainfall forecasts for TC Phailin (Figure 2), rendering these products valuable to decision-makers in preparation for disaster mitigation efforts. For example, the NCEP–HWRF model suggested that the northern parts of the Odisha state would

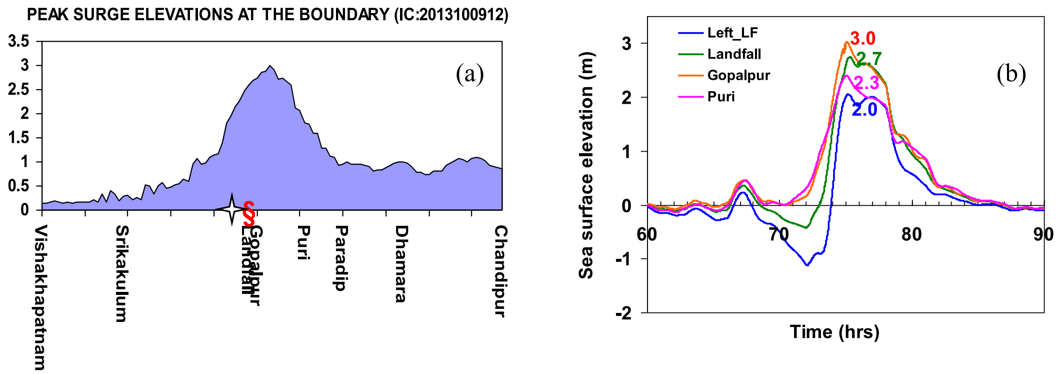

Figure 3. Guidance of (a) peak surge (m) and (b) sea surface elevation (m) from the one-way coupled ARW and dynamical storm surge models.

receive heavy to very heavy rainfall (~40 cm) during landfall, which was validated by the observations after the event. The IMD also issued an extremely heavy rainfall (25 cm or more in 24 h) warning for 12 and 13 October 2013. The intent here was to demonstrate how the cloud-resolving version of the NCEP–HWRF actually depicts genesis, movement, intensity, and landfall, which will be adapted as an operational model for TC forecasting at IMD under the memorandum of understanding between NOAA and MoES.

4. Storm surge prediction for TC Phailin

Beyond the wind- and rain-induced flooding, storm surge creates havoc in low-lying densely populated coastal areas worldwide, particularly along the east coast of India where there are a large number of river systems. About 80% of the mortality in the case of the Orissa supercyclone (1999) and VSCS Nargis (2008) was related to storm surge. The Orissa supercyclone produced a storm surge of about 5–6 m and carried seawater almost 35 km inland, while Nargis produced 4-m surge and inundated 40-km inland (Webster 2008). Therefore, storm surge forecast and dissemination is vital for disaster mitigation and management.

In India, IMD is responsible for storm surge forecasts associated with TCs. Since 2008, IMD uses dynamical surge models (Johns et al. 1981, 1983; Dube et al. 1985, 1997) developed at the IIT Delhi and a statistical–empirical method (Ghosh 1977) prior to 2008. The operational storm surge model is limited to 24-h forecast guidance primarily due to lack of more realistic inputs of TC track, intensity, and size at longer lead times (Dube et al. 1997; Heo et al. 2009). As a part of the advanced weather research program at IIT Bhubaneswar, the dynamical storm surge model (Dube et al. 1985, 1997) was one-way coupled with the ARW Model that showed better performance over the NIO basin (Osuri et al. 2013) to produce a longer-range surge forecast (72–96 h). The experimental real-time forecast of this coupled ARW–storm surge modeling system during Phailin was shared with IMD. Figure 3 shows (Figure 3a) peak surge envelope along the coast during landfall with a lead of 3 days and (Figure 3b) sea surface elevation (maximum surge) at different locations on either side of the landfall position between 60–90 h of forecast time. This dynamical approach predicted the surge of 3 m, providing reasonable guidance 3 days prior to the landfall time (Figure 3b). It also showed that the maximum surge occurs in the right of the landfall location (Gopalpur) and minimum in the left of the landfall (Left_LF). The 24-h forecast of peak surge at Gopalpur was 2.6 m (not shown), which is in good agreement with the observed surge of 2–2.5 m at Gopalpur (the postsurvey analysis report of Phailin is available at http://www.imd.gov.in/section/nhac/dynamic/phailin.pdf). The IMD utilized the storm surge model guidance of IIT Bhubaneswar, IIT Delhi, and the Indian National Center for Ocean Information Services (INCOIS), Hyderabad, for surge forecasts (RSMC 2013). Further, the output from the experimental coastal inundation model of INCOIS was utilized to provide information on the expected location-specific extent and depth of inundation due to Phailin. Thus, an ensemble of operational and experimental model products was used by forecasters for improved storm surge and coastal inundation forecast guidance aiding in the evacuation of 1 million people from hazard-prone coastal regions, minimizing the death toll. The lack of such an early storm surge warning along with the track and intensity during the Orissa supercyclone (1999) resulted in the loss of thousands of human lives and impacted millions of dollars in property.

