Tropical Cyclone Predictions
Eye on the storm
Tropical cyclones are one of the deadliest and costliest weather phenomena worldwide. As a killer, tropical cyclones are far ahead of many other natural disasters. The word ‘Cyclone’ was coined in 1848 by Henry Piddington, British meteorologist, and is derived from the Greek word ‘kuklos’ i.e. the coil of a snake as the air flow of the storm resembles it. The nomenclature of tropical cyclones is different in different parts of the world. In the Atlantic and eastern Pacific, they are known as ‘hurricanes’ and in western Pacific as ‘typhoons’. In the Indian region, they are simply known as ‘tropical cyclones’. Almost all these storms form within 25° latitude on both sides of the equator except over the 5 °N to 5 °S equatorial region.
In the Atlantic region, tropical cyclones form during June to October. However, the genesis of tropical cyclones over the Indian seas is highly seasonal, with primary maximum in the post-monsoon season (mid-September to December) and secondary maximum during the pre-monsoon season (April and May). The post-monsoon storms are more devastating in nature. As a storm intensifies from a loosely organized state, it passes through several stages. Based on pressure drop and maximum sustainable surface wind, the World Meteorological Organization (WMO) broadly classifies the tropical cyclones over the Indian Seas into seven categories and the same is provided in Table 1. These classifications are also used by the India Meteorological Department (IMD), New Delhi.

The Bay of Bengal (BoB) is a potentially active region for the formation of tropical cyclones. Table 2 shows the total number of cyclones that crossed different parts of the BoB coastal region based on 120 years of track and intensity data ranging from 1891 to 2010. The climatology of cyclone genesis shows that a total of 606 cyclonic disturbances (which include DD, CS and SCS) formed in the Bay of Bengal. Out of 606 cyclones, 325 (54%) crossed India, 95 (16%) Bangladesh, 61 (10%) Myanmar, 25 (4%) Sri Lanka and as many as 100 (17%) dissipated over the sea.

Figure 1: Schematic representation of tropical cyclone with characteristic, Pressure drop (ΔP=1013 – Pc), Maximum sustained wind (Vmax), Radius of maximum wind (R)
Cyclones in India

The Indian seas- Bay of Bengal (BoB) and the Arabian Sea (AS) - are impacted by only 5-6 global tropical cyclones each year. However, the Indian sub-continent accounts for the highest number of cyclone related fatalities globally. The Indian region is unique in nature in comparison to any other basin in the world and as far as the genesis/period of occurrence of cyclones and death tolls due to such systems are concerned. These are:

- Two cyclone seasons: Pre-monsoon (April-May) and Post-monsoon (October-December) with primary maxima in the month of November.
- Cyclones are of relatively moderate intensity as compared to West Atlantic hurricanes and West Pacific typhoons.
- Only 7% of the world’s total cyclone genesis but highest death toll amongst all regions.
- Of the 23 recorded deadly storms (>10,000 fatalities over last 300 years), 20 cyclones were formed over the BoB.
- High death toll is the consequence of highly vulnerable storm surges in east coast of India.

These unique features are mainly due to:
- Shallow bathometry (relatively highest surge: 8-12 m).
- Near funnel shaped coastline.
- Densely populated coastal region.
- Large stretch of low lying delta regions in the cyclone prone east coast of India with presence of relatively large number of river systems (in particular the Odisha coast).

Table 3 shows the total number of cyclones that crossed different parts of the Arabian Sea coastal region based on 120 years (1891 – 2010) of track and intensity data. The climatology of cyclone genesis shows that a total of 58 cyclonic disturbances (which include DD, CS and SCS) formed over the Arabian Sea. Out of these, 53% crossed India, 9% to Pakistan, 35% to Iran, Arabia and the coast of Africa and 3% dissipated over the sea. The detailed climatology of Arabian Sea tropical cyclones is provided in Table 3.

