National Workshop on Enhanced and Unique Cyclonic Activity during 2013
(24-25 July, 2014)

Abstracts

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Typical Satellite imagery of Cyclonic Storm PHAILIN

Cyclone Warning Division
India Meteorological Department
Ministry of Earth Sciences
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Half a century of Progress of operational Research Aspects of Tropical Cyclones over North Indian Ocean

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Research on Tropical Cyclone over North Indian Ocean began in the middle of 19th Century and the operational warnings system was first established near about 150 years before. The first 100 years, i.e. from 1865-1965, were the early years in which research and operations were monthly based on surface observation. However, since the IIOE, the operational systems as well as monitoring aspects of Tropical Cyclones over area have been immensely enhanced, the paper will review the input changes occurred in different stages in the infrastructure development and research efforts.

The infrastructure development was technically drawn by computers, weather radars and weather satellite. The present observational system has considerably improved particularly in relation to application of radar and satellite data whereas conventional observations particularly with radar-sonde have received set back. The high resolution models on the global / regional scales have been adopted in India with the availability of high performing computing. India today is almost at par with the advanced countries. However, research is mostly based on the area of work done in the advanced countries. It is time that new ideas are developed in India. The paper will review the developments and suggest some measures for organizing urgent research efforts in the country.
Collaborative Mechanism for Monitoring and Prediction of Tropical Cyclones over the North Indian Ocean

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Tropical Cyclones (TCs) are one of the most devastating weather events affecting the Indian region. In the past, more than 75% of the total global TCs causing the death toll of 5000 or more have occurred over the North Indian Ocean (NIO), though the frequency of TCs over the NIO accounts for 7% of the global frequency and the TCs are relatively less intense compared to those over the Northwest Pacific and North Atlantic Oceans. However, the death toll due to TCs in recent years has reduced significantly, being limited to only two-digit figures due to various initiatives with respect to preparedness, early warning and mitigation. As early warning is a major component, Ministry of Earth Sciences (MoES), Government of India and India Meteorological Department in particular have taken various measures for upgradation of early warning components including monitoring, prediction, warning products generation and dissemination, triggering mechanism, public education and awareness and confidence building measures. National and international collaborations have played a dominant role with respect to upgradation of monitoring and prediction of TCs leading to reduction in forecast errors. However, still there is a scope for further improvement; as for example, IMD’s TC track forecast errors are about 50 km higher than that of National Hurricane Centre, USA for North Atlantic TCs in 48 hour lead period. Hence, a review has been undertaken on the existing national and international collaborative mechanisms so as to plan for future collaborations.

The international collaboration for TC monitoring dates back to 1st April 1960 with IMD’s use of satellite imageries from TIROS-I satellite of the USA, though real-time reception of satellite imagery commenced in December 1963 through an Automatic Picture Transmission station at Mumbai, donated by the USA. On national front, the first collaborative effort goes back to 1983 with launching of geo-stationary satellite, INSAT by Indian Space Research Organization (ISRO). Apart from collaboration in space, the collaboration with Department of Ocean Development commenced in 1997 with launch of national data buoy programme in addition to the existing ship observations through Indian Voluntary Observing Fleet programme. Currently, there is collaboration with many organizations including the Indian Air Force, Indian Navy, ISRO, sister organizations of the MOES like INCOIS, NCAOR, NIOT and many academic institutes like the IITs, IISc, universities for observations through operational and research campaigns. With respect to prediction, the first TC-specific prediction model was established in the IMD with the operationalisation of the Limited Area Model (LAM) adapted from the USA in 1991 followed by a Quasi-Lagrangian Model (QLM) from the USA in 2001 after testing during 1997-2000. Currently, IMD has collaboration with the USA, the UK, France, Japan etc., to run/ avail various deterministic and ensemble based global and regional numerical weather prediction models and with various national centres for regional models. Apart from these, there has been collaboration for (i) R&D campaigns and (ii) capacity building through training, exchange visits, knowledge transfer, exchange of data and information etc. There are various national and international collaborations also for issue of warnings and advisories including WMO/ESCAP panel on TC and TC advisory for international civil aviation. Collaboration has helped in improving the dissemination through global telecommunication system and national network, with the help of Department of Telecommunication (DOT), ISRO, police, Aeronautical Fixed Terminal Network (AFTN). The future plan for enhanced collaboration in all these sectors and additional sectors is also presented.
Characteristic features of cyclonic disturbances during 2013

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During the year 2013, 10 cyclonic disturbances against the normal of 13.5 developed over north Indian Ocean (NIO) including one deep depression over Arabian Sea (AS), one land depression and 8 cyclonic disturbances over Bay of Bengal (BOB). Out of 8 disturbances in BOB, 3 intensified into Very Severe Cyclonic Storm (VSCS), one each into a Severe Cyclonic Storm (SCS) & Cyclonic Storm (CS), and three upto depressions. Considering season-wise distribution, out of 10 disturbances, 2 developed during pre-monsoon, 2 during monsoon and 6 during post-monsoon season. Five out of six disturbances during post-monsoon season occurred over the BOB. The total life period of cyclonic disturbances during 2013, was maximum (42.6 days) as compared to previous years (1990-2012). The annual cyclone energy over the NIO has also been significantly higher in 2013.

There were five cyclones over the BOB and no cyclone over the AS against the long period average of 5.5 per year over the entire NIO with ratio of 4:1 over BOB and AS. Five cyclones developed over the BOB for the first time after 1987. Four SCSs developed over BOB for the first time since 1982. Three VSCSs occurred over NIO for the first time since 1999.

Post-monsoon season (Oct.-Dec.) was very active over the BOB with formation of three VSCSs and one SCS. Four such SCSs during post-monsoon season occurred over BOB in the year 1922 & 1966 based on the data of 1891-2012 and three VSCSs occurred in the year 1967, 1971, 1977 & 1981 during the period 1965-2012.

Intensity prediction during 2013 was more challenging, as all the cyclones except Viyaru experienced weakening over the sea before the landfall. Though there were five cyclones, only one cyclone (Phailin) crossed coast as VSCS and other two (Viyaru and Helen) as CS. Other two cyclones (Lehar and Madi) crossed the coast as depressions. However, cyclone Lehar crossed Andaman and Nicobar Islands as SCS. It was the first SCS that crossed Andaman and Nicobar Islands since November 1989. While track of Lehar was straight moving, tracks of all other cyclones were recurving in nature. While Phailin recurved after landfall, cyclone Viyaru recurved northeastwards over the sea, cyclone Helen recurved west-southwestwards just before landfall and cyclone Madi recurved southwestwards over the sea. Comparing the tracks, the track of Madi was most unique in nature and had a rare analogue with past records. All these characteristic features have been analysed and discussed in this paper.
Conducive factors for Enhanced Cyclonic Activity during 2013 over the north Indian Ocean

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Environmental impacts on tropical cyclone (TC) formation and intensity change have been studied for many years. These impacts may be expressed in terms of thermodynamic effects (e.g. sea-surface temperature, middle tropospheric instability) or dynamical effects (e.g. vertical wind shear, cyclonic vorticity). In addition to atmospheric parameters, it is now realized that the ocean thermal structure (OTS) plays a critical role in the intensity change of tropical cyclones, due to the energy supply from the ocean to the TC. From the perspective of TC, OTS typically concerns temperatures in the top 200–300 m, because the interaction between TC and the ocean takes place within this layer. The upper ocean heat content (UOHC) plays a vital role in the intensification of storms rather than sea-surface temperature (SST). Hence UOHC /D26 (depth of 26°C isotherm) gained an importance in forecasting the intensification and movement of storms. It has been shown that a threshold value of about 60 kJ/cm² may be necessary for the genesis and intensification of the storms in Bay of Bengal (BOB) during post-monsoon season. There is a possibility to estimate translation speed in advance from the predicted storm track using the UOHC of the pre-storm conditions.

The year 2013 witnessed heightened TC activity in the north Indian Ocean. Total 6 cyclonic systems formed in the post-monsoon season out of which except one deep depression in Arabian Sea (AS) all were in BOB and three of them were very severe cyclonic storms. In the year 2012, two cyclonic storms occurred in the post-monsoon season one in AS and other in BOB. The season was calm except one deep depression in the AS and two in the BOB. There was no pre-monsoon cyclonic activity. The OTS which might have caused the enhanced cyclonic activity during 2013 as compared to 2012 and other earlier years, is examined. NCEP GODAS (Global Ocean Data Assimilation System) data is used to study upper ocean characteristics. Different parameters such as SST, barrier layer, salinity, D20, D26, TCHP which have effect on TC intensity and movement, are analysed. Monthly SSTs for the months of October, November and December 2013 are found to be greater than that for 2012 or 2011 in the BOB. D26 and D20 are in the range of 70-80 m and 100 m respectively, for the year 2013, which are deeper in agreement with earlier studies, supporting increased TC activity. Low values of salinity and existence of barrier layer is also seen from Pentad data for the individual cases (Phailin, Leher, Madi) supporting intensification of the cyclonic storm. Atmospheric conditions are not unimportant. Parameters like wind shear and middle tropospheric instability from NCEP products, are also found to be supportive for increased TC activity during 2013.
Analysis of tropical cyclones using NOAA AMSU-89 and 32 GHz channel using Direct-Broadcast receiving system at IMD, New Delhi

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Currently, at Satellite Meteorology Division of India Meteorological Department, center positions and intensities of tropical cyclones are estimated by the Dvorak method, which uses infrared and visible imagery from the INSAT/Kalpana-1 geostationary meteorological satellite. While the Dvorak method is the most popular technique for analyzing tropical cyclones through infrared and visible imagery, it is not good at estimating the center positions of tropical cyclones that are covered by upper cirrus cloud and do not have a clear eye in their developing stage, especially during periods when visible imagery is not available.

To combat this difficulty, we used microwave imagery from the NOAA/METOP satellites received at IMD, New Delhi to analyze the inner structures of tropical cyclones, which cannot be seen in infrared or visible imagery. We have also tried to develop a method to estimate center positions of tropical cyclones using this microwave imagery analysis. Verification using the tropical cyclones from 2013 showed that the accuracy of center positions estimated by microwave imagery was almost the same as that obtained by other agencies. As a result, our method was proven to be an effective means of improving the accuracy of center positions estimated by the Dvorak method.
Slow poisoning of the Tropical Cyclone

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Tropical convection, thunderstorm and cyclone are the major sources of stratospheretroposphere exchange (STE) in short-spell by modulation of tropopause characteristics. In this aspect, a co-ordinated experiment was conducted with multi-institutional support using multi-instruments, i.e. ground-based MST (Mesosphere Stratosphere Troposphere) radar, insitu balloon borne experiments (radiosonde and ozonesonde) and space borne satellite (Kalpana and Megha-Tropiques) observations during the passage of tropical cyclone Nilam and Phailin. MST radar at Gadanki (13.5°N, 79.2°E) was operated in three different modes including a special experiment (multibeam) by tilting the off-zenith beam from east-west and north-south. Enhanced turbulent activities and isotropic layer structure in the ‘vicinity of tropopause (VOT)’ were observed in the radar backscatter echoes, when the cyclone eye was close to the radar site. The tropopause is observed to be weakened due to the presence of strong updrafts and downdrafts accelerated by convectively generated gravity waves in the VOT. Radiosonde observations at the radar site also showed an increase in the cold-point-tropopause height when the cyclone eye was close to the radar site, thereby favoring STE. The CPT temperature is below 191K which is favorable for the occurrence of freeze-dry mechanism at upper troposphere and lower stratosphere (UTLS) region. Simultaneously, ozonesondes were also launched from Trivandrum (8.5°N, 76.5°E). The height profiles of ozone mixing ratio observed at Trivandrum shows a significant enhancement in the mid- and upper-troposphere during overhead cyclone which is attributed due to the weakening and modulation of the tropopause by gravity waves. The most significant and new observation is that the enhancement of the upper tropospheric ozone (30-40 ppbv) extended down to the middle and lower troposphere intruding at the rate of 0.87-1 km per day during the passage of cyclonic/severe cyclonic storms. Interestingly, secondary enhancement is also observed in the upper troposphere during very severe cyclonic storms. Estimated mass-flux around the tropopause is found to be 0.6-0.8 kg/m²/s. Space borne observations of relative humidity, using SAPHIR (Sondeur Atmospherique du Profild’Humidite Intertropical par Radiometrie) on board Megha-Tropiques satellite, indicate the presence of dry air in the upper and middle troposphere. All these observations clearly indicate the intrusion of dry air into the upper and middle troposphere is of stratospheric origin, hence poising the lower troposphere. These observations constitute quantitatively the first experimental evidence of enhanced tropospheric ozone due to the passage of tropical cyclones. Detailed results will be presented and discussed in the upcoming symposium.
Governing factors associated with intensification of tropical cyclone-A diagnostic study of VSCS PHAILIN and LEHAR

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Very severe cyclonic storm (VSCS) Phailin and Lehar emerged over Andaman Sea area on 08 October & 23 November 2013 respectively as a remnant of cyclonic circulation from the South China Sea. Phailin had landfall at south Orissa-north Andhra coast as VSCS whereas Lehar had landfall over Andhra Pradesh coast as a Depression. Both of them caused widespread destruction to life and property including agricultural production over the coastal belts of the respective states.

As destruction of tropical cyclone is associated with its intensity, accurate forecasting of cyclone intensity is very vital. Keeping this in view, in the present study, we assessed the oceanic and environmental parameters over the Bay of Bengal for two very severe cyclonic storm (VSCS) Phailin and Lehar formed during 2013 by addressing the following factors namely: (i) Sea surface temperature (SST), (ii) lower-tropospheric absolute vorticity (iii) lower level convergence and upper level divergence and (iv) vertical shear of horizontal wind to improve the understanding about forecasting of cyclone intensity.

In depth analysis of the above parameters reveals that in case of Phailin SST maintained its steady state throughout its life span. More over, the value increased to its peak (29-31) degree Celsius 24 hrs before its landfall. The case was reverse for Lehar. At the time of landfall the SST value decreased to below 26 degree Celsius from the initial value 28-29 degree Celsius.

The absolute vorticity at 850 hPa showed that the range for Phailin started initially by 15 unit and increased significantly during its course of movement and reached to 46 unit before its landfall whereas in case of Lehar the vorticity range started from 26 unit initially and fluctuated during its movement, reached 36 unit and then reduced significantly to 16 before its landfall. The vertical wind shear (VWS) also played significant role in intensification/weakening of the cyclones. It has been observed that VWS for Phailin started from the range 10-20 (Low-Moderate) then reduced to 10-15 during its movement and further reduced to 5-10 (Low) during middle of its path upto landfall whereas in case of Lehar it started at high range (15-25) became moderate (10-20) during its movement and increased again to its high range before 24 hours of its landfall. Similarly convergence parameter was also very high through out the life period of Phailin.

