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# Tropical Cyclone Activity over the North Indian Ocean

# Hydro-meteorological Aspects of Tropical Cyclone Phailin in Bay of Bengal in 2013 and the Assessment of Rice Inundation due to Flooding

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## 1. Introduction

Tropical Cyclones (TCs), one of the most destructive of all the natural disasters, are capable of causing loss of life and extensive damage to property. The Bay of Bengal is a potentially energetic region for the development of cyclonic storms and approximately 7% of the global annual tropical storms form over this region with two cyclone seasons in a year (Gray, 1968). Much of the TC related damage is attributed to storm surges, high winds, damage associated with strong thunderstorm complexes and TC-induced heavy rainfall. Predicting rainfall associated with TCs is a major operational challenge. Over the last few decades flooding from TCs at landfall has become a threat to human lives in India. Although track-forecasts continue to improve, quantitative precipitation forecasts (QPF) for TCs have shown little skill. One of the uncertainties in QPF is a lack of precipitation data over the open oceans to evaluate and validate numerical weather prediction (NWP) model results. TC rainfall forecasting techniques are lagging behind those of the track forecast. However, significant progress has been made in recent years due to the advance in remote sensing observations and the improvement of mesoscale models and data assimilation techniques. Until relatively recently, TC rainfall prediction was carried out mainly using empirical methods and subjective experience on the part of the forecaster. However, advanced techniques for Quantitative Precipitation Estimate (QPE) are currently employed in operational applications in some major forecasting centres, which already have greatly improved the forecasting for TC-related rainfall. Minakshi Devi et al. (2014) have shown predicted tracks of a few cyclonic events such as SIDR (Nov, 2007), Aila (May, 2009) and Laila (May, 2010) along with their contribution to precipitation in the NE India. Recent studies have indicated that some high resolution dynamical model simulations are capable of capturing the rainfall pattern of TCs. Lee and Choi (2010) investigated the torrential rainfall associated with Typhoon Rusa in South Korea in 2002 through numerical simulation using Weather Research Forecast (WRF) model. Haggag and Yamashita (2009) studied the hydro-meteorological features of TC Gonu using coupled atmosphere, ocean and land surface modelling with an atmospheric component based on the MM5 model. There are other studies on performance of models including, Raju et al. (2012), Osuri et al. (2012), Abhilash et al. (2012), Routray et al. (2013) and Srivastava, et al. (2011). All these studies indicate that the high resolution along with the improved data assimilation, especially DWR and satellite based data can improve the rainfall forecast by the models. Though heavy rainfall prediction is still a challenge, Hurricane WRF (HWRF) is a promising model for this purpose. A number of studies have examined the track, intensity, structure and genesis of TCs, however very few studies have considered the rainfall dynamics associated with TCs. The Hydro-meteorological aspects of TC have been dealt mainly in terms of coastal storm surge and inundation studies only.

Recent TC Phailin was the most intense cyclone that crossed India coast on 12 October 2013 after Odisha Super Cyclone of 29 October 1999. It affected around 12 million people. The cyclone prompted India's biggest evacuation in 23 years with more than 5,50,000 people moved up from the coastline in Odisha and Andhra Pradesh to safer place. At the time of landfall on 12 October, maximum sustained surface wind speed in association with the cyclone was about 115 knots (215 kmph) and estimated central pressure was 940 hPa. It caused very heavy to extremely heavy rainfall over Odisha leading to floods. Maximum rainfall occurred over northeast sector of the system centre at the time of landfall and 36 h thereafter. Maximum 24 h cumulative point rainfall was 38 cm in Odisha. The NWP and dynamical statistical models provided good guidance with respect to its genesis, track and intensity. However, there was spatiotemporal displacement and large intensity error in the forecast rainfall with respect to actual rainfall.

The main objective of this paper is to investigate the heavy rainfall caused by TC Phailin. In this paper, we have analysed the rainfall associated with TC Phailin before and after landfall. We also use the observed manual data after the landfall and also buoy and satellite merged data for sea area to arrive at the behavior of rainfall during the Cyclone period. In this study, we use HWRF model to study the rainfall predicted daily for 24 and 48 h along the track of cyclone and its comparison with the observed rainfall.

## TC Phailin Track

The very severe cyclonic storm (VSCS) Phailin originated from a remnant cyclonic circulation from the South China Sea. The cyclonic circulation lay as a low pressure are over Tenasserim coast on 6 October 2013. It lay over North Andaman Sea as a well marked low pressure area on 7 October. It concentrated into a depression over the same region on 8 October near latitude 12.0°N and longitude 96.0°E. Moving west-northwestwards, it intensified into a deep depression on 9 morning and further into cyclonic storm (CS), 'Phailin' in the same day evening. Moving northwestwards, it further intensified into a severe cyclonic storm (SCS) in the morning and into a VSCS in the forenoon of 10 October over east central Bay of Bengal. The VSCS, Phailin crossed Odisha and adjoining North Andhra Pradesh coast near Gopalpur (Odisha) around 2230 h IST of 12 October 2013 with a sustained maximum surface wind speed of 200–210 kmph gusting to 220 kmph. The track of the TC is shown in Fig. 1.

