

Evolution of IMD's operational extended range forecast system of tropical cyclogenesis over North Indian Ocean during 2010-2020

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सार – मॉनसूनोत्तर ऋतु (अक्टूबर-दिसंबर; OND) को उत्तर हिंद महासागर (NIO) और विशेष रूप से बंगाल की खाड़ी (BoB) में अधिक तीव्रता के उष्णकटिबंधीय चक्रवातों (TCs) की उत्पत्ति के लिए जाना जाता है। 2010 से 2020 के दौरान गतिकीय मॉडल पर आधारित चक्रवातजनन की संभावना के प्रचालनात्मक विस्तारित अवधि पूर्वानुमान (ERF) विकसित करने पर चर्चा की गई है। ECMWF तथा CFSv1 गतिकीय मॉडल पर आधारित चक्रवातजनन की संभावना के प्रचालनात्मक विस्तारित अवधि पूर्वानुमान (ERF) का आरंभ वर्ष 2010 में नवंबर के प्रथम सप्ताह के दौरान बने प्रचंड चक्रवाती तूफान 'जल' के युक्तिसंगत निष्पादन के साथ हुआ था। वर्ष 2015 की सक्रिय अरब सागर और निष्क्रिय बंगाल की खाड़ी सहित चक्रवात ऋतु में भी भली भाँति वास्तविक समय ERF निष्पादित किए गए थे।

भारत मौसम विज्ञान विभाग द्वारा 2017 में प्रचालनात्मक ERF के लिए CFSv2 युग्मित मॉडल लागू किया गया और इसके आधार पर चार सप्ताह के लिए गतिकीय परिवर्ती जैसे भ्रमिलता, अपसारिता, ऊर्ध्वाधर पवन अपरूपण तथा मध्य-स्तर सापेक्षिक आर्द्रता के माध्यम से जेनेसिस पोटेंशियल पैरामीटर (GPP) की गणना की जाती है तथा 24-30 नवंबर, 2017 के 'ओखी' चक्रवात हेतु इसका परीक्षण किया गया था। 'ओखी' चक्रवात के मामले में केवल एक सप्ताह के लीड समय के साथ ERF में GPP का भली भाँति पूर्वानुमान किया गया।

उन्नत GPP (IGPP) का उपयोग वर्ष 2019 से किया जा रहा है, जिसे महासागर और भूमि दोनों क्षेत्रों में प्रयोग किया जा सकता है। IGPP के मामले में GPP की भ्रमिलता तथा मध्य क्षोभमंडलीय आर्द्रता की शब्दावली को यथावत रखा गया है, परंतु तापगतिकी की शब्दावली को मापन तथा 1000 और 500 hPa के मध्य औसत समकक्ष विभ्रव तापमान (θ_e) के रूप में संशोधित किया गया। प्रत्येक गिड बिंदु के लिए 850 और 200 hPa के बीच ऊर्ध्वाधर अपरूपण को 100 और 200 कि.मी. के बीच एक कुंडलाकार क्षेत्र में मापन तथा औसत किया जाता है। महाचक्रवात 'अम्फन' के मामले में इसके द्वारा प्रथम तथा द्वितीय सप्ताह के पूर्वानुमान में प्रणाली की उत्पत्ति तथा प्रेक्षित मार्ग के अनुसार ही इसके उत्तर-पूर्व की ओर मुड़ने का संकेत दिया था। अरब सागर में चक्रवात 'निसर्ग' तथा भारत के पश्चिमी तट की ओर इसके मार्ग को 27 मई, 2020 की प्रारंभिक स्थिति के आधार पर प्रथम सप्ताह के पूर्वानुमान में अच्छी तरह से प्रेक्षित कर लिया गया था। IGPP में तीन तीव्र चक्रवात जैसे, 21-24 नवंबर के दौरान 'गति', 22-26 नवंबर के दौरान 'निवार' तथा 30 नवंबर से 5 दिसंबर के दौरान 'बुरेही' और अक्टूबर 2020 के दो अवदाबों की उत्पत्ति का पूर्वानुमान करने में ERF में तर्कसंगत कौशल देखने को मिला। बंगाल की खाड़ी के उष्णकटिबंधीय चक्रवात की उत्पत्ति में मैडेन जूलियन ऑसिलेशन (MJO) की महत्वपूर्ण भूमिका को देखते हुए भारत मौसम विज्ञान विभाग द्वारा MJO के वर्तमान तथा पूर्वानुमान, उष्णकटिबंधीय चक्रवात उष्णता विभ्रव आदि जैसे अन्य मापदंडों के साथ प्रचालनात्मक IGPP का उपयोग किया जा रहा है तथा प्रत्येक गुरुवार को दो सप्ताह के लिए चक्रवातजनन संभाव्यता आउटलुक जारी किया जा रहा है।

ABSTRACT. The post monsoon seasons (October-December; OND) are known to produce tropical cyclones (TCs) of severe intensity over the North Indian Ocean (NIO) and particularly over the Bay of Bengal (BoB). The evolution of operational extended range forecast (ERF) of cyclogenesis probability during 2010 to 2020 based on dynamical models have been discussed. The ERF of cyclogenesis probability based on ECMWF and CFSv1 dynamical models had a modest beginning in 2010 with reasonable performance in case of severe cyclonic storm 'Jal' formed during the first week of November. The 2015 cyclone season with active Arabian Sea and inactive BoB was also very well captured in the real time ERF.

IMD implemented CFSv2 coupled model for operational ERF in 2017 and based on it the Genesis Potential Parameter (GPP) is calculated for four weeks by using the dynamical variables like vorticity, divergence, vertical wind shear & mid-level relative humidity and was tested for the 'Ockhi' cyclone of 24-30 November, 2017. The GPP in case of 'Ockhi' cyclone was well predicted in the ERF, however, with a lead time of only one week.

The Improved GPP (IGPP) is used since 2019, which can be applied both over the Ocean and the land region. In the case of IGPP the vorticity and middle tropospheric humidity terms of GPP have been retained but the thermodynamic term is modified as the scaled and averaged equivalent potential temperature (θ_e) between 1000 and 500 hPa. The vertical shear between 850 and 200 hPa is scaled and averaged over an annular region between 100 and 200 km radii for each grid point. In case of Super cyclone ‘‘Amphan’’ it indicated the genesis of the system in ‘‘Week 1’’ and ‘‘Week 2’’ forecast and also its re-curvature northeastward like the observed track. The cyclone ‘‘Nisarga’’ over the Arabian Sea and its track towards western coast of India was well captured in week 1 forecast based on Initial Condition of 27 May, 2020. The IGPP also showed reasonable skill in ERF in predicting the genesis of three intense cyclones viz., ‘Gati’ during 21-24 November, ‘Nivar’ during 22-26 November and ‘Burehi’ during 30 November to 5 December and the two depressions of October, 2020. Considering the significant role of Madden Julian Oscillation (MJO) in BoB TC genesis, IMD is making use of the operational IGPP along with other parameters like current and forecast MJO, Tropical Cyclone Heat Potential etc and the value-added cyclogenesis probability outlook is being issued for two weeks on every Thursday.

Key words – Tropical cyclone, Extended range forecast, Bay of Bengal, North Indian Ocean, Coupled model, Genesis potential probability.

1. Introduction

The extensive coastal belt of India covering more than 7000 km is very vulnerable to the cyclonic storms. Initially it forms over the north Indian Ocean (NIO) as low-pressure areas with maximum sustained surface wind of ≤ 17 kts and then intensify into depressions (maximum sustained surface wind is between 17-33 kts) and sometime become tropical cyclones (when the surface wind > 33 kts). For the tropical cyclones (TCs) only it has the bimodal peaks with one peak during pre-monsoon season from Mar-May and the other peak is during the post-monsoon season (October to December; OND) (Pattanaik, 2005). The strong winds, heavy rains and storm surges due to TCs are the factors lead to loss of life and property. The cyclonic storms over the Bay of Bengal (BoB) after the landfall can cause severe damages to life and property over many countries of south Asia surrounding the BoB. The highest population density with low socio-economic conditions in combination with the shallow coastal plain over the south Asian countries in the vicinity of the BoB has resulted in several land falling cyclones becoming devastating natural disasters. The strong winds, heavy rains and large storm surges associated with tropical cyclones are the factors that eventually lead to loss of life and property. Heavy rains associated with cyclones are another source of damage. The combination of a shallow coastal plain along with a thermodynamically favourable environment allow TCs to impart high surface winds, torrential rains and significant wave heights (wave setup plus storm surge) as these systems move inland. In addition, the world’s highest population density coupled with low socio-economic conditions in the region has resulted in several land-falling TCs becoming devastating natural disasters (Mohapatra *et al.*, 2013).

With the improvement in numerical model and use of wide ranges of non conventional data in the assimilation system of the model there has been considerable improvement in the forecast skill of tropical cyclones particularly in the short range up to 72 hrs (references). This provides the likelihood of TC genesis

during next 72 hrs In India, many studies have demonstrated the utility of TCs forecasts up to 3 days using Global and regional models (Sikka, 1975; Mohanty and Gupta, 1997; Pattanaik and Rama Rao, 2009, etc.). There have been some earlier studies (Roy Bhowmik, 2003; Pattanaik *et al.*, 2003) to define the Genesis Parameter (GP) based on some dynamical variables, viz., low-level vorticity, low level divergence and vertical wind shear. Both the studies have indicated a clear-cut differentiation between developing (system intensified into a cyclone) and non-developing (dissipated prior to cyclonic storm) over the Bay of Bengal in terms of magnitude of the dynamical parameters. Roy Bhowmik (2003) observed that a low-pressure system with GP value around 20×10^{-12} at T. No. 1.5 has the potential to intensify into a severe cyclonic storm. Subsequent study by Kotal *et al.* (2009) used the genesis potential parameter (GPP), which is defined as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability and the inverse of vertical wind shear and found that the composite GPP value is around three to five times greater for developing systems than for non-developing systems. However, the forecasting of genesis of tropical cyclone and associated rainfall in the extended range time scale (about 2 weeks in advance) has not been addressed adequately, although, it is very useful in many respects. There have been limited works done in the area of predictability of NIO TCs using the latest generation of global numerical weather prediction systems in the extended range. Very few studies have been devoted to assessing the performance of ensemble prediction systems for tropical cyclones. A recent study by Belanger *et al.* (2010) have shown some skill in forecasting tropical cyclones using dynamically based ensemble products from ECMWF monthly forecast system (Vitart, 2004). They have shown that the forecast system can capture large-scale regions that have a higher or lower risk of TC activity on the intra-seasonal time scale. Their study also found that the predictability of TC activity is sensitive to the phase and intensity of the Madden-Julian Oscillation (MJO) at the time of model initialization. Fu

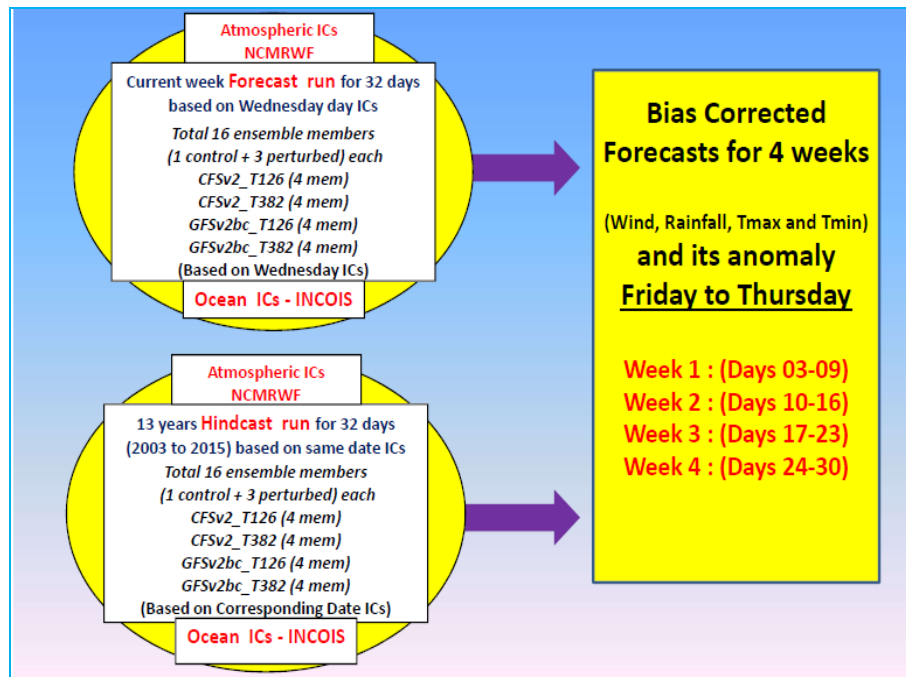


Fig. 1. IMD's operational extended forecast system based on CFSv2 coupled model implemented in 2016

and Hsu (2011) using a conventional atmosphere-ocean coupled system initialized with NCEP FNL analysis has successfully predicted a tropical cyclogenesis event in the northern Indian Ocean with a lead time of two weeks.