Thus the study revealed that out of above four the two significant parameters namely SST and VWS were responsible for maintaining intensification till landfall of Phailin and weakening of Lehar to Depression before its landfall.
Correction of wind fields during VSCS Phailin using bulletins from IMD & JTWC and ship-mounted INCOIS real-time AWS network


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Ocean General Circulation and wave models are forced by winds. Hence, the quality of oceanic parameters simulated by these models is mainly dependant on the quality of winds. Several past studies unraveled that winds from most of the re-analysed/forecast models drastically under-estimate beyond wind speeds of 15 m/s, which existed during depressions/cyclones. Also, for such high wind speed, the magnitude of bias is found to be directly proportional to the wind speed. In the present study, a bias-correction technique/methodology has been applied to correct the wind bias in the ECMWF and NCMRWF forecast/re-analysis products during the course of VSCS Phailin. The wind speed has been divided into different ranges/bins of 1m/s width. Since the wind speed of<15m/s are common, range-wise biases have been found out and kept ready for ranges up to 15 m/s, especially using the network of ESSO-Indian National Centre for Ocean Information Services (INCOIS) real-time AWSs mounted onboard Indian ships. But, during depressions/cyclones, observations of high wind speed (say >15 m/s), which are from the satellites, are available only from the bulletins issued by the operational cyclone warning centres like India Meteorological Department (IMD), India and Joint Typhoon Warning Centre (JTWC), USA. They periodically issue and keep on updating these bulletins during the course of depressions/cyclones. Hence, the biases within the wind bins of > 15 m/s wind speed have been found out using these observations. The range-wise biases/uncertainties, derived upto maximum observed wind speed, have been removed from the direct forecast/re-analysed output products of ECMWF and NCMRWF. These newly derived wind products have also been evaluated using in-situ observations from NIOT/MoES buoys and CSIR-NIO coastal AWS at Gopalpur, Kakinada and Paradip, and found to have reasonable agreement. Thus a new dataset of wind fields were prepared, which were evaluated using in-situ observations, and used for forcing operational ocean state forecast models at INCOIS during the VSCS Phailin. The same methodology has already been incorporated in the operational ocean state forecasting set up at INCOIS.
DWR data utilization in Cyclone track and intensity prediction with special reference to Phailin

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Doppler Weather radars have been utilized for the track and intensity prediction in terms of radial velocity associated with the cyclone, heavy rainfall, speed of movement of the system, estimated time of landfall and storm surge estimation. Despite the limited range of observation (300-400 km), high resolution information is available for the track and landfall prediction, about 8-12 Hrs in advance with a high accuracy with reference to time of landfall and velocity of winds around the eye of the cyclone. Additionally, the eye diameter and vertical extent of the clouds associated with the wall cloud region can be well measured using the DWR data. During Oct 2013, very severe cyclonic storm, Phailin hit the coast of Odisha near Gopalpur which was observed by DWR Visakhapatnam few hours before the landfall. In the present paper, utilization of DWR products have been discussed for some of the cyclones occurred in the Bay of Bengal. Analysis of reflectivity and velocity products of Phailin has also been done in details. This has been found that DWR products provide very good information about the structure of the cyclone, accurate time of landfall, passage of the system over the place of landfall and the expected damage potential in terms of velocity and storm surge height. Crossing of the eye of the cyclone after the landfall and issue of de-warning may be done with a very high accuracy for the public safety and disaster management.
Simulation of vortical hot towers in pre-cyclogenesis environment: Development of high resolution analysis.

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Recent marsupial theory of tropical cyclogenesis suggests that vortical hot tower (VHT) play a vital role in cyclogenesis activity in pre-cyclogenesis environment. The process of pouch formation and development of vortical hot towers in protected environment are key mechanisms in tropical cyclogenesis. The meso-scale process such as alignment, re-organization and merging of these VHTs finally leads to tropical cyclogenesis. The main difficulty in studying these physical phenomena is the lack of high resolution analysis required for physical understanding of these mechanisms.

In this work we have developed high resolution analysis (6km) for pre genesis environment using mesoscale model WRF and three dimensional variational data assimilation. Additional in-situ observations from NCEP global upper air, surface prepbufr observations and satellite radiances are assimilated in GFS initial condition for 7 days prior to tropical cyclone identification by IMD. The WRF 3.5.1 model is used to simulate cyclones in cyclic mode till period of dissipation of cyclones. The analysis cycle is based on 6hr forecast and output analysis is made for each 5 minutes. Domain specific background error statistics are created separately for both pre-monsoon and post-monsoon seasons from WRF forecasts using 60 days forecast of 24 hrs based on cyclic initial condition and GFS boundary conditions (NMC method). The developed analysis is used to understand various physical mechanisms associated with tropical cyclogenesis occurred in the North Indian Ocean cyclone season 2013. The important results from this study will be briefed in the presentation.
Energetics of tropical cyclone over Bay of Bengal during post monsoon season and relation with ENSO.

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Prognostication of track and intensity of tropical over north Indian ocean are challenging work because circulation feature and associated convection are connected with global circulation features. Normally five cyclones develop annually over the north Indian Ocean during. In 2013 five cyclonic storm formed over Bay of Bengal and none of them form over Arabian sea. Four out of five cyclonic storms formed during post monsoon 2013. Three storms namely “Phailin”, “Lehar” and “Madi” intensified into Very Severe Cyclonic Storm(VSCS) and remaining one “Helen” intensified into Severe Cyclonic Storm(SCS). Genesis, intensification and movement of the cyclonic storm depend on atmospheric circulation and convection over the ocean. Best track data show that cyclonic storm generally intensify over the ocean and occasionally rapidly intensify into VSCS. The cyclonic storm hit the coast of Bay of Bengal leading to huge loss of lives and properties over coastal belt due to heavy rain, strong wind and storm surge. Sometime episodic intensification and weakening process continually occur over the ocean and vagary of the cyclone becomes unpredictable. Number of studies have made over West Pacific ocean to relate annual cyclone energy with El Nino –Southern Oscillation (ENSO) and no such study has been made over Bay of Bengal. Therefore the objective of this study is to compute Seasonal Cyclone Energy(SCE) during post monsoon and examine impact of El Nino and La Nina in enhancing genesis and intensification of cyclonic storm. Correlations between Outgoing Long Wave Radiation (OLR) and Sea Surface Temperature(SST) have also been computed over Bay of Bengal during the season to ascertain relationship between environmental parameter and SCE. Velocity potential and stream function have also been analysed to investigate its characteristics and magnitude in association with intensification processes.

Last twenty year Southern Oscillation Index (SOI) and best track wind speed data have been extracted. Wind speed is converted into m/s and six hourly kinetic energy has been calculated over the basin for each cyclonic storm. Only those cyclonic disturbances have been considered which could intensify into cyclonic storm and mean SCE is calculated for the season. The highest SCE of 836.00 J/Kg is found 20% with occurrence VSCS SIDR during 11 – 15 November 2007 which crossed Bangladesh coast. In 2013 the energy was computed as 470.7 J/Kg. Decrease in cyclone energy in 2013 is attributed to weakening of VSCS Lehar and Madi before landfall over the basin. Both the cyclones weakened over the oceanic area due to low ocean thermal energy (d” 100 KJ cm $^{-2}$) and high wind shear over. SCE is found to be maximum in La Nina year and lowest in El Nino year as intensification of cyclonic disturbances is strongly impeded. Hence dynamical parameters viz., stream function and velocity potential at various atmospheric standard levels have been derived from NCEP reanalysed data provided by Physical Science Division, Earth System research laboratory of NOAA. Lower tropospheric level stream function and upper tropospheric level velocity potential create favourable condition for intensification of cyclonic disturbances over Bay of Bengal. Correlation coefficient between SCE – SST and SCE –OLR has been computed and found that mean SST and OLR during the cyclone period are not significantly related with SCE. Result clearly shows that generally more than mean SCE is found during La Nina year and less inEL Nino year.
An assessment of storminess of cyclonic activity over North Indian Ocean: Multi-neuro net approach

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Precise forecast of the track and intensity of tropical cyclones remains one of the top priorities for the meteorological community. In the present study multilayer feed forward neural nets with different architectures are developed to identify the best neural net for forecasting the track and intensity of tropical cyclones over the North Indian Ocean (NIO) with 6, 12 and 24 hours lead time. Forecast errors are estimated with each neural net. The result reveals that neural net architecture 1 (NNA -1) with ten input layers, two hidden layers, five hidden nodes and two output layers provides the best forecast for both the track and intensity of the tropical cyclones over NIO. Two cyclones of the same category in Saffir–Simpson Hurricane Scale, Nargis and Phet, occurred over the Bay of Bengal and the Arabian Sea of NIO basin are considered in the present study for validation. The result reveals that the prediction errors (%) with NNA – 1 model in estimating the intensity of the cyclones Nargis and Phet during the validation are 3.37, 8.29 and 9.74 as well as 6.38, 11.26 and 18.72 with 6, 12 and 24 hours lead time respectively. The mean track errors for 6, 12 and 24 hours forecast are observed to be 45, 69 and 89 km for cyclone Nargis and 54, 87 and 98 km for cyclone Phet. NNA – 1 model is observed to perform better than NNA – 2 and NNA – 3 models and the existing numerical models.
Role of oceanic parameters SST, D26 and TCHP in intensification/weakening of tropical cyclones Viyaru, Phailin and Madi over Bay of Bengal in 2013

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The ocean thermal energy plays a significant role for a tropical cyclone to develop and intensify for which the thermal conditions of both the surface and subsurface of the ocean are very much important. The ocean thermal energy or tropical cyclone heat potential (TCHP), defined as a measure of the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm (D26) is computed globally from the altimeter-derived vertical temperature profiles estimates in the upper ocean (Shay et al., 2000). The higher the sea surface temperature (SST), the thicker the subsurface warm layer (D26), and consequently, the larger the upper ocean heat content (TCHP), the more favorable the ocean conditions for tropical cyclone intensification. Both the atmospheric conditions and the ocean thermal energy are considered in forecasting the intensification/weakening of a cyclone.

In this paper, the role played by the oceanic parameters such as SST, D26, TCHP and the atmospheric parameters viz., vertical wind shear and cold dry air entrainment during the cyclones Viyaru, Phailin and Madi over Bay of Bengal have been studied. The data of SST, D26, TCHP have been downloaded from www.aoml.noaa.gov/phod/cyclone. The cyclonic storm ‘Viyaru’ (10-16 May 2013) which had one of the longest track had high values of SST (29-31°C), D26(90-110m) and TCHP (90-110 KJ/cm²) around the centre of the system from 8th to 15th May’13 but could not reach the expected higher intensity due to the constraint of wind shear aloft. The very severe cyclonic storm(VSCS) ‘Phailin’ (8-14 Oct’13), the most intense cyclone after Odisha super cyclone (29th Oct’99) that crossed as VSCS without weakening near Gopalpur as values of SST (28-29°C), D26(75-100m) and TCHP (60-80KJ/cm²) around the centre of the system were maintained throughout the track and at the time of landfall the values of SST:31°C, D26:90-100m and TCHP:80-90KJ/cm² and high vertical wind shear was not present to shear off the cyclone to weaken. During the developing stage of the VSCS ‘Madi’ (6-13 Dec’13) the the vertical wind shear was light(5-10 kts) and the values of SST, D26 and TCHP were 28-29°C, 75-100m and 70-90 KJ/cm² respectively and from 9th Dec’13, the values started decreasing to 25-27°C, 60-80m and 40-50KJ/cm² respectively. Strong vertical wind shear also prevailed around the system along with the cold dry air entrainment from the southern semicircle of the cyclone. Hence due to both the atmospheric conditions and the oceanic surface and subsurface conditions, the system started weakening. Furthermore from 11th Dec’13, the values were SST (25-27°C), D26(<30m) and TCHP (<40 KJ/cm²) around the centre of the system that made the system further to weaken. From these 3 cyclones, it is found that the values of D26(>75m) and TCHP(>60 KJ/cm²) along with the SST(>26°C) are required for developing and intensification of a cyclone.
Over the years, there has been a significant improvement in monitoring the location and intensity due to upgradation in observational tools and techniques and monitoring procedures, over the North Indian Ocean region, like other ocean basins. As a result, there has been preparation of best-tracks of cyclonic disturbances by the India Meteorological Department for every six hours with detailed information on location and intensity since 1990. Therefore, the best-track information from 1990-2013 provides the minute details about the life cycle of cyclonic disturbances. It may be mentioned that the post-monsoon season of 2013 experienced one of the longest duration of cyclonic activity considering the total life period of the cyclonic disturbances which has raised the queries on the impact of climate change, if any, on the life cycle of the cyclonic disturbances. Therefore, a study has been taken to analyze the life period of the cyclonic disturbances over the North Indian Ocean with respect to basin of formation, season of formation, intensity of the storms and nature of the track. Also, the linear trend co-efficients in the life period of the cyclonic disturbances during 1990-2013 has been calculated and analysed.

It is found that, about 9 cyclonic disturbances occurred per year over the North Indian Ocean and adjoining land region during 1990-2013. It included about 2.7 Depressions, 2.5 Deep Depressions, 1.6 Cyclonic Storms, 0.8 Severe Cyclonic Storms, 1.2 Very Severe Cyclonic Storms and 0.2 Super Cyclonic Storms. North Indian Ocean and adjoining land region experienced about 29.4 days of disturbances (Depression and above) including 5.7 days in Depression, 7.6 days as Deep Depression, 5.9 days as Cyclonic Storm, 3.1 days as Severe Cyclonic Storm, 6.2 days as Very Severe Cyclonic Storm and 1.0 days as Super Cyclonic Storm. Considering the mean life period of cyclonic disturbances, it is about 2 days for Depression, 3 days for Deep Depression, 3.5 days for Cyclonic Storm, 4 days for Severe Cyclonic Storm, 5 days for Very Severe Cyclonic Storm and 6 days for Super Cyclonic Storm over the North Indian Ocean.
The characteristic warm core, where the temperature in the centre of the cyclone is warmer than its environment, is one of the important features that distinguish tropical cyclone from its counterpart over the extra-tropics. The two most common variables used to characterize the warm core are its strength, which is the magnitude of maximum perturbation temperature and its height, the level where the maximum perturbation occurs. The strength of the warm core generally increases with the intensity of the cyclone. Numerous past studies have assessed the structure of the warm core through observational, numerical or theoretical means. In this study, geostationary sounder data from India's latest satellite INSAT-3D have been extensively used to analyze the warm core of different cyclones, viz Phailin, Helen, Lehar and Madi, formed over the North Indian Ocean during 2013. Along with INSAT-3D sounder data, scatterometer winds from Oceansat-2 and ASCAT are also used to assess the strength of the north Indian Ocean cyclones during 2013. The warm core height depends on the divergence level or the steering current level, where the maximum difference in core temperature and the environment temperature occurs. Among four different cyclones analyzed, the very severe cyclonic storm Phailin showed intense warm core compared to the other three during the season.
Track and Intensity of cyclonic disturbances over North Indian Oceans with respect to translational speed

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Tropical cyclone is one of the severe disasters causing loss of property and life. Therefore, it is essential to provide accurate track and intensity forecast of the cyclonic disturbances with long lead time so that effective measures can be taken by the disaster managers. Though there have been significant improvement in track and intensity forecast in recent years due to modernisation programmes of IMD and other measures, there is still scope for the further improvements, especially in case of rapidly changing Tropical Cyclones. The review of past studies indicates that the translational speed apart from the other factors of the cyclone, controls the environment and hence affects track and intensity changes of cyclones. As studies over North Indian Oceans on the role of translational speed is limited, a study has been undertaken, to analyse various characteristics of translational speed and their effect on track and intensity of cyclonic disturbances over North Indian Ocean. For this purpose, the six hourly best track data from 1990 to 2013 (24Years) of India Meteorological Department have been considered. Mean translational speed for 06/12/24 hours period ending at 0000, 0600, 1200 and 1800 UTC during the cyclonic disturbance period has been calculated and analysed.

