M. Mohapatra
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L.S. Rathore *Editors*

Tropical Cyclone Activity over the North Indian Ocean

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Preface

Tropical cyclones (TCs) are one of the most devastating natural disasters. The North Indian Ocean is one of the highly vulnerable regions for TC activity. This may be attributed to various factors including geographical conditions and limitations of observations, prediction systems, understanding of physical processes, early warning systems and disaster management processes, apart from the socio-economic conditions of the region. Understanding the patterns of genesis, intensity and movement of TCs and associated adverse weather like heavy rainfall assumed even more importance in recent years in the scenario of global climate change.

Because of the significance of the TCs to India, the India Meteorological Department (IMD), Ministry of Earth Sciences (MoES), Government of India, organised a National Workshop on Tropical Cyclones during 24–25 July 2014 at New Delhi, in order to shed light on the scientific basis and the complexities inherent in combating hazardous impacts of TCs. The purpose of the workshop was to advance the science of TC monitoring and prediction, particularly for nations surrounding the North Indian Ocean.

Considering the significant findings presented in the workshop by various scientists and the recommendations made in the workshop, it was decided to publish the selected papers presented during the workshop as a book after the peer review of the manuscripts. We requested several scientists who participated in the workshop for their interest in developing a volume dedicated to the science of TCs over the North Indian Ocean region. The response was overwhelming, and these authors have generously contributed to the chapters considered in this volume.

This book is relevant to TC forecasters and researchers, managers, policymakers and graduate and undergraduate students. The papers presented in the book also intend to stimulate thinking and hence further research in the field of TCs, especially over the Indian Ocean region. We have attempted to offer the recent progress on understanding and prediction of tropical cyclogenesis, intensification and movement as well as landfall processes like heavy rainfall based on latest observational and numerical weather prediction (NWP) modelling platforms. Further attempt has been made to include the TC management issues like early warning system, recent high-impact TC events, disaster preparedness, policy decisions, etc. We hope this book will provide high-quality reference materials to all the users as mentioned above and will incite further research and their applications in the management of TCs over the Indian Ocean region.

As editors of this volume, we are highly thankful to all the authors for their efforts and cooperation in bringing out this publication. We are sincerely thankful to all reviewers, viz. Dr. D.R. Pattanaik, Dr. G.C. Debnath, Dr. S. Balachandran, Ms. Suman Goyal, Dr. Kamaljit Ray, Dr. S.D. Kotal, Dr. Geeta Agnihotri, Mr. R.P. Sharma, Dr. B. Geetha and Ms. Monica Sharma of the India Meteorological Department, Dr. Someshwar Das and Dr. R. G. Ashrit of the National Centre for Medium Range Weather Forecasting and Dr. Osuri Krishna of the National Institute of Technology, Rourkela, for their continued efforts in reviewing and adding value to the manuscripts. We are grateful to IMD, MoES and all the members of the Local Organising Committee at New Delhi. We want to place our appreciation in record to the Cyclone Warning Division of the India Meteorological Department for the tireless efforts made for the organisation of the conference and significant contribution in the edition and compilation of the manuscripts and publication of this volume.

New Delhi, India

M. Mohapatra
B.K. Bandyopadhyay
L.S. Rathore

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About the Editors

M. Mohapatra is the Head of Weather Forecasting Services of the India Meteorological Department and WMO-recognised Regional Specialised Meteorological Centre for Tropical Cyclones at IMD, New Delhi. His main research interests include high-impact weather events, especially tropical cyclones. He has 22 years of experience in meteorological services and research and is the author of 60 research papers published in peer-reviewed journals. He has received a number of recognitions including the 25th Biennial Mausam Award and Young Scientist Award of the Ministry of Earth Sciences (MoES), Government of India, for his research contributions in the field of atmospheric sciences.

B.K. Bandyopadhyay got his postgraduate degree in solid state physics in 1976 from the Indian Institute of Technology, Kharagpur. He joined as a Research Scholar the Indian Institute of Tropical Meteorology, Pune, and during the next three years, he was associated with research on microphysical characteristics of clouds. He joined the India Meteorological Department in 1981 and was engaged in operational weather forecasting for the past 30 years which mainly included cyclone and heavy rainfall warning services and allied meteorological research. He has made significant research contributions mainly on tropical cyclones. He has about 40 research publications in the national and international journals.

L.S. Rathore is the Director General of Meteorology, India Meteorological Department, and Permanent Representative of India to the World Meteorological Organization. He is Co-Vice Chairman of the Intergovernmental Board on Climate Services (IBCS) and former Vice President of the Commission for Agricultural Meteorology, WMO, and presently on its management board. He is former President of the Indian Meteorological Society and President of the Association of Agro-meteorologists. He made a significant contribution in setting up an integrated agro-meteorological service in India. He has 35 years of experience in meteorological services and research and has published about 100 research papers and seven books. He is recipient of the Dr. Lakhi Ram Memorial Award, 2011, constituted by the Society for recent development in agriculture. He has been conferred fellowship by the Indian Meteorological Society.

Part I
Tropical Cyclone Impact and Early Warning System

Collaborative Mechanism for Tropical Cyclone Monitoring and Prediction over North Indian Ocean

L.S. Rathore, M. Mohapatra, and B. Geetha

1 Introduction

Tropical Cyclones (TCs) are intense synoptic scale weather systems which originate over warm oceans of the world, develop into massive vortices composed of swirling winds, intense clouds and torrential rains by drawing energy from the ocean. When they move over land, they cause large scale destruction to life and property over the coastal areas of the world. India, with an extensive coastline of about 7500 km is vulnerable to the destructive features associated with landfalling TCs of the North Indian Ocean (NIO) basin comprising of the Bay of Be ngal (BOB) and the Arabian Sea (AS).

Generally, under favourable environmental conditions, a pre-existing low pressure area develops into a cyclonic disturbance (CD) (maximum sustained wind speed (MSW) of 17 knots or more) which intensifies into a TC (MSW: 34 knots or more) or a severe TC (MSW of 48 knots or more) or even a very severe TC (MSW of 64 knots or more). On an average, about 11 CDs develop over the NIO during a year including 9 and 2 over the BOB and AS (Mohapatra et al. 2014). Out of these, about five intensify into TC (4 over BOB and 1 over the AS), 3 into severe TC (2 over the BOB and 1 over the AS) and 1–2 into very severe TC. Low lying coastal belts of West Bengal, Odisha and Andhra Pradesh have borne the brunt of the fury of these very severe TCs (IMD 2002; Mohapatra et al. 2012a; Mohapatra and Sharma 2015). Adverse impact of destructive TCs in the past over Indian coasts emphasized the need for a storm warning service in the country. As an effort towards mitigating the disastrous effects of landfalling TCs, the Government of India appointed a committee in 1865 to formulate a scheme for TC warning and based on the recommendations of the committee, the first storm warning centre in

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India was established at Kolkata in 1865 (Mohapatra et al. 2012b). Subsequently, India Meteorological Department (IMD), the National Weather Service of India was established in 1875 and the important mandate of monitoring and forecasting of TCs over the NIO was vested with it. Since then, IMD is involved in detection, tracking and forecasting the movement and intensity of TCs over the NIO, which has been a highly challenging task during the early years with data sparse sea areas of BOB and AS. Further, the following few peculiarities of the NIO basin added to the challenging task:

1. Though TCs are in general seasonal phenomena, with most tropical ocean basins having maximum frequency of formation during the late summer to early autumn period, TC frequency over the NIO shows bimodal character with primary peak during the post-monsoon season (October to December) followed by the secondary peak during the pre-monsoon season (March to May). During the southwest monsoon season of June to September, intense systems usually do not develop due to northward shift of the convergence zone over the land and high vertical wind shear (Rao 1976).
2. NIO basin is a smaller oceanic basin compared to other vast oceanic basins of the globe and, it's further division into two sub-regions, viz., the BOB and the AS with intervening South Asian land mass adds to its peculiarity.
3. The average life period of a TC over the NIO is only about 3–5 days, in contrast to longer life periods over other oceanic basins, which reduces the forecast lead time for landfall forecast.
4. The unique coastal geometry as well as bathymetry and topography of the BOB further pose greater challenges to TC forecasting.