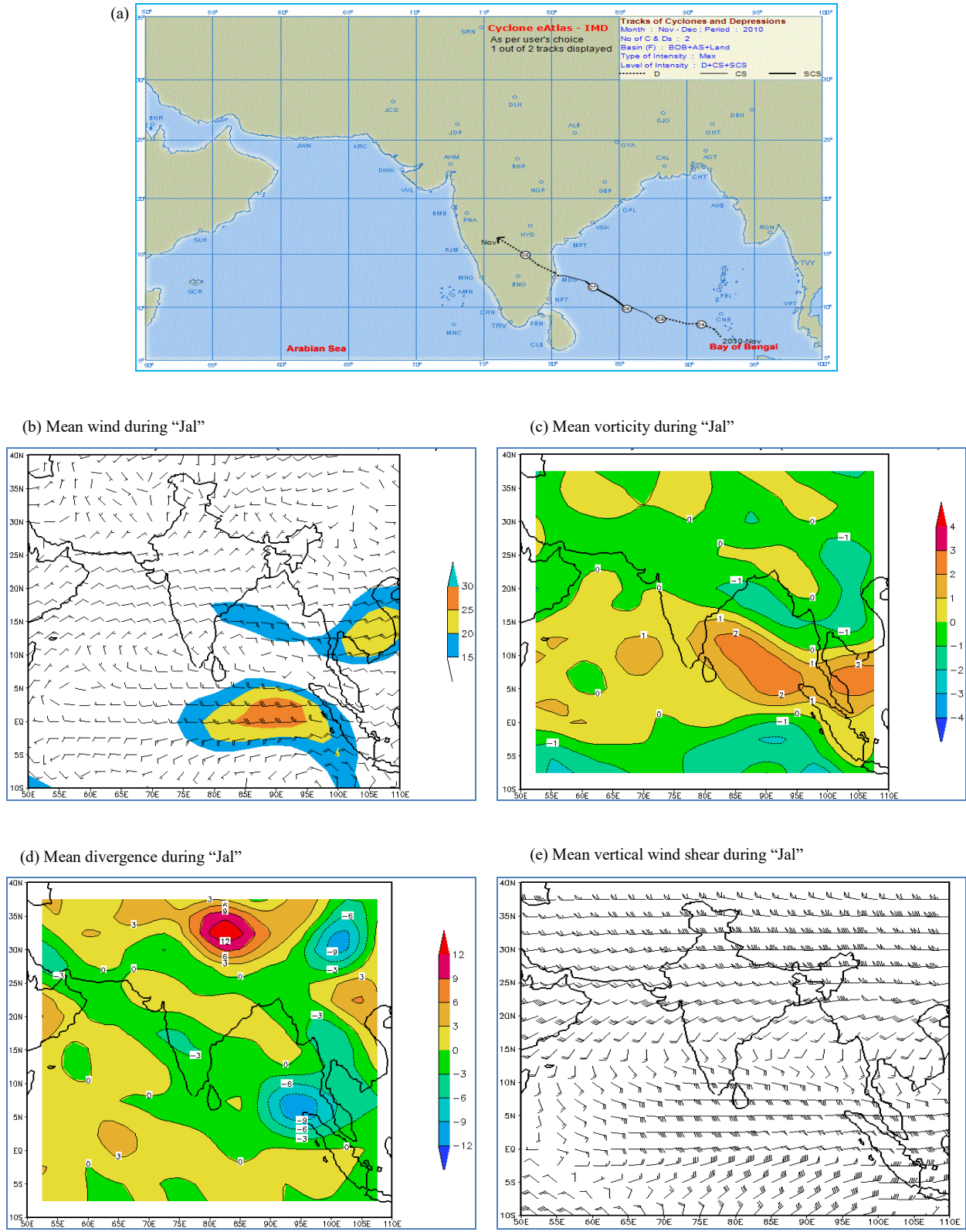
As a part of the daily operational mandate, India Meteorological Department (IMD) issues a daily tropical weather outlook, which assesses the possibility of tropical depression development in the Bay of Bengal and the Arabian Sea. With the genesis of a depression IMD begins issuing TC forecast advisories for valid for 72 hrs (IMD, 2003). The forecasting of genesis of tropical cyclone and associated rainfall in the extended range time scale (about 2 weeks in advance) is also very useful for applications in disaster risk reduction (Pattanaik *et al.*, 2013; Pattanaik & Mohapatra, 2014). IMD has started using the dynamical models outputs for forecast of cyclogenesis in the extended range time scale since 2010 (Pattanaik *et al.*, 2013b; Pattanaik & Mohapatra, 2014). With operational implementation of coupled modeling system for ERF the genesis forecast of tropical cyclone has also improved over the time. In the present paper the evolution of operational ERF for tropical cyclogenesis for north India Ocean during last one decade has been presented.

2. Dynamical ERF System of IMD for cyclogenesis

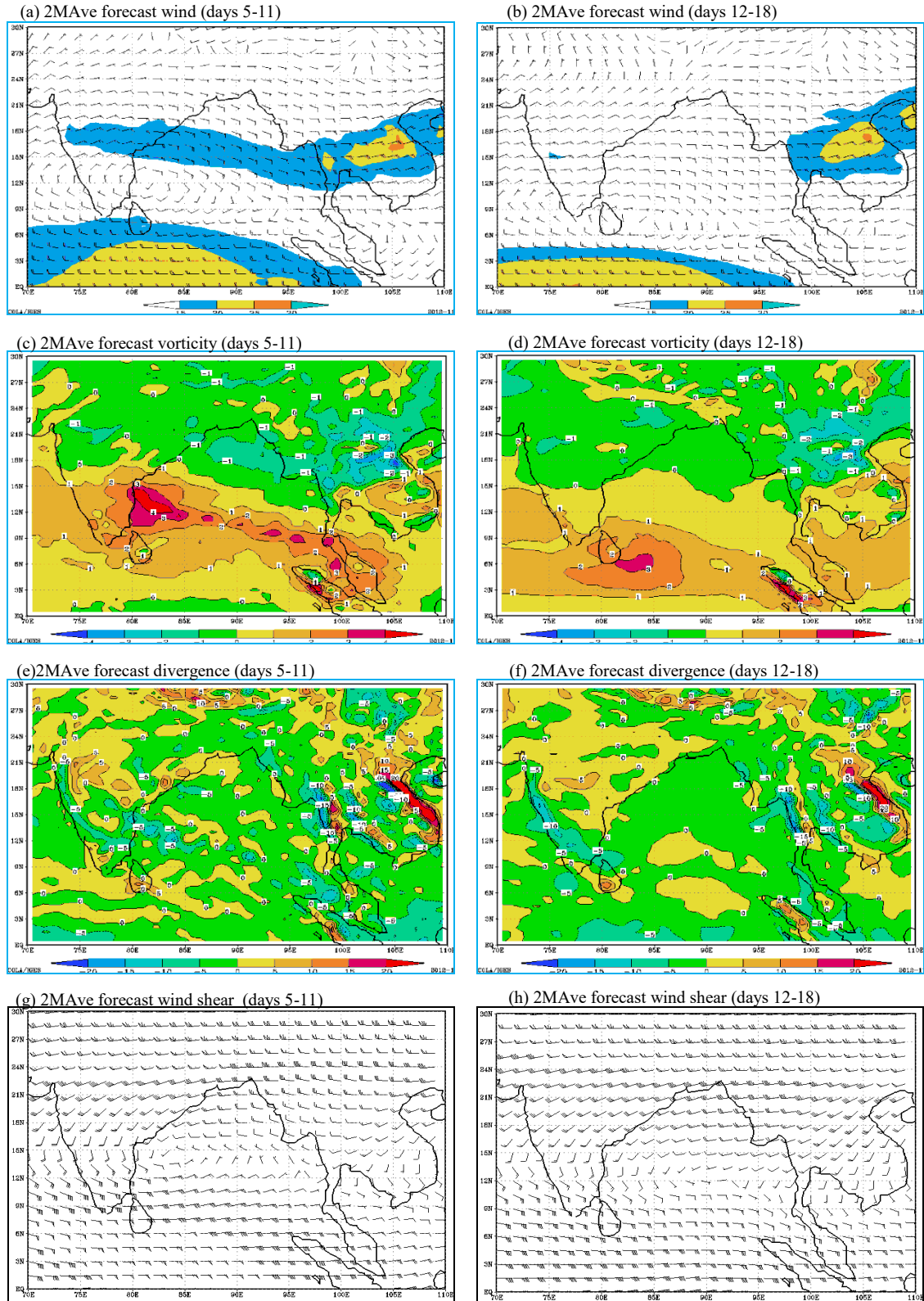
The evolution of operational ERF system for monsoon forecast during its inception in 2008 has been discussed in a review paper by Pattanaik *et al.* (2019). As

discussed in the paper the dynamical model outputs available from various modeling centres like the NCEP's CFS version 1 (CFSv1), JMA's ensemble prediction system and European Centre for Medium Range Weather Forecasting (ECMWF) monthly forecast system etc were used initially since 2008 for preparing operational multi-model ensemble (MME) products for various applications. The MME based products were used for the preparation of real time ERF in IMD during the period from 2010 to 2016.