It is found that translational speed increases with increase in intensity of cyclonic disturbances. Further it also increases after recurvatures of track, especially when cyclone recurves north-eastwards over the Bay of Bengal. Translation speed is higher during Monsoon season followed by Pre-Monsoon season. In general, translation speed of cyclonic disturbances is higher over Bay of Bengal than over the Arabian Sea.
Appraisal of the prevalence of severe tropical storms over Indian Ocean by screening the features of tropical depressions

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Tropical cyclones are one of the nature's most violent manifestations and potentially the deadliest of all meteorological phenomena. It is a unique combination of violent wind, heavy rainfall, and mountainous waves in sea. Tropical cyclones with maximum sustained surface wind speed of <17 ms⁻¹ (34 knots, 39 mph) are called tropical depressions. Once the tropical cyclones attain the wind speed of at least 17 ms⁻¹, are typically called tropical storm and assigned a name. The maximum sustained wind speed, minimum sea level pressure, and the radius of maximum winds are important parameters for understanding a particular tropical cyclone and to differentiate it from a depression to tropical storms. The objective of this particular paper is to identify a possible range of maximum sustained wind speed, minimum sea level pressure, and radius of maximum winds which facilitates tropical depressions to lead to tropical storms over Bay of Bengal and Arabian Sea of Indian Ocean basin. The method of rough set theory which is based on condition—decision support system is implemented for the purpose. It observed that if a combination of mean sea level pressure is ≤996 hPa, radius of maximum wind is ≤30 km, and maximum sustained wind speed is ≤35 knots is associated with a TD over Indian Ocean, then there is a definite possibility of the occurrence of TS. The result reveals that the threshold ranges of the maximum sustained wind speed, minimum sea level pressure and radius of maximum winds associated with tropical depression are possible that can aid in the predictability of tropical storm over Indian Ocean. The results are validated with significant tropical storms of 2009 and 2010 observations through Doppler and satellite imageries.
Surface Wind Structure of Tropical Cyclones over North Indian Ocean

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India Meteorological Department (IMD) is the nodal agency for tropical cyclones (TC) monitoring, prediction and issue of warnings over north Indian Ocean region. The TC wind field monitoring and forecast issued by IMD contains forecast upto five days in the interval of 12 hrs and issued four times a day based on 00, 06, 12 & 18 UTC observations. Wind field monitoring and forecast are important for mariners, ships on sea and modeling group for creation of synthetic vortex and storm surge & coastal inundation forecasting. Among others, a multiplatform satellite surface wind analysis developed by Co-operative Institute for Research in the Atmosphere (CIRA), USA for the TCs are referred by IMD for generation of surface wind field monitoring and forecast of wind radii of different threshold like 34, 50 and 64 knots in four geographical quadrants of TC. Hence, a study has been undertaken to analyse the mean characteristics of surface wind distribution and hence the structure of TC based on the real time data available from CIRA during 2007-2013, which includes 19 cyclones over the Bay of Bengal (BOB) and 6 over Arabian Sea (AS). The maximum radial extent of winds reaching threshold values of 34, 50 & 64 knots in each of the four geographical quadrants has been segregated with respect to season, basin and intensity and its mean and standard deviation calculated. The objective is to develop a reference surface wind structure of TC with respect to basin of formation, season of formation and intensity of TC. This study can be utilized as a reference for (i) validation of NWP model analyses and forecasts, (ii) real time monitoring and forecast and (iii) better understanding of physical processes in TC life cycle over the NIO.

Over the BOB and AS, the size (radius of 34 knot wind threshold) of the TC increases with increase in intensity in both pre and post-monsoon seasons. During pre-monsoon season, the asymmetry is limited to the outer core (34 knot wind radii) of the storm over AS and only in very severe cyclonic storm (VSCS) stage and no significant asymmetry in TCs over the AS during post-monsoon season. The outer core winds are significantly asymmetric in all stages of intensity of TCs over the BOB during pre and post-monsoon seasons. The wind distribution in the inner core (wind radii of 50 and 64 knot threshold) is symmetric around the centre of the TC in both the seasons over AS, post-monsoon season over BOB and in case of VSCS or higher intensity TCs during pre-monsoon season over BOB. Similar to western-north Pacific, low level environment like enhanced cross equatorial flow and relative humidity in lower and middle troposphere determines the size and asymmetry in outer core wind.
The case study of the tracks and energy of Enhanced and Unique Cyclonic Activity during 2013 in the context of fluid dynamical source and sink

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It is a review work of the paper published in the Journal Mausam entitled “Ocean Atmospheric Coupled Model to Estimate Energy and Path of Cyclone near the Coast” on the case study of the Enhanced and Unique Cyclonic Activity during 2013 in the Bay of Bengal. The present study of tracks and energy and land fall of Enhanced and Unique Cyclonic Activity during 2013 have been made on the context of its fluid dynamical energy. Here it has been done considering fluid dynamics of atmosphere. In this review work, it has been considered that the Eye of the cyclonic system that consist of fluid dynamical source and fluid dynamical sink at a small distance apart thus constitute the fluid dynamical doublet of the cyclonic system. This fluid dynamical doublet represents the energy of the cyclones considered. It has been observed in this review work that the said energy for the cyclones were always following the rules of the products of some parameters dealing with the distance of the Eye of the cyclone from seashore and zonal current. In this review work, it is also depicted that landfall of the cyclone follows the rules according to the fluid dynamical energy which were theoretically well established in the said entitled paper.
Environmental factors responsible for the Enhanced Tropical Cyclone Activity over the Bay of Bengal during the post monsoon season of 2013

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The tropical cyclone (TC) activity over the north Indian Ocean is mainly observed in two seasons, the pre-monsoon and post-monsoon seasons. During the 2013 post monsoon season, an enhanced TC activity was observed. During the season, six low pressure systems formed, out of which three were very severe cyclonic storms and one severe cyclonic storm.

In this paper, we examine the environmental factors responsible for the enhanced TC activity during the 2013 post monsoon season. The analysis with the global climate data suggests, an active anomalous low level trough extending from central India to west Pacific across the Bay of Bengal in association with low vertical wind shear. SSTs over the Bay of Bengal just before the seasons were above the threshold of TC genesis. The oceanic heat content over the Bay of Bengal was on above normal during the season, which is consistent with the on-going warming trend of the north Indian Ocean.

In this study, the relationships between TC activity and the global forcings like El Nino/Southern Oscillation (ENSO), Indian Ocean Dipole and Quasi Biennial Oscillation (QBO) phases were also revisited.
Role of Large Scale Environment for enhanced cyclogenesis/ their intensification

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The fact that the tropical cyclone (TC) frequency is increasing over Bay of Bengal in the recent decades particularly for the month of May and November has been well documented by many studies (Singh et al., 2000, Niyas et al., 2009 and many others). However a consensus about the reason behind such increasing trend has yet to be reached. There are hypothesis of influence of aerosol modulating the solar radiation and finally weakening the vertical wind shear over the region and helping in the increasing frequency of TC (Evans et al. 2011) but such theories have been questioned by Wang et al. (2012). A very recent study by Balaguru et al. (2014) has actually emphasized that changes in environmental parameters are responsible for the observed increases in TC intensity. They have suggested that Sea Surface Temperature and upper ocean heat content are responsible behind such increase in TC frequency over Bay. The large scale moist static energy (MSE) increase has facilitated the increased cyclogenesis. We have noticed similar increase of MSE over Arabian sea also. Although SST, ocean heat content and large scale MSE show a clear indication that may be attributed to increased cyclogenesis, the reason behind weakening of wind shear is still not clear. To understand these processes, we have carried out few experiments to understand the role of aerosol, which shows that up to certain range of aerosol number concentration (1 x E103 cm^{-3}) perturbation, the intensity of cyclone increases but high concentration causes a TC weakening. Increased TC activity of 2013 needs to be understood not as an isolated case but as a part of the systematic large scale Ocean-Atmosphere changes. This can be done by carrying out suitably designed numerical experiments.
The influences of ENSO on tropical cyclone activity in the Bay of Bengal during October–December

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Tropical Cyclones (TCs) in the Bay of Bengal (BoB) occur more frequently in the months of October–December (primary season) and April–June (secondary season). Considering the dense population in the BoB rim countries, particularly along the coastal belt, TCs which form in the BoB can create catastrophic destruction when they make landfall. Hence, the understanding of the background environmental conditions which lead to inter-annual variability of TCs characteristics (frequency, intensity, genesis, rapid intensification (RI)) in the BoB may be useful for TC operational and coastal disaster management agencies for better preparedness and mitigation measures. Further, such details will be useful for improvement in model simulation of TC life cycle in the study region.

The El Niño-Southern Oscillation (ENSO) and Madden-Julian Oscillation (MJO) are the dominant modes of tropical coupled oceanic-atmospheric variability on interannual and intraseasonal time scales. The phase locking of ENSO can be observed most readily as the peak of ENSO events tend to occur during October-January. During this ENSO peak, the impacts are the strongest and most widespread, when the water temperature reaches its annual maximum in central Pacific. Hence, ENSO may significantly influence the environmental conditions in the BoB during the primary TC peak season than secondary TC peak season.

The MJO and their combined influence on TC activity (frequency, genesis location, and intensity and Rapid intensification) in BoB during the primary TC peak season (October–December) are studied. The study shows that during primary TC peak season, accumulated cyclone energy in the BoB is negatively correlated with Niño3.4 sea surface temperature anomaly. Under La Niña regime number of extreme TC cases (wind speed >64 kt) increases significantly in the BoB during the primary TC peak season. Moreover, the RI of TC cases are higher in La Niña than El Niño regime during the primary TC season in the BoB. The analysis further shows that negative Indian Ocean dipole year is also favorable for extreme TC activity in the BoB during the primary TC peak season. The genesis location of TC shifts to the east (west) of 87°E in the BoB during La Niña (El Niño) regime. In addition, when the MJO is active over the BoB (phase 3–4; characterized by enhanced convective activity in the BoB) under La Niña regime, environmental conditions were more conducive for enhancement of TC activity and RI of TCs compared to corresponding MJO phase under El Niño regime.

An empirical index, called genesis potential index (GPI), is used to quantify the relative importance of four environmental parameters responsible for the modulation of TCs characteristics. The combined effect of enhancement (reduction) in mid-tropospheric humidity (primary factor) and relative vorticity (secondary factor) played a major role in the enhancement (reduction) of the TC activity under La Niña (El Niño) regime. Increase in mid-tropospheric humidity and reduction in vertical wind shear were identified as the primary and secondary factors enhancing the likelihood of RI of TCs in the BoB during phase 3–4 of MJO under La Niña regime. Further, the role of accumulated tropical cyclone heat potential (ATCHP) on the RI of TC during primary TC season is also investigated. Analysis demonstrates that ATCHP is large for TCs which undergo RI compared to TCs not undergoing RI.
The influence of Madden Julian Oscillation on the Bay of Bengal Tropical cyclogenesis during the year 2013

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The year 2013 witnessed both relatively weak and very severe cyclonic storms during pre and post monsoon period in the Bay of Bengal region. The prominent Cyclonic storms which affected the Indian Peninsula during the year 2013 are Viyaru (Mahasen(10-16th May)), Phailin (8-14th Oct), Helen (19th -20th November), Lehar (24th to 28th November) and Madi (6-13th December). Apart from higher sea surface temperatures, weak wind shear that had been the primary causative factors, Madden-Julian Oscillation (MJO) was also one of the many factors that contributed to the cyclonic activity during period. The Madden-Julian Oscillation (MJO) is the major fluctuation in tropical weather on weekly to monthly timescales. The MJO can be characterized as an eastward moving ‘pulse’ of cloud and rainfall near the equator that typically recurs every 30 to 60 days. The MJO is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall, observed mainly over the Indian and Pacific Ocean.

An attempt has been made to correlate the role of the Madden-Julian Oscillation (MJO) with the genesis of the cyclonic storms that occurred during the year 2013 in the Indian Ocean/Bay of Bengal region. The passage of the “active” phase of the MJO through a region enhances the convective activity locally. It is also seen that when cyclones are formed, a strong index strengthens Tropical cyclogenesis, The strength/amplitude of the MJO is determined using RMM1 and RMM2. RMM1 and RMM2 are mathematical methods that combine cloud amount and winds at upper and lower levels of the atmosphere to provide a measure of the strength and location of the MJO. It is seen that Tropical cyclogenesis is likely near the peak of the MJO. Also P3 and P4 phases of MJO have the favorable conditions for cyclogenesis in BOB. It is also observed that when the enhanced convection of MJO is over the maritime continent and the adjoining eastern Indian Ocean, it creates the highest favorable environment for cyclogenesis in the Bay of Bengal.
Sea Surface Temperature anomaly over Nino 3.4 region and number of tropical storms over Bay of Bengal and Pacific Ocean

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Tropical storms (TSs) are the most devastating weather phenomena that cause large number of human casualties and loss of property. To understand the genesis of TSs, it is necessary to understand the important factors that are necessary for its genesis. Sea surface temperature (SST), thermodynamically unstable atmosphere and weak vertical wind shear are some of the important components. The genesis of TSs is a complex phenomenon, as it is influenced by several coupled ocean atmospheric phenomena such as El-Nino, El-Nino Modki, Indian Ocean Dipole and Madden-Julian oscillation. The El-Niño is manifested as an anomalous warming of the eastern and central tropical Pacific Ocean and La-Niña refers to an anomalous cooling of the eastern and central tropical Pacific Ocean. The SST of Niño 3.4 region (170°W to 119°W and equator to ±5° north and south) is commonly used as threshold, if departure from normal e+0.5°C and d-0.5°C is El-Nino and La-Nina respectively.In present study last 54 years (1960 to 2013) data have been analysed for Northwest Pacific Ocean and North Indian Ocean (NIO). In case of Northwest Pacific Ocean it was observed that the average frequency (Average of last 54 years) of Tropical systems over pacific Ocean is 73 (including Tropical Depression) and average of systems which attains typhoons intensity are 47. Similarly for north Indian Ocean the normal frequency of total number of tropical systems (including Tropical Depression) is 5.9 and average of systems which attains cyclonic storm intensity are 3.7. The most of the typhoons formed in the Northwest Pacific Ocean are during May and November and in NIO the tropical storms occur more frequently in the months of October–December (primary TC peak season) and April–June (secondary TC peak season). Relatively high (28–30°C) sea surface temperature (SST), thermodynamically unstable atmosphere, and weak tropospheric wind shears are favorable for the TC development during these months. Thus we tried to correlate El-Nino 3.4 region SST anomaly data for May to November with frequency of TSs in northwest Pacific Ocean and April to June and October to December with frequency of TSs in NIO. In case of Tropical systems (Tropical Depressions, Total storms, Typhoons& Super Typhoons) originated in North West Pacific Ocean, it was found that in the above normal frequency of 26 years, 14 years were El-Nino years, 6 La-Nina and 6 neutral years. In below normal frequency of 12 years, 4 were El-Nino, 7 La-Nina and 7 were Neutral years. Similarly in cases of tropical storms(Total storms, Typhoons& Super Typhoons ), in the above normal frequency of 14 years, 8 years were El-Nino years, 4 La-Nina and 2 neutral years. In below normal frequency of 18 years, 4 were El-Nino, 13La-Nina and 1 were Neutral years. In NIO in cases of tropical systems (tropical depressions and tropical storms) in above normal frequency of 14 years, 5 were El-Nino, 5 La-Nino and 4 were neutral years and in below normal frequency of 21 years, 9 were El-Nino, 8 La-Nina and 4 were Neutral years. In case of TSs, it was found that in above normal frequency of 16 years, 7 were El-Nino years, 6 La-Nina and 3 neutral years and in below normal frequency of 12 years, 3 were El-Nino years, 5 La-Nina and 4 neutral years.

Thus we may conclude that frequency of Tropical Storms over Northwest Pacific Ocean are higher in El-Nino years and lower in La-Nina years. This relation is not significant in North Indian Ocean. There is no one to one relation in frequency of TSs over north Indian Ocean with SST anomaly in Nino 3.4 region.
Our study investigated the possible correlation between large-scale heat fluxes, vertical motions and intensity change associated with landfall of Severe Cyclonic Storm. A severe cyclonic storm Helen crossed Andhra Pradesh coast close to south of Machilipatnam (near lat. 16.1°N and long. 81.2°E) between 0800-0900 UTC of 22nd Nov. 2013 as a cyclonic storm with a wind speed of 80-90 kmph gusting to 100 kmph. The data for sea level pressure and wind speed were obtained from Cyclone Warning Division, India Meteorological Department, for the period November 19 to 23, 2013. We developed an empirical model and a program using C++ to calculate surface potential temperatures and heat fluxes using the data sources mentioned. The results show maximum large-scale heat fluxes of 4960 W/m² during landfall with a central pressure of 990 mb on 21 November 2013. We also used the NCAR Numerical model (WRF/ARW) with data assimilation to ascertain our model’s performance with respect to hurricane tracking and intensities associated with cyclone Helene. Results from our model’s are in good agreement with the actual observations. Our model also reproduced the precipitation, intensity change and track associated with cyclone Helene. The model presented could form an early warning system to predict land falling tropical cyclones and associated severe weather over the Bay of Bengal.
Recent initiatives for FDP Planning follow up meetings between Indo-US groups have culminated to the organizational planning of the FDP over Bay of Bengal on the lines of NOAA-HRD and NCARs experience on cyclone probing over the Atlantic region. The Pilot Phase of the programme started in 2008 based upon the available observational, NWP and communication infrastructure. It continued in 2009, 2010, 2011 and 2012 with the upgraded observational network and numerical weather prediction (NWP) modelling system. Based on the experience of these past pre-pilot phases of FDP, the implementation plan was modified for the year 2013. The objective of the programme was met by conducting a joint observational communication and NWP effort by several institutes in the country during the period 15Oct.-30 Nov. 2013. There were Intensive Observational Phases (IOP) within this period tuning actual cyclone events. The overall campaign will be monitored and guided by a Weather Monitoring and Advisory Group (WMAG) at IMD, New Delhi.