Despite these constraints, IMD has been striving hard towards reliable early warning services.

In the year 1914, an arrangement was made for receiving voluntary weather observations by wireless directly from ships at sea. Also, weather bulletins were transmitted to the ships by wireless communications since the same year. Thus, an exchange of information between the Indian Meteorological Service and Ships at sea began in 1914, and it continues even to this day. This service, which initially took the form of wireless transmission to individual ships, was soon enlarged into a regular twice-a-day broadcast service. These bulletins were broadcast from coastal radio stations to all ships. Later on NAVTEX stations of shipping authorities of Government of India were used for transmission of coastal weather bulletins (NAVTEX is an international automated direct-printing service for delivery of navigational and meteorological warnings and forecasts, as well as urgent marine safety information to ships). At present, coastal weather bulletins are being transmitted up to 465 km in the sea through NAVTEX stations along east and west coast of India as well as Andaman and Nicobar islands and Lakshadweep islands.

Around 1924–1925, IMD introduced an arrangement of issuing on loan, meteorological instruments to individual Masters of ship, so as to assist them in taking meteorological observations. Later a system of recruitment of ships for voluntary meteorological work known as Voluntary Observing Fleet (VOF) was commenced in 1946 under the auspices of International Meteorological Organisation. About 200 VOFs have been registered with IMD for taking meteorological observations over the BOB and AS region. With the advent of weather satellites in 1960s, lack of observations over the sea region has been addressed and subsequent technological advancements led to improve satellite observational systems with high resolution state-of-the-art instrumentation for microwave observations over the oceanic region.

Recently, there has been a paradigm shift in early warning services of TCs over the NIO due to various initiatives of IMD and the Ministry of Earth Sciences (MoES), Government of India including the modernisation programme of IMD (Mohapatra et al. 2013a). Under this programme, there has been upgradation of observational systems, monitoring, analysis and prediction techniques, generation and dissemination of warning products, capacity building, outreach programmes, liaison with disaster management agencies, etc. Collaboration among various institutes in national and international levels in all these aspects has also helped tremendously in improving the early warning service of TCs over the NIO.

In this paper, specific international and national collaborative efforts undertaken by IMD so far and the improved results achieved in TC monitoring and prediction over NIO are presented. Section 2 deals with current status of TC forecasting in India, Sect. 3 on the collaborative mechanisms involved in TC monitoring, forecasting and warning dissemination, Sect. 4 discusses conclusions and future scope.

2 Current Status of TC Forecasting in India

2.1 Early Warning System in TC Forecasting

TC forecasting basically deals with prediction of genesis, location/track and intensity of the TC during the next few days. Also it aims at predicting associated adverse weather like heavy rain, gale wind, high waves, storm surge and coastal inundation. The early warning component of TC disaster management includes skill in monitoring and prediction of TC, effective warning products generation and dissemination, coordination with emergency response units and the public perception about the credibility of the official predictions and warnings. IMD's early warning system is shown schematically in Fig. 1. It is important to continuously upgrade all the components of early warning based on latest technology for effective management of TCs. In this regard, it may be mentioned that, as a part of its modernisation programme, IMD has embarked upon replacement of the existing cyclone detection radars (CDRs) along the coastline by the state-of-the-art Doppler Weather Radar (DWRs) and is also constantly upgrading Numerical Weather Prediction (NWP) capabilities.

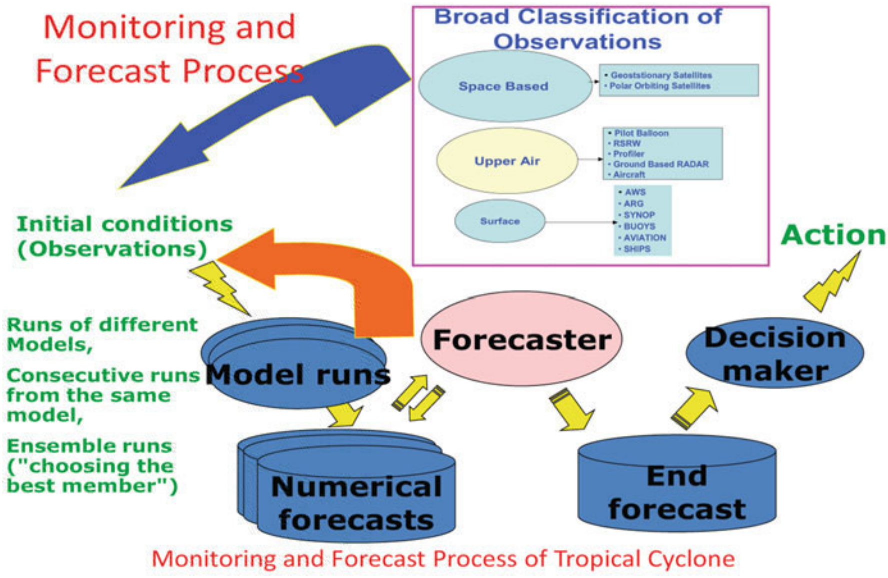


Fig. 1 Monitoring and forecasting process of tropical cyclone (Mohapatra et al. 2013a)

2.2 TC Analytical Procedure

IMD's TC analysis procedure is detailed in Standard Operating Procedure Manual (IMD 2013). The TC analysis, prediction and decision-making process are made by blending scientifically based conceptual models, dynamical and statistical models, meteorological datasets, technology and expertise. For this purpose, a decision support system (DSS) in a digital environment is used to plot and analyse different weather parameters, satellite, Radar and NWP model products.

In this hybrid system, synoptic method could be overlaid on NWP models supported by modern graphical and Geographical Interface System (GIS) applications to produce high quality analyses and forecast products, prepare past and forecast tracks upto 120 h, depict uncertainty in track forecast and to forecast wind in different sectors of TC. Also, additional help is taken from websites to collect and analyse radar data and products from IMD's radar network and neighbouring countries, satellite imageries and products from IMD and international centres and data, analysis and forecast products from various national and international centres. The automation of the process has increased the efficiency of system, visibility of IMD and utility of warning products leading to minimum loss of life (Mohapatra et al. 2013a).