In 2016 IMD has implemented coupled modeling system for operational ERF, which is based on NCEP CFSv2 coupled model (Saha *et al.*, 2014). It runs once in a week on every (Wednesday) and the forecast is generated for 4 weeks starting from subsequent Friday to Thursday and so on (Fig. 1). The oceanic component is the GFDL Modular Ocean Model V.4 (MOM4). The operational suite of models consists of (i) CFSv2 at T382 (≈ 38 km) (ii) CFSv2 at T126 (≈ 100 km) (iii) GFSbc (bias corrected SST from CFSv2) at T382 and (iv) GFSbc at T126 with 4 members each (Total 16 members). This is based on the Ensemble Prediction System (EPS) of IITM developed by Abhilash *et al.* (2014, 2015). For 2016 operational forecast the hindcast run is performed for 13 years (2003 to 2015) and the year 2018 is added into hindcast run for the forecast of 2019 and so on. This ERF system has the capability of predicting active-break cycle of monsoon which can be used for various applications. The performance of ERF forecast for 2017 and 2018



Figs. 2(a-e). (a) Cyclonic storms of post monsoon season from October-December, 2010. The dark black lines indicate severe cyclone "Jal". (b) Observed 850 hPa mean wind during SCS "Jal" (1-7 November, 2010). (c) Same as 'a' but for mean relative vorticity ($1 \times 10^{-5} \text{ sec}^{-1}$) (d) Same as 'a' but for mean divergence ($1 \times 10^{-6} \text{ sec}^{-1}$) and (e) Same as 'a' but for mean vertical wind shear (W200-W850) in kts. (Source : Pattanaik et al., 2013)



Figs. 3 (a-h). (a) 2 MAve 850 hPa forecast based on 28 October (days 5-11 forecast) mean winds during SCS “Jal” (1-7 November, 2010). (c), (e) and (g) same as ‘a’ but for mean relative vorticity ($1 \times 10^{-5} \text{ sec}^{-1}$), mean divergence ($1 \times 10^{-6} \text{ sec}^{-1}$) and mean vertical wind shear (W200-W850) in kt (b), (d), (f) and (h) same as ‘a’, ‘c’, ‘e’, ‘g’ but for days 12-18 forecast based on 21 October, 2012. (Source : Pattanaik *et al.*, 2013)

TABLE 1
Dynamical parameters like vorticity and divergence from the forecast fields in case of SCS “Jal”

Dynamical Parameters	Mean and Anomaly	Week 1 (days 5-11) forecast Based on 28 October and valid for 1-7 November, 2010 (Area : 80° E-90° E, 5-15° N)			Week 2 forecast (days 12-18) Based on 21 October and valid for 1-7 November, 2010 (Area : 80° E-90° E, 05-15° N)		
		ECMWF	NCEP	2MAVE	ECMWF	NCEP	2MAVE
850 hPa max_vor ($1 \times 10^{-5} \text{ sec}^{-1}$)	Mean	5.52	4.36	4.94	3.42	3.47	3.36
	Anomaly	4.33	3.81	4.05	2.00	2.81	2.32
850 hPa min_div ($1 \times 10^{-5} \text{ sec}^{-1}$)	Mean	-3.02	-0.72	-1.65	-1.57	-0.60	-0.88
	Anomaly	-3.03	-0.58	-1.57	-1.42	-0.48	-0.80

monsoon has been published in a recent paper by Pattanaik *et al.* (2020). Another report highlighting verification of ERF forecast skills for monsoon, cyclogenesis, heat wave, cold wave etc for the entire year 2017 is published by IMD, which is also available online (http://nwp.imd.gov.in/ERF_Report_2017.pdf).

3. Evolution of operational ERF of tropical cyclogenesis in IMD during 2010-2019

3.1. ERF of cyclogenesis during 2010 & 2011

Based on the available dynamical models outputs the forecasting of genesis of tropical cyclone and associated rainfall in the extended range time scale (about 2 weeks in advance) for applications in disaster risk reduction had a modest beginning in IMD in 2010, where it started using the dynamical models outputs from various models for forecast of cyclogenesis in the extended range time scale (Pattanaik *et al.*, 2013; Pattanaik & Mohapatra, 2014). As shown in Fig. 2(a) obtained from the cyclone e-Atlas (IMD, 2012) the severe cyclonic storm (SCS) ‘Jal’ during 1st week of November, 2010 was first observed as a low pressure area over the south Andaman Sea and neighbourhood on 2nd November, gradually intensified into a SCS on 6th November and crossed north Tamil Nadu-south Andhra Pradesh coasts on 7th November and caused lot of damage in Tamil Nadu and south Andhra Pradesh coast associated with not only strong wind but also due to heavy rainfall due to the cyclone. To see the observational features of SCS ‘Jal’ the weekly mean variables during the period from 1-7 November, 2010 [Figs. 2(b-e)] shows very prominent low level cyclonic circulation over the southern Bay of Bengal with associated cyclonic vorticity more than $20 \times 10^{-6} \text{ sec}^{-1}$. The horizontal convergence at 850 is also found to be around $9 \times 10^{-6} \text{ sec}^{-1}$ in the weekly mean along with low to moderate (10 to 15 kts) vertical wind shear.

As shown by Pattanaik *et al.* (2013) the genesis of the cyclone “Jal” was very much captured in the two models’ average (2MAve) of CFSv1 and ECMWF with two weeks lead time. It shows cyclonic circulation over the Tamil Nadu coast and adjoining coastal Andhra Pradesh region during 1-7 November even in the forecast valid for 12-18 days based on the initial condition of 21 October and for days 5-11 forecast based on 28 October, 2010 [Figs. 3(a&b)] like that of observed patterns shown in [Fig. 2(b)]. The corresponding low level vorticity forecast at 850 hPa based on 2MAve also indicated cyclonic vorticity of about $40 \times 10^{-6} \text{ sec}^{-1}$ near Tamil Nadu in days 5-11 and days 12-18 forecasts [Figs. 3(c&d)]. The positive cyclonic vorticity in the 2MAve forecast field is also associated with negative divergence as shown in [Figs. 3(e&f)]. The 2MAve forecast vertical wind shear during days 5-11 and days 12-18 forecast valid for the period “Jal” (1-7 November) as shown in [Figs. 3(g&h)] is almost matching with the observed vertical wind shear shown in Fig. 2(e). Quantitatively the dynamical parameters like vorticity and divergence from the forecast fields in case of SCS “Jal” obtained from CFSv1, ECMWF and 2MAve models are given in Table 1. Table 1 provides the values of maximum low-level vorticity (highest positive value for cyclonic vorticity; max_vor) and minimum low level convergence (highest convergence; min_div) over the area bounded by 90° E-100° E, 15° N-25° N for the individual model from ECMWF and NCEP CFSv1 along with the ensemble average (2MAve).

The mean of the two model forecast appears to be better option in order to reduce the uncertainty. The forecast from individual model and 2MAve shows a value of max_vor and its anomaly of about $4 \times 10^{-5} \text{ sec}^{-1}$ associated with min_div and its anomaly exceeding $-1.5 \times 10^{-5} \text{ sec}^{-1}$ in the 2MAve forecast. In addition to the max_vor and min_div the wind shear is also very small about 10 to 15 kts as shown in Figs. 3(g&h). Thus, the study indicated that even in the ERF time scale the

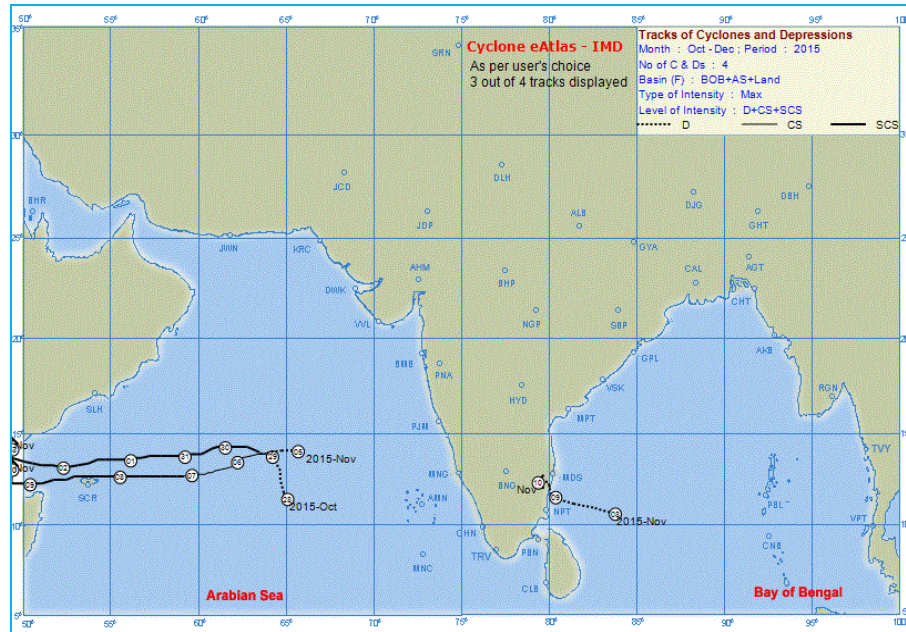


Fig. 4. Tracks of the systems over North Indian Ocean during 28 October - 10 November, 2015

cyclogenesis potential probability can be defined for a developing cyclone. Like in case of 2010 cyclone season the cyclogenesis probability forecast up to 2 to 3 week time scales during 2011 post-monsoon season is also discussed by Pattanaik and Mohapatra (2014). These studies have indicated that the MME based ERF could very well predict the genesis of the system and associated rainfall distribution due to the cyclones. These studies have indicated that the forecast threshold values of dynamical parameters like the low-level vorticity, low-level circulation, vertical wind shear etc. can be defined like it is done in the medium range time scale for developing system, which can intensify into a tropical cyclone.

3.2. ERF of cyclogenesis during 2015 cyclone season

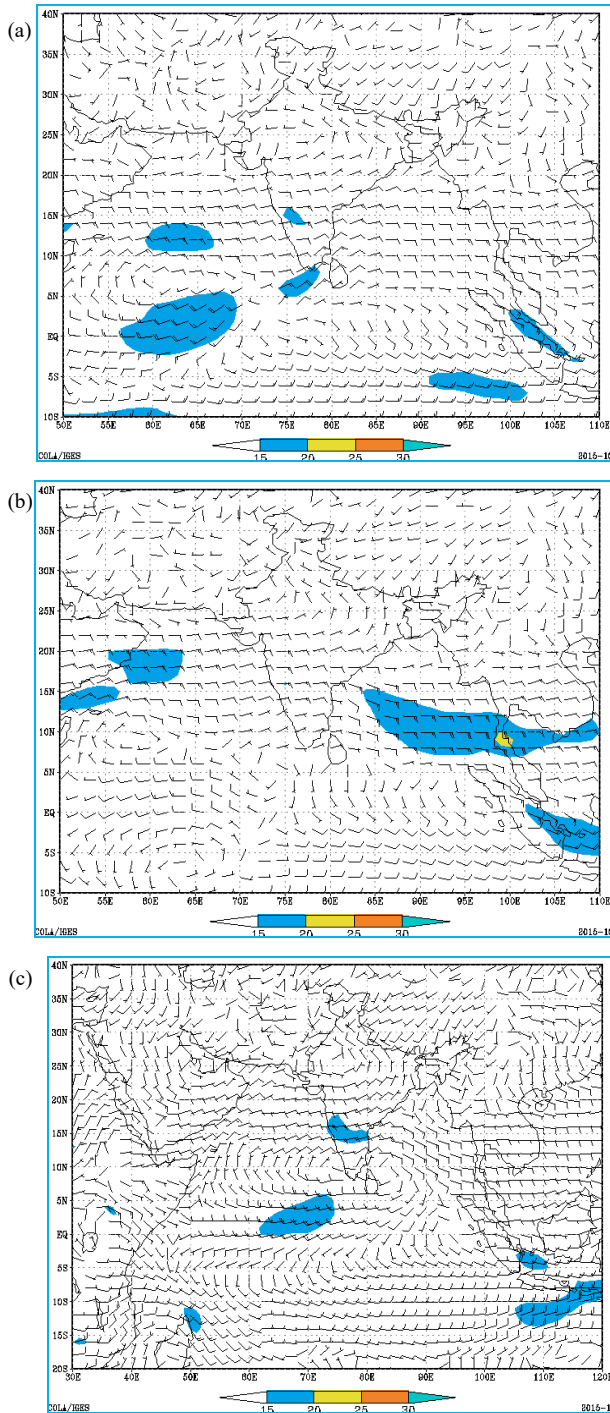
3.2.1. Cyclonic disturbances during October-December, 2015 over North Indian Ocean

The post-monsoon season of 2015 from October to December witnessed active Arabian Sea with two Extremely Severe Cyclonic Storm (ESCS) and one Deep Depression (DD), whereas, the BoB witnessed only one DD, viz., (i) DD over the Arabian Sea (9-12 October); (ii) ESCS “Chapala” over the Arabian Sea (28 October - 4 November); (iii) ESCS “Megh” over Arabian Sea (5-10 November) and (iv) DD over the BoB (8-10 November). Thus, the period from 28 October -10 November was very active with two cyclones and one depression and the observed track for the same can be seen in the Fig. 4. The life cycle of these systems are :

The ESCS 'Chapala' formed from a low-pressure area over southeast Arabian Sea which concentrated into a depression in the morning of 28th October. It moved north-northwestwards and gradually intensified into an ESCS in the morning of 30th and crossed Yemen coast on 3rd November as a VSCS. The ESCS 'Megh' formed over the east-central Arabian Sea on 5th morning from a low-level circulation over Lakshadweep and neighborhood. It moved westwards/west-south-westwards and intensified into a cyclonic storm and gradually intensified into a VSCS on 7th and rapidly intensified into an ESCS on 8th. The peak intensity of the system was maintained for a short period and weakened gradually into a DD on 10th. During the weakening period of 'Megh' in the Arabian Sea another DD is formed during 8-10 November, 2015 over southwest BoB close to north Tamil Nadu and Sri Lanka coasts and made the landfall on 9th evening. Due to its proximity to the coast throughout the day, it caused exceptionally heavy rainfall over north Tamil Nadu on 9th November.