Four cyclonic storms formed during FDP period (October to December 2013). These were Very Severe Cyclonic Storm (VSCS) PHAILIN (08-14 October 2013), Severe Cyclonic Storm ‘HELEN’ (19-23 Nov 2013), Very Severe Cyclonic Storm ‘LEHAR’ (23-28 Nov. 2013) and Very Severe Cyclonic Storm VSCS ‘MADI’ (06-13 December 2013). Generally preparation of bulletin and issuance of IOP Cyclone take place during 15 October to 30 November. But it was extended due to the formation of VSCS ‘MADI’ on 06th December and continued till 13 December 2013.

The FDP programme helped in better monitoring and prediction of cyclones as it minutely recorded daily cyclogenesis features including synoptic and environmental features, Satellite and radar observations and NWP Models analysis/forecast based on a check list and roadmap for the purpose. The Environmental features consist of Gray’s parameters like Sea Surface Temperature, Ocean thermal Energy, Relative Vorticity at 850 hPa, Lower level convergence, Upper level Divergence, Wind Shear, Wind Shear Tendency, Upper tropospheric ridge and M.J.O. Index, moist static stability, middle level relative humidity etc. NWP Models included IMD GFS Model, IMD WRF Model, NCMRWF GFS Model, UK Model, JMA Model, ARP Model and ECMWF Model. The characteristic features of FDP-2013 alongwith the lessons learnt are presented and analysed in this paper.
Rossby Radius Ratio: A Possible Predictor of Cyclogenesis over World Ocean Basins

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Present study aims at identifying a threshold value of Rossby Radius Ratio (RRR) as a possible predictor of cyclogenesis over world ocean basins. RRR is the ratio of Rossby Radius of Deformation (RROD) and the average radius of the system. The ocean basins considered are North Indian (NI), South Indian (SI), North Atlantic (NA), South Atlantic (SA), West Pacific (WP), East Pacific (EP) and South Pacific (SP). The dataset used include the average radius of cluster, cloud top height in km, latitude and longitude. The total data is divided into two sets. The first set contains the developed tropical cloud cluster (TCC) and the second set comprises the non-developed TCC. The Brunt-Viasala frequency (BVF), RROD and RRR are computed for each cluster. The statistical skill score analysis is implemented to determine a threshold value of RRR for a TCC to grow into a cyclone over the ocean basins. The result shows that the threshold values of RRR for NA, NI, EP, WP, SP and SI are 270, 450, 280, 270, 250 and 360 respectively. The analyses further show that the threshold value of RRR for SA is not significant. The receiver operating curve (ROC) shows that the possibility of cyclogenesis with the threshold value of RRR is high over NI basin. It is further observed that RRR for NI is positively correlated with RRR for WP. The inter-annual variation shows that the cyclogenesis over NA varies inversely with sea surface temperature (SST) anomaly over NINO 3 and NINO 3.4 regions whereas cyclogenesis over WP and EP varies inversely with Trans-Nino index (TNI). Spatial distribution shows that SST anomaly over WP may be considered as a favorable predictor of cyclogenesis over WP.
Intraseasonal and Interannual variation of Accumulated Cyclone Energy and Power Dissipation Index over North Indian Ocean

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Tropical cyclone accumulated cyclone energy (ACE) and power dissipation index (PDI) have exhibited strikingly large global intraseasonal and interannual variability during the past years. The ACE and PDI which are proportional to square and cube of the maximum wind speed respectively use the maximum sustained wind speed over time to quantify cyclone activity by season. These indices are considered important to analyse the impact of the climate change on cyclone activity, as these indices consider frequency, duration and intensity of the cyclones over an Ocean basin. While cyclone ACE, which is otherwise known as cyclone destruction potential, is associated with the evolution of the character of observed large-scale climate mechanisms including various large scale features, PDI is a measure of tropical cyclone threat as loss is related with cube of the wind speed over the total storm area. The ACE also provides a measure of the overall impact of cyclones on the earth’s climate. Considering the recent years, the ACE and PDI were significantly higher in 2013, especially over the Bay of Bengal during post-monsoon season (October-December). There are many studies world-wide for different Ocean basins on the ACE and PDI. However, these studies are limited over the North Indian Ocean. Considering all these, a study has been undertaken to analyse the intraseasonal and interannual variation of ACE and PDI for the north Indian Ocean as a whole and Bay of Bengal and Arabian Sea based on the data of 1990-2013 (24 years). Large scale features like EL-Nino and Indian Ocean dipole have also been analyzed.

The results show that both the annual ACE and PDI were maximum in 2013, which experienced three very severe cyclonic storm (VSCS), all over Bay of Bengal in post-monsoon season. It was followed by 2007 which witnessed one VSCS, SIDR (10-16 November) and another super cyclone, Gonu (1-7 June) and 1999, which witnessed one VSCS (10-16 October) and Odisha super cyclone (25-31 October). However, the linear trend analysis indicates significant decreasing trend in ACE & PDI over Arabian Sea during post-monsoon season and over Bay of Bengal and North Indian Ocean as a whole during premonsoon season, though there is no significant trend in the frequency of cyclones during the same period. Considering the relationship with EL-Nino, ACE and PDI are significantly less in postmonsoon season over Bay of Bengal during warm anomaly years than in cold anomaly and normal years.
Cyclonic activity in the SAARC Region during 2013 and the impact of Climate Change on South Asia

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In the South Asia region, Tropical Cyclones have increased both in frequency, intensity and magnitude in the recent past. This can be clearly attributed due to Climate Change. The Intergovernmental Panel on Climate Change (IPCC) argues that Tropical Cyclones and other extreme events are increasing globally due to greenhouse gas emissions. The climatological conditions under which Tropical Cyclones occur have been well established. These include a requirement for warm sea surface temperatures, low vertical wind shear and a large scale relative vorticity in the lower layers of the troposphere. It is also well established observationally that over the past several decades the tropical sea surface temperatures over most tropical ocean basins have increased by between 0.25 – 0.5 degrees Centigrade. The most likely primary cause for this is long term increase in greenhouse gas concentrations. It is expected that tropical sea surface temperatures will further increase by an even greater amount in the near future. The link between Climate Change and Tropical Cyclones remains controversial. This may be due to the fact that Cyclones are subject to long term cycles. Hence it may be difficult to detect changes in underlying frequencies, intensities and severity.

Though Tropical Cyclone formation and intensity change and tracking are difficult to predict, the SAARC member countries like Bangladesh, India, Pakistan and Sri Lanka have made significant improvements in forecasting Cyclones. However, there is a need to further strengthen and assimilate R&D output from various organization and institutes in the South Asia region into operational system for further improvement of cyclone forecasting in the SAARC region. There is also a need to further strengthen the mechanism of exchange of relevant data among the various departments in the countries of SAARC region.

This paper briefly discusses the Cyclonic activity in the South Asia region during 2013 and the impact of Climate Change on South Asia and the various measures needed for further improvement in observation, exchange of data, modeling and products dissemination and mechanisms to strengthen and assimilate R&D output from various organizations/institutes in the South Asia into operational system for further improvement in cyclone forecasting and tracking.
Seasonal Forecast of Tropical Cyclogenesis over Bay of Bengal during Post-Monsoon Season

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Over the North Indian Ocean and particularly over the Bay of Bengal, the post-monsoon season from October to December is known to produce tropical cyclones, which, cause damages to life and property over many countries surrounding the Bay of Bengal. Although, there have plenty of work done with respect to the seasonal forecast of tropical cyclone frequency over the other two Ocean basins such as the Atlantic and Pacific there have been very limited work done in the area of seasonal forecast of frequency of tropical cyclogenesis over the North Indian Ocean. Earlier studies have shown that the seasonal forecast of TC frequency over the north Indian Ocean is usually poor in dynamical models. In view of that an attempt is made to develop am empirical model for the prediction of TC frequency over the north Indian Ocean during the post monsoon season.

The relationship of frequency of tropical disturbances (TDs) over BoB during October to December (OND) with the Sea Surface Temperature during June to September (JJAS) and OND season, Sea level pressure, strength of upper level easterly jet and low level westerly jet; strength of Australian High during the peak monsoon months of July and August and frequency of monsoon disturbances during JJAS are analysed during the period of 43 years from 1971 to 2013. Based on significant relationship 5 parameters were selected to develop a Principal Component Regression (PCR) model with cross validation window of 1 year. These parameters are (i) meridional wind speed over the Indian Ocean at 850 hPa during Jul-Aug, (ii) strength of U200 during Jul-Aug, (iii) strength of monsoon westerly at 850 hPa during Jul-Aug, (iv) Sea Level Pressure over Australian high during Jul-Aug, (v) SST over the northwest Pacific and (vi) Nino4 SST during July-August. The PCR model was developed for a training period of 40 years (1971 to 2010) and the latest three years are used for validation. The performance of the PCR model is found to highly significant both for the deterministic forecast and probability forecasts (Fig. not shown). The CC between forecast TD frequency and observed TD frequency is found to be 0.77 during the period with RMSE and mean absolute error ≤1. With respect to the category forecast the Hit score is found to be about 63%.
Prediction of Post-monsoon Seasonal Cyclonic Activity over North Indian Ocean

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Tropical cyclones (TC) cause major disasters including many human deaths and great loss of property mostly in coastal areas. Process contributing to inter-annual variability of TC activity are broadly classified into thermal and dynamical process. A number of attempts were made earlier to predict seasonal TC activity over various oceanic basins. Landsea et. al (1998) developed regression model for forecasting Atlantic Hurricane activity. Chan et. al (1998) developed an operational statistical model for seasonal tropical cyclone activity over West North Pacific and South China Sea using the climate indices like ENSO. For Indian region works were carried out by Sikka (1972), Rajeevan and Butala (1990) and Krishnakumar et al. (2007). While there are inter-annual variability in the number of TC at the same time climate indices and environmental conditions influence variability in the life period of TC. In the present study, statistical prediction of number of days of cyclonic activity during post monsoon season, which is the primary season of TC genesis, is attempted using well known climate indices and regional circulation features. Potential predictors are identified using correlation analysis and optimum number of predictors are chosen using screen regression technique. A qualitative prediction model using conditional means and quantitative model based on multiple regression for seasonal cyclonic activity were developed based on the data during 1971-2000 and their validation for the period 2001–2013 are presented.
Impact of cyclonic disturbances on the changing rainfall pattern along the east coast of India: 1891-2011

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This study has examined the temporal variation in seasonal & annual rainfall along the east coast of India for the period 1891-2011. Study also examined the temporal variation in the frequency of cyclonic disturbances (CDs) that crosses the east coast and its impact on seasonal & annual rainfall of the region. For this purpose, monthly rainfall of the sub-divisions along the east coast namely, Gangetic West Bengal (GWB), Orissa, Coastal Andhra Pradesh (CAP) and Tamilnadu & Puducherry (TN) has been collected from IITM Pune website for period 1891-2011. Afterwards, monthly rainfall series for the entire east coast has been calculated by taking the average of monthly rainfall of all the sub-divisions. The data of CDs (includes Depression/Deep Depression, Cyclonic Storms & Severe Cyclonic Storms) that crossed east coast during 1891-2011 has been constructed from Cyclone E-Atlas of IMD. Normality of the data is checked by using Kolmogorov-Smirnov test. The trend analysis to all the series are calculated by using the linear regression method and Mann-Kendall test. The study shows a significant (confidence level more than 95%) increasing trend in annual rainfall along the east coast. In sub-division based annual rainfall analysis, significant increasing trend is observed over CAP and no significant change is observed over GWB, Orissa & TN. In CDs annual frequency analysis, insignificant increasing trend is observed in frequency of severe cyclonic storms (SCS) and highly significant decreasing trend is observed in the frequency of CDs as a whole that crossed east coast. Study also indicates that frequency of CDs that crosses the east coast are significantly correlated with annual rainfall along the east coast. In sub-divisionwise analysis, significant correlation is observed in frequency of CDs that crossed Orissa & CAP with respective sub-divisional annual rainfall. Significant correlation is also observed in east coast as a whole and all the sub-divisions pre-monsoon rainfall with frequency of CDs crossing respective coasts except GWB, where the major rainfall activity mainly occurs due to pre-monsoon thundershower activity. In post-monsoon season, significant correlation is also observed in east coast as a whole and all the sub-divisions rainfall with frequency of CDs crossing the respective coasts except TN, where the rainfall activity in this season mainly occurs due to northeast monsoon.
Prediction of TCs in 2013 over Bay of Bengal using state-of-the-art mesoscale models

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During the year 2013, five tropical cyclones (TCs) developed over Bay of Bengal during pre- and post-monsoon seasons. Out of 5 TCs, 3 intensified into Very Severe Cyclonic Storm (VSCS) such as Phailin (8-14 Oct), Lehar (23-28 Nov) and Madi (6-13 Dec). Helen (19-23 Nov) intensified into a Severe Cyclonic Storm (SCS) and Viyaru (10-16 May) into Cyclonic Storm (CS). Two state-of-the-art mesoscale models, such as National Center for Atmospheric Research (NCAR) version of Weather Research and Forecasting (ARW), and the National Oceanic Atmospheric Organizations (NOAA) Hurricane WRF (HWRF) system, were used to predict 2013 cyclones.

In spite of the large spread in movement of the systems in 4–5 days lead time forecast by different operational agencies, the HWRF and ARW models produced more accurate landfall forecast for all these systems. Though ARW model was good for track predictions, intensity was underestimated because of poor representation of initial vortex. The role of the HWRF were appreciable for track, intensity, size, and structure i.e., asymmetry during and after landfall. For example, during Phailin the HWRF model suggested that the northern parts of the Odisha state would receive heavy to very heavy rainfall (~40 cm) during landfall that was validated by the observations after the event. The IMD also issued an extremely heavy rainfall (25 cm or more in 24 h) warning for 12 and 13 October 2013. Though ARW model also suggested similar rainfall intensity, the location is not accurate when compared with IMD observations. A dynamical storm surge model was one-way coupled with the ARW model to produce a longer-range surge forecast (72–96 hr). This dynamical approach was able to predict the surge of 3 m well in advance of landfall (with 72 h lead time) that is in acceptable agreement (considering 72 h lead) with the observed surge of 2.5 m at Gopalpur during IMD post-survey analysis.