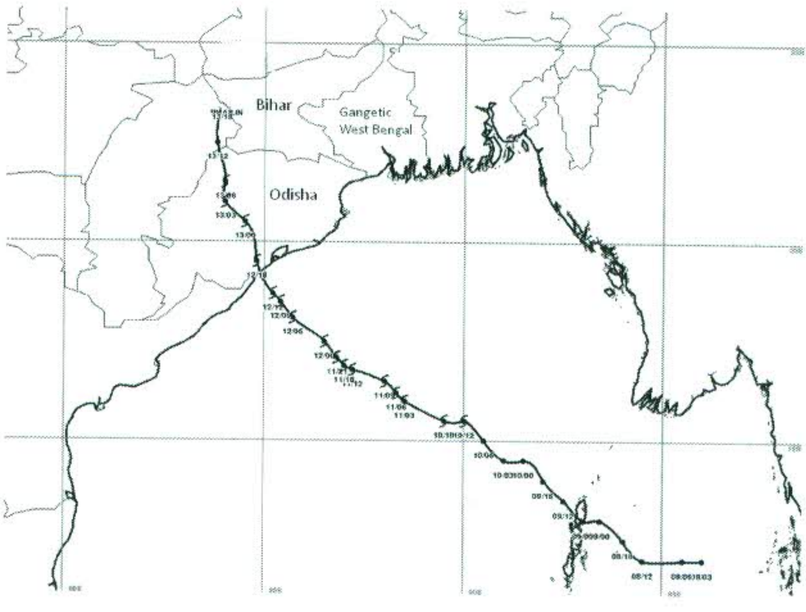


**Fig. 1:** Track of VSCS Phailin in Bay of Bengal (North Indian Ocean) (8–13 October 2013).

# 2. Rainfall due to TC, Phailin

## 2.1 Rainfall Monitoring Process of IMD

At the genesis stage, the rainfall was monitored mainly with satellite observations, supported by meteorological buoys, coastal and island observations. As the system entered into the east central Bay of Bengal moving away from Andaman and Nicobar Islands, it was mainly monitored by satellite observations, supported by buoys. On 12 October, when the system lay within the radar range, the DWR at Visakhapatnam was utilised and continuous monitoring by this radar started from 0100 UTC of 12 October when the system was at approximately 310 km east-southeast of Visakhapatnam coast and continued till 1800 UTC of that date. In addition to the observations from satellite and Radar, data from conventional observatories and Automatic Weather Stations (AWS) were used.

India Meteorological Department (IMD) has a synoptic observatory network of 552 stations, 2868 raingauges under Daily Rainfall Monitoring Scheme and 675 Automatic Weather Stations which record rainfall. In addition State Governments are maintaining over 3540 raingauge stations whose data are made available to IMD from Indian Railways, Forest and Agriculture Departments and other organisations which maintain about 5039 non-reporting raingauge station to meet their specific needs and also to provide data to IMD.

## 2.2 Rainfall Estimates Based on Point Raingauge Stations

The VSCS Phailin caused very heavy (13–24 cm/day) to extremely heavy rainfall (≥ 25 cm/day) over Andaman and Nicobar Islands and Odisha and isolated (< 25% of area), heavy (7–12 cm) to very heavy rainfall over adjoining eastern India. The daily precipitation on 13 and 14 October averaged for the state as a whole was 92% of the monthly rainfall of October and 71% of the post-monsoon seasonal (October–November–December) rainfall for Odisha state.

Maximum 24 h cumulative rainfall of 380 mm was reported by an automatic raingauge in Banki in Cuttack district of Odisha. The highest 24 h cumulative average rainfall of 187 mm was recorded in Nayagarh district on 13 October (ending at 0830 h IST on 13 October) and highest 48 h cumulative rainfall of 232 mm was recorded in Mayurbhanj district on 14 October (ending at 0830 h IST of 14 October 2013). The districts in the north of Odisha (Balasore, Bhadrak and Mayurbhanj) recorded as much as 300–400 mm and other parts of Odisha received between 200 and 300 mm as Phailin made landfall on the night of 12 October 2013. Figure 2 depicts the 24 h cumulative rainfall as on 13 October (ending 0300 UTC) averaged districtwise over the Odisha state. Hourly rainfall data of the self recording rain gauge (SRRG) at Gopalpur recorded observations until 1600 UTC after which data is not available due to blowing away of the instrument due to the cyclone. Till 1600 UTC, it recorded maximum hourly rainfall of 17 mm at 1430 h IST. The maximum hourly rainfall (80 mm), directly attributable to the cyclone occurred at Rairangangpur station