2.3 TC Forecasting

Under the collaborative efforts of the World Meteorological Organisation and the United Nations' Economic and Social Commission for Asia and Pacific (WMO-ESCAP), IMD is also serving as Regional Specialised Meteorological Centre for Tropical Cyclones (RSMC, New Delhi) and extends TC forecasts to the WMO-ESCAP panel member countries in the NIO region. RSMC, New Delhi keeps a continuous watch over the BOB and the AS for monitoring and prediction of cyclogenesis. It issues Tropical Weather Outlook for the NIO region at 0600 UTC every day (based on observations at 0300 UTC of that day) for the benefit of the member countries. The outlook describes the current weather situation over BOB and AS and also provides probability of cyclogenesis during next 72 h based on NWP, synoptic, statistical and dynamical–statistical inputs. This probabilistic forecast is issued in terms of nil, low, fair, moderate and high probability corresponding to 0 %, 1–25 %, 26–50 %, 51–75 % and 76–100 % probability of occurrence.

Although, the synoptic, statistical and satellite/radar guidances help in short range forecast (upto 12/24 h), the NWP guidance is mainly used for 24–120 h track and intensity forecasts. Consensus forecasts that gather all or part of the numerical forecast, synoptic and statistical guidance are utilised to issue official forecast. IMD introduced the objective cyclone track forecast valid for next 72 h in 2009 and up to 120 h in 2013. When the low pressure system (LPS) is a depression (17–27 knot), the track forecast is issued subjectively indicating the expected direction of movement and also the probable area of landfall (if any). This forecast is issued five times a day based on 00, 03, 06, 12 and 18 UTC observations. From the stage of deep depression (28–33 knots), in case it is anticipated to intensify into a TC (34 knots or more), IMD issues TC track and intensity forecasts valid upto 120 h. This forecast is also issued five times a day based on 00, 03, 06, 12 and 18 UTC observations. When the LPS attains the intensity of a TC, TC forecast is issued eight times a day at the interval of 3 h, i.e., based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC observations. The forecasts are issued about 3 h after the above mentioned observation time. The *cone of uncertainty (COU)* in the forecast track of the centre of a TC and the likely error in the forecast track based on predictive skill of past years has been introduced with effect from the TC, 'WARD' during December, 2009 (Mohapatra et al. 2012c). It is helpful to the decision makers as it indicates the standard forecast errors in the forecast. The observed track lies within the forecast COU in about 60–70 % of the cases like other Ocean basins. A typical track forecast along with the COU issued in respect of TC Phailin (08–-14 October 2013) is presented in Fig. 2. Considering the recent improvements in track forecast, the radii of circles used to construct cone of uncertainty has been reduced since 2014. The radii used for the purpose are 20, 35, 55, 85, 110, 150, 185, 220, 250, 280, 305, 335 & 360 km for forecast lead times of 00, 06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 h.

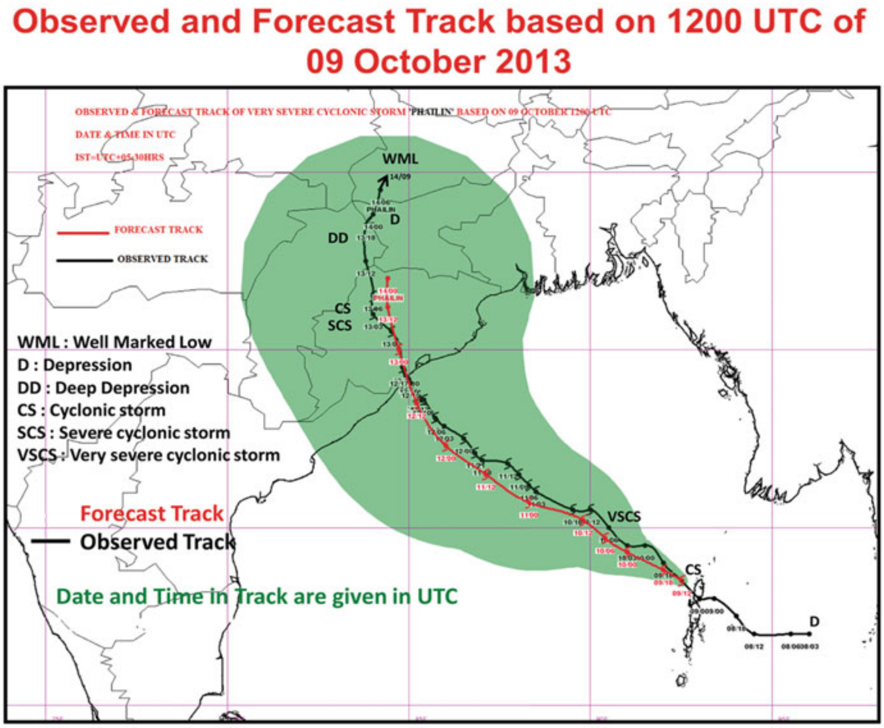


Fig. 2 An example of forecast track along with cone of uncertainty issued on 9th October 2013 in respect of VSCS Phailin (8–14 Oct 2013)

For intensity forecasting, in the satellite method, region of maximum reflectivity and mesoscale vortices are assumed to be associated with higher wind. In radar technique, the direct wind observations are available through radial velocity measurements. The wind estimates from satellite and radar and other observations are extrapolated to forecast the wind. MSW is also available from other sources like Scatterometry wind from Satellite, Buoy, Ships etc., apart from estimate by Dvorak technique. Though the wind forecasts by the NWP models are underestimated, the initial condition of wind from the model can be corrected based on actual observations and accordingly model forecast wind are modified. A statistical–dynamical model (Kotal et al. 2014) has been implemented for real time forecasting of 12 h intensity up to 72 h. For the real-time forecasting, model parameters are derived based on the forecast fields of IMD GFS model.

The cyclone wind radii representing the maximum radial extent of winds reaching 34 knots (kts), 50 (kts) and 64 (kts) in each quadrant (NW, NE, SE and SW) of TC are generated as per requirement of ships. The initial estimation and forecast of the wind radii of TC is rather subjective and strongly dependent on the data availability, climatology and analysis methods. The subjectivity and reliance on climatology is amplified in the absence of aircraft observations. However,