Concentrating on the Indian coast, there are 8 maritime states along the eastern and western coast of India that have deeply suffered from tropical cyclones. Figure 2 describes the total number of cyclones that crossed different maritime states of India during 1890 to 2011. This clearly reflects the higher frequency of tropical cyclones over the BoB, of which maximum crossed through the Odisha coast. The Super cyclone of the century (OSC99) struck the Odisha coast on October 29,
1999, with an intensity of about 300 kmph accompanied by a 7 meter high storm surge. Out of a total of 30 Districts, 11 coastal districts were heavily affected, leading to a death toll of more than 10,000 people. The track of the OSC99 with the NOAA METEOSAT satellite picture is shown in Figure 3.

Tropical cyclones can cause a variety of damages. The major causes of destruction are strong winds, heavy precipitation and storm surges. The potential damages due to several factors associated with tropical cyclones are depicted in Figure 4.

The Indian Seas tropical cyclone with climate change perspective clearly shows that though the occurrence of tropical cyclones remains steady, the frequency of severe cyclonic storms is increasing. A significant increase of nearly 46% with a confidence level of 99% is noticed for severe cyclonic storms, while the increase of cyclonic disturbances and cyclones is not statistically significant.

Thus advanced forecasting techniques with improved warning systems are expected to lead to a significant reduction in loss of life and property owing to these natural weather events. There is a need for further enhancement in observing networks such as coastal Doppler Weather Radar (DWR), aircraft reconciliation, drop sondes, satellite products etc.

There have been considerable advancements in research and operational models which have demonstrated significant improvements in prediction of the movement of tropical

<table>
<thead>
<tr>
<th>Country</th>
<th>Total No. of Tropical systems</th>
<th>Total number of cyclonic and severe cyclonic storms</th>
<th>Total number of severe cyclonic storms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of total systems</td>
<td>% of total in the respective country</td>
<td>% of total systems</td>
</tr>
<tr>
<td>India</td>
<td>325 (54%)</td>
<td>190 (53%)</td>
<td>109 (55%)</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>95 (16%)</td>
<td>67 (19%)</td>
<td>47 (24%)</td>
</tr>
<tr>
<td>Myanmar</td>
<td>61 (10%)</td>
<td>44 (12%)</td>
<td>23 (11%)</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>25 (4%)</td>
<td>16 (6%)</td>
<td>9 (5%)</td>
</tr>
<tr>
<td>Dissipated over Sea</td>
<td>100 (17%)</td>
<td>44 (12%)</td>
<td>9 (5%)</td>
</tr>
<tr>
<td>Total</td>
<td>606</td>
<td>362</td>
<td>197</td>
</tr>
</tbody>
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Table 2: Number of cyclones that crossed different maritime states of India during 1890-2011.

<table>
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<tr>
<td></td>
<td>% of total systems</td>
<td>% of total in the country</td>
<td>% of total systems</td>
</tr>
<tr>
<td>India</td>
<td>31 (53%)</td>
<td>22 (51%)</td>
<td>16 (53%)</td>
</tr>
<tr>
<td>Pakistan</td>
<td>5 (9%)</td>
<td>4 (9%)</td>
<td>4 (13%)</td>
</tr>
<tr>
<td>Iran, Arabia &amp; Africa</td>
<td>20 (35%)</td>
<td>17 (40 %)</td>
<td>10 (33 %)</td>
</tr>
<tr>
<td>Dissipated over Sea</td>
<td>2 (3%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>58</td>
<td>43 (74%)</td>
<td>30 (52%)</td>
</tr>
</tbody>
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Table 3: Number of cyclones that crossed different countries surrounding Arabian Sea during the period 1891-2010.
The India Meteorological Department (IMD) has operationalized a state-of-the-art mesoscale model (WRF system) for tropical cyclone prediction over the Indian seas. In recent years, IMD has also enhanced its observational network with coastal DWR, automated weather stations (AWS) and automatic rain gauge (ARG) systems. In India, a number of research / academic institutes have been working in R&D mode to improve the skill of the mesoscale models for track and intensity prediction of tropical cyclones by utilizing the high spatial and temporal observations through an advanced data assimilation technique. The IMD in collaboration with academic and research organizations has recently launched the Forecast Demonstration Project (FDP) for improvement in monitoring and prediction of tropical cyclones over the Indian seas. The Centre for Atmospheric Sciences, Indian Institute of Technology Delhi (IIT Delhi) mesoscale modeling group has been very actively involved as a leading team in the country in simulation and prediction of tropical cyclones and associated storm surges.