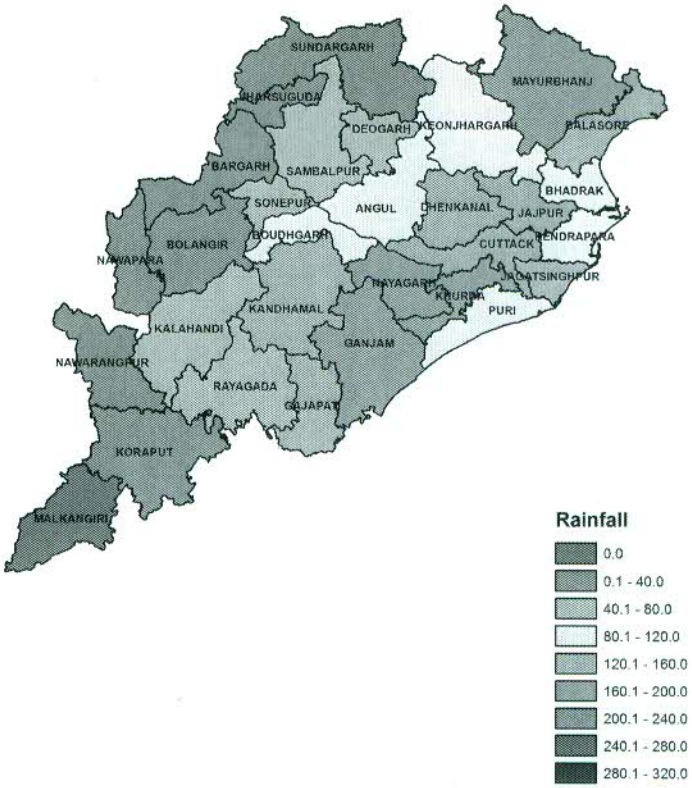


**Fig. 2:** 24-h accumulated, districtwise rainfall (in mm) over Odisha based on rain gauge observations recorded as on 13 October 2013, 0300 UTC.

of Mayurbhanj district in Odisha at 0300 h IST of 13 October (5 h after the landfall). The isohyetal analysis of 24 h accumulated rainfall as on 13 October, 0300 UTC based on automatic weather and rain gauge stations is shown in Fig. 3. Maximum rainfall occurred over northeast sector of the system centre at the time of landfall. Maximum 24 h cumulative rainfall of 38 cm was reported over Banki in Cuttack district of Odisha.

## 2.3 QPE Based on Merged Data Set of Raingauge and Satellite

IMD has also developed a new high spatial resolution ($0.25 \times 0.25°$) daily IMD-NCMRWF merged TRMM TMPA 3B42 Satellite derived rainfall dataset which includes Land and North Indian Oceanic regions (Mitra et al., 2009). An example of this product for TC Phailin is shown in Fig. 4.

The daily Indian precipitation analysis formed from a merge of IMD rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates showed Cyclone Phailin's heaviest rainfall ($\geq$ 800 mm) occurred over open waters of east central Bay of Bengal. The merged data was used to create a map of rainfall generated by Cyclone Phailin as it marched through Bay of

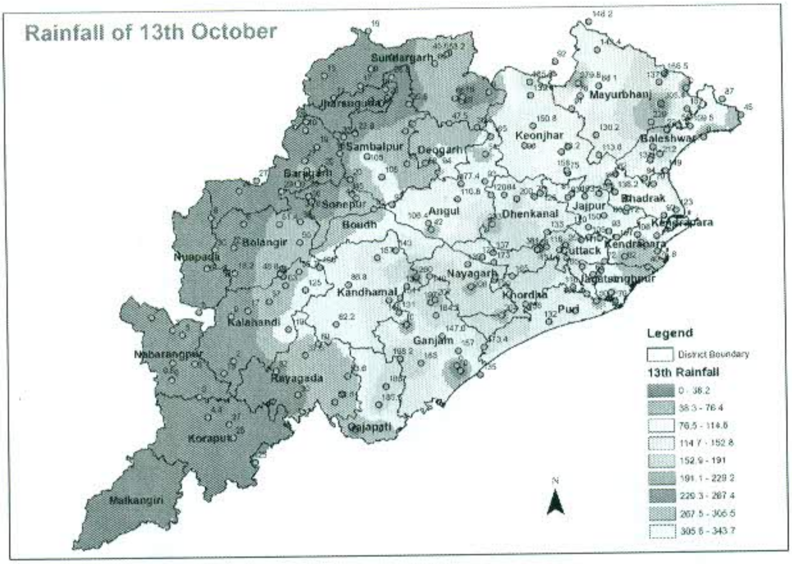


**Fig. 3:** Isohyetal analysis of 24 h accumulated rainfall (in mm) over Odisha from 12 October/ 0300 UTC to 13 October/0300 UTC based on various surface rainfall observations.