3.2.2. ERF of genesis of systems during 28 October-10 November, 2015

As shown in Fig. 4 during the period from 28th October to 10th November, 2015 two cyclonic storms (Chapala during 28 October-4 November) and “Megh” (5-10 November) formed over the Arabian Sea and one depression (8-10 November) formed in the BoB. The ERF of low-level mean wind based on the initial condition of 21st October, 2015 indicates low-level cyclonic circulation over south-central Arabian Sea in week 1 forecast valid for the period from 23-29 October, 2015 [Fig. 5(a)]. The



Figs. 5(a-c). Ensemble forecast of 850 hPa mean wind based on 21 October, 2015 and valid for (a) 23-29 October, (b) 30 October-5 November and (c) 6-12 November, 2015

week 2 forecast valid for the period 30 October-5 November also indicates presence of low-level cyclonic circulation over the south-west Arabian Sea [Fig. 5(b)]. Thus, the week 1 and week 2 forecasts clearly indicated the possibility of cyclogenesis over the Arabian Sea and it

may be mentioned here that the systems ESCS ‘Chapala’ and ESCS ‘Megh’ had formed over the Arabian Sea during this period (Fig. 4). It is further seen that the week 3 forecast valid for the period 6-12 November, 2015 as shown in Fig. 5(c) also indicated low-level cyclonic circulation over the south-west Bay of Bengal close to Chennai coast, which is consistent with the formation of the DD over the region.

Further, to quantify the genesis potential the other dynamical parameters are calculated. The forecast low-level vorticity ($1 \times 10^{-5} \text{ Sec}^{-1}$) based on the initial condition of 21st October, 2015 and valid for three weeks from 23 October to 12 November is shown in Figs. 6(a-c). The corresponding vertical wind shear (W200 - W850) for the three weeks is also seen in Figs. 6(d-f) respectively. As seen from Figs. 6(a-c) the vorticity maximum of values greater than $4 \times 10^{-5} \text{ Sec}^{-1}$ is noticed during week 1 and week 2 forecasts over the south-central and south-west Arabian Sea valid for the week from 23-29 October and 30 October-5 November, 2015 respectively. The vertical wind shear forecasts [Figs. 6(d-f)] for three weeks based on the initial condition of 21 October, 2016 also indicates low to moderate shear (5 to 10 knots) over the region of maximum vorticity thereby conducive for the formation of a system over the Arabian Sea during the week from 23-29 October and 30 October-5 November and over the Bay of Bengal during the period from 6-12 December, 2016 coinciding with the three systems shown in Fig. 4.

3.3. ERF of Very Severe Cyclonic Storm, Ockhi (29 November – 6 December, 2017)

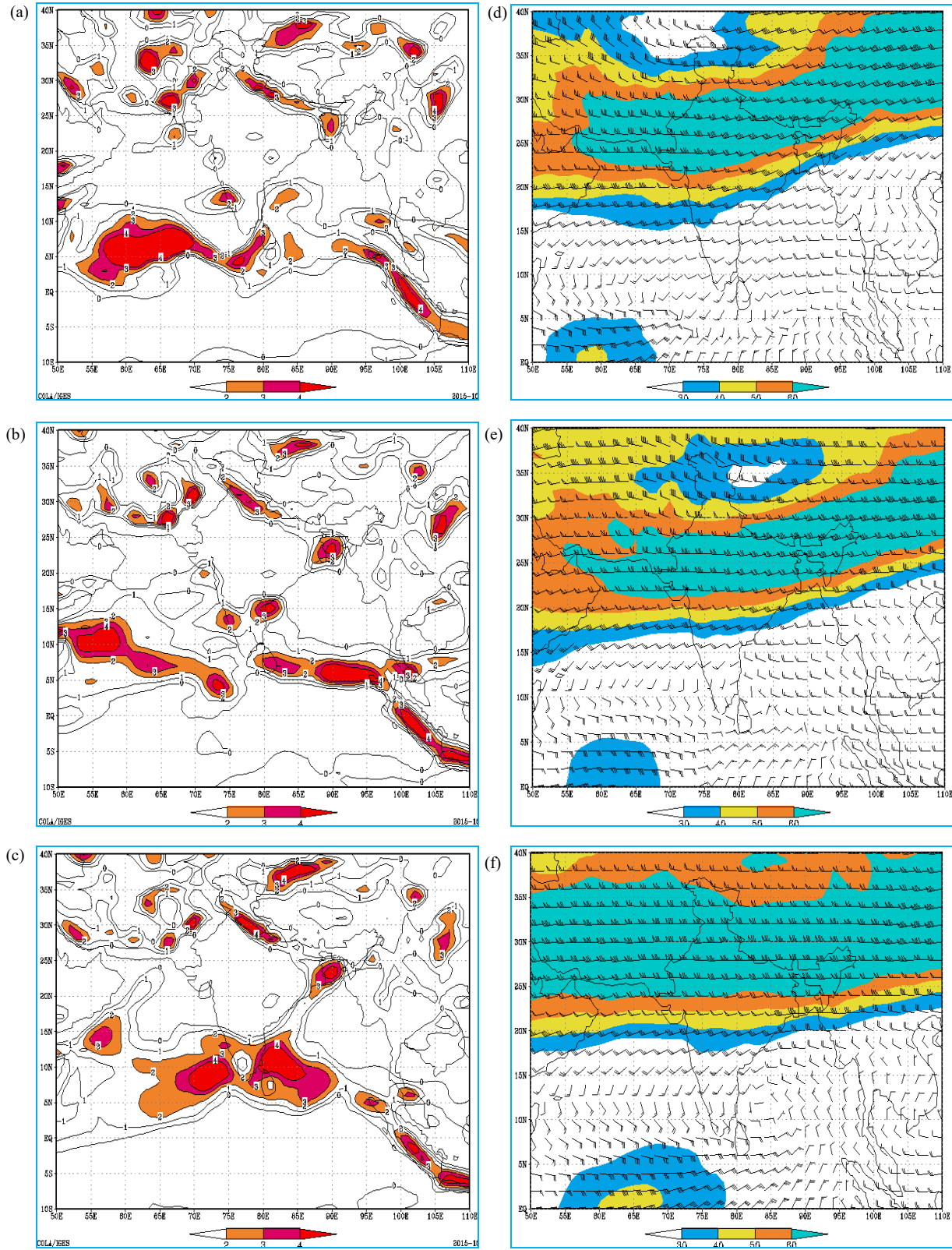
3.3.1. ERF of Genesis Potential Parameter (GPP)

In order to quantify the dynamical and thermodynamical parameters for the TC genesis forecast the GPP index has been calculated from the ERF model outputs. The GPP is being used by IMD operationally for the medium range forecast model (Kotal *et al.*, 2009; Kotal & Bhattacharya, 2013). As shown by them the GPP consist of low-level relative vorticity (ξ at 850 hPa), shear parameter (S) is vertical wind shear between 200 and 850 hPa, humidity parameter (M) obtained from scaled middle tropospheric relative humidity (RH) (700-500 hPa) and middle tropospheric instability (I) between 850 and 500 hPa constitutes the GPP defined as:

$$\text{GPP} = \frac{\xi_{850} \times M \times I}{S}; \text{ if } \xi_{850} > 0, M > 0 \text{ and } I > 0 \quad (1)$$

$$= 0 \quad ; \text{ if } \xi_{850} \leq 0, M \leq 0 \text{ and } I \leq 0$$

$$\text{where, } M = \frac{(\text{RH} - 40)}{30} \text{ and } I = (\text{T}_{850} - \text{T}_{500})$$



Figs. 6(a-f). Ensemble forecast of 850 hPa mean relative vorticity ($1 \times 10^{-5} \text{ Sec}^{-1}$) based on 21 October, 2015 and valid for (a) 23-29 October, (b) 30 October-5 November, (c) 6-12 November, 2015. (d), (e) and (f) same as 'a', 'b' and 'c' but for vertical mean shear (W200-W850)

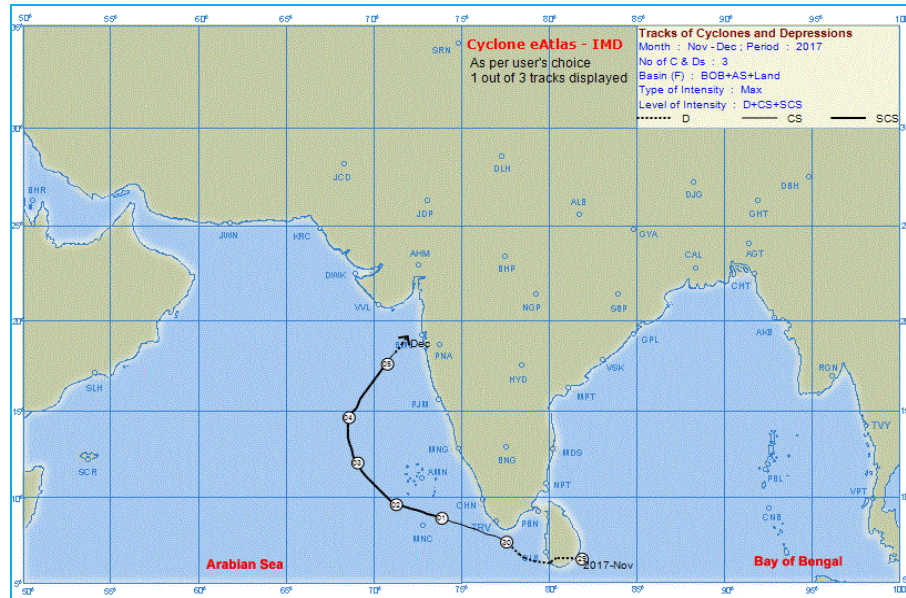


Fig. 7. Observed track of the Very Severe Cyclonic Storm (VSCS) 'Ockhi' during 29 Nov - 6 Dec, 2017