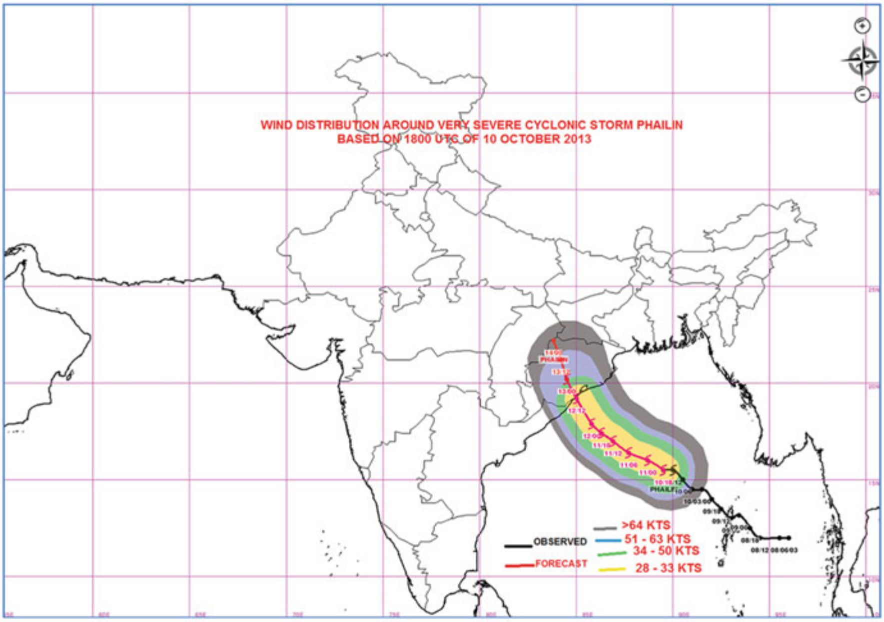


Fig. 3 An example of wind radii forecast issued in respect of VSCS Phailin (08–14 October 2013) based on 1800 UTC of 10th October 2013

recently with the advent of easily accessible remotely sensed surface and near surface winds (e.g., Ocean Sat., Special Sensor Microwave Imager (SSMI), low level atmospheric motion vectors and Advanced Microwave Sounder Unit (AMSU) retrieval methods), multi satellite surface winds, Doppler Weather Radar (DWR), coastal wind observations and advances in real time data analysis capabilities, IMD introduced TC wind radii monitoring and prediction product in October 2010 valid upto 72 h (Mohapatra and Sharma 2015). It has been extended to 120 h in 2013. The consensus forecast issued by IMD is based on numerical forecast from NWP models and synoptic & statistical guidance (IMD 2013). An example of wind radii forecast issued by IMD in respect of TC Phailin (08–14 October 2013) is shown in Fig. 3.

2.3.1 Adverse Weather Forecasting

A TC causes three types of adverse weather, viz., heavy rain, gale wind and storm surge during its landfall. Forecasting procedures for these adverse weather phenomena (IMD 2013) are presented herewith briefly.

The forecast/warning of heavy rainfall includes (i) time of commencement, (ii) duration, (iii) area of occurrence and (iv) intensity of heavy rainfall. The methods for prediction of heavy rainfall include (i) synoptic, (ii) climatological,

(iii) satellite, (iv) Radar and (v) NWP techniques. Although NWP models provide prediction of rainfall for different lead period; satellite and radar provide quantitative precipitation estimates during past 3/12/24 h. The intensity and spatial distribution of rainfall estimated by satellite and radar are extrapolated to issue forecast. In synoptic and climatology method, synoptic climatology of rainfall intensity and spatial distribution are used. The final forecast is the consensus arrived from various methods as mentioned above.

The forecast of gale wind along the coast for landfalling TCs includes (i) time of commencement, (ii) duration, (iii) area of occurrence and (iv) magnitude of gale wind. The methods for prediction of gale wind include (i) synoptic, (ii) climatological, (iii) satellite, (iv) radar, (v) NWP and (vi) dynamical statistical techniques.

Storm surge is the rise of sea water above the astronomical tide due to TC. The storm surge depends on pressure drop at centre, radius of maximum wind, point of landfall, and interaction with sea waves, astronomical tide, rainfall, river run off, bathymetry, coastal geometry, etc. The forecast of storm surge includes (i) time of commencement, (ii) duration, (iii) area of occurrence and (iv) magnitude of storm surge. The methods for prediction of storm surge and coastal inundation include (i) IMD Nomogram (Ghosh 1977), (ii) IIT Delhi Storm surge model (Dube et al. 2009) and (iii) Indian National Centre for Ocean Information Services (INCOIS), Hyderabad Storm surge and coastal inundation model (Rao et al. 2012).

2.4 TC Forecast Accuracy

Mohapatra et al. (2013b) evaluated the TC track forecast issued by IMD during 2003–2011 (9 years) by calculating the Direct Position Error (DPE) and skill in track forecast. Figure 4 shows the 24-, 48- and 72-h TC track forecast errors and skill of IMD verified against the IMD best-track dataset for TCs over the NIO during 2003–2013. The average DPE is about 124, 202 and 268 km and skill is about 36 %, 53 % and 62 %, respectively for 24, 48 and 72 h forecasts over the NIO as a whole during 2009–2013. It indicates that the error has decreased and skill has increased during the recent years. There is also similar improvement in landfall forecast of TCs (Mohapatra and Sharma 2015).

IMD's official TC intensity forecast error and skill during 2005–2013 are presented in Fig. 5. Similar to track forecast skill, TC intensity forecast skill has also improved over the years (Mohapatra et al. 2013c).

Track predictions of very severe cyclonic storm (VSCS), Phailin and Madi over BOB during 2013 are very good examples of the success stories (RSMC, New Delhi 2014). The correct track forecast, especially landfall point and time with 4 days lead period in the former case led to large scale evacuation and hence minimum loss of human lives (only 21 people died). Similarly, the correct track forecast in case of VSCS Madi which had the rarest of rare tracks led to no evacuation of coastal population leading to saving of economy.

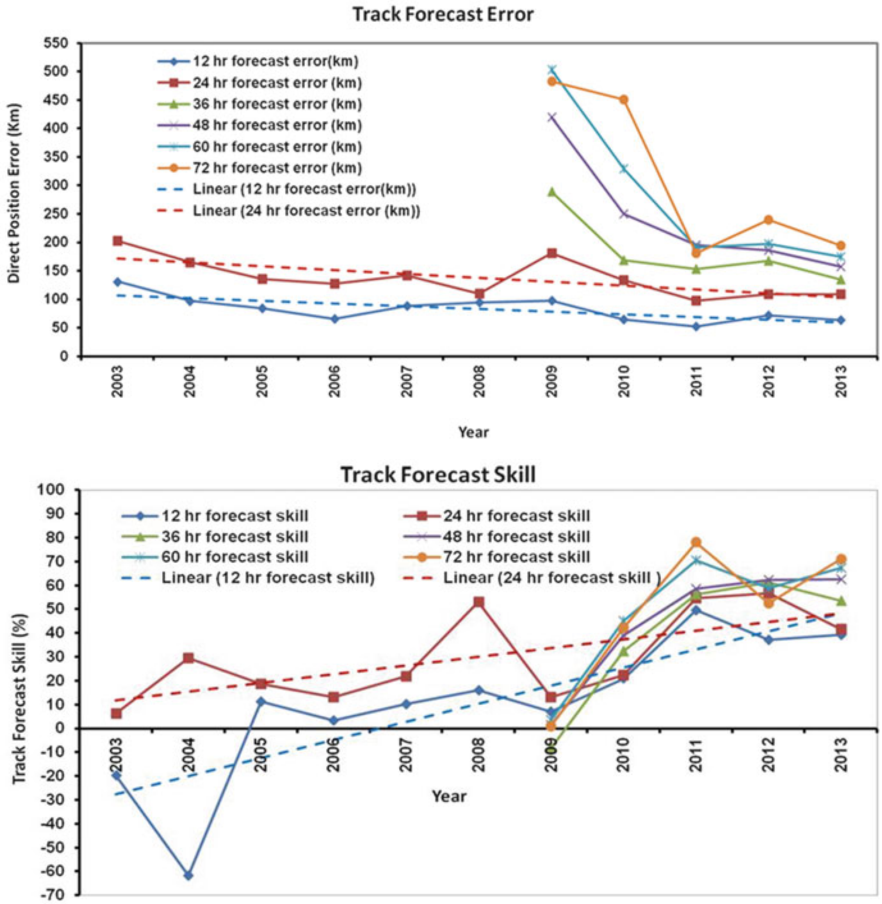


Fig. 4 IMD's Official track forecast error and skill during 2003–2013 over the North Indian Ocean