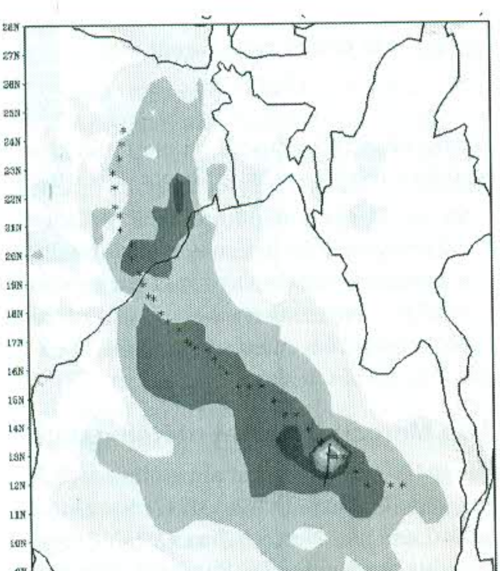


**Fig. 4:** Total accumulated rainfall during the life period of TC Phailin (08 October to 14 October 2013) based on IMD-NCMRWF's satellite (TRMM TMPA 3B42) – gauge merged rainfall (in mm) data. Dots indicate IMD's best track positions of TC Phailin.

Bengal from 8 October to 12 October. Phailin gave maximum cumulative rainfall of around 740 mm in the Southwest sector of the track over east-central Bay of Bengal near Andaman Islands, when it intensified from a deep depression into a cyclonic storm. It was seen that the rainfall was generally confined up to 400 kms south–southwest and 200 km north–northeast of the storm centre till the TC was in the sea. As it approaches coast, the rainfall sector shifts to within 400 km N and NE of the storm centre. The area of heaviest rainfall was within 200–300 kms in the SW sector from the storm centre and within 100 km in the N–NE sector from the storm centre.

## 2.4 Radar Based QPE

Radar Images from Vishakhapatnam are shown in Fig. 5. The eye of the cyclone was beyond 250 km range of the DWR and thus the maximum rainfall zone was not captured. How-so-ever at 13:31 UTC of 12 October a narrow

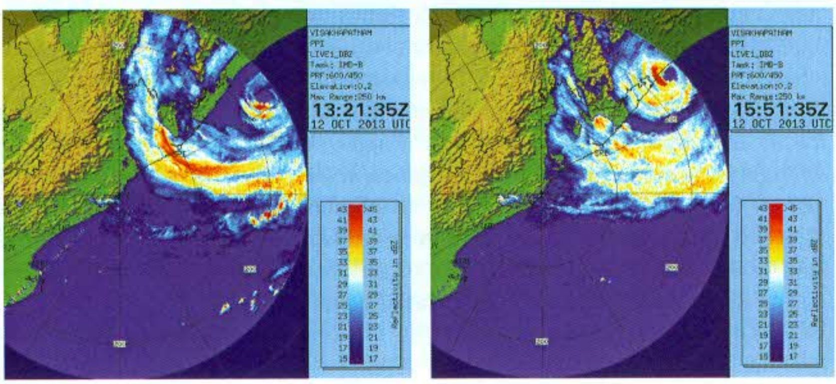


**Fig. 5:** (a) Reflectivity of Cyclone Phailin before and during landfall as seen from nearest Doppler weather Radar at Visakhapatnam.

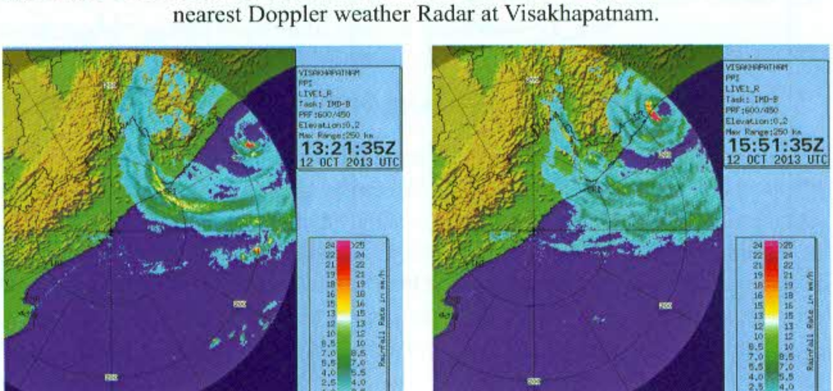


**Fig. 5:** (b) Surface rainfall intensity of Cyclone Phailin before and during landfall as seen from nearest Doppler weather Radar at Vishkhapatnam.

rainband, very well developed in the outer wall cloud region of the Cyclone near Srikakulam station of Vishakhapatnam extended east west across the Andhra Pradesh Coast. The rainband was stationary and separate from the spiral rainfall system of TC and gave 10 cm of rainfall to that district of Andhra Pradesh along with thunder squalls, giving an impression of Cyclone crossing, few hours before the actual landfall (Figs. 5a and 5b). At 1551 UTC, the rainfall intensity was maximum to the Southeast to Southwest sector of the eye. The rainfall intensity had decreased considerably in the southern periphery of the TC by 2000 UTC as the maximum rainfall intensity had shifted north–eastwards.