Additional experiments have been conducted using ARW model to study the impact of 6-hrly updating NCEP SST. It is noted that all the above mentioned real time runs used fixed SST during model integration/forecast. Results highlight the importance of SST for intensity prediction. The intensity of Phailin is improved by 5-7 ms⁻¹ in varying SST runs as compared to fixed SST runs. This positive impact is significant in case of severe or more intensity cyclones. It is also observed that NCEP product underestimates the SST as compared to SST analyses (from GODAS) provided by INCOIS which is more realistic when compared with that of SSMI. Experiments underway to study the impact of INCOIS-SST on intensity predictions.
Evaluation of operational Short Range NWP Tropical Cyclone forecasts over North Indian Ocean (NIO)

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During the last few decades there have been significant advances in tropical cyclone (TC) track forecasts along with the remarkable progress of numerical weather prediction (NWP) systems. India Meteorological Department (IMD), which is a World Meteorological Organization (WMO) designated Regional Specialized Meteorological Centre (RSMC), provides the official tropical cyclone forecasts and warnings over the North Indian Ocean (NIO). The current TC operational model in use at the IMD, New Delhi is the Hurricane Weather Research and Forecast (HWRF) with 27/9 km horizontal resolution with 42 vertical levels, apart from, global and regional models like the Global Forecasting System (GFS) and the WRF-ARW and statistical models MME, GPP, SCIP, RI for track and intensity prediction. IMD operationally running Quasi-Lagrangian Model (QLM) since year 2000 for its operational track forecast. The QLM during 1998-2008 average track errors are shown 152 km for 24 hours, 235 km for 48 hrs and 375 km for 72 hrs. However, QLM is only track prediction model which has limitation in prediction of intensity. Based on advancement of HWRF modelling system over other basins, recently, IMD adapted HWRF model (based on EMC, National Centers for Environmental Prediction (NCEP), USA) for its operational track and intensity forecast guidance to RSMC, New Delhi over NIO region in July 2011. As part of validation of the model, case studies of 9 major cyclonic storms formed during 2010-13 over the Bay of Bengal and Arabian Sea were undertaken to test the ability of the model for Indian Seas. The model was integrated for 5-days forecast with basic input from India Meteorological Department (IMD) Global Forecast System (GFS) spectral fields. The model basic fields, track and intensity errors are evaluated. The average track errors for 9 cases had shown 83 km in 12 hrs, 135 km 24 hrs, 176 km in 36 hrs, 186 km for 48 hrs, 233 in 60 hrs and 319 km for 72 hrs. The HWRF track forecast errors show an improvement 7% in 36 hours, 27% in 48 hours, 25% in 60 hrs and 15% in 72 hours over IMD operational forecast. Also the HWRF model with 3 km nested resolution shows a significant improvement in track forecast with 12 to 46 per cent over 9 km resolution. In addition to HWRF, as part of WMO Program to provide a guidance of tropical cyclone (TC) forecasts in near real-time for the ESCAP/WMO Member Countries based on the TIGGE Cyclone XML (CXML) data, IMD implemented JMA supported software for real-time TC forecast over Bay of Bengal/Arabian Sea. Under this program, deterministic and ensemble track and intensity forecast from ECMWF, NCEP and UKMO are available from depression stage onwards. The evaluation of these models based on 2010-13 TCs shows that the deterministic ECMWF, NCEP model errors over Bay of Bengal varies from 50 to 250 km in 72 hours forecast length. Also the magnitudes of cross track (CT) errors are less compared to along track (AT) errors for all forecast lengths. Hence the models are more accurate in predicting TC landfall location than landfall time over Bay of Bengal. Over Arabian Sea, the ECMWF, UKMO, NCEP has large Track errors in both Deterministic and Ensemble Forecasts with 60 to 500 km in 72 hours forecast length. The High Resolution models (ECMWF, HWRF with 3km Res.) shows only marginal improvement in intensity forecast of 5 to 8 per cent over IMD operational forecast in 48 hours to 72 hours. The detailed track verification statistics and intensity of these models with the special emphasis on TCs formed during 2013 are discussed in detail.
Predictability of Global Numerical Weather Prediction Models

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During last two decades, the accuracy of weather prediction has improved significantly through improvement in understanding of underlying physical and dynamical processes, quality and quantity of meteorological observations, especially from satellites and availability of progressively increasing computing power. However, the predictability of day-to-day weather patterns over the Indian monsoon region is still limited to 4-5 days. The NCMRWF Global Forecast System (NGFS) has a resolution of approximately 22 km in horizontal and has 64 levels in the vertical. The vertical coordinate used is a hybrid sigma-pressure which is terrain following (sigma) near the lower levels and constant pressure levels in the stratosphere and beyond. The associated 3-D VAR data assimilation system (namely, Gridpoint Statistical Interpolation [GSI]) which is used to initialize the global model has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geostationary satellites. Ensemble forecasting is a practical way of estimating forecast uncertainty and making probabilistic forecasts. The NCMRWF Global Ensemble Forecast System (NGEFS) has a resolution of T190L28. The system features a control run initialized using the analysis of the deterministic system (T574L64) and 20 members obtained using the perturbed initial conditions. The perturbation method is the ensemble transform with rescaling (ETR). Ten day probabilistic forecasts are generated from NGEFS daily.

NCMRWF is now focused on the development of the seamless NCUM (NCMRWF Unified Modelling) system for predicting/simulating monsoon from days to season under the National Monsoon Mission (NMM) programme of MoES. The NCUM's dynamical core uses a semi-implicit semi-Lagrangian formulation to solve the non-hydrostatic, fully compressible deep-atmosphere equations of motion (Davies et al., 2005). The primary dry atmospheric prognostics are the three-dimensional wind components, potential temperature, Exner pressure, and density, whilst moist prognostics such as the mass mixing ratio of water vapour and prognostic cloud fields are advected as free tracers; the same is also true of other atmospheric loadings. The NCUM is a grid-point model and has a resolution of N512L70 (approximately 25 km in the mid-latitudes and 70 vertical levels). It has a 4-D VAR assimilation system which has a huge advantage as it extracts more information from observations consistently, in a better way. Ten day forecasts are generated everyday from both the NGFS and NCUM systems with the initial conditions of 00UTC. The magnitude of the 850hPa wind vector (RMSEV) of the day 03 forecasts against the radiosonde observations (fig. 1) over India from the NGFS (blue) and the NCUM (pink). The overall decrease in the RMSEV can be attributed to the increase in the resolution of the model, increase in the amount of data being assimilated and improvements in data assimilation techniques.

Fig. 1 The performance of the short and medium range predictions made by NCMRWF during 2013 will be presented in the workshop.
Performance of NCMRWF model TC track forecasts during 2013

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In the North Indian Ocean basin, cyclones are most common from April to December, with peaks in May and November. On an average there are approximately 4.8 tropical cyclones observed in the NIO every year. A majority of these cyclones are formed in the Bay of Bengal and make landfall on the east coast of India causing extensive damage to life and property. Timely prediction of cyclone track and the landfall location as well as time is therefore a top priority for weather forecasters in these regions.

During May-December 2013, there were 5 tropical cyclones observed in the Bay of Bengal namely: Viyaru (May 10-17), Phailin (Oct 4-14), Helen (Nov 19-23), Lehar (Nov 23-28) and Madi (Dec 6-13). This report deals with the real time prediction of these cyclone tracks by the NCMRWF Global Forecast Systems (NGFS, NCUM and NGEFS). Along with this a verification of the tracks based on average forecast track error in comparison with the observed track is also presented.
Post monsoon 2013 - Tropical Cyclones in Bay of Bengal: ECMWF based Extended Range Operational Forecasts

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In Bay of Bengal, 2013 Post-monsoon cyclone season was very active and observed three very severe cyclonic storms, one severe cyclonic storm and one tropical depression. Extended Range Tropical cyclone genesis and track predictions based on a sophisticated analysis of the ECMWF Variable Ensemble Prediction System (1-15 day), was used for operational forecasting of Very Severe Cyclones Phailin, Helen and other two cyclones (Lehar and Madi).

Ensemble Prediction System, a Bayesian-based genesis risk approach was used with ECMWF forecast products and utilizing historical analysis of the large-scale environment under which tropical cyclones have formed. Sea Level Pressure, Mid -Levels Moisture availability, 850-500 hPa Shear, 850-200 hPa Shear, 850-500 hPa Zonal shear, 850-200hPa Zonal shear, 950 to 200 hPa Vorticity, etc from ECMWF Operational model fields that are being used in a study to examine their forecast ability for tropical cyclogenesis in the Bay of Bengal. In prediction system, tropical cyclone identification and bias-corrected tracking scheme is applied to each of the 51 unique ensemble members of the ECMWF forecast. This allows for the creation of more reliable probabilistic track density forecasts and a dynamic cone of uncertainty at a basin-wide level. Ensemble clustering techniques are used to identify the highest probability track of both pre-genesis and existing tropical cyclones. Tropical cyclone track density forecasts uses the tracking scheme and the same is applied to each ensemble member of the ECMWF forecast to create a track density forecast. A multi-model ensemble track density analysis is enabled by an interactive tool that allows the user to select track groupings from available model forecasts.

Very Severe Cyclonic Storm (VSCS) PHAILIN (08-14 October 2013): On 30th September 2013, ECMWF Ensemble prediction system indicated the low pressure area genesis probability over North East Andaman Sea with 20% of reliability during 7th – 8th October. Subsequently probability increased to 80% on 3rd October and bias-corrected tracking scheme of the 51 unique ensemble members indicated the landfall over south coastal Orissa during 11 – 12th October. The system was first noted as a tropical disturbance on October 4, 2013 within the Gulf of Thailand, and on 6th October, it moved out of the Western Pacific Basin and emerged into the Andaman Sea on 7th October and moved west-northwest named Phailin on October 9, after it had developed into a cyclonic storm and passed over the Andaman and Nicobar Islands into the Bay of Bengal. Ensemble prediction system was able to predict the Phailin Cyclone genesis with lead time of 7 days. Phailin made landfall on 12th October, near Gopalpur in Odisha coast at around 2230 IST (1700 UTC). Ensemble track predictions showed 90% accuracy of landfall location with 9 days lead time.
Impact of Assimilating Scatterometers Winds on the Simulation of Tropical Cyclone Lehar by High Resolution Global NWP Model

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Tropical cyclone track forecast is one of the most challenging tasks in numerical weather prediction (NWP) mainly due to the scarcity of conventional observations over the ocean region where tropical cyclone occurs and evolves. Accurate knowledge of ocean surface wind fields is vital for the simulation and prediction of a tropical cyclone. Scatterometer is a unique sensor in determining ocean surface wind vectors, hence very crucial for accurate prediction of the tropical cyclone. Present study assesses the impact of assimilating both Ku-band Oceansat-2 and C-band ASCAT Scatterometers (SCAT) winds in NCMRWF Global forecast system at T574L64 resolution (NGFS) in the simulation of very severe cyclonic storm ‘Lehar’ formed over Bay of Bengal during 23rd to 28th November, 2013. ‘Lehar’ was simulated with (SCAT) and without (CTRL) assimilating scatterometers winds in NGFS. In SCAT run, along with the data used in CTRL, vector winds from OSCAT/ASCAT are also assimilated. To determine the location of the cyclone, relative vorticity maximum, geopotential height minimum, wind speed minimum and the minimum in MSLP are tracked. Assimilation of SCAT wind vectors in NGFS does not show much impact in the analysis of the cyclone position and intensity, however it shows improvement in the track predictions of the same.
Assimilation of OSCAT data in 4D-VAR System

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A four dimensional Variational (4D-Var) Data Assimilation system based on Unified Model (UM) is recently made available in India at National Center for Medium Range Weather Forecasting (NCMRWF), NOIDA. It has three main components viz, Observational Processing System (OPS), Varitional Analysis system (VAR) and the model and the data pre-processing system for the same were developed indigenously at NCMRWF. This whole system is named as NCMRWF Unified Model (NCUM).

India also has prestigious space programme and launching many Oceanographic and Meteorological satellites such as INSAT series, MeghaTropiques and Oceansat series. Ocean surface wind vectors derived from the Scatterometer, onboard of Oceansat-2 (OSCAT) is one of the useful observations from these satellite. The NCUM analysis system has no provision to handle the data from Oscat and it was developed recently. This study was carried out to test the impact of the Oscat data in particular and scatterometer data has whole on the assimilation and forecasting system. The results of experiment clearly demonstrate positive impact of the data over tropical regions. The study period includes the whole life period of very severe cyclone, Phailin. The results clearly proved that scatterometer data sets are very useful for NCUM system in simulating as well as in forecasting the cyclone with reasonable accuracy.
Impact of satellite radiance data assimilation on real time forecasting of tropical cyclogenesis

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One of the key question in the development of tropical cyclones is to understand how tropical cyclone evolves from meso-ã scale vortices in pre-genesis environment. The various dynamical mechanisms present in pre-genesis environment leads to development of mature tropical cyclone. Forecasting this development in pre-cyclogenesis environment is a challenging task because of multi-scale processes involved in this study. To resolve the development of meso-ã scale vortices, we have used mesoscale model WRF and assimilated satellite radiance data using 3D-var technique. Domain specific background error calculated based on two months model forecast using NMC method. The satellite radiances from satellites like Metop, Suomi NPP, NOAA-15,16,18,19 and surface and upper air observations are used in this study. The WRF model was used for 75 hour simulation using cold start run and GFS initial and boundary conditions. The tropical cyclones forecastsince seven days prior to first detection of tropical cyclones occurred over North Indian Ocean in the year 2013. The forecast run is carried out till the dissipation of the cyclone.

In this work, we have studied the impact of lead time for simulation of pre-genesis environment using data assimilation technique. The impact of data assimilation on simulating cyclones at various stages of cyclones will be also discussed. The analysis of model output is presented with the aim that it will be useful for early detection of tropical cyclogenesis.
During May-December 2013, there were 5 tropical cyclones observed in the Bay of Bengal namely: Viyaru (May 10-17), Phailin (Oct 4-14), Helen (Nov 19-23), Lehar (Nov 19-28) and Madi (Dec 6-13). The track error for the all the Tropical cyclones during 2013 have been investigated. Forecast track error is lower in NCUM forecasts with values less than 100 km upto 72 hours in case of Phailin as compared to NGFS while in case of Helen and Lehar cyclones; NCUM shows higher forecast track error as compared to NGFS with increasing lead time.

Rainfall forecast verification predicted by NGFS and NCUM for cyclones during 2013 after the landfall has been carried out using the Contiguous Rain Areas (CRA) technique. Phailin and Madi tropical cyclones persisted over land upto 24 hrs to 72 Hrs after hitting the coast. So the rainfall forecast verification for only these two cyclones has been studied. For Tropical cyclone Phailin, NCUM forecasts have higher (lower) correlation and ETS (RMSE) as compared with NGFS. The NGFS forecast has higher RMSE (68.8 mm/day) with main contribution form displacement error (54.5%) while the RMSE in the NCUM forecast is lower (51 mm/day) with main contribution from the pattern error (53%) in Day-3 forecast. Further, CRA analysis based on different thresholds (1, 10, 20, 40 and 80 mm/ day) has also been carried out.
Objective Technique for Monitoring the Cyclonic Circulation in Global Model Analysis and Forecasts at NCMRWF

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An objective technique is used for monitoring the cyclonic features such as center of the cyclonic circulation, maximum wind and its location in National Centre for Medium Range Weather Forecasting GFS (NGFS) analysis as well as forecast fields. In order to identify the cyclonic circulation, a methodology based on wind pattern matching index is used. Low level winds from NGFS analyses and forecasts to find out such features. This method is applied only when system turned into the cyclonic storm. However, it can be extended at formation stage of the system also. In this study, 4 tropical cyclones (PHAILIN: 09-12 OCT, HELEN: 19-22 NOV, LEHAR:23-28 NOV, MADI:06-12 DEC) are tested which formed over the North Indian Ocean in 2013. The direct position error in analysis and forecast are compared with respect to India Meteorological Department (IMD) best track positions.
Cyclone path prediction over land surface using PDT technique

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Cyclone is the large-scale system of winds that spiral in toward a region of low atmospheric pressure. Most of cyclones generate over ocean water body and surge toward land surface because of dissimilarity in temperature pattern. After voyage of oceanic and sea part cyclone strike over the surface and damage a large amount of natural and cultural properties. It is an evidences from historic cyclonic event, they change their path with respect to topographic situation of any surface. Hence the physiographic data training (PDT) and its assimilation will support for future path tracing of any cyclone in specific region. The Advanced Spaceborne Thermal Emission and Reflection Radiometer, Shuttle Radar Topography Mission and Cartosat DEM (Digital Elevation Model) etc. are most supportive remote sensing data tool for surface representation. The DEM training and processing in GIS environment, generate the high precise information of surface topography which will be loyal for cyclone warning system expansion.
The current study deals with the track forecast verification of Indian Ocean tropical cyclones in 2013 using the NCMRWF Global Ensemble Forecast System (NGEFS). This is a 21 member ensemble model with a resolution of T190L28 (~70 km and 28 levels) produces ensembles of cyclone tracks in real time. This ensemble is also used to determine the strike probability of a cyclone. The verification is done by calculating the average forecast track error (km) between the observed track from JTWC and the average track obtained from the ensemble members of NGEFS. It is seen that NGEFS track forecast errors are lower than its parent deterministic model NGFS.

Further an attempt is made to calibrate the NGEFS output by using statistical post processing (bias correction) methods. This bias correction is based on the method of moment adjustment and the output is obtained after the adjustment of the first moment which is simply the correction in the mean of the ensemble. It is seen that this calibration helps to improve the forecast track from the model which is reflected in the reduced track errors. The highest improvement of about 52% (reduction in the track error) was observed at 24 h lead time in the case of Lehar and the lowest improvement was about 0.5% in the case of Phailin at 72 h lead time.
Numerical Experiments with WRF-ARW to understand the impact of Sea Surface Temperature on the Evolution of the Tropical Cyclones over Bay of Bengal

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In this study an attempt is made to understand the role of SST on the movement and intensity of the TCs by performing numerical simulations with ARW mesoscale model. The case of a very severe cyclone Thane-2011 is simulated with a high resolution (9 km). The model is initialized at 00 UTC of 27 Dec 2011 and integrated up to 84 hours using NCEP 50 km GFS analysis and forecasts. A series of experiments are performed by altering the SST from a domain-wide uniform threshold value of 26.5 °C in steps of +1, +2, +3, -1, -2, -3 °C. IMD best track estimates for intensity and vector track positions are used for comparisons of simulated intensity and track parameters.