It should be mentioned here that these improvements in TC forecasting can be attributed to many factors including modernisation programme of IMD and Ministry of Earth Sciences (MoES), Government of India. Collaboration with a host of national and international agencies involved in the highly challenging task of early warning process also contributed significantly to this success. Generation of high resolution data and products, access to numerical model products, real time data exchange and early dissemination of warnings are integral parts of the collaborative mechanism. In the following section, the major collaborations are discussed to bring out the roles of the collaborating agencies towards the progress achieved in TC forecasting and warning.

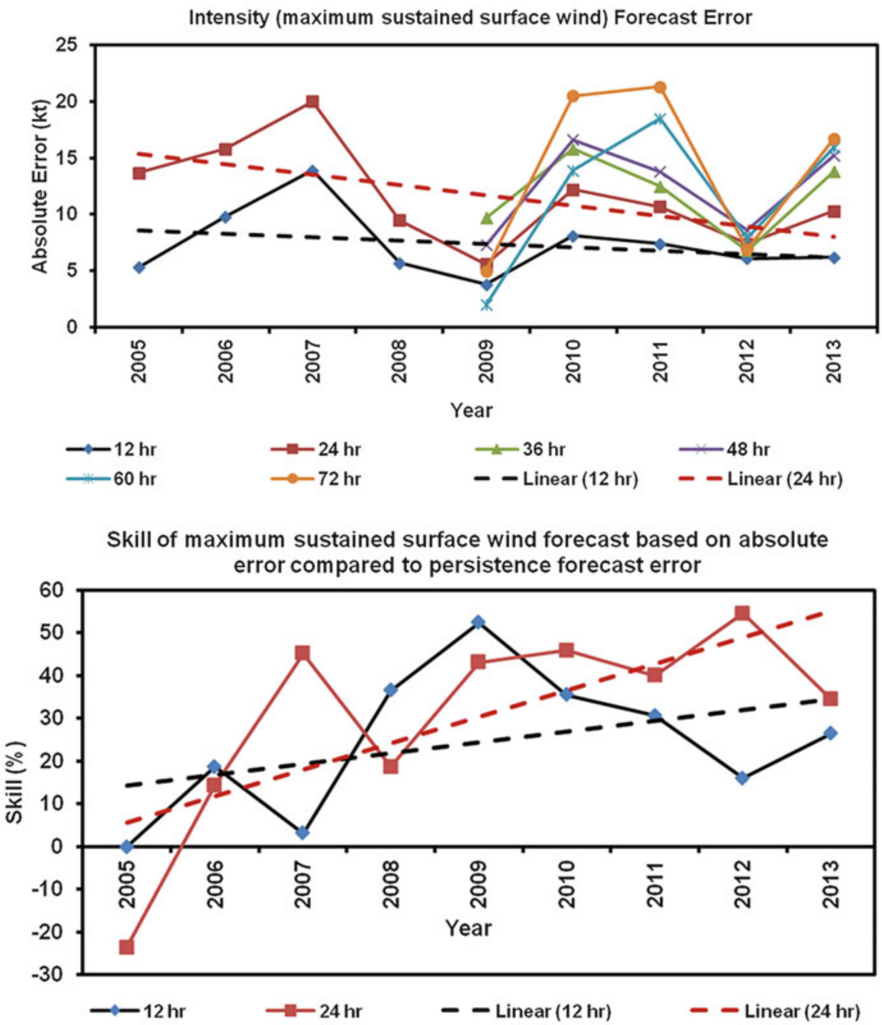


Fig. 5 IMD's Official TC intensity forecast error and skill during 2005–2013 over the North Indian Ocean

3 International and National Collaborations in Early Warning Mechanism

Commissioning of state-of-the-art observing systems throughout the country with their networking and integration, utilising them in high resolution numerical models in high performance computing facility, their visualisation, archival and dissemination to the user community in a skilful manner have resulted from several initiatives undertaken to augment the existing observational set up, telecommunication networks, analytical tools and generation of warning products as detailed below.

3.1 Observational System

Oceanic observations are vital for monitoring and prediction of TC. The NIO being a data sparse region, TC monitoring mainly depends on satellite based observations. International collaborations for satellite-based TC monitoring started with the launch of TIROS (Television and Infra Red Observational Satellite) series of polar orbiting weather satellites by the USA in 1960 (Koteswaram 1971a) when the first Automatic Picture Transmission (APT) facility, donated by the USA, was installed at Mumbai in December 1963 and real time satellite imageries were received for TC analysis and forecasting (Mohapatra et al. 2012b). Subsequently, launch of INSAT series of satellites by Indian Space Research Organisation (ISRO) since 1982 with on-board meteorological pay loads enabled availability of satellite products more frequently for continuous monitoring of TCs over the NIO. High-resolution cyclone-specific satellite imageries and products are generated using meteorological payloads on board INSAT-3A/3D and Kalpana geostationary satellites in collaboration with ISRO. Under international understanding, US National Oceanic & Atmospheric Administration (US-NOAA), Moderate Resolution Imaging Spectro-radiometer (MODIS) and EUROPEAN-Meteorological Operational (METOP) satellite data are received at IMD's three ground receiving and processing stations and the imageries and products generated are uploaded in the web and made available to the TC forecaster on real time. A sample product (NOAA-OceanSAT-2 wind observation) is presented in Fig. 6. In an Memorandum of Understanding (MoU) between the Ministry of Earth Sciences (MoES), India and NOAA, USA signed in 2008, both countries have agreed upon an open data policy to share past and current *in situ* and satellite data related to earth observations and earth sciences (www.moes.gov.in).

US National Aeronautics and Space Administration (NASA)–Japan collaborative project for rainfall measurement, viz., Tropical Rainfall Measuring Mission (TRMM) generates rain rate estimates based on sensors on-board TRMM satellites. Using this data, under IMD–National Centre for Medium Range Weather Prediction (NCMRWF) collaboration, gauge merged rainfall data at $0.5 \times 0.5°$ resolution is generated daily (Mitra et al. 2009). This product is being used for validating NWP-based TC rainfall forecasts.

Satellite-based products generated by Co-operative Institute of Meteorological Satellite Studies (CIMSS), University of Wisconsin, USA and TC specific products of Co-operative Institute for Research in Atmosphere (CIRA) at the Colorado State University, USA, US-NOAA-Atlantic Oceanographic and Meteorological Laboratory's (AOML) oceanographic products and Madden Julian Oscillation (MJO) forecasts from various global NWP centres are regularly used by TC forecasters for analysis.