## 3. Synoptic Environment Related to Rainfall due to Phailin

We analyse the NCEP reanalysis data to investigate the synoptic environment associated with TC Phailin. Figure 6 shows the wind vectors at 850 hPa at 0000 UTC of 12 October and 13 October. As the TC was approaching the coast, the moist Southerly to SE'ly winds with wind speed more than 18 m/s from Bay of Bengal were directing massive moisture flux to coastal Odisha, Bihar and adjoining Gangetic West Bengal. The low level southerly flow brought in massive moisture convergence in the NE sector of the TC, which led to very heavy rains over Bihar Jharkhand and adjoining West Bengal (Eastern India). Figure 7 depicts the vertical velocity (Omega) on 12 October and 13 October. The upward motion of the air is supported by the windward lifting of the southerly flow in association with TC.

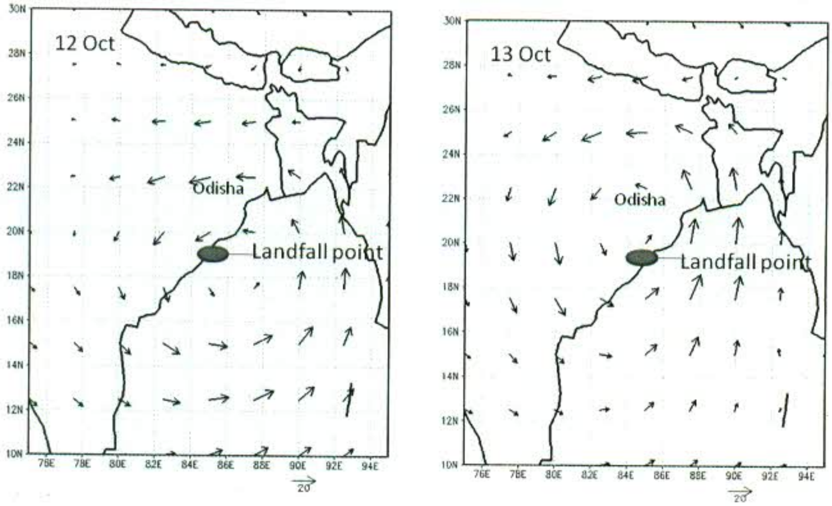


**Fig. 6:** 850 mb mean vector wind (m/s) on 12 October and 13 October 2013.

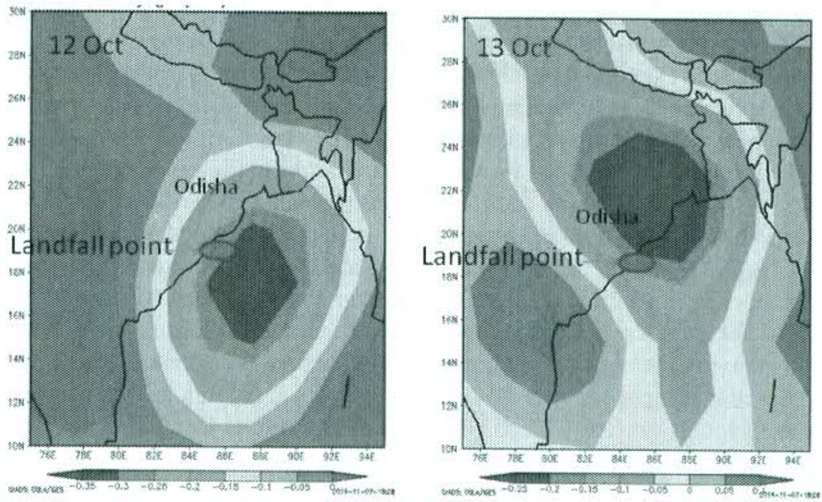


**Fig. 7:** 500 mb mean vertical velocity (Pa/s) on 12 October and 13 October 2013.

It is observed that orography influenced the rainfall distribution and intensity in addition to the factors as discussed above. The east coast of India and the neighbouring countries surrounding the Bay of Bengal have diverse features which include mountainous ranges, plains and deltas. A study by Debnath and Mandal (2012) on the orographic effect on rainfall shows that orographic effect is very much prominent in producing heavy rainfall in association with passage of a TC. In case of Phailin, the rainfall at the time of landfall was also influenced by orography as the interior part of north Odisha is a plateau region with a few hill peaks in Balasore and Mayurbhanj district, which helped in orographic lifting of moist air from north coastal Odisha and hence higher rainfall over north interior Odisha.