In the US, the National Oceanic and Atmospheric Administration (NOAA) has been continuously improving its observational network to track and monitor hurricanes over the Atlantic (Figure 5).

NOAA, has been continuously striving towards improving tropical cyclone forecasts to save life and property. For instance, today’s average 5-day track forecast is as good as the 3-day track forecast was ten years ago (Figure 6). These improvements have been possible because of improved numerical models, observations in the region of tropical cyclones and data assimilation techniques for initialization of these forecast models. In an unprecedented effort, NOAA has initiated the Hurricane Forecast Improvement Project (HFIP) to further improve the tropical cyclone...

Figure 3: Track of the Odisha Super Cyclone 1999 with satellite imagery.

Figure 4: Potential damages due to tropical cyclones.

**TROPICAL CYCLONES**

- Low Pressure, Large Pressure Gradient and Strong, Low Level Convergence of Mass, Heat and Moisture

- Strong Winds
- Storm Surge
- Heavy Rainfall

- Damage due to Structures
- Loss of Power and Communications
- Loss of Life and Injuries
- Generation of Devastating Storm Surges
- Destruction of Vegetation Crops and Livestock

- Flooding of Coastal Areas
- Erosion of Beaches
- Loss of Soil Fertility from Saline Intrusions
- Loss of Life
- Damage of Structures

- Loss of Life
- Desecution of Vegetation Crop and Livestock
- Contamination of Water Supply
- Land Subsidence
- Flooding of Land Area

Figure 5: Tracking and monitoring of hurricanes over the Atlantic by NOAA, USA.

Figure 6: Potential damages due to tropical cyclones.
forecast skills by 20% in 5 years and 50% in 10 years. Through the development of the advanced high-resolution Hurricane Weather Research and Forecast (HWRF) modeling system and the associated data assimilation techniques at the Atlantic Oceanographic and Meteorological Laboratory (AOML) and National Centers for Environmental Predictions (NCEP), NOAA has started making significant advances in tropical cyclone track, intensity and structure forecasts.

The HWRF modeling system became operational at NCEP in 2007 and has undergone significant improvements with annual upgrades ever since its initial implementation. For the first time, an advanced high-resolution HWRF model operating at cloud-permitting 3km resolution was implemented into NCEP operations for the 2012 hurricane season. The HWRF is composed of several key components for providing accurate tropical cyclone track and intensity forecast guidance. These include the Weather Research and Forecasting (WRF) software infrastructure, the Non-Hydrostatic Mesoscale Model (NMM) dynamic core, the three-dimensional Princeton Ocean Model (POM), and a physics suite tailored to the tropics, including air-sea interactions over warm water and under high wind conditions, boundary layer and cloud physics developed for hurricane forecasts. The HWRF model employs an advanced hurricane vortex initialization and cycling technique coupled to NCEP’s Gridpoint Statistical Interpolation (GSI) data assimilation system for representing the initial vortex structure of the storm.

In October 2010, NOAA signed an Implementing Arrangement (IA) and Memorandum of Understanding (MoU) with Ministry of Earth Sciences (MoES), Govt. of India to improve tropical cyclone forecasting over the Indian seas. Researchers from NOAA AOML, NCEP and Purdue University from
the US side and IMD and IIT Delhi from Indian side are working closely in this project. Under this IA, NOAA has transferred the state-of-the-art operational HWRF modeling system to IMD and its partnering research institute IIT Delhi. In order to share advanced understanding and forecasting techniques acquired in the last few years by NOAA and its partnering institutions in the USA, a 6-day advanced workshop and training was organized by IIT-Delhi and IIT-Bhubaneshwar at Bhubaneshwar, Odisha, India during 9 - 14 July 2012. The program was coordinated by Dr. S.G. Gopalakrishnan (AOML, NOAA), Prof. U.C. Mohanty (IIT-D) and Prof. Subhasish Tripathy (IIT-Bhubaneshwar).