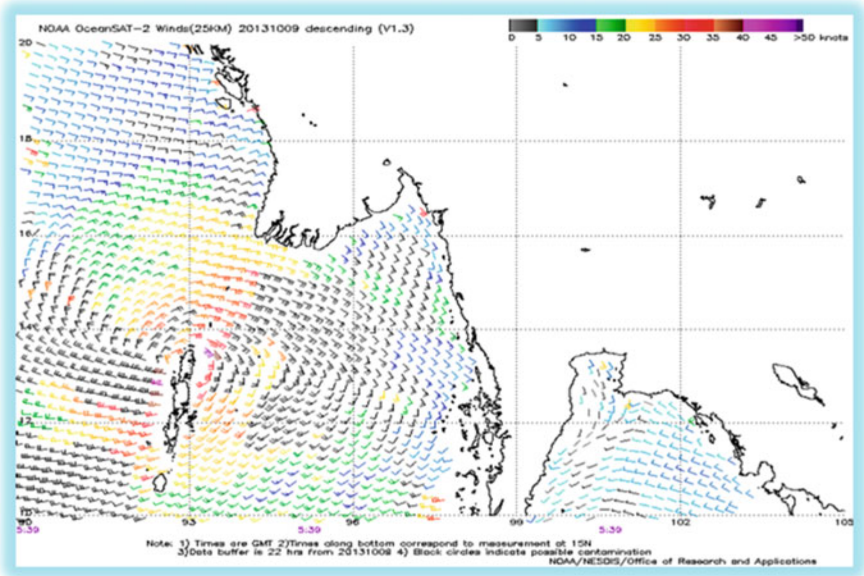


Fig. 6 A sample of NOAA-OceanSAT-2 wind observation

Under the Ocean Observation Network (OON) programme of MoES, the Ocean Observation Systems (OOS) of National Institute of Ocean Technology (NIOT), develops and maintains data buoy observational network (Fig. 7a) since 1996 which provide very vital data of surface pressure, wind, sea surface temperature and wave height over the data sparse sea region. Surface wind and mean sea level pressure data over the BOB on 27 December 2011/0300 UTC in association with the VSCS Thane (25–31 December 2011) is shown in Fig. 7b. INCOIS provides information on wave heights. These observations are crucial to study the ocean parameters as well as to validate remotely sensed observations from satellite, NWP-based products and issue of sea area and coastal weather bulletins (RSMC, New Delhi 2014). Figure 7c presents sea surface temperature and salinity variations observed from the data buoy observation during TC Phailin (08–14 October 2013).

With the introduction of high-resolution satellite-based observations and data buoy network, the services of VOF have reduced considerably during the recent years.

The coastal observations are very important to the structure characteristics of TC as well as to determine the landfall characteristics. The TCs crossing the border areas of two countries can be properly monitored only with the observations from the neighbouring countries. It may be mentioned here that observations of DWR Kolkata contribute significantly in tracking TCs moving towards Bangladesh coast. For example, special hourly observations taken at CDR Paradip and subsequent round-the-clock observations taken at DWR Kolkata provided valuable inputs in monitoring and prediction of TC Rashmi (25–27 October 2008) that crossed

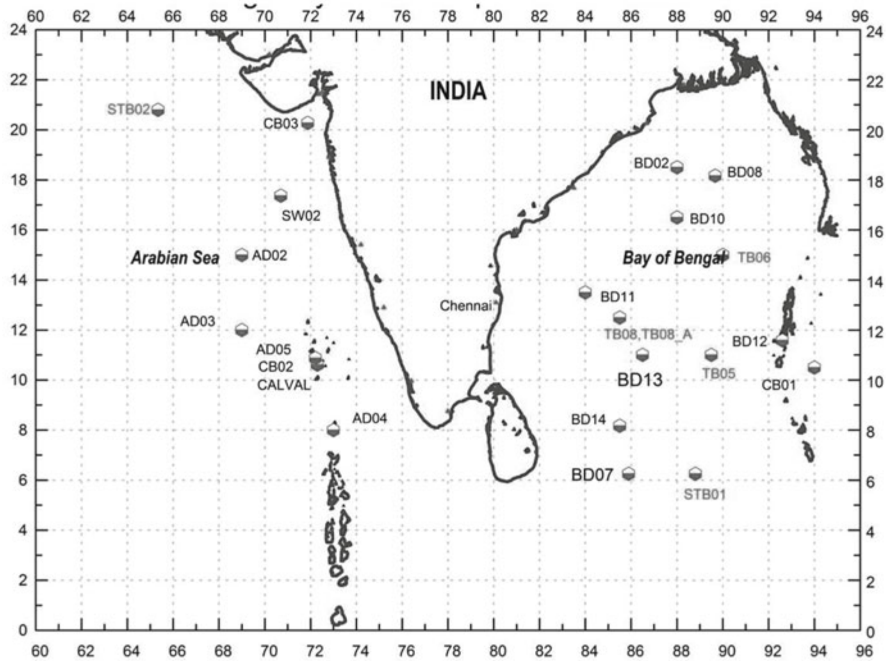


Fig. 7a NIOT's buoy network

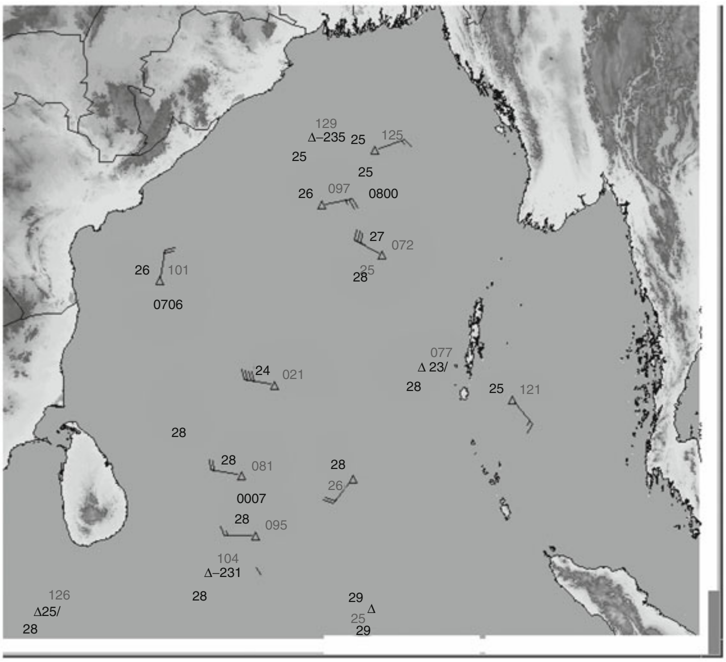
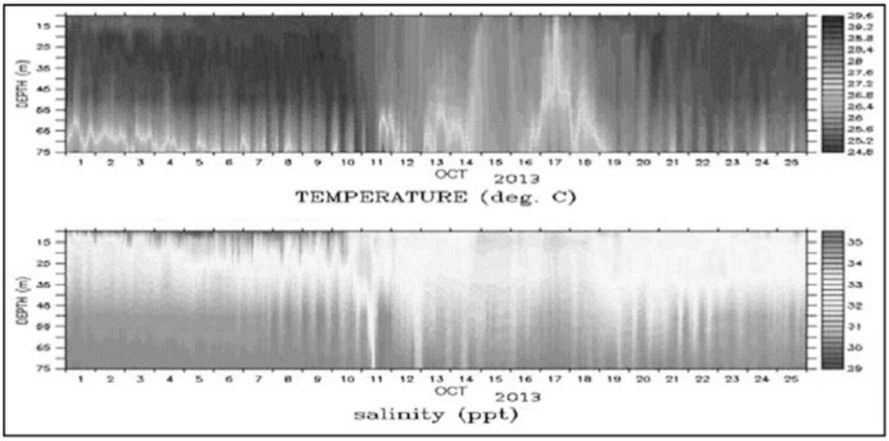