## 4. HWRF Model Performance

Recently, under Indo-US joint collaborative program, IMD adopted Hurricane Weather Research and Forecast system (HWRF) model for TC track and intensity forecast for North Indian Ocean (NIO) region for its operational requirements. The basic version of the model HWRF (V3.2+) which was operational at Environmental Monitoring Centre (EMC), National Centre for Environmental Prediction (NCEP), USA was ported in IMD's IBM P-6/575 machine with nested domain of 27 and 9 km horizontal resolution and 42 vertical levels with outer domain covering the area of 80 × 80° and inner domain 6 × 6° with centre of the system adjusted to the centre of the observed cyclonic storm. The outer domain covers most of the North Indian Ocean including the Arabian Sea and Bay of Bengal and the inner domain mainly covering the cyclonic vortex moving along the movement of the system. The model has special features such as vortex initialisation coupled with ocean model to take into account the changes in SST during the model integration and diagnostic software to provide the graphic and text information on track, intensity and rainfall. The operational version of the model is run incorporating vortex re-location and moving nesting procedure on real time twice a day based on 00 and 12 UTC initial conditions to provide 6-h track, intensity and rainfall forecasts valid up to 120 h. The model uses IMD GFS-T574L64 analysis/forecast as initial and boundary conditions.

Figure 8 shows the error in 24 h Rainfall forecast by HWRF from 9 October to 12 October 2013, in comparison with the observed rainfall. The model forecast was on the higher side with an average error of more than 300 mm for the maximum rainfall. Table 1 gives the maximum rainfall observed in comparison with HWRF forecast. The maximum rainfall observed on 9 October was 168 mm as compared to the model forecast of 647 mm (error of 447 mm). The model indicated a lag in track forecast by 12–24 h (average land fall point error was 144 km) and thus a location error of around 100 km for the daily maximum rainfall. The model also could not capture the rainfall in the northeast sector of the TC after crossing. The error was more than 100 mm over Odisha state on 12 October for 24 h forecast based on 0000 UTC of 12 October.

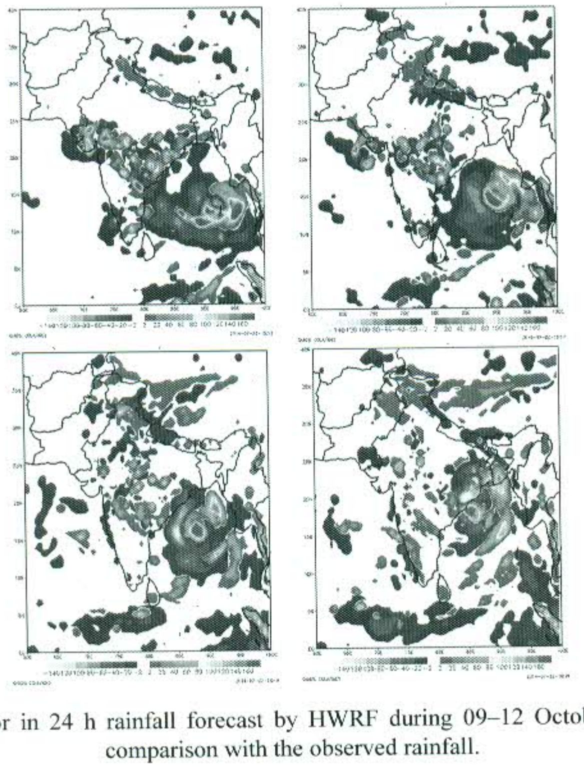

**Fig. 8:** Error in 24 h rainfall forecast by HWRF during 09–12 October 2013, in comparison with the observed rainfall.

**Table 1:** Observed and 24-hr HWRF forecast of maximum rainfall during 09–12 October 2013

| *Date* | *Observed rainfall in mm (recorded on next day at 0830 h)* | *HWRF model rainfall (24 h forecast)* | *Error in mm* |
|---|---|---|---|
| 9 October | 168 | 647 | 479 |
| 10 October | 128 | 508 | 380 |
| 11 October | 175 | 711 | 536 |
| 12 October | 216 | 512 | 296 |

## 5. Assessment of Rice Inundation Area

The heavy rainfall and the storm surge of 2 m along the coast associated with the Phailin, led to flooding in coastal Odisha districts. The water could not recede back due to swollen sea and thus led to damage of standing rice crop. Rice being the major crop during this period in Odisha, an attempt was made to assess the Rice crop inundation due to flood using microwave remote sensing data from Indian SAR (Synthetic Aperture Radar) satellite RISAT-1. This satellite provides SAR data in C band at 25 m resolution (in MRS mode) and 24-day repetivity (Misra et al., 2013).