Dr. Shailesh Nayak (Secretary, Ministry of Earth Sciences) delivering the Inaugural Address at the Indo-US Workshop on ‘Modeling and Data Assimilation for Tropical Cyclone Predictions’.

Figure 7 (a) Observed structure of tangential wind obtained after composing Doppler data from several flight missions carried out by the Hurricane Research Division of NOAA compared with (b) the 3-km version of HWRF model forecast for tropical cyclone Earl.
This event was jointly sponsored by the Indo-US Science and Technology Forum (IUSSTF), Council of Scientific and Industrial Research (CSIR), MoES, NOAA and the US National Science Foundation (NSF). The IIT Bhubaneswar is one of the leading academic and research institute in Odisha. The institute has established a “School of Earth, Ocean and Climate Sciences” and an “Innovative Centre for Climate Change” to provide an intellectual and congenial research atmosphere on integrated earth-ocean-atmosphere interaction processes. Recently, the School emphasized the research on extreme weather events and climate science studies. These initiations may lead to the better prediction of high impact weather events and associated hazards emergent to Odisha state and the east coast of India as well.

Dr. Shailesh Nayak, Secretary, MoES, inaugurated the workshop in the presence of Dr. L.S. Rathore, Director General of IMD, Dr. Nishritha Bopana (Science Officer, IUSSTF), and a gathering of more than 100 eminent dignitaries from India and USA. The week-long workshop brought together 12 eminent scientists from NOAA and USA universities, 5 Indian experts, 4 NSF sponsored students from USA, and 27 young scientists from various organizations across India including IMD, National Centre for Medium Range Weather Forecasting (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), Indian Institute of Tropical Meteorology (IITM), Indian Air Force, Indian Navy, Indian Space Research Organization (ISRO), Indira Gandhi Centre for Atomic Research (IGCAR), Indian Institute of Technology campuses, and other Indian universities. All the participants have active R&D efforts for advancing tropical cyclone predictions. The workshop consisted of 36-hours of lectures and 10 hours of colloquium besides several hours of discussion and interactions among the resource persons and participants. The US delegation was led by Dr. Frank Marks, Director of the Hurricane Research Division (HRD) of AOML/NOAA and Principal Investigator (PI) of Indo-US MoU, along with two other Co-PIs of the project, Dr. Vijay Tallapragada, (NCEP/NOAA) and Prof. Dev Niyogi (Purdue University).

The workshop accomplished the prime goal of capacity building and infrastructure sharing under the NOAA-MoES agreement for weather ready nations (US and India). In addition, the exchange of state-of-the-art knowledge and prediction techniques immensely benefited not only the participants but also the resource persons from both countries. The proceedings from this workshop will be published as a special monograph on Modeling and Data Assimilation for Tropical Cyclone Predictions, which will serve as a useful reference for students and researchers.

The outcome of this event has set the stage for extensive advancement in tropical cyclone and heavy rainfall prediction over the Indian monsoon region so as to reduce the current track prediction errors by at least 20% by 2015. Further, present intensity and rainfall forecast skill of 3-days may be achieved in the 5-day forecast by 2015. It should be noted that the NOAA’s state-of-the-art HWRF modeling system (atmospheric component) is in use at IMD in a collaborative mode with active participation of IIT Delhi scientists. It will be the basis for pursuing the joint efforts among IMD, IIT Delhi and INCOIS and USA counterparts at NOAA-AOML, NCEP, and Purdue University to have a coupled HWRF system for the Indian monsoon region in the future. In this endeavor the Indo-US Science & Technology Forum is expected to play a pivotal role in fostering such bilateral collaboration and exchange of visits.