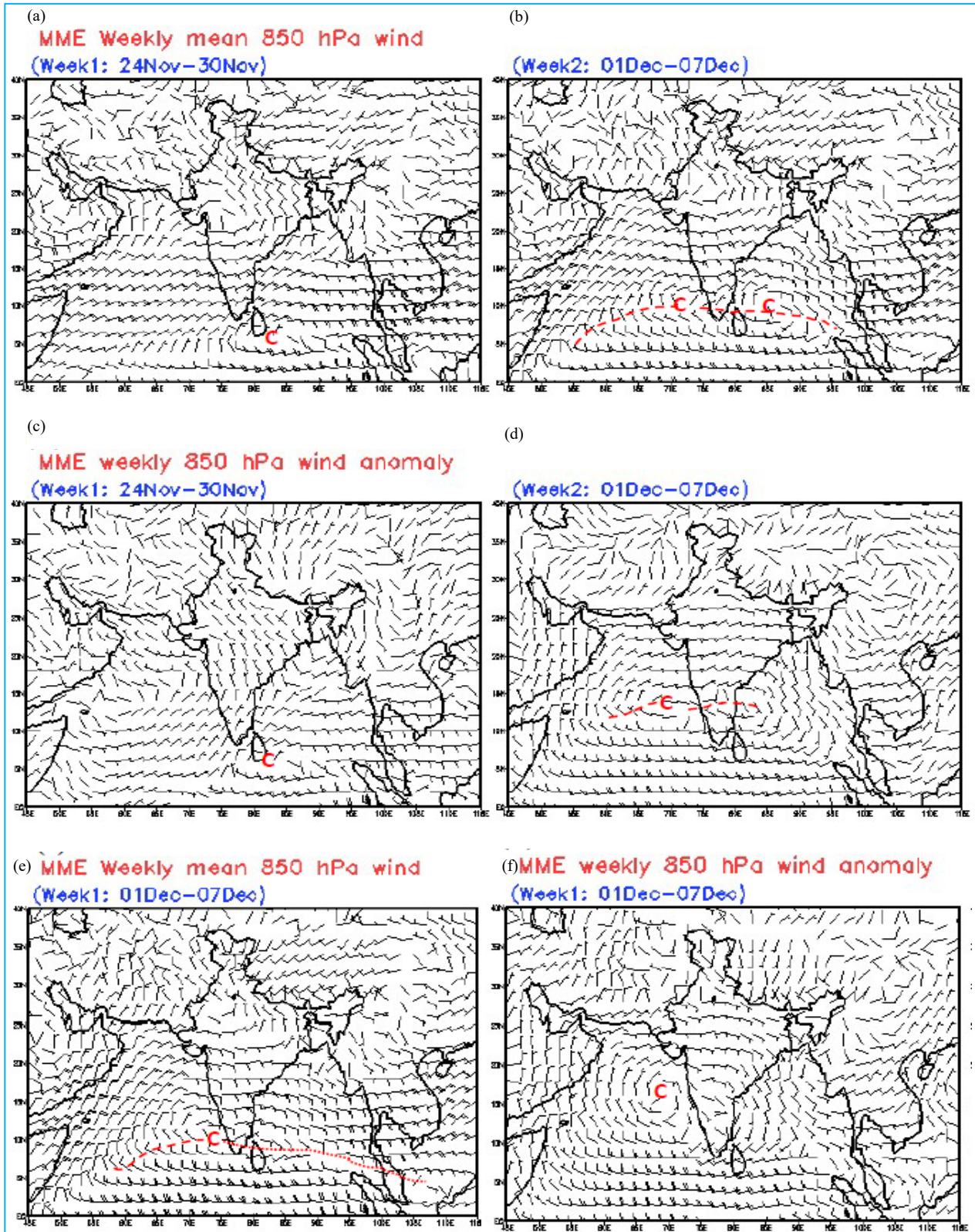
3.3.2. Genesis Potential Parameter (GPP) during VSCS "OCKHI"

The GPP based on operational ERF is tested for the VSCS "Ockhi". The "Ockhi" originated from a low pressure area over southwest Bay of Bengal. Under favourable environmental conditions, it concentrated into a Depression over southwest Bay of Bengal off southeast Sri Lanka coast in the morning of 29th November (Fig. 7). Moving westwards, it crossed Sri Lanka coast after some time. Continuing its westward movement, it emerged in Comorin Area in the evening of 29th and intensified into a DD in the early hrs of 30th. It further moved northwestwards intensified into CS in the morning of 30th November, into a SCS over Lakshadweep area in the early morning of 1st December and VSCS over southeast Arabian Sea to the west of Lakshadweep in the afternoon of 1st December. It then moved northwards and reached its peak intensity in the morning of 4th December. It then moved north-northeastwards and weakened gradually and crossed South coast of Gujarat as a low pressure area in the early morning of 6th. 'Ockhi' was the most intense tropical cyclone in the Arabian Sea since Cyclone 'Megh' in 2015. It was the third and the strongest storm over north Indian Ocean during 2017. Cyclone 'Ockhi' is noted for its very unusual track. It originated from a low pressure area over southwest Bay of Bengal and ended over south coastal Gujarat and neighbourhood and had a track length of about 2540 km.

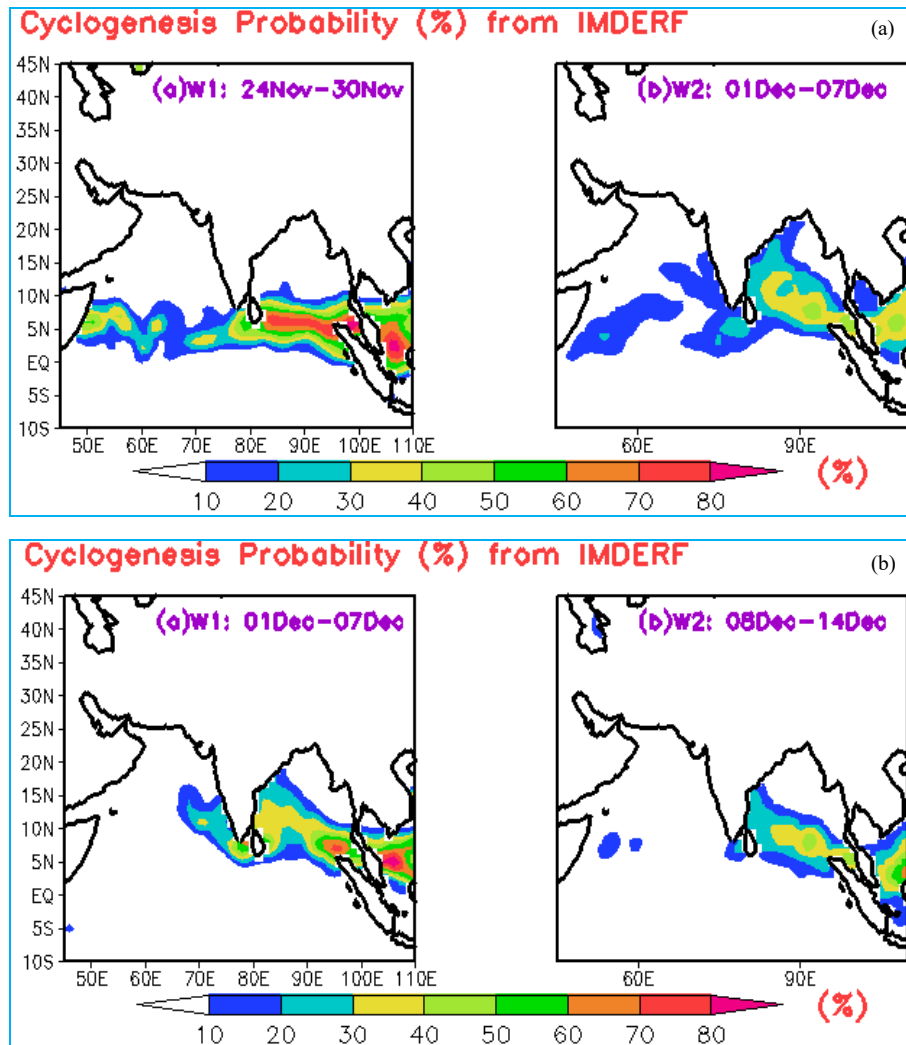
For the genesis of VSCS 'Ockhi' the ERF of low level wind based on the initial conditions of 22nd November and 29th November, 2017 are considered.

As seen in Figs. 8(a-f) the week 1 and week 2 forecast of low level mean wind [Figs. 8(a&b)] based on the initial condition of 22nd November, 2017 indicates cyclonic circulation off the Sri Lanka coast in week 1 forecast valid for 24-30 November, 2017 which extends westward into the Arabian Sea in week 2 forecast valid for the period from 1-7 December, 2017. The corresponding wind anomaly forecasts for week 1 and week 2 indicated anomalous cyclonic circulation off the Sri Lanka coast during 24-30 November and anomalous trough associated with east-west trough extending from southeast Arabian Sea to southwest Bay of Bengal [Figs. 8(c&d)]. The ERF based on the initial condition of 29th November, 2017 and valid for week 1 (1-7 December) forecast as shown in Figs. 8(e&f) indicated cyclonic circulation over the southeast Arabian Sea both in the mean wind and anomaly wind respectively. Thus, the 'Ockhi' cyclone genesis was reasonably captured in the model based on 22nd November and was slightly better with the IC of 29th November, 2017.

The GPP of cyclogenesis probability is also calculated based on equation 1 in the operational ERF and is shown in Figs. 9(a&b). As seen from Fig. 9(a) the forecast for week 1 indicate GPP more than 70% over the Sri Lanka coast based on the initial condition of 22nd November and valid for the period from 24-30 November, 2017. The week 2 forecast valid for the period from 1-7 December, 2017 indicated GPP of about 40% (mainly over the Bay of Bengal). Based on 29th November initial condition the GPP was between 30% to 50% over the southeast Arabian Sea and over the western part of Bay of Bengal [Fig. 9(b)]. Thus, the GPP over the Bay of



Figs. 8(a-f). (a) and (b) Based on 22nd November initial condition the forecast mean wind for two weeks valid for (24-30 November) and (1-7 December, 2017), (c) and (d) same as 'a' and 'b' but for wind anomaly. (e) and (f) week 1 forecast 850 wind and anomaly based on the initial condition of 29th November, 2017 valid for 1-7 December, 2017



Figs. 9(a&b). (a) Based on initial condition (IC) of 22nd November, 2017 the GPP (genesis potential probability) of cyclogenesis for two weeks valid for 24 November-7 December and (b) Same as 'a' but with IC of 29 November, 2017

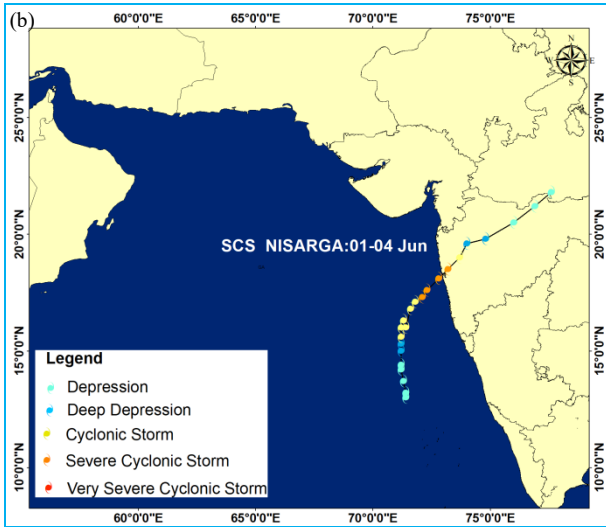
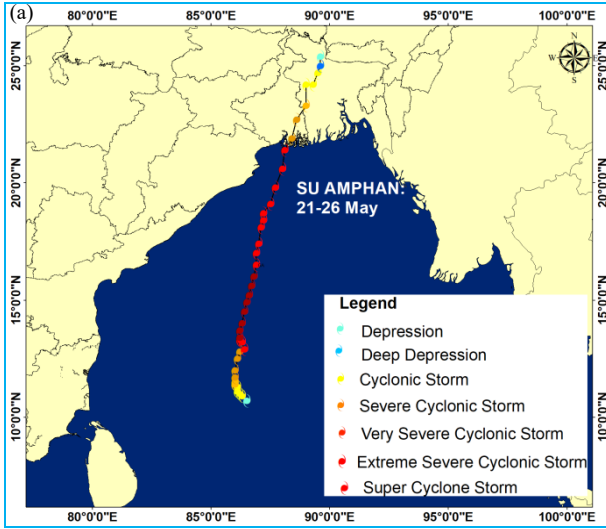
Bengal off Sri Lanka coast during the period from 24-30 November, 2017 based on 22nd November initial condition was reasonably indicated in the week 1 forecast near the Sri Lanka coast. However, the week 1 forecast based on 29th November indicated the re-curved of 'Ockhi' in the Arabian Sea. Thus, it is apparent that one more initial condition between 22nd & 29th November, 2017 would have given slightly better analysis of the ERF as the cyclone was formed on 30 November, 2017.