It has been found that the cyclone moves to the north (south) of the observed track with positive (negative) increments of SST from the threshold value (26.5 °C) with larger track deviations obtained with higher SST changes. The experiment with SST-2 °C provides minimum track errors with a reduction of 54%, 119%, 192% at 24h, 48h, 72h predictions. Unlike the track, a reverse impact is found on the intensification of the storm with SST changes with positive (negative) increments of SST leading to enhancement (reduction) in pressure drop and maximum tangential winds. The experiment with an increase of SST by 2°C from 26.5 °C provided a realistic intensity with least errors in CSLP and maximum winds. Results suggest SST has differing impacts on the movement and intensification of the storm. Similar results are found in the stream of experiments using real SSTs derived from GFS global analysis and alteration of SST as in previous experiments. Analysis of upward fluxes of sensible, latent heat and moisture averaged over an area of 4deg x 4deg (~400 sq.km ) around the storm indicated that all the three fluxes are enhanced throughout the life cycle of the storm with higher SST values. These results suggest that enhancement of SSTs leads to enhancement in the transport of energy to the cyclone leading to amplification of intensity. At the same time the increased convection is likely to alter the dynamics of the system like the relative vorticity, advection, divergence terms which may influence the motion of the cyclone. The results of the above experiments provide a mechanism for the air-sea interaction through SST parameter and its impact on the TC development. Further experiments are planned to determine an optimum SST that would provide least errors in the intensity as well as the track predictions.
Data Assimilation Experiments with ARW - 3DVAR for Tropical Cyclone Extreme Weather Predictions over Bay of Bengal

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The performance of the Operational WRF model implemented in the Early Warning System (EWS) for Department of Atomic Energy (DAE) site at Kalpakkam for Tropical Cyclone Prediction over the Bay of Bengal region is assessed using data assimilation experiments. Eight recent severe cyclones (PHAILIN, NILAM, THANE, JAL, LAILA, AILA, KHAI-MUK, NISHA) that had landfall along east coast were considered. A fixed double nested domain configuration with grid spacing of 27 and 9 km and 35 vertical sigma levels were employed. The initial and boundary conditions were derived from the 3 hourly 0.5 deg resolution NCEP Global analysis and forecasts in all runs. In assimilation experiments the first guess was enhanced with assimilation of NCEP global Prepbufr observations, AMSU satellite radiances using 3DVAR in separate experiments. The best track parameter data (intensity/vector track positions) from the India Meteorological Department (IMD) and multi-satellite observations on structure from Cooperative Institute for Research in the Atmosphere (CIRA) were used to assess model performance by computing mean error, standard deviation in the predicted fields of maximum sustained winds (MSW), central sea level pressure (CSLP) and the vector track distance. It is found that the model overestimates the intensity of the storms in both control and assimilation runs. The mean errors are 80, 128, 128, 223 km in the vector track position, 13.1, 17.4, 11.3, 5.3 hPa in central pressure, -11.5, -10, -4.4, 0.8 m/s in winds at 24, 48, 72, 96 h forecasts respectively in the 3DVAR experiments. An improvement of about 11-30% in track, 5-10% in central pressure, 8-45% in maximum tangential winds and 8-78% in radius of maximum winds in 24h to 96h lead time forecasts are noted with observation assimilation. Assimilation of AMSU radiance data merely influenced the intensity of the simulated storms. The forecast improvements are found to be associated with changes in pressure, wind, temperature and humidity distributions in the initial conditions after data assimilation.
An Analysis of Forecast Errors of IMD NWP based Objective Cyclone Prediction System (CPS)

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A five-step objective cyclone prediction system (CPS) was introduced for real time prediction of tropical cyclone (TC) over the North Indian Ocean (NIO). The five-step CPS consists of prediction of (i) Cyclogenesis, (ii) Track, (iii) Intensity, (iv) Probability of rapid intensification and (v) Decaying intensity after the landfall. A statistical analysis of forecast errors of CPS is performed over the NIO for the cyclones during 2008-2013 TC seasons. The purpose was to compute a numerical measure of the quality of forecasts in order to provide the statistics required to issue guidance and to assess the improvement of CPS. The TC genesis forecast technique (GPP) and intensity forecast by dynamical-statistical model (SCIP) have been introduced in 2008. The high probability of detection (POD) and low false alarm ratio (FAR) along with higher critical success index (CSI) shows the skill of genesis prediction by GPP. The average intensity forecast error of SCIP ranged from 5.4 kt at 12 h to 16.9 kt at 72 h. A multi-model ensemble (MME) technique for track forecast has been introduced in 2009. The forecast analysis shows that MME forecast was most consistent compared to individual NWP models. The average track forecast errors of MME during the period 2009-2013 ranged from 74 km at 12 h to 200 km at 72 h. The year-to-year variation shows that the average track errors reduced by about 27% to 52% for 36 h to 72 h forecast but no significant improvement occurred for shorter forecast ranges (up to 24 h). The probabilistic rapid intensification forecasts are found to be skillful compared to climatology. The 6-hourly decaying intensity forecast (upto 24 h) after the landfall shows that errors ranged from 3 kt to 4.9 kt. The five step collective approach provided useful guidance to the forecasters for real time forecasting of tropical cyclones.
Role of variable Sea Surface Temperatures in the prediction of intensity of Tropical Cyclones

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Previous studies address the skillful predictions of tropical cyclones (TCs) in terms of tracks. However, the improvements in intensity predictions are not that much and there could be many possible reasons. One of the important parameters among them is sea surface temperatures (SSTs) along with high resolution, improved initial conditions and better physics. Most of the previous studies used constant SSTs throughout the model integration. Studies over other parts of the world demonstrated the impact of SST on TC intensity. Hence, the current study focused on the impact of variable SST in comparison with the constant SST, in the simulation of landfalling TCs using WRF-ARW modeling system. Study has been conducted on the five cyclones during 2013 i.e., Viyaru (CS), Phailin (VSCS), Helen (SCS), Lehar (VSCS) and Madi (VSCS).

In the present study, we conducted a set of two experiments, one with providing of constant SST throughout the integration of model. Second experiment is performed by updating SST obtained from NCEP/MMAB every 6-hr during model integration. WRF-ARW model has been initialized using GFS analyses and boundary conditions are provided from GFS forecast products. The daily SST analysis is generated using most recent 24-hours buoy and ship data, satellite-retrieved SST data. It has been found that the inclusion of variable SST in place of constant SST does improve the intensity of the TC.
Track and Intensity prediction of land-falling Bay of Bengal cyclone Madi using WRF model

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Land-falling tropical cyclones (TCs) are one of the most devastating weather phenomena in the nature. The devastations are mainly due to strong wind, heavy rainfall and associated storm surge. Disaster can be reduced by providing more accurate prediction of the track, landfall and intensity of the storm. Accurate prediction of track and intensity of land-falling TC is of the great importance in weather prediction in making an effective TC warning. This study examines the prediction of a very severe Bay of Bengal cyclonic storm ‘Madi, which formed in December 2013. For this purpose, the customized version of Advanced Research core of Weather Research and Forecasting (ARW-WRF) model with two-way interactive double nested model at 27 km and 9 km resolutions is used to predict the storm. The model initial conditions are derived from the FNL analysis and the lateral boundary conditions are provided every 3 hourly from GFS forecast. Seven numerical predictions are conducted with model integration starting at 0000 UTC and 1200 UTC of 07 Dec, 08 Dec, 09 Dec and 0000 UTC of 10 Dec. The model predicted track and intensity of the storm are compared with the India Meteorological Department (IMD) best-fit track. Results indicate that predictions are faster moving cyclones with higher intensity relative to the IMD best-fit track. The prediction with initial time at 0000 UTC of 09 Dec shows best prediction of track, landfall (including time and location) and intensity of the storm. The mean vector displacement errors (VDEs) at 24h, 48h 72h and 96h in model predictions are 80 Km, 170 Km, 265 Km and 265 Km respectively. The mean VDEs and intensity error are also compared with other Numerical Weather Prediction (NWP) models. In this study prediction of all cyclonic storms during 2013 is also discussed. It is found that customized WRF-ARW also well predicted BOB cyclone with less intensity error than other NWP model.
Simulation of Tropical Cyclones over Bay of Bengal during 2013 using different Cloud Microphysical and Planetary Boundary Layer Parameterization Schemes In WRF Model

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The numerical models based on fundamental dynamics and well-defined physical processes provide a useful tool for understanding and predicting Tropical Cyclones (TC). The performance of the high-resolution Advanced Research Weather Research and Forecasting (WRF-ARW) model for TC prediction over Bay of Bengal region in the northern Indian Ocean is assessed through a study of 5 cyclones (VIYARU, PHAILIN, HELEN, LEHAR and MADI) developed in the year 2013. For accurate forecast of TC, it is essential that numerical models must incorporate realistic representation of important physical and dynamical processes as they play crucial role in determining genesis, intensification and movement.

The track and intensity of the cyclones are predicted with two initial conditions (at 120 and 72 hours) using different micro physical parameterization (MP) schemes such as Lin et al. (LIN), Ferrier (FERR), WSM6 class graupel Scheme (WSM6)& Thompson graupel scheme (THOMP) and Yonsei University (YSU) & Mellor-Yamada-Janjic (Eta) TKE (MYJ) Planetary Boundary Layer (PBL) schemes in combination with Kain-Fritsch (KF) as cumulus scheme. These results are compared with the India Meteorological Department (IMD) observations. The track error is minimum in MYJ scheme for VIYARU, LEHAR & MADI and YSU scheme for PHAILIN & HELEN at 120 hours prediction. However the track error is same in all MP schemes. But at 72 hours of prediction, YSU scheme provides minimum track error for all the cyclones. Also the strongest intensity is shown by YSU scheme for all the cyclones. These results are further investigated using potential vorticity, surface energy flux (sum of latent and sensible heat flux), hydrometeors, reflectivity and radial velocity. The reflectivity and radial velocity are compared with the Doppler Weather Radar data. The 48 hours simulated precipitation is compared with precipitation obtained from Tropical Rainfall Measuring Mission (TRMM) satellite.
Verification of Cyclogenesis technique developed by Satellite Application Centre (SAC), Ahmebabad

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One of the severe weather systems which affect the Indian region, mainly coastal areas is tropical cyclones. They originate in the Bay of Bengal or Arabian Sea mainly in pre & post monsoon seasons. When the systems cross the coast, torrential rain, high speed wind and storm surge make havoc in the storm affected areas in terms of loss of life & properties, disruption of communication damage of road & railways etc. Early prediction of formation and movement of tropical systems can reduce probable loss substantially. Therefore whenever any low level circulation forms over the Indian Seas, the prediction its intensification into cyclone is very essential for management of cyclone disaster.

Satellite Application Centre (SAC), Ahmebabad has developed a technique to predict the Tropical Cyclogenesis based on scatterometer-derived winds from the polar orbiting satellite QuikScat & Oceansat-II. The QuikScat satellite was operational from 19 June 1999 to 19 November 2009. India’s polar-orbiting satellite, Oceansat-2, was launched on 23rd September 2009. India Meteorological Department (IMD) has acquired the technique and verified it for the year 2010 to 2013 for operational use. The model is based on the concept of analogs of the sea surface wind distribution at the stage of low level circulation or vortex (T 1.0) as per Dvorak’s classifications which eventually leads to cyclogenesis (T 2.5). The validation results this model based on the cyclonic disturbances developed over the north Indian Ocean are analysed and presented. The results indicate that the developed model could predict cyclogenesis on about 50% of the total cases. This model has a limitation, as it does not consider the dynamics of the Ocean and atmospheric parameters, which governs the cyclogenesis over the region.
Basin-Scale HWRF modeling system for the prediction of Tropical Cyclones over Bay of Bengal

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Based on the 2013 version of operational HWRF system, the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory (AOML) with its partners at Environmental Modeling Center (EMC), National Centers for Environmental predictions (NCEP) have developed a basin scale HWRF system that can operate with multiple moving nests spanning at resolution down to 3 km. The same system has been adapted now for Indian Ocean covering both Bay of Bengal and Arabian Sea. More than 80-90% of the deaths due to Tropical Cyclones (TCs) are caused by fresh water flooding and storm surge; and hence realistic TC size and structure predictions are important at landfall for disaster management. The 2013 Bay of Bengal cyclones namely Phailin, Lehar and Madi, were simulated and noticed improved predictions in terms of track, intensity, size and structure. This model clearly showed superiority for longer range forecast (4-5 days) compared to real-time forecast of ARW model. The rainfall amount and structure is improved significantly, particularly, in case of Phailin, model showed the peak rainfalls over Northern parts of Odisha. In case of Lehar, model indicated the depletion of moisture associated with the weakening over the Bay of Bengal when the system started interacting with the land.
Cumulus (Cu) convection is one of the most important features of any weather system. In tropical cyclones (TC) there are clusters of cumulus cells that contribute to cumulative impact in determining the character of the system. The impact of the convection within the system and with that of the surrounding is studied and parameterized by various researchers time to time for improvement of NWP models’ performance in respect of track and intensity prediction of TC. Weather Research and Forecasting (WRF) mesoscale model runs operationally using initial and boundary conditions from global model. Various Cu Parameterization schemes viz Kain-Fritsch (new Eta) scheme, Betts-Miller-Janjic (BMJ) scheme, Grell-Devenyi ensemble (GDE) scheme, Old Simplified Arakawa- Schubert (SAS), New Grell scheme (G3), Tiedtke scheme, New GFS SAS from YSU, Old Kain-Fritsch scheme are compatible for use in WRF-ARW Model.

In this study, 35 cases of tropical cyclones over the North Indian Ocean during 2001 and 2012 are simulated by WRF-ARW Model using each of all the above Cu Parameterization schemes with NCEP final analysis data as initial and boundary conditions. The result shows that there has been significant scheme wise variation in the prediction of central pressure (CP), both in temporal and spatial scales. There were cases of failures as well as reasonable accuracy in predictions. In five cases there were extreme failures in analysis of CP. The absolute average errors (AAE) were calculated for all the pre-monsoon and post monsoon cases both over the Bay of Bengal (BOB) and the Arabian Sea (ARB). The errors are also calculated for different seasons and for both the Bay of Bengal and the Arabian Sea. The overall AAEs show that the BMJ, GDE and Tiedtke Scheme performed better. The scheme BMJ is found to have performed better for BOB and the scheme Tiedtke performed better for ARB. The result also shows that the error in BMJ scheme for recurved systems is less than others. However, in the case of track forecasting, the SAS and New GFS SAS schemes are found to have performed better than other schemes in general. A detailed result will be presented in the seminar.
Tropical cyclogenesis Prediction in North Indian Ocean during 2013 using OSCAT derived surface wind observations

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The Indian sub-continent is one of the most adversely affected cyclone active basins that experience on an average 4-5 cyclones every year. Though the cyclones formed in this region are considered to be much weaker in intensity and smaller in size as compared to other regions, yet the number of deaths in the region is highest in the globe (3,00,000 human deaths were estimated from TC associated storm surge in Bangladesh in 1970). To overcome such loss the advance predictions of cyclone in terms of their genesis, track and intensity is highly important. These advance timely information can save the life of people and help in decision making for taking the preventive measures like evacuation during the cyclone landfall.