The SAR, an active sensor, transmits pulses of microwave and detects echo, which carries information about the surface. Due to relatively long wavelengths in microwave, radar signals are capable of penetrating clouds in the atmosphere and are independent of sunlight. These characteristics of SAR are particularly useful in monitoring floods over large areas, while accurate flood mapping using optical imagery are limited, because of cloud cover associated with cyclone. Satellite-derived flood inundation maps in near-real time are invaluable to state or national agencies for disaster monitoring and relief efforts. Precise mapping of the maximum flood extent is also required for detecting deficiency in existing flood control measures and for arbitrating damage claims late. Due to unique signature of water correspondence to other features, flood affected area has been extracted through the detailed analysis of the SAR image. SAR appears to be an ideal sensor for detecting flooding in extensive areas, since the backscattering signature is so distinctive for water, compared to the vegetation.

Rice area of Odisha state was mapped using multi-date (3 date) C-band SAR data of RISAT-1 following a logical classification approach (Chakraborty et al., 1997). This was overlaid by the flood inundation map received from National Remote Sensing Centre, which had been prepared using SAR data. From the Fig. 9, it is clearly seen that coastal areas have maximum rice coverage mainly in Puri, Bhadrak, Kendrapara, Balasore and Jagatsinghpur districts. The maximum rice area inundated due to floods is in Balasore, Bhadrak, Jajpur,

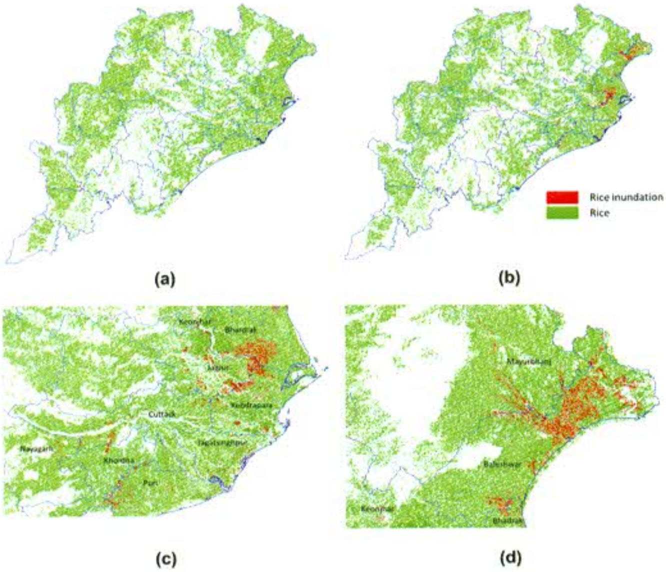


**Fig. 9:** Map showing the (a) rice cropped area, (b) flood inundated rice area of Odisha, and zoomed images showing rice inundation in (c) Bhadrak district, and (d) Balasore and Mayurbhanj districts.

**Table 2:** Districtwise rice area inundated over Odisha in association with passage of TC Phailin

| *District* | *Rice cropped area (ha)* | *Rice inundation area (%)* |
|---|---|---|
| Baleshwar | 160569.1 | 22.3 |
| Bhadrak | 115012.5 | 17.8 |
| Jajpur | 98380.2 | 16.4 |
| Kendrapara | 100548.3 | 15.7 |
| Puri | 100596.8 | 11.2 |
| Jagatsinghpur | 58852.0 | 12.2 |
| Cuttack | 121855.8 | 5.9 |
| Mayurbhanj | 302197.8 | 2.3 |
| Ganjam | 199323.6 | 2.3 |
| Khordha | 96846.0 | 4.2 |
| Keonjhar | 188705.5 | 0.5 |
| Nayagarh | 86855.0 | 1.4 |
| Dhenkanal | 117850.1 | 0.6 |
| Boudh | 65364.4 | 0.02 |

Jagatsinghpur and Kendrapara districts (Fig. 9 and Table 2). Among these the highest rice inundated area was in Balasore followed by Bhadrak district. The total rice inundated area was 132.4 thousand hectares. A field visit was carried out to check accuracy of the inundated area mapping. Out of 18 sites visited, 16 were found to be correctly mapped using remote sensing data. This showed the efficacy of microwave SAR data in rice inundated area mapping.

## 6. Conclusions

Another low pressure area that formed over the Bay of Bengal led to extremely heavy rainfall over Odisha during 21–28 October. Due to previous standing water over the region due to TC, Phailin, the rainfall due to low pressure area caused unprecedented flood over Odisha. As a result the floods in association with low pressure area caused more human death and economic loss than the flood due to TC, Phailin. It also happened in case of cyclone, Nilam (28 October–1 November 2012) over Bay of Bengal. In the case of CS Nilam (28 October–1 November 2012), at the time of landfall, the cloud mass was significantly sheared to the northeast of the system during its dissipation stage leading to heavy rainfall activity over entire Andhra Pradesh and adjoining Odisha. The prediction of heavy rainfall during slow movement or practical stationarity of TC near the coast is a challenge for the forecasters. Further, the forecasters are proved to be over-warning in case of TCs rapidly weakening near the coast and also the TCs moving rapidly just before landfall. Though heavy rainfall prediction is still a challenge, HWRF is a promising model for this purpose (although it showed over estimation of intensity in case of Phailin). Assimilation of DWR data can improve the potential of this model to accurately predict the heavy rainfall during landfall. Microwave remote sensing could be successfully used to map the rice inundated area post-Phailin cyclone.