4. Extended range forecast of cyclogenesis during 2020 with new GPP

4.1. Improved Genesis Potential Parameter (IGPP)

In order to improve the GPP, which can be used both during cyclone as well as monsoon depression even over

the land region the GPP as defined by Kotal *et al.* (2013) has been improved and here after it is called as IGPP (Improved GPP or IGPP) as defined by (Ganesh *et al.*, 2020). In the case of IGPP the vorticity and middle tropospheric humidity terms of GPP have been retained. However, the thermodynamic term is modified as the scaled and averaged equivalent potential temperature (θ_e) between 1000 and 500 hPa so as to include the effect of sea surface temperatures, surface heat fluxes and also to include the effect of middle tropospheric warming due to latent heat release associated with conditional instabilities or positive feedbacks associated with cyclogenesis. The vertical wind shear between 850 and 200 hPa is scaled and averaged over an annular region between 100 and 200 km radii for each grid point to highlight the effect of background shear and scaled according to the Genesis Potential Index (GPI) defined earlier (Emanuel, 1986;



Figs. 10(a&b). (a) Observed track of the Super Cyclone (Su) 'Amphan' during the period 16-21 May, 2020 and (b) Observed track of Severe Cyclonic Storm 'Nisarga' during the period from 29 May to 1 June, 2020

Free *et al.*, 2004). The GPI is a climatological index using potential intensity, relative humidity (H) at 600 hPa, absolute vorticity (ζ) at 850 hPa and vertical wind shear (V) between 850 and 200 hPa scaled and defined as GPI. Thus,

$$\text{Thermodynamic term, } I = \frac{(\theta_{e1000} + \theta_{e500})}{2} \quad (2)$$

$$\text{Scaled as; } T = \frac{I - 273.15}{6} \quad (3)$$

Mean middle tropospheric relative humidity ; MRH
 = $(RH_{700} + RH_{500})/2$

$$\text{Scaled as (Gray, 1975), } H = \frac{(\text{MRH} - 40)}{30} \quad (4)$$

$$\text{Relative vorticity at 850 hPa, } V = \zeta_{850} \times 10^5 \quad (5)$$

Scaled magnitude of vertical wind shear (200-850 hPa) (V_{shear}) averaged over an annular region (Chen and Fang, 2012) between 100 and 200 km from each grid point;

$$S = (1 + .1V_{\text{shear}})^{-2} \quad (6)$$

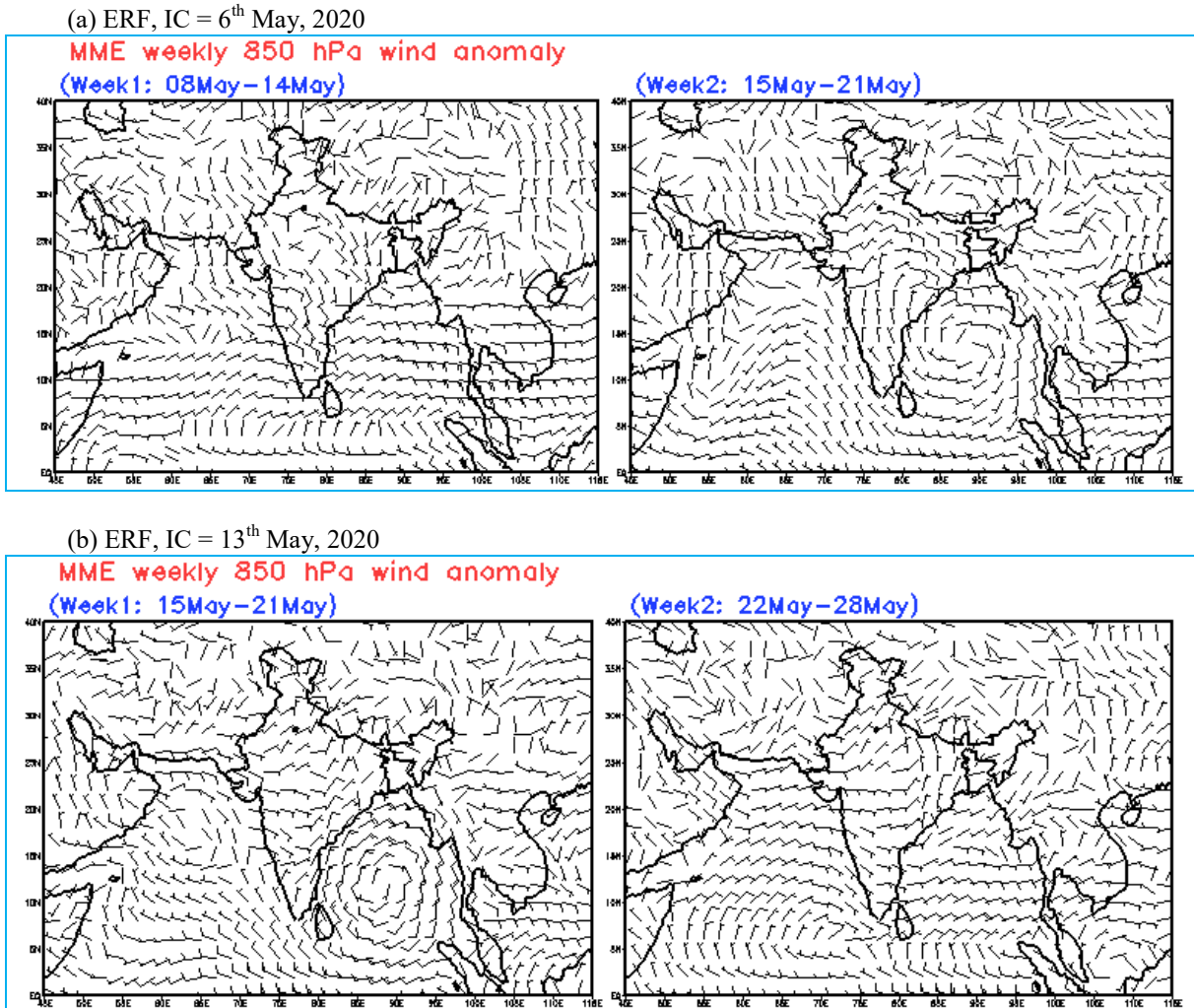
Thus, IGPP is defined as:

$$\text{IGPP} = V \times H \times T \times S, \text{ where, } V > 0, H > 0, T > 0, S > 0 \\ = 0, \text{ otherwise} \quad (7)$$

4.2. Improved Genesis Potential Parameter (IGPP) for cyclone 'Amphan' & 'Nisarga'

The improved GPP (IGPP) initially developed at IITM (Ganesh *et al.*, 2020) has been implemented in IMD recently, which is being used operationally for the cyclogenesis potential probability. Over the Bay of Bengal the Super Cyclonic Storm (SuCS) "Amphan" initially formed as a Low Pressure Area over southeast Bay of Bengal and adjoining south Andaman Sea, in the morning of 13th May, 2020. It gradually intensified into a depression, cyclonic storm and finally into a Super Cyclone around noon of 18th May, 2020, which can be seen from the observed track [Fig. 10(a)]. The SuCS "Amphan" over Northwest Bay of Bengal moved north-northeastwards and crossed West Bengal - Bangladesh coasts as a VSCS in the afternoon of 20th May, 2020. IMD predicted accurately the landfall point and time, track and intensity as well as associated adverse weather like wind, rainfall and storm surge due to SuCS 'Amphan'.

Another Severe Cyclonic Storm 'Nisarga' over Arabian Sea was also very unusual formed during the first week of June 2020, which can be seen from the observed track shown in Fig. 10(b). The severe cyclonic storm, 'Nisarga' originated from a Low Pressure Area which formed over southeast & adjoining east-central Arabian Sea and Lakshadweep area in the early morning of 31st May, 2020 and concentrated into a depression over east-central and adjoining southeast Arabian Sea in the early morning of 1st June, intensified into DD over east-central Arabian Sea in the early morning and into cyclonic storm in the noon of 2nd June, 2020. It moved northwards till evening of 2nd June and gradually recurved northeastwards and intensified into a severe cyclonic storm in the early morning of 3rd June, 2020. Continuing to move northeastwards, it crossed Maharashtra coast as a

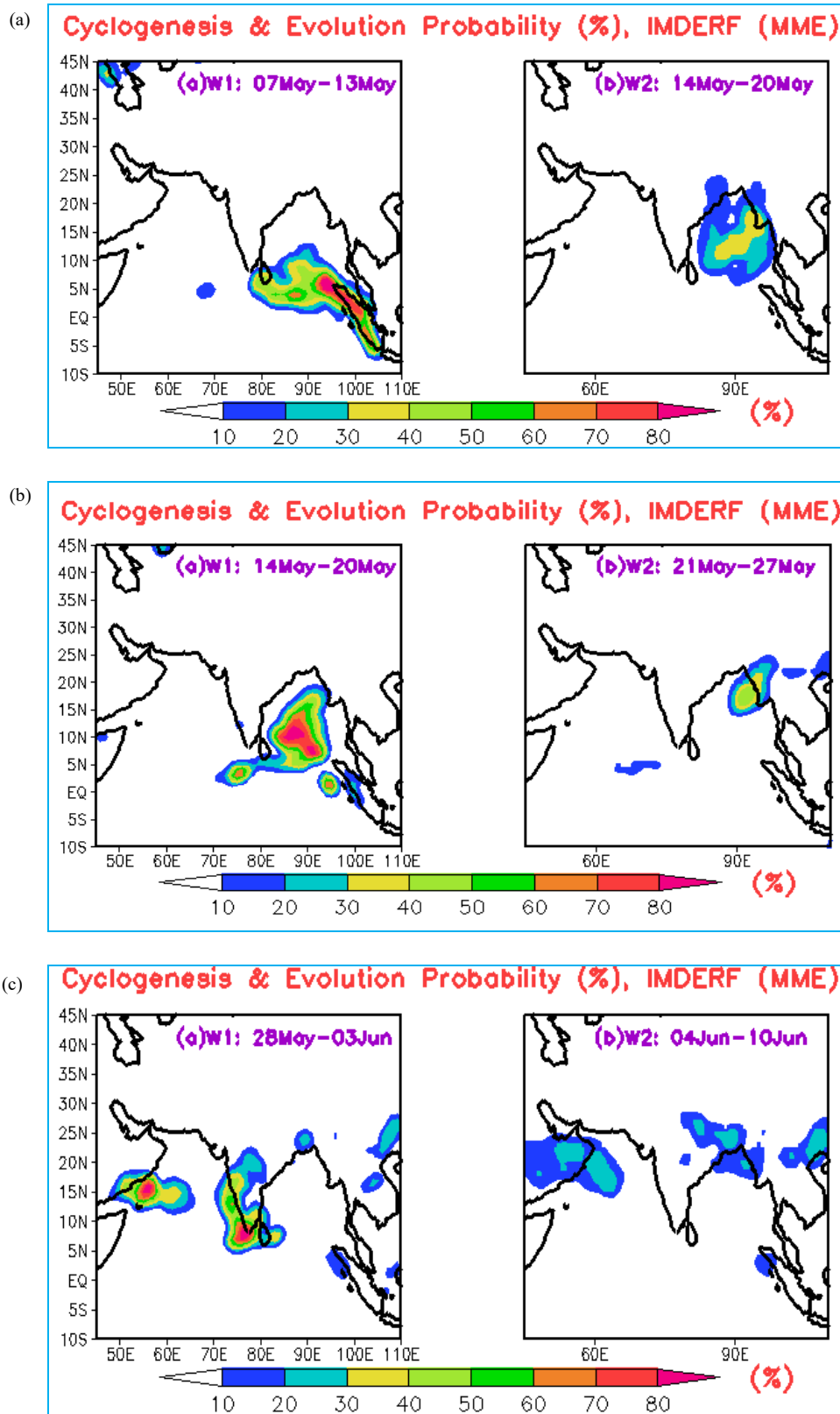


Figs. 11(a&b). The 850 hPa forecast wind anomaly for 2 weeks with initial conditions of (a) 6th May and (b) 13th May, 2020

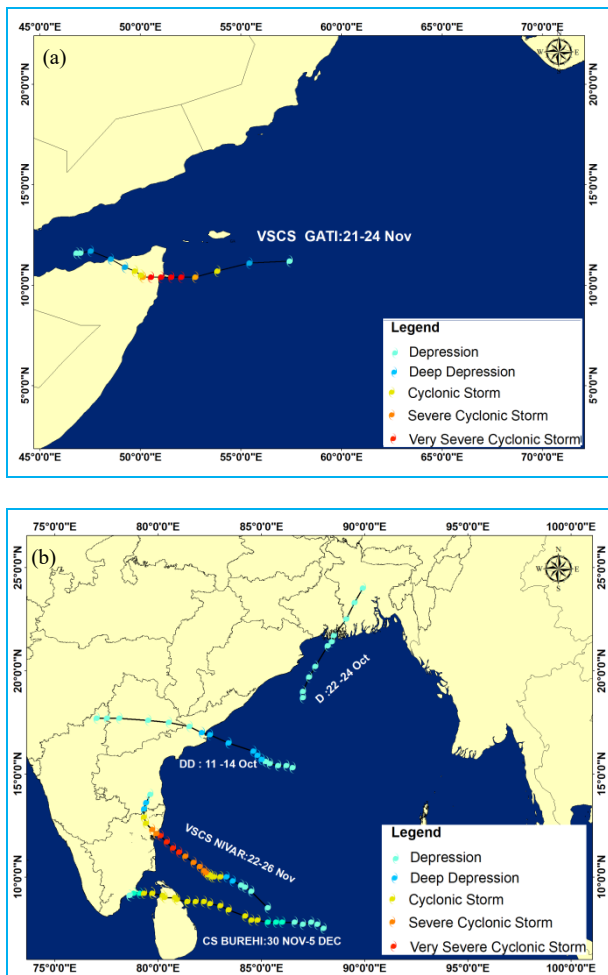
SCS on 3rd afternoon. It further weakened into a depression over western parts of Vidarbha and neighbourhood in the early morning and into a well marked low pressure area over central parts of Madhya Pradesh in the evening of 4th June.

The operational ERF system of IMD was used to provide the cyclogenesis potential probability. The ERF of 850 hPa wind anomalies clearly indicated the presence of anomalous cyclonic circulation indicating the formation of a system over the Bay of Bengal during the period from 15-21 May, 2020 both with week 1 and week 2 lead time based on the initial conditions of 6th [Fig. 11(a)] and 13th May [Fig. 11(b)], 2020 respectively. The IGPP is also calculated based on the real-time ERF by considering all 16 ensemble members separately. In the present case the IGPP is modified as discussed above. The real time IGPP for two weeks based on ERF of 6th May, 13th May and 27th May initial conditions are shown in Figs. 12(a-c)

respectively to see the cyclogenesis forecasts for ‘Amphan’ and also the ‘Nisarga’. It indicated the genesis of the system ‘Amphan’ and also its re-curvature northeastward in “Week 1” and “Week 2” forecast based on ICs of 13 and 6 May, 2020 [Fig. 12(a&b)]. Thus, the ERF had predicted the genesis of the system and also indicated that the system would intensify further and move initially north-northwestwards and re-curve north-northeastwards thereafter towards the North Bay of Bengal without crossing eastern coastal states of India like Tamil Nadu, Andhra Pradesh and Odisha. Considering the huge damage potential of a cyclone this early information about the genesis of the Super Cyclone ‘Amphan’ could save huge loss of life and property by mitigating the disaster through early warning and by taking other appropriate measures by the disaster managers to reduce the gravity of damage. The cyclone ‘Nisarga’ over the Arabian Sea and its track towards Maharashtra coast was also well captured in week 1 forecast based on IC of 27 May, 2020 [Fig. 12(c)].



Figs. 12(a-c). The IGPP (improved genesis potential probability) of cyclogenesis for two weeks based on (a) 6th May and (b) 13th May for 'Amphan' cyclone and (c) based on 27th May, 2020 for 'Nisarga' cyclone



Figs. 13(a&b). (a) Observed track of the VSCS ‘Gati’ in the Arabian Sea during 21-24 November, 2020 and (b) Observed tracks of two depressions, VSCS ‘Nivar’ and CS ‘Burehi’ formed over the Bay of Bengal during October-December, 2020

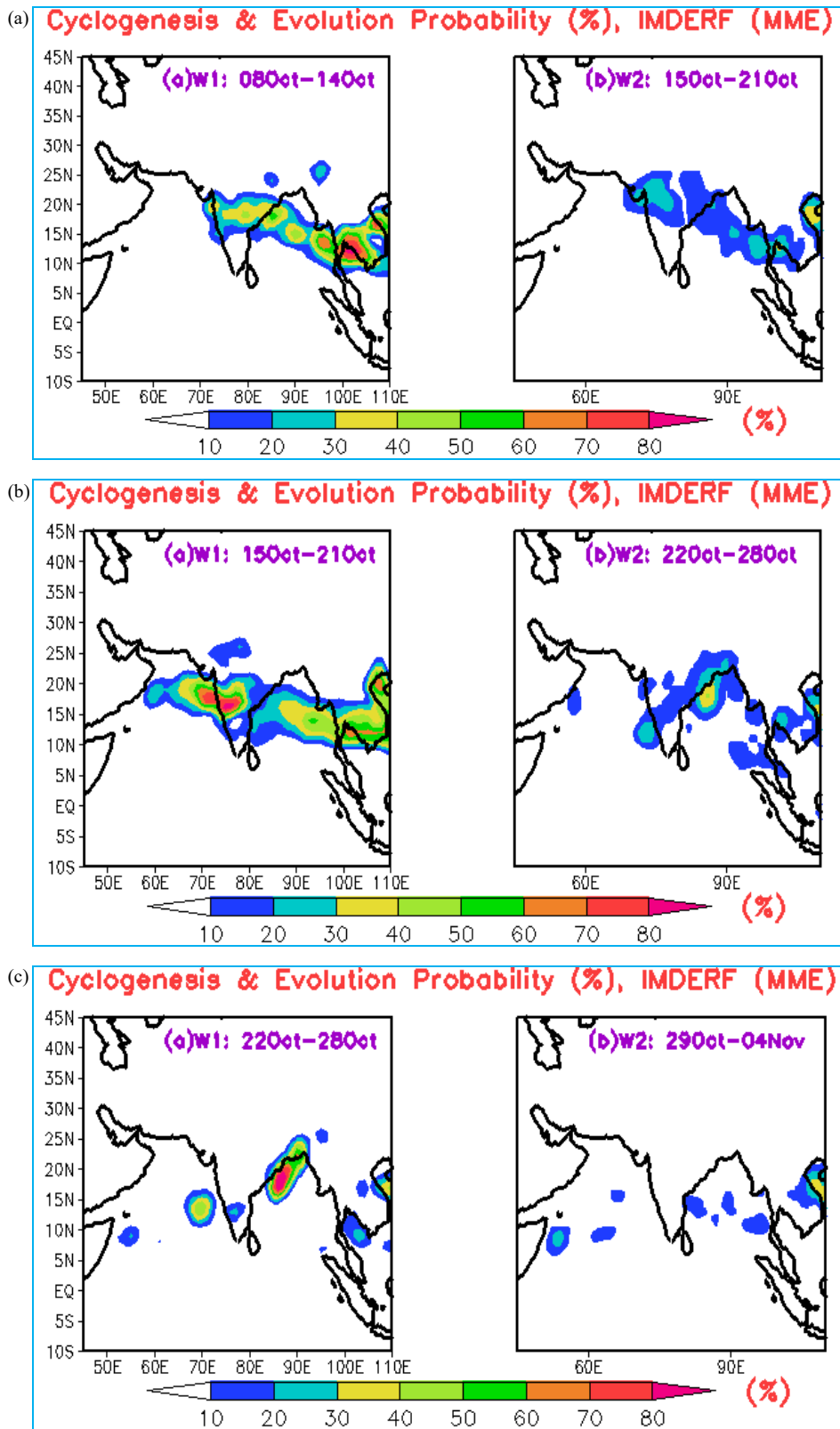
4.3. Improved Genesis Potential Parameter (IGPP) during post monsoon season of 2020

The post-monsoon season of 2020 witnessed five cyclonic systems including 3 cyclonic storms, viz., VSCS ‘Gati’ over Arabian Sea (21-24 November), VSCS ‘Nivar’ over Bay of Bengal (22-26 November), Cyclonic Storm ‘Burevi’ over Bay of Bengal (30 November-5 December), Deep Depression over the Bay of Bengal during 11-14 October and another Depression over the Bay of Bengal during 22-24 October. The observed tracks of these systems are shown in Fig. 13(a) for Arabian Sea system ‘Gati’ and in Fig. 13(b) for Bay of Bengal systems. The tracks of three cyclonic storms, viz., VSCS ‘Gati’ during 21-24 November, VSCS ‘Nivar’ during 22-26 November and CS ‘Burehi’ during 30 November-5 December formed in the month of November, 2020 is shown

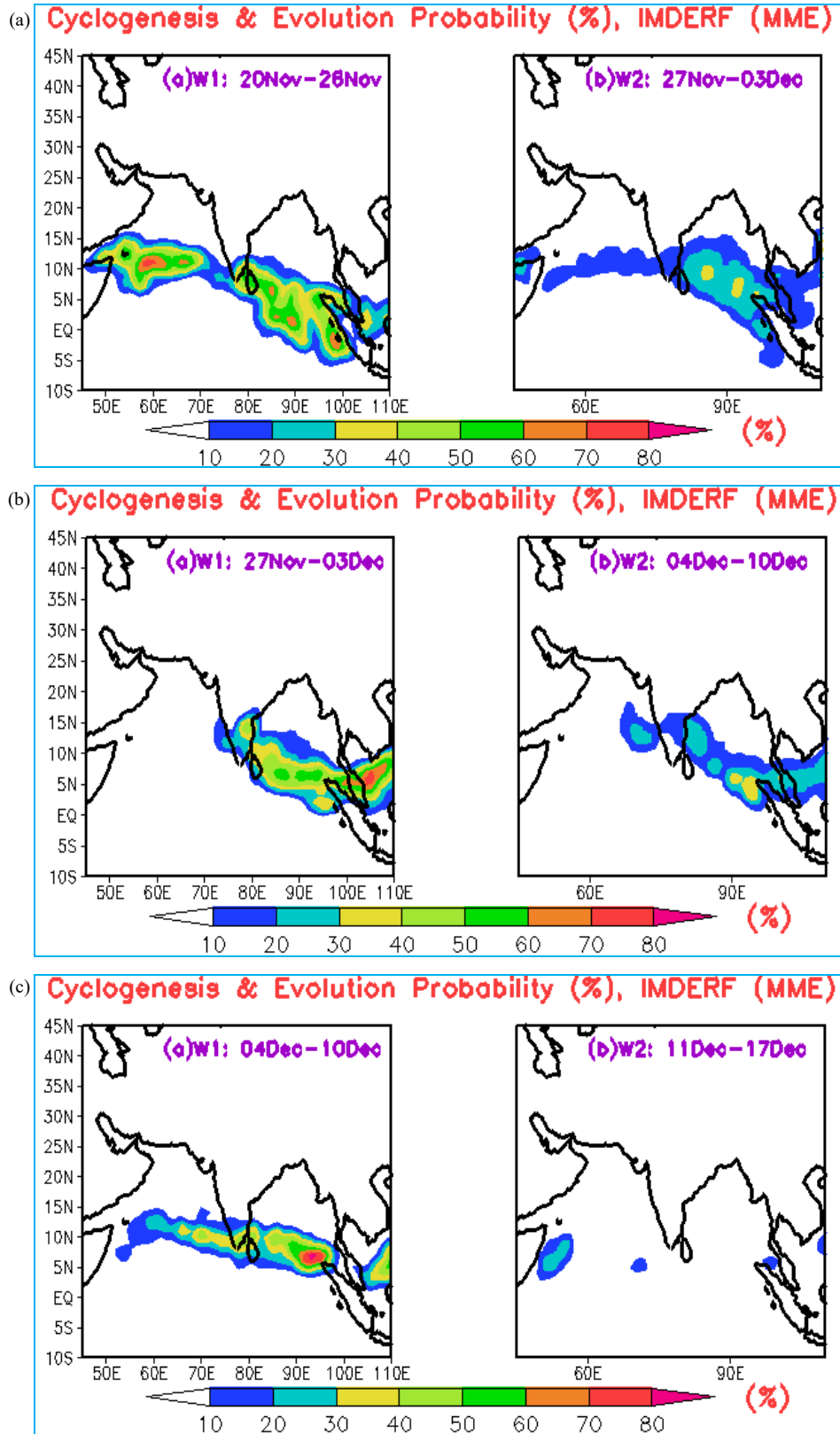
in Figs. 13(a&b). The VSCS ‘Gati’ crossed Somalia coast on 22 November and the VSCS ‘Nivar’ crossed Tamil Nadu & Puducherry coasts on 25th November with estimated wind speed of 120 kmph. The CS ‘Burevi’ on the other hand was a slow moving system, remained practically stationary for nearly 36 hours over Gulf of Mannar close to Ramanathapuram district. The cyclonic storm, ‘Burevi’ originated as a Low Pressure area in the equatorial easterly wave over South Andaman Sea and adjoining areas of Southeast Bay of Bengal & Equatorial Indian Ocean on 28th November, 2020, which became a well marked low pressure area over Southeast Bay of Bengal & adjoining areas of South Andaman Sea and Equatorial Indian Ocean on 29th. It crossed Sri Lanka coast close to north of Trincomalee on 2nd December, 2020 as a Cyclonic.

As shown in Fig. 13(b) the DD over the BoB crossed north Andhra Pradesh coast on 13th October morning, continued to move west-northwestwards and weakened into a Depression over Telangana around noon of the same day. It moved west-northwestwards as a Depression across Telangana and North Interior Karnataka to Maharashtra till evening of 14th October. The DD had impacts over Odisha, Andhra Pradesh, Telangana, Karnataka & Maharashtra in terms of heavy to extremely heavy rainfall and squally winds. The other depression during 22-24 October [Fig. 13(b)] crossed West Bengal & adjoining Bangladesh coasts on 23rd October as a Depression. Further moving north-northeastwards, it weakened into a well marked low pressure area over central Bangladesh & neighbourhood on 24th October. The system caused heavy rainfall over many parts of eastern coastal states of India, Bangladesh and northeastern states of India.

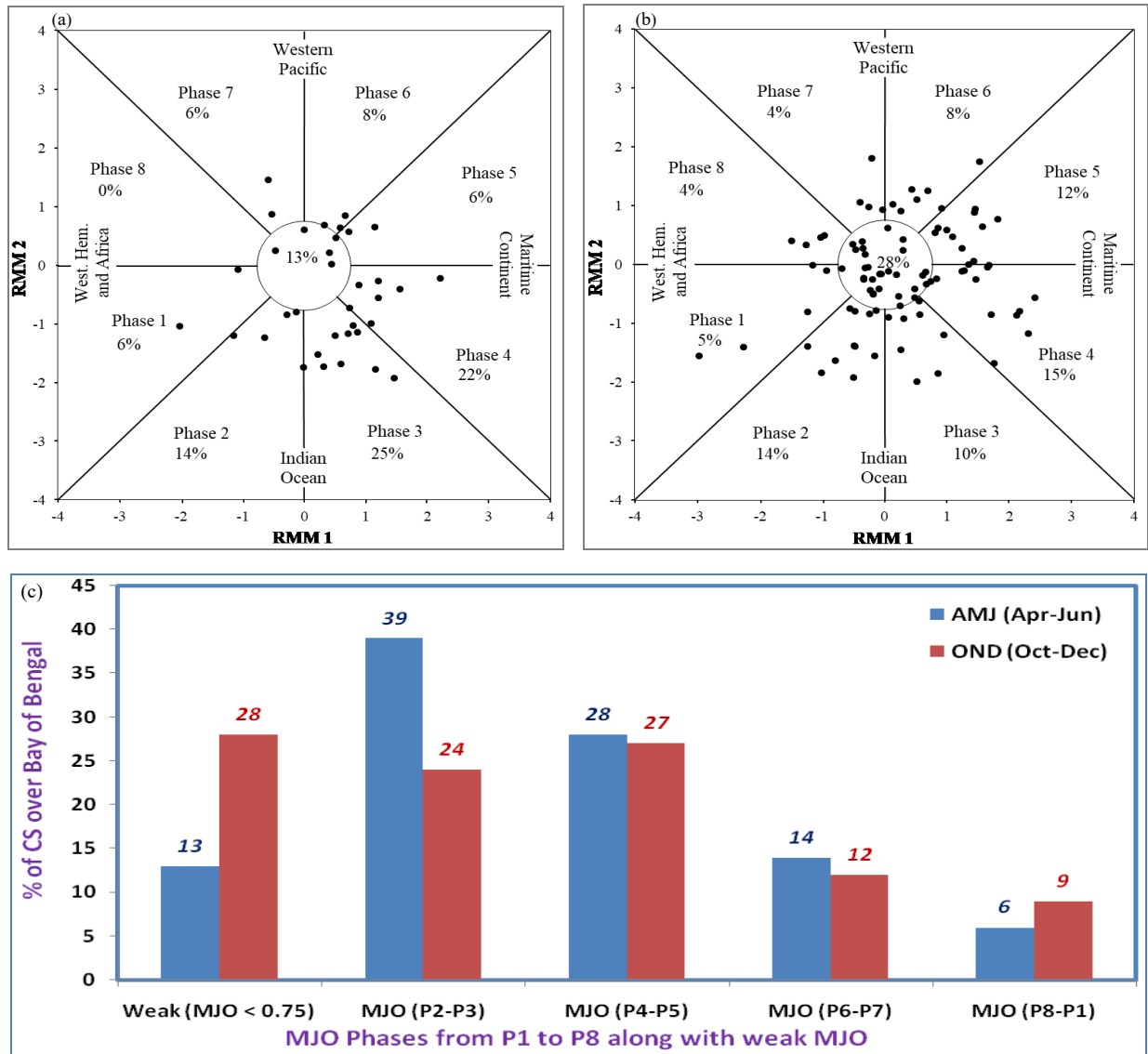
The two weeks forecast of IGPP based on the initial conditions of 6, 13 and 20 October is shown in Figs. 14(a-c). The IGPP based on the IC of 6th October has captured the genesis and its movement over the land region during 11-14 October very well [Fig. 14(a)]. It moved across Maharashtra and emerged as a well marked low pressure area over east-central Arabian Sea off Maharashtra coast on 16th morning. (Subsequently it re-intensified once again into a Depression over the Arabian Sea and moved away westwards during 17-19 October). The week 1 forecast based on 13th October also captured very well the genesis and its movement into the east-central Arabian Sea, which can be seen from Fig. 14(b). The week 2 forecast IGPP valid for the period 22-28 October based on 13th October also captured the genesis of the second system during 22-24 October with moderate probability [Fig. 14(b)], which was very well captured with high probability in the week 1 forecast based on the IC of 20th October shown in Fig. 14(c).



Figs. 14(a-c). The IGPP (improved genesis potential probability) of cyclogenesis for two weeks based on (a) 7th October, (b) 14th October and (c) 21 October, 2020 for the two depressions of October, 2020



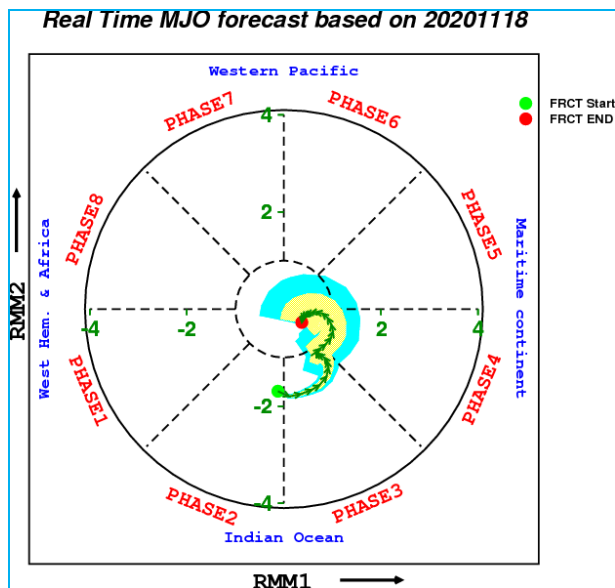
Figs. 15(a-c). The IGPP (improved genesis potential probability) of cyclogenesis for two weeks based on (a) 18th November, (b) 25th November and (c) 2nd December, 2020 for the three cyclonic storms (Gati, Nivar and Burehi)



Figs. 16(a-c). The relationship between TCs genesis and MJO phases during (a) pre-monsoon and (b) post-monsoon season from 1974 to 2019 (excluding 1978). The black dots represent the cyclogenesis days. The circle in the center with amplitude 0.75 represents days with weak MJO activity. (c) Represents the statistics from 'a' and 'b' during MJO phases from P1 to P8 and weak MJO conditions

In order to see the performance of cyclogenesis of three cyclonic storms formed in the month of November-December 2020 as shown in Figs. 13(a&b), the two weeks forecast of IGPP based on the initial conditions of 18 November, 25 November and 2 December, 2020 is shown in Figs. 15(a-c), which clearly captured the genesis forecast of these systems. The IGPP based on the IC of 18th November clearly indicated the active Arabian Sea associated with probability of cyclogenesis