In the present study the cyclogenesis prediction of cyclones formed during the year, 2013 in the North Indian ocean have been discussed. The technique used in this work is inspired by the pattern matching approach which is based on the assumption that there is some degree of similarity in low level wind circulation among the low pressure systems that turn into cyclones at later stages, which can be utilized to distinguish them from non-developing systems. This similarity of wind patterns in the real time observed wind vectors and the past developing systems have been measured quantitatively using a vector pattern correlation coefficient, termed as the “matching index”. If the matching index have been found to exceed the pre-determined threshold, the cyclogenesis has been predicted. The Oceansat-2 satellite onboard scatterometer (OSCAT) derived surface wind vectors have been used in the real time to predict the signatures of cyclogenesis. The advance cyclogenesis of the all five systems developed in the North Indian Ocean during the year 2013 have been predicted using this approach in the real time. The limitation of the technique is that it depends on the availability of scatterometer pass over the region of developing system. The cyclone, Viyaru was declared as tropical storm on 11 May, 06Z however, its genesis was predicted by the proposed method on 10 May, 5Z. The very severe cyclone, Phailin was formed on 9th October, 12Z and the cyclogenesis of Phailin was predicted on 8th October. Similary the cyclogenesis of cyclone, Helen, Lehar and Madi was predicted 1-5 day advance based on the above approach. The mean prediction lead time of the technique has been estimated as 60 hours.
Simulation of Tropical Cyclone ‘PHAILIN’ Using WRF Modeling System

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An attempt is made to evaluate the impact of the model resolution for simulation of the very severe tropical cyclone ‘PHAILIN’ formed in 8th – 14th October 2013 over Bay of Bengal using high-resolution Weather Research and Forecasting (WRF) mesoscale model. For this purpose, the model is configured with two-way interactive nested domains with fine resolution of 27 km (D01) and 9 km (D02) for the region covering the Bay of Bengal and the model is integrated from 00 UTC 9 October 2013 to 12 UTC 13 October 2013 (108hrs) using FNL global analyses as initial and boundary conditions (IBCs) for the WRF model.

The evolution of intensity of the TC in 12-hour interval (MSLP and 10m surface wind) is reasonably well simulated in D02 experiment as compared to D01 experiments. The trend of evolution of intensity from D02 simulation is more close to India Meteorological Department (IMD)-observed trend. The root mean square errors (RMSE) of intensity in terms of MSLP and 10m surface wind are smaller in the D02 as compared to the D01 simulation. The landfall time accurately simulated by D02 experiment, however, landfall time of the TC is delayed by 6hr in D01 simulation. The rainfall amount and intensity of reflectivity are well simulated in D02 experiment as compared to the D01 experiment. The features are well matched with the satellite (TRMM) rainfall and observed reflectivity from Visakhapatnam radar. From D02 simulation, the track of TC is well matched with IMD best track as compared to D02 simulation. Similarly, the track errors are significantly reduced in the D02 simulation as compared to D01 simulation throughout the forecast period. The mean track error is also less in D02. The study suggested that the intensity and track of the TC is well represented in high-resolution model experiment.
Representation of Upper Ocean Heat Content in numerical model for prediction of Bay of Bengal cyclones

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Increase in in-situ observations over the Bay of Bengal (BoB) on implementation of IndOOS (Indian Ocean Observing System) has encouraged studies to investigate the influence of upper ocean thermodynamics on cyclone intensity. A number of such studies infer that the subsurface mesoscale eddies significantly modulate the intensity of cyclones through exchange of air-sea fluxes around the storm environment and suspected to be the root cause for rapid intensification of hurricane Opal in Atlantic Ocean and the cyclone Nargis in BoB. Sea Surface Temperature (SST) is conventionally used as a representative of Upper Ocean Heat Content (UOHC) in Numerical Weather Prediction (NWP) models. Some recent studies suggested that SST is not a good representative of UOHC and Sea Surface Height Anomaly (SSHA) obtained from satellite altimeter observation can well represent the subsurface mesoscale eddies in the ocean.

The present study deals with representation of UOHC in numerical model for mesoscale simulation of cyclones over North Indian Ocean (NIO). In an attempt to find a good representative of UOHC, a detailed analysis of satellite derived AVHRR-SST and SSHA is carried out in relation to the intensity and track of NIO cyclones. It indicates that SSHA has good correlation with cyclone intensity. The upper ocean thermal structure is derived using the two layer reduced gravity model by approximating the mixed layer depth. The Tropical Cyclone Heat Potential (TCHP) is then estimated by integrating the derived thermal structure using polynomial interpolation in order to fit the classic in-situ thermal profile. TCHP is computed at every 0.25° x 0.25° grid over NIO (10°S-35°S & 50°E-115°E). The derived TCHP is validated with the TCHP computed using in-situ observations and found to be more accurate compared to TCHP obtained using conventional methodology. Thus TCHP derived as mentioned above is a better representative of UOHC but cannot be directly incorporated in NWP models. Hence a new state variable called Upper Ocean Mean Temperature (UOMT) is defined as

\[ UOMT = \frac{TCHP_{2layermodel}}{C_p \rho \* D_{26}} + 26 \]

where \( D_{26} \) is the mean depth of 26° isotherm.

The impact of the derived UOMT and AVHRR-SST on intensification of NIO cyclones is analysed for all cyclones during 2006-2013. It is observed that the intensity of the cyclones decreased on passing over low UOMT zones (cold eddies) and increased sharply while passing over high UOMT zones (warm eddies). It is also observed that UOMT has better correlation with cyclone intensity than SST and the correlation is higher in the pre-monsoon than the post-monsoon. Analysis of in-situ Argo profiles reveals that the decrease in correlation in the post-monsoon season is primarily due to inaccurate representation of haline stratification of the upper ocean which is not included in the estimation of TCHP.

The impact of UOMT and SST in the mesoscale prediction of tropical cyclones is investigated using WRF-ARW model. The results indicate that the intensity of the cyclones is better simulated with UOMT than SST. However, there is no significant improvement in simulation of track of the cyclones.
Prediction of water levels and extent of coastal inundation due to a cyclonic storm along the Indian coasts

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The devastation due to the combined action of storm surge flooding and extreme wind waves generated by the cyclones is a severe apprehension along the coastal regions of India. Numerical ocean models are considered today as an essential tool to predict the sea level rise and associated inland extent of flooding that could be generated by a cyclonic storm crossing any coastal stretch. For this purpose, the advanced two-dimensional depth integrated (ADCIRC-2DDI) circulation model is practical for the simulation of surges and associated water levels off the coasts of India. It is believed that this study would help the coastal authorities to develop a short and long-term disaster management and vulnerability reduction action plan and emergency response in the event of storm surge flooding. The ADCIRC model based on finite-element formulation is ideal for computations of storm surges and associated inundation, as its flexibility allows for large spatial scales to be represented in the domain while permitting higher degree of grid refinement near the landward boundary. The main objective of this study is to configure ADCIRC storm surge inundation model for identifying vulnerable coastal stretches of inundation in the event of any cyclone crossing the coastal regions of India.

In order to properly describe the physics of storm surges, a numerical model must resolve coastal features that can affect storm surge generation and propagation. This means the model domain must necessarily incorporate complex coastal geometries. In this context, a finite-element based model is the best choice as it allows flexibility to represent a larger spatial domain while permitting higher grid resolutions near the landward boundary. In the present work, the ADCIRC model is configured for all the maritime states of India. The model is integrated using wind stress forcing representative of the recent past cyclones of Viyaru and Phailin. The model computes water levels using 30-sec GEBCO and SRTM on-shore topography associated with extreme surges generated by the cyclonic wind field. The simulations of water levels along with horizontal extent of inundation are useful to provide early warnings to low-lying areas, guide evacuation of local population, and rescue operations.
Monitoring and Prediction of heavy rainfall due to landfalling Tropical Cyclones over the North Indian Ocean

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The tropical cyclone (TC) is considered to be multi-hazard as it causes heavy rainfall leading to flood, gale wind leading to structural damage and storm surge leading to coastal inundation. Over the Indian region, the cumulative rainfall due to a TC exceeding 50 cm is very common near the point of landfall which creates flood threat over the vulnerable river plains. However, the rainfall due to TC shows large scale spatial and temporal variations enhancing the forecast difficulty level of heavy rainfall. In addition to the above, the forecast becomes more challenging when there is change in the characteristics of the TC such as (i) slow motion / stationarity or rapid movement before the landfall, (ii) recurving TCs where the convective clouds are sheared far away from the centre leading heavy rainfall to a larger radial extent in a particular sector, (iii) Movement of TC over orographically dominant regions like Eastern/ Western Ghats / Northeastern Hill ranges as dominance of orography leads to more meso-scale nature of heavy rainfall in a large synoptic scale forcing, (iv) Movement of the TC over deltaic region where the feedback mechanism of hydrological cycle helps in enhancing the rainfall, (v) rapid intensification before landfall and (vi) structural changes during landfall leading to sudden change in region of occurrence of heavy rainfall etc., Considering all the above, a review of research work done on monitoring and prediction of heavy rainfall due to landfalling TCs over the Indian region has been carried out based on the work done during the last 10 years on the above aspects as well as role of physical processes like environmental conditions such as wind shear, vorticity, convergence etc,

There has been significant improvement in monitoring of rainfall with the (i) modernization programme of India Meteorological Department which has resulted in 675 Automated Weather Stations (AWSs) and about 1300 Automated Rain gauges (ARGs) in addition to 552 synoptic observatories, (ii) development of gridded rainfall data, (iii) development of observational and satellite based merged gridded rainfall data and (iv) quadrant based climatology of TC rainfall using the above. Though there has been significant improvement in rainfall prediction by Numerical Weather Prediction (NWP) models with (i) introduction of High-resolution Hurricane Weather Research and Forecast (HWRF) models and other global and regional models, (ii) improvement in initial and boundary conditions with better data assimilation and (iii) improvement in track and intensity forecast, still there is scope for further improvement as most of the models have limitations in accurately predicting the heavy rainfall both with respect to space and time scales. The operational aspects of forecasting and warning of heavy rainfall as per users requirements are also reviewed. The future scope with respect to monitoring, prediction and warning services for heavy rainfall due to landfalling TCs over the Indian region have been reviewed and presented.
Experimental storm surge forecast for Very Severe Cyclonic Storm Phailin

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Coastal regions are generally vulnerable to storms and associated surges. The inundation caused by the surges have devastating impacts. The East coast of India is experiencing frequent land falling cyclones almost at the rate of one or two events every year. However, while the capability to predict the landfall locations of tropical cyclones exists in the country, the capability to forecast the inundation due to storm surge is still in infancy. In response to this gap ESSO - INCOIS has taken initiative to establish an operational storm surge warning system in collaboration with ESSO - IMD. A fully parallel Advanced Circulation model (ADCIRC) has been used for the experimental storm surge forecast during Very Severe Cyclonic Storm “Phailin” that made landfall at Odisha coast. Using High Performance Computing system, ESSO - INCOIS generated the model output such as surge heights and inland inundation extent. These output were shared with ESSO - IMD within 3 to 6 hourly advisory cycles and the same were used by IMD to brief disaster managers. An attempt has been made to compare the forecast results with available observations from the nearest tide gauge station and from the field survey records. Field results were obtained by conducting GPS surveys within a few days of landfall. Fortunately, no serious inundation was observed due to the storm surge by ‘Phailin’ cyclone. Similar results were obtained by our simulation with maximum surge height being about 2.8m. The storm surge impact of ‘Phailin’ was subdued due to low tide conditions during landfall on the coastal areas. The study results clearly indicate that the results obtained by ADCIRC modeling of storm surges are good enough to be used for forewarning the disaster management authorities.
Hydro-meteorological aspects of Tropical Cyclone Phailin in Bay of Bengal in 2013


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Tropical Cyclone Phailin is the second strongest tropical cyclone ever recorded in the Bay of Bengal after the Odisha super-cyclone of October, 1999. The Very Severe Cyclonic Storm, Phailin crossed Odisha & adjoining north Andhra Pradesh coast near Gopalpur (Odisha) around 2230 hrs IST of 12th October 2013 with a sustained maximum surface wind speed of 200-210 kmph gusting to 220 kmph. It caused very heavy to extremely heavy rainfall over Odisha leading to floods. Maximum rainfall was recorded over northeast sector of the system centre at the time of landfall. Maximum 24 hr cumulative rainfall of 380 mm was reported by an automatic raingauge in Banki (Cuttack district) of Odisha. The highest 24 hr cumulative average rainfall of 187 mm was recorded in Nayagarh district on 13 October (ending at 0830 Hrs IST on 13 October) and highest 48 hr cumulative rainfall of 232 mm was recorded in Mayurbhanj district on 14 October (ending at 0830 hrs IST of 14 October, 2013). The daily Indian precipitation analysis formed from a merged data set of IMD rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates showed Cyclone Phailin’s heaviest rainfall (>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 progressed through Bay of Bengal (BoB) from 8 October to 12 October. Phailin gave maximum rainfall of around 800 mm in the Southwest sector of the track over east-central BoB near Andaman Islands, when it intensified from Deep depression into a cyclonic storm on 9 October, 2013. The districts in the northeast Odisha (Balasore, Bhadrak and Mayurbhanj) recorded as much as 300-400 mm and other parts of Odisha received between 200 to 300 mm as Phailin made landfall on the night of 12 October. The 24 hr rainfall forecast of HWRF during the Cyclone period were used to generate similar map and it was seen that the model overestimated as compared to the observed rainfall, though it could capture the spatial pattern.

Post-cyclone there was large scale flood in coastal districts of Odisha. This resulted in the extensive inundation of Rice fields. Satellite data based mapping of rice inundated area was carried using Microwave Remote Sensing Data from RISAT-1 and Radarsat-2. The total rice flooded area was 1.32 lakh ha, upto 17 October, 2013. Total ten districts were affected by flooding, out of which Baleshwar, Bhadrak, Jajpur and Kendrapara were worst affected.

Thus this study assessed all the hydrological aspects of Cyclone Phailin, including the rainfall pattern and flood impact on agriculture.
Management of Post-landfall Riverine Flooding

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Tropical cyclones are the most significant weather phenomena in North Indian Ocean (NIO), where it affects the Indian sub-continent and particularly India. The inherent vulnerability of tropical cyclone lies with a long coastline of about 7,516 km of flat coastal terrain, shallow continental shelf, geographical location and physiological features of its coastal areas in the Basin. Besides these, the other factors which may influence vulnerability are limitation of observations, prediction systems, understanding of physical processes, early warning systems and disaster management, apart from the socio-economic conditions of highly dense population of the country.

The character of tropical cyclones is associated with adverse weather conditions like heavy rainfall, gale winds and storm surges. The impact of these characters is extremely vulnerable when there is a combination of heavy rains, high velocity wind and storm tide. Of these, storm tide is responsible for 90 percent of the loss of lives. The storm tide is dependent on several factors, of which, the tidal cycle at the time of the surge, the topography over which the surge intrudes and the strength of the low pressure system in the atmosphere. This leads to sea level coastal flooding, which is produced by strong winds and low atmospheric pressure over an area.

Research on coastal flooding is highlighted with identification of reasons and appropriate measures, whereas the possibility of post-landfall riverine flooding is not properly discussed in disaster management literature. It is generally observed that fairly widespread or with isolated heavy rains occurred in coastal region starting from the genesis of a cyclone to landfall of a cyclone. The interior parts/ upstream catchments of coastal/non-coastal State(s) also experienced with fairly widespread or isolated heavy rains, where severe flow of water passes through in river channels/ in their catchments. This led to riverine flooding in downstream areas after the landfall of a cyclone.

While addressing the issue of management of post-landfall riverine flooding, this paper will discuss the issues of priority (1) density of forecasting technology for rainfall prediction in upper/lower catchment areas, (2) data sharing of forecasting of rainfall in real-time and monitoring of flood risk in lower catchments among the agencies like IMD, CWC, and State government(s), (3) coordination of major agencies for issuing flood early warning and (4) finally planning to synergise all the stakeholders for effective/ appropriate actions by the concerned state government(s).
The diurnal-scale variability of precipitation pattern during the cyclone

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The diurnal and seasonal cycles form the most fundamental forced modes of variability of the global climate as they closely follow the motion of Earth and the associated solar forcing. The diurnal variation is one of the important characteristics of precipitation over a region and is often related to the physical processes governed by the geographical features or atmospheric dynamics controlling rainfall over that area. South Asia experiences two monsoons, the summer monsoon during June to September and the winter monsoon during October to December. While the summer monsoon is responsible for a major portion of the annual rainfall over India, rainfall received during the post monsoon is also important, especially for south India.