5. Forecast dissemination and disaster preparedness

In 1999, TC warnings by the IMD were not as exhaustive as today and dissemination was limited to radio, television, and newspapers. Further, the warnings failed to communicate the severity of the hazard associated with supercyclone intensity storms, and being a rare event, the public were not equipped with sufficient protective measures. The limitations in forecast accuracy and dissemination systems caused a huge disaster, although a few thousand people (~44 500) were evacuated from vulnerable regions to 23 Red Cross cyclone shelters. A similar situation occurred during VSCS Nargis (2008) in Myanmar, although the IMD provided warnings on the track and intensity based on high-resolution mesoscale model forecast guidance to Myanmar's Department of Meteorology and Hydrology well in advance (~5 days) (RSMC 2009). Also, the ECMWF VarEPS identified the genesis of Nargis on 27 April 2008 (5 days in advance from the 22 April 2008 forecast cycle) and a high probability of landfall across the Irrawaddy delta some 10–12 days later (Webster 2008). However, the response from the Myanmar government was poor, and the public ignored the warnings (Webster 2008). The absence of a predisaster plan and appropriate communication strategies led to the tremendous loss from Nargis.

In recent years, and particularly during Phailin, the IMD adopted advanced strategies for TC forecast generation and dissemination of text- and graphics-based warnings. These include forecast uncertainty with the inclusion of the cone of uncertainty, wind distribution in four quadrants, timely dissemination of warning bulletins (within 3 h of observation), frequent national/RSMC bulletins (every 3 h), and hourly updates during the day of landfall through dedicated web, SMS texts, e-mail, telephone, telefax, television, radio, and other social networks to the public in India as well as the respective state governments, port officials, National Disaster Management Authority (NDMA), control room of the National Disaster

Management Cell of the Ministry of Home Affairs, government of India, and so on. In addition, a wide range of telecommunication channels such as VHF/high-frequency radio transmitter (HFRT), satellite-based cyclone warning dissemination system (CWDS), aeronautical fixed telecommunication network (AFTN; aviation), and interactive voice response system (IVRS) were implemented for forecast dissemination. The network of 252 analog and 101 digital CWDS received warning messages in local languages using *INSAT*/*Kalpana-1* satellites and was found to be reliable and useful, particularly during severe weather conditions and TCs when terrestrial links were disrupted.

Another important aspect was the triggering mechanism adopted by the IMD during TC Phailin. Daily press releases and conferences with press and electronic media were organized, and two press conferences were held on the day of landfall. On a few occasions, IMD forecasters and the chief disaster managers at the national and state level conducted the press conference jointly. The consistency in the forecast and warnings issued by the IMD together with regular coordination with the disaster managers helped to maximize the effectiveness of the warnings.

The government of India paid attention to capacity building when faced with a hydrometeorological disaster. This included informing and empowering national, state, and district level disaster management authorities, publication of national TC management policy guidelines, shifting of disaster management approach from relief and rescue operations centric to preparedness and prevention measures in addition to risk mitigation approaches. After the Orissa supercyclone (1999) disaster, the first state agency called the Odisha State Disaster Mitigation Authority (OSDMA) was established to focus on both structural and nonstructural intervention. The state constructed 285 multipurpose cyclone and flood shelters in remote areas and 163 more buildings were being constructed under the National Cyclone Risk Mitigation Project and Integrated Coastal Zone Management Project with assistance from the World Bank.

6. Concluding remarks

The improved numerical model forecast guidance for movement, intensity, structure, and storm surge (in advance of 4–5 days prior to the landfall) of TC Phailin and enhanced warning products generation and dissemination systems collectively helped disaster management to evacuate over a million people (around 850 000 in Odisha and 150 000 in Andhra Pradesh) from likely affected areas to cyclone shelters, safe houses, and inland locations. Thus, collective efforts reduced the death toll and property damage dramatically compared to that of the Orissa supercyclone (1999) and VSCS Nargis (2008). Successful evacuation of a million people in the South Asian region is not a small task. This cannot be merely achieved by kicking the entire state machinery into top gear for 4–5 days following a cyclone warning. This took years of planning, construction of disaster risk mitigation infrastructure, establishing evacuation protocols, identification of potential safe buildings to house communities, and, most importantly, working with communities and community-based local organizations to set up volunteer teams.

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