Fig. 7b Plots of ocean buoy observations on 27th December 2011/0300 UTC in association with the VSCS Thane (25–31 Dec 2011) over the BOB



Temperature and Salinity variations during Phailin Cyclone at BD10_16.5N/88E in October 2013

Fig. 7c Temperature and salinity variation studies in respect of TC Phailin (08–14 Oct, 2013) based on buoy data (Source: National Institute of Technology (NIOT), Chennai, India)

Bangladesh coast. In this context, the collaboration achieved through WMO and WMO/ESCAP panel on TCs are noteworthy. A dense network of 675 Automatic Weather Stations (AWS) and 1300 Automatic Raingauge Stations (ARG) were planned and implemented in a phased manner.

The then existing CDRs installed along the coastal region in the 1970s are being replaced by DWRs. DWRs at Chennai, Kolkata, Visakhapatnam and Machilipatnam are of German-make. However, it should be mentioned here that under IMD–ISRO collaboration, an indigenous DWR is functioning at Sriharikota since 2004. Recently, India's BEL has installed at Mumbai and Bhuj.

3.2 Data Exchange and Automation

Observational data would transform into meaningful analysis and forecast products only when they are made available to the forecasting and modelling communities in real time. Hence, global data exchange is one of the key objectives of the WMO and Global Telecommunication System (GTS) is one of its chief components for near real time data exchange. World Weather Watch Program (WWWP) is an important project of WMO wherein GTS has long been its key elements. In accordance with the WMO's objectives, IMD set up directorate of telecommunications in the year 1969 to cater to the needs of national meteorological service and to strengthen the meteorological telecommunication in India. Since its inception, IMD maintains an extensive telecommunication network for speedy transmission of meteorological information over the globe. IMD serves as a Regional Telecommunication Hub (RTH) of the WMO. Initially, it was a manual or semi-automatic operational frame work requiring a large number of personnel to carry out the day-to-day operational activities. However, gradually, the communication system, techniques and protocols have undergone significant changes on adopting world-wide application of TCP/IP based services. In its present form, the existing RTH Automatic Message Switching System 'TRANSMET' is a state-of-the-art technology system which has the ability to retrieve message from e-mail and submit that message to GTS in addition to various other facilities. Under the automation project, manual decoding, plotting and analysis of limited volume of surface and upper air observations have been replaced by automatic decoding and analysis. Use of High Performance Computing System (HPCS) for running NWP models has shifted the focus from telecommunications to Information Systems and Services in IMD since 2009. The WMO Information System (WIS) is a project designed to fill gaps in the existing regional and global connectivity. Under this project, in addition to GTS, another component, DAR (Discovery, Access and Retrieval) is also integrated into all WMO programmes. With the upgradation of IMD's telecom network into Information Systems and Services, IMD serves as a Global Information System Centre (GISC) under the WIS project.

3.3 NWP Guidance

The seed for NWP was sown in India in late fifties (Das and Bose 1958), but, its further evolution commenced only in 1970s. An objective technique for TC track prediction was developed in India for the first time based on climatology and persistence (CLIPER) by Sikka and Suryanarayana (1972). Subsequently, a few analogue and simple dynamical models were developed by Indian scientists. A detailed review is available in Sikka (2006).

IMD acquired a mainframe third generation computer system IBM 360/44 with 256 KB memory in 1973 and several versions of the primitive equation model were developed in IMD and the Institute of Tropical Meteorology, Pune, presently known as Indian Institute of Tropical Meteorology (IITM) as a collaborative activity (Datta et al. 2008). Forecasting the movement of TCs over the Indian seas using a non-divergent barotropic model was attempted by Sikka (1975) from IITM. Around the same time, numerical prediction of storm surge associated with TCs over BOB was also attempted under joint efforts of IMD and Indian Institute of Technology (IIT) New Delhi (Das 1972, 1994; Das et al. 1974). In the year 1979, Centre for Atmospheric Sciences (CAS) was set up at IIT New Delhi with IMD as a co-sponsor. Since then, CAS, IIT New Delhi has been actively involved in developing improved models for storm surge prediction in the Indian region under collaboration with Florida State University (FSU), USA (Dube et al. 1994, 2009).

Under INDO-US Science and Technology Initiative in 1985, the then latest NWP models and data assimilation systems capable of ingesting all synoptic and asynoptic data including remote sensing data received on GTS in large numbers, developed in National Meteorological Centre, Washington, FSU and other research institutions of USA were implemented in IMD (Datta et al. 2008). Further, development of a Limited Area Model (LAM) for the Indian region was started at IIT-Delhi in collaboration with the Naval Research Laboratory (NRL), North Carolina State University, USA and the Indian Air Force in mid-eighties (Mohanty et al. 1989; Tyagi et al. 1994). In the mean time, a Centre for Atmospheric and Oceanic Sciences (CAOS) was established at Indian Institute of Science (IISc), Bangalore which was another major development for studies on atmosphere and ocean models in India (Das 2008).

A major boost to NWP in India occurred with the establishment of NCMRWF in 1988 and subsequent procurement of first supercomputer CRAY-XMP-14. Initially, a R40 model of NCEP, USA was installed at NCMRWF with the help of Centre for Ocean Land and Atmosphere (COLA), USA. Simultaneously, the global model T79 of ECMWF was tested for its suitability over the Indian region. However, a major problem of assimilating data from the GTS into the model was faced. Subsequently, an agreement was signed with National Centre for Environmental Prediction (NCEP), USA to obtain its Global Forecasting System (GFS) including T80 model, data decoder and a Global Data Assimilation System (GDAS) based on Spectral Statistical Interpolation (SSI) scheme based on which routine 3-day forecasts were commenced at NCMRWF from June 1994 (Das 2008).

Around the same time, a semi-implicit semi-Lagrangian multi layer primitive equation Limited Area Model (LAM) adopted from Florida State University (Krishnamurti et al. 1990) was installed and used in IMD for TC track prediction up to 48 h since 1994 after installing CYBER-2000U computer system (Tyagi et al. 2008). Here, a synthetic analytical vortex based on satellite observations was used to define the storm circulation. Subsequently, a specialized Tropical Cyclone model known as Quasi-Lagrangian Model (QLM) was adopted for track and intensity prediction of TCs upto 72 h from 1998 after Mathur (1991).