During the year 2013, NCMRWF employed the following two global models namely (1) a high resolution spectral (T574L64) Global Forecast System (NGFS) for generating ten day forecasts from the initial conditions of 00UTC every day. The forecast model has a resolution of approximately 22 km in horizontal and has 64 levels in the vertical. The associated 3-D VAR data assimilation system namely, Grid-point Statistical Interpolation (GSI) which is used to initialize the global model has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geostationary satellites (2) a high resolution grid point Unified Model (NCUM).

In this study, the diurnal variability of precipitation pattern predicted by the NGFS and NCUM are examined and compared with the rainfall estimates obtained from the Tropical Rainfall Measuring Mission (TRMM) satellites for the following three cyclones during the year 2013 in the Bay of Bengal (a) Helen 19~23 Nov (b) Lehar 23~28 Nov (c) Madi 6~13 Dec.

In this study we present the following topics:- (i) spatial distribution of the observed rainfall accumulated during these cyclone period (ii) spatial distribution of the model predicted hourly precipitation (iii) hourly rainfall maximum intensity (iv) hourly rainfall-TRMM and precipitation-model averaged over the various regions and accumulated for each cyclones (v) distribution of rain rate in terms of rain fraction (vi) composite analysis of the above three cyclones
Interactions between a tropical cyclone (TC) and its environment lead to structural and intensity variation of the TC and such interactions can be quantified by calculating momentum transports due to azimuthal eddies. The dynamical role of upper level eddy fluxes of angular momentum in TC intensification was explored by Challa and Pfeffer (1980) through the response of radial-height TC secondary circulations to eddy momentum force. Since the inertial stability of the tropical cyclone is very large in the lower troposphere, eddy angular momentum fluxes (EFC) in the upper troposphere can have the greatest impact on the symmetric tropical cyclone. Also, environmental interactions determine the asymmetry in rainfall distribution around TCs.

In the present study, the variation of EFC and intensity changes of Very Severe Cyclonic Storm (VSCS) \textit{MADI} that formed and moved over North Indian Ocean during (06-13 Dec 2013) is discussed. During its life cycle, between 7-11 December, \textit{MADI} moved northward up to 15.4° N and then recurved southwestward towards Tamil Nadu coast with intensity changing from Very Severe Cyclone stage to Deep Depression stage. Using 1° x 1° NCEP FNL data, the upper level eddy angular momentum fluxes were computed in storm relative cylindrical co-ordinate system with radial interval $\Delta r = 1°$ and azimuthal interval $\Delta x = 15°$ using bilinear interpolation during the life period of \textit{MADI} at 6-hourly intervals. Evolution of upper level EFC during the northward movement and subsequent re-curvature period is discussed. Further, associated with environmental impacts, the spatio-temporal variations in the rainfall asymmetry around the \textit{MADI} centre is also analysed by Fourier analysis using 0.25° x 0.25° TRMM rain rate data. Cyclonic shift in the asymmetry maximum as well as outward propagation of wavenumber–1 asymmetry are observed during the intensification of \textit{MADI}. 

\textbf{Diagnostics of Upper Level Dynamics and Rainfall Asymmetry of Very Severe Cyclonic Storm \textit{MADI} (2013)}

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Rapid weakening of Very Severe Cyclonic Storm ‘Lehar’- A Case study

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The very severe cyclonic storm ‘Lehar’ formed over the Bay of Bengal during 23-28 November, 2013. Moving northwestwards, it rapidly weakened from the stage of very severe cyclonic storm to depression (75 to 25 knots) within 18 hrs. on 27th November, 2013 over the westcentral Bay of Bengal off Andhra Pradesh coast. This rapid weakening of the system could not be anticipated well by the forecasters and most of the numerical weather predication models. Though there is dynamical statistical model for prediction of rapid intensification, there is no such model to predict rapid weakening. Considering all these, there is a need for in-depth understanding of the process leading to rapid weakening. Therefore a study has been undertaken to analyse the environmental conditions leading to rapid weakening of Lehar.

Analysis indicates that rapid weakening was mainly due to (i) high vertical wind shear of horizontal wind (> 20 kt) (ii) system entering into colder sea where the ocean thermal energy was less than 50 kJ/cm² and (iii) incursion of dry and cold air from central and northern parts of India into the core of the system. The detailed results are presented and discussed in this paper.
Tropical Cyclone MADI – A Case Study

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During the year 2013, 10 cyclonic disturbances developed over north Indian Ocean. They include one deep depression (DD) over Arabian Sea, one land depression and eight cyclonic disturbances over Bay of Bengal (BOB). Out of these eight cyclonic disturbances, three intensified into Very Severe Cyclonic Storm (VSCS), one each into a Severe Cyclonic Storm (SCS) & Cyclonic Storm (CS) and three up to depression stage. Five cyclones developed over the BOB for the first time after 1987. Post-monsoon season was very active during the year. Though there were five cyclones, only one cyclone (PHAILIN) crossed coast as VSCS and other two (VIYARU and HELEN) as CS. Other two cyclones (LEHAR and MADI) crossed the coast as depressions. However, cyclone LEHAR crossed Andaman and Nicobar Islands as a SCS. While the track of LEHAR was straight moving, tracks of all other cyclones were re-curving in nature. While PHAILIN recurved after landfall, cyclone VIYARU recurved northeastwards over the sea, cyclone HELEN re-curved west-southwestwards just before landfall and cyclone MADI re-curved southwestwards over the sea. Comparing the tracks, the track of MADI was most unique in nature and had a rare analogue with past records. In this paper a case study about tropical cyclone MADI is attempted.
Rapid Movement of Cyclone Viyaru Just Before Landfall-A Case Study

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A cyclonic storm, Viyaru crossed Bangladesh coast near lat 22.8°N and long. 91.4°E, about 30 km south of Feni around 1330 hrs IST of 16th May 2013 with a sustained maximum wind speed of about 80-90 kmph. The genesis of the disturbance took place in a lower latitude, near 5 degree North. It recurved northeastward after initial northwestward movement. It was one of the longest track over NIO in recent period after the very severe cyclonic storm, Phet over the Arabian Sea (31 May-07 June, 2010). The cyclonic storm moved very fast (about 40-50 km per hour) on the day of landfall, i.e. on 16th May 2013. Such type of fast movement of the cyclonic storm is very rare as the normal translational speed of cyclone is about 15 kmph. It led to relatively higher track and landfall forecast error, especially with respect to time as actual landfall occurred well before the predicted time of landfall. As a result the lead time for the disaster managers were less.

Considering this a study has been undertaken to analyse the characteristic features associated with this rapid movement so that forecast can be improved in such cases in future. For this purpose the best track data of IMD has been utilized to compare the movement of cyclone Viyaru with the past cyclones during 1990 to 2012. Further the synoptic and environmental features governing the movement of cyclone have been analysed. It is observed that the system got rapid steering for the northeastward movement due to upper air trough in middle latitude westerlies which ran along long. 77°E on 15th and came further closer to the cyclone on 16th May. An anticyclonic circulation in upper troposphere which lay near lat. 14°N and long. 95°E on 12th May moved gradually westwards leading to more northerly component of movement of the cyclone. Due to the rapid movement, the cyclone did not intensify though it had one of the longest travel over the warmer sea. Further details are presented in this paper.
Very Severe Cyclonic Storm (VSCS) MADI over Bay of Bengal, 6-13 December - A diagnostic study

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From the IMD e-atlas (1891-2013), it is seen that the month of December accounts for about 19% of the intense systems (depression and above) that form over the Bay of Bengal during post monsoon season. Out of the 50 cyclonic storms/severe cyclonic storms that formed in December, 50% weakened into depressions before they crossed the coast or dissipated over the Sea while moving in different direction. About 50% of the storms, that weakened, moved northeastwards. Previous studies indicate that higher rate of weakening when the system moves northeastward is due to wind shear associated with westerlies. Also, when the storms moved southwestward they were definitely subjected to weakening. The very severe cyclonic storm (VSCS), “Madi’ that formed in the month of December over the Bay of Bengal displayed unique characteristics in its movement, intensification and weakening. Gray’s dynamic and thermodynamic parameters are studied for the genesis and intensification and various tropical cyclone motion parameters are examined.

It is found that all the parameters were satisfied during the genesis. The system intensified while moving north/northeastwards and weakened during its southwesterly course. The sea surface temperature (SST >26°C), moderate wind shear (10-20 knots), and tropical cyclone heat potential (TCHP >50 kJ/cm²) were responsible for intensification while SST (<26°C), high wind shear (>20 knots), TCHP (<50 kJ/cm²) and entrainment of dry and cold air from Indian landmass led to weakening. The entrainment of dry and cold air isolated the core from the warm and moist feed from southeast sector and there was a reduction in up-draft parcel buoyancy. During its weakening stage, the system again entered into the area with SST > 26°C and hence could maintain the intensity of depression till the time of landfall in spite of the fact that low relative humidity (RH < 40 %) prevailed at mid-tropospheric level (500 hPa) due to the entrainment of relatively dry and cold air into the core of the cyclone. The movement during its intensification stage was steered by the ridge at 200 hPa lying close to its north in association with an anticyclonic circulation to the northeast of the system. The reasons which led to its unique southwestward movement during its weakening stage was the lower and middle tropospheric steering instead of the upper tropospheric steering. The VSCS, Madi is a very good example to demonstrate the fact that the intensity of a cyclone also plays a dominant role in determining the steering flow and hence the track of the cyclone.
Impact of enhance(suppress) Post monsoon's Cyclogenesis over NIO on fog/smog formation over north India from their time series data 1989-2014 and Case studies

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There are some cyclones in post monsoon season over Bay of Bengal which cause prolonged spell of smog/fog over northwest India including Delhi e.g. “Nilam and its remnant at Andhra coast” followed with record smog/fog during Oct-Nov 2012, “Thane at Tamilnadu Coast” during 25-30 Dec 2011 followed a prolonged dense fog event at Delhi. But in contrast to it, in recent Oct to mid-Dec 2013, irrespective of enhanced cyclogenesis, there was fair and sunny days and clean air over this same region during that period. Similarly, cases of cyclones like “Rashmi” (25-28 Oct 2011) which crossed Bangladesh coast, “Khi-Muk” (13-16 Nov 2011) which crossed Andhra Pradesh coast, “Nisha” (25-29 Oct 2011) which crossed Tamil Nadu coast, have also caused high duration longer spell of smog/fog over northern India while most days in month of Nov-Dec-Jan 2007-2008 and Dec 2000, 2009 had hardly any dense fog. Old record shows even cyclone formation at Arabian sea near to west coast, had also caused record breaking dense fog days which was present almost all days during 10 Dec 1998 till 31 Dec 1998 over most Indo-Gangetic plains including Delhi, associated with direct moisture/cirrus out flow from a severe cyclonic storm that crossed Oman coast during 11-17 Dec. Today, when global warming and anthropogenic pollution have been proved to have dominating influence on frequencies, duration and intensity of all types of weather event and their scale interaction, dynamical and moisture budget, linking of two events such as fog at north India and cyclone at coasts of India may be very complex. It is because both events are of different scales and they form in contrast atmospheric and vertical temp conditions where mechanism of clouding and dynamics of winds and aerial circulation associated with both events are opposite to each other. But real time monitoring and forecasting of post-monsoon cyclones and fog/smog coverage during last few years finds such interaction as a reality.

In this study, we carried out critical analysis of both events using their Individual case data and events from longer period of data since 1997 and time series data from 1989 (cyclogenesis time series of depression and above for north Indian Ocean (NIO) of post monsoon and fog time series of intensity <1000m and <200m as total duration over Delhi for Oct to Feb, satellite fog data of individual coverage for 1997-2013. We find besides total frequencies formed in each season for Oct-Dec influencing total seasonal and monthly fog formation, areas where they formed at time scale of days to week also influence duration, intensity and scale of fog/smog formation concurrently or following it. Their time series are also positively linked to total occurrences. The study of the correlation of both time series in seasonal and monthly scale, shows to be of positive correlation value of 0.3 between seasonal frequency of cyclonic disturbances and both for Dec, Oct to Feb, and negative correlation with Jan fog total duration. Case study shows during recent of Oct-mid-Dec 2014, the northern plains had few smog and not a single case of dense fog till 14 Dec 2013 because of strong winds leading to filling of the strong cyclones at eastern part of India throughout that period. In addition, in such cyclone periods, there was hardly any western disturbance (WD) penetrating to plains of north India, and thus fill the region with some moist or cold air which otherwise would have favoured fog conditions. Rather, the eastern and central Indian region was under the stronger impact of these intense cyclone formations of 6 systems, forming one after other at north Bay of Bengal to the north of 13°N forcing the WD to stay very far to the north. When such cyclogenesis pattern fully subsided by 13 Dec 2013, the northern belt including Delhi was suddenly hit by unexpected Dense fog spell by 15 Dec and then followed with a record fog formation in Jan 2014. Similarly, case studies from cyclone favouring fog formation of longer period were seen in case of Nilam, Thane, and many other cases, when both their formation and its track were near south-eastern coast of India. They have enhanced scale, duration of fog formation and their intensification at northwestern plain of Indian states in concurrence or following dates. The northwestern India, due to land locked, dry region and no convection activities, provides a space for subsidence cell which helps in weakening of those cyclones crossing southeast coast of India. One of the objectives of the present study is to determine factors which affect fog/smog durations and their events at Delhi and other stations across north India in peak winter of Dec to Feb at seasonal or extended range time scale.
Impact of Phailin cyclone on standing Kharif crops of India

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A 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 area over Tenasserim coast on 6th October 2013. It lay over north Andaman Sea as a well marked low pressure area on 7th October. The monster cyclone Phailin, packing heavy rains and destructive winds, hit very close to Gopalpur on the Odisha coast. The VSCS, PHAILIN mainly affected Odisha, coastal Andhra Pradesh, West Bengal, Chhattisgarh and Jharkhand.

The impact was observed on coastal area of West Bengal and very low impact in the district of South 24 Parganas but some impact was found in the district Purba Medinipur which is near to the border of Odisha. The heavy rainfall and strong wind were causing lodging of rice plant and stagnation of water.

The crops on five lakh hectares were damaged in the very severe tropical cyclone. The worst hit was the Ganjam district of Odisha as over 200,000 hectares of agricultural land were destroyed, as per the state government. Balasore and Mayurbhanj districts were severely affected by heavy floods. The total area under the paddy cultivation during this kharif season was 3.6 million hectares. The coconut plantations across 3,200 hectares in the Srikakulum district have been damaged. More than 20 percent crops were damaged by Cyclone Phailin and subsequent floods.

Odisha contributes about a seventh of India’s total rice production. Hence it affected additional rice production. It has affected the grain, cash crops and orchard crops likes paddy, pulses, oilseeds; sugarcane, cotton, coconut, mango, cashew etc. The economic losses due to different crop losses are rice: 2400 crore, sugarcane: 210 crore, cotton: 800, groundnut: 800 crore, pulses and oilseeds: 100 crore, vegetables, etc 200 crore. Now it is estimated to decrease by 18 lakh tons in the state. The total loss standing crop due to damage to has been about 4510 crore rupees Odisha state.
The Role of Information System in data/ product/ warning dissemination and future improvements

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Study of any weather system requires exchange of large amount of data/information almost in near real time and its processing. Information System and Services Division (ISSD) of India Meteorological Department (IMD) caters to the need for exchange of all types of Meteorological data/products, weather related disaster warnings like cyclone, heavy rainfall, flood, cloud burst etc. at national and international level. The responsibility of IMD increases during the adverse weather conditions (specially during cyclonic storm) for timely dissemination of forecast and warnings to the concerned Government officials/agencies involved in the disaster mitigation in the likely affected area, public and neighbouring countries. Such services are delivered through state-of-the art technology information systems of IMD, SMS, FAX, Email and websites (www.imd.gov.in and www.indiaweather.imd.gov.in) etc. The paper describes about various latest information systems in IMD and role of such systems in the aid of weather analysis and warning dissemination. The utilization of information systems for cyclone warning dissemination (especially through IMD website) for cyclone activities 2013 has been analysed. Mechanism for further improvements in data exchange and product dissemination including warnings has also been highlighted.
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Abstracts

Photograph of Damage due to cyclone PHAILIN

Typical Satellite imagery of Cyclonic Storm PHAILIN

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