## Acknowledgement

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## REFERENCES

Abhilash, S, Sahai, A.K, Mohanakumar, K, George, J.P. and Das, S. (2012). Assimilation of Doppler Weather Radar Radial Velocity and Reflectivity Observations in WRF-3DVAR system for Short-Range Forecasting of Convective Storms. *Pure and Applied Geophysics*, **169**, 2047–2070.

Chakraborty, M, Panigrahy, S. and Sharma, S.A. (1997). Discrimination of rice crop grown under different cultural practices using temporal ERS-1 SAR data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **52**, 183–191.

Debnath, G.C. and Mandal, P. (2012). The role of orography in producing extremely on the role of orography in producing extremely heavy rainfall induced by cyclonic storm Aila – A WRF model analysis for disaster management. *In*: WMO Technical Document on Proceedings of Second International Conference on Indian Ocean Tropical Cyclones and Climate Change (IOTCCC-II) held at New Delhi, India during 14–17 Feb, 2012, WWRP 2013–4.

Gray, M.W. (1968). Global view of the origin of tropical disturbances and storms. *Monthly Weather Review*, **96**, 669–700.

Haggag, M. and Yamashita, T. (2009). Environmental simulator application to the analysis of the tropical cyclone Gonu in 2007. *Jl. of Int. Development and Cooperation*, **15**, 1–2, 47–63.

Lee, D.K. and Choi, S.J. (2010). Observation and numerical prediction of torrential rainfall over Korea caused by Typhoon Rusa (2002), *J. Geophys. Res.*, **115**, D12105. doi: 10.1029/2009JD012581.

Minakshi Devi, Kalita, S, Das, S, Goswami, H. and Barbara, A. (2014). Model prediction of cyclonic tracks over Bay of Bengal and resultant precipitation in the north-east region. Geomatics, *Natural Hazards and Risk,* **5:2**, 93–114. doi: 10.1080/19475705.2013.775186.

Mitra, A.K, Bohra, A.K, Rajeevan, M. and Krishnalmurti, T.N. (2009). Daily Indian precipitation analysis formed from a merge of rain-guage data with TRMM TMPA satellite derived rainfall estimates. *Journal of the Meteorological Society of Japan*, **87A**, 265–279.

Misra, T, Rana, S.S, Desai, N.M, Dave, D.B, Jyoti, R, Arora, R.K, Rao, C.V.N, Bakori, B.V, Neelakanthan, R. and Vachchani, J.G. (2013). Aperture Radar payload on-board RISAT-1: Configuration, technology and Performance. *Current Science*, **104**, 446–461.

Osuri, K.K, Mohanty, U.C, Routray, A. and Mohapatra, M. (2012). The impact of satellite-derived wind data assimilation on track, intensity and structure of tropical cyclones over the North Indian Ocean. *International Journal of Remote Sensing*, **33**, 5.

Raju, P.V.S, Potty, J. and Mohanty, U.C. (2012). Prediction of severe tropical cyclones over the Bay of Bengal during 2007–2010 using high-resolution mesoscale model. *Natural Hazards*, **63**, 1361–1374, doi: 10.1007/s11069-011-9918-1.

Routray, A, Mohanty, U.C, Osuri, K.K. and Kiran Prasad, S. (2013). Improvement of monsoon depressions forecast with assimilation of Indian DWR data using WRF-3DVAR analysis system. *Pure and Applied Geophysics*, **170**, 2329–2350. doi: 10.1007/s00024-013-0648-z.

Srivastava, K, Rashmi, B. and Roy Bhowmik, S.K. (2011). Assimilation of Indian Doppler Weather Radar observations for simulation of mesoscale features of a land-falling cyclone. *Natural Hazards*, doi: 10.1007/s11069-011-9835-3.

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and L.S. Rathore (Eds)

# Tropical Cyclone Activity over the North Indian Ocean

This book deals primarily with understanding, monitoring and prediction of Tropical Cyclones (TCs) over the North Indian Ocean (NIO). There is special emphasis on TC genesis, intensification, movement and associated adverse weather like heavy rainfall and gale wind. It highlights current state of research on TCs over the NIO and recent improvements in early warning system due to advances in observational, analytical and numerical weather prediction techniques. The chapters in the book are authored by leading experts from research and operational environments.

This book is relevant to TC forecasters and researchers, managers, policy makers, graduate and undergraduate students. The papers presented in the book intend to stimulate thinking and hence further research in the field of TCs, especially over the NIO region. It provides high quality reference material for all the users for management of hazards due to TCs.

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