With the advancements in internet technology and USA's open data access policy, the NCEP–GFS model products were made available in the public domain in the early twenty-first century. The model has evolved from the earlier NCEP models of 1980s and 1990s. In its present version, the GFS model (T574) is a spectral model with an approximate horizontal resolution of 13 km for the first 10 days and 27 km from 240 to 384 h (16 days). In the vertical, the model is divided into 64 layers and temporally, it produces forecast output every hour for the first 12 h, 3 hourly through day 10 and 12 hourly through day 16.

Under the modernisation programme of IMD, a High Performance Computing System (HPCS) was commissioned in December 2009 and US-NCEP based Global Forecast System (GFS T574/L64) was made operational using Global Statistical Interpolation (GSI) scheme as the global data assimilation method. The model is run twice a day (based on 00 and 12 UTC initial conditions). NWP based objective forecast products are prepared to support cyclone warning service. Initially, forecasts were generated up to 72-h lead time during the period 2009–2012 and subsequently since 2013, 120-h forecast guidance is provided to operational forecasters. In addition to this, the regional Advanced Weather Research and Forecasting (WRF) Model with 3 dimensional variational (3D VAR) data assimilation is being operated twice a day, at 27, 9, and 3 km horizontal resolutions for the forecast up to 3 days using initial and boundary conditions from the IMD GFS-T574/L64 (horizontal resolution over the tropics ~22 km).

Further, Hurricane WRF (HWRF) (ver 3.2+) is also installed in IMD and commissioned since 2013 in collaboration with NCEP, USA for tracking TCs over the NIO. The model which was run initially at 27×9 km resolution is now being run at 9×3 km resolution over a domain of $80 \times 80°$ with a moving nest of $6 \times 6°$ centred at the vortex centre. 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, tracker and diagnostic software to provide the graphic and text information on track and intensity prediction for real-time operational requirement.

Using the NCEP based IMD-GFS model products, a dynamical–statistical genesis potential parameter (GPP), for the NIO basin has been developed (Kotal and Bhattacharya 2013) as the product of four variables, viz., vorticity at lower levels, middle tropospheric relative humidity, middle tropospheric instability, and the vertical wind shear. The GPP is used for predicting cyclogenesis at their early development stages. The grid point analysis and forecast of the genesis parameter up to 7 days are generated on real time for operational forecasting guidance.

NCMRWF's GFS (NGFS) is also based on NCEP-GFS and is presently run at a horizontal resolution of about 23 km (T574) with 64 vertical levels. The NGFS replaces the model vortex with a synthetic vortex developed using the TC vital data provided by IMD (based on satellite and synoptic data) and generates forecast guidance on real time. Under a joint collaboration with United Kingdom Meteorological Office (UKMO) signed in 2008, UKMO's Unified Model (MO) global forecast suite (version 7.4) was implemented in NCMRWF in April 2010 with 4D-VAR data assimilation scheme (www.ncmrwf.gov.in/). The model run (NCUM) generates 168-h deterministic forecasts based on 00 UTC analysis every day and the products are available in the web for the TC forecaster. Presently, the model is upgraded to version 7.6 and is run at resolution T512L70 since June 2011. Further, probabilistic forecasting technique based on NCEP-Global Ensemble Forecast System (GEFS), has also been introduced at NCMRWF (NGEFS). The NGEFS runs at resolution T574L64 and generates forecasts up to 10 days.

In addition, NWP guidance from many global model products such as US-NCEP, European Centre for Medium Range Weather Forecast (ECMWF), Japan Meteorological Agency (JMA) and the cloud-resolving version of National Oceanic and Atmospheric Administration (NOAA)-HWRF are now readily available to forecasters. Aside from the individual model guidances, IMD has also implemented Multi Model Ensemble (MME) prediction using five global models – IMD GFS T574, ECMWF T799, JMA T899, UKMO and NCEP GFS.

Under the joint project of World Weather Research Program (WWRP) and Tropical Cyclone Program (TCP) of the WMO-ESCAP, a guidance of tropical cyclone forecasts based on the THORPEX (THe Observing system Research and Predictability EXperiment, a World Weather Research Program under WMO) Interactive Grand Global Ensemble (TIGGE) in near real-time for the WMO/ESCAP and Typhoon Committee Members and forecasters participating in the Severe Weather Forecasting Demonstration Project (SWFDP) in Southeast Asia was implemented in IMD in 2012 with the support of JMA (http://tparc.mri-jma.go.jp/cyclone/). The products generated include deterministic and ensemble TC track forecasts, Strike Probability Maps, Strike probability for cities within the range of 120 km (RSMC, New Delhi 2014). A sample of deterministic forecast of track of TC Phailin during October 2013 by various models along with the observed track is presented in Fig. 8. A sample probabilistic forecast based on TIGGE-Ensemble Prediction Scheme (EPS) for landfall of TC Phailin is presented in Fig. 9.

IIT-Delhi and INCOIS-Hyderabad run storm surge prediction models have been implemented by RSMC, New Delhi to provide storm surge guidance to disaster managers on real time. Storm surge guidance based on IIT-Delhi model is being provided to WMO/ESCAP panel countries since April 2009. A sample storm surge guidance by IIT-Delhi and INCOIS in association with landfall of TC Phailin (08–14 October 2013) is presented in Fig. 10.

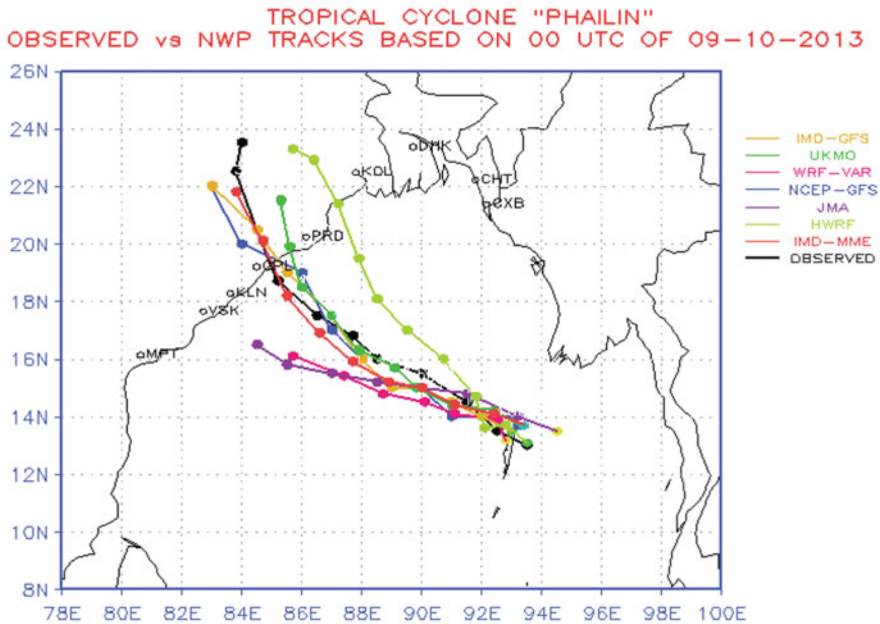


Fig. 8 A sample deterministic track forecast of TC Phailin (8–14 October 2013) by NWP models based on 09 October 2013/0000 UTC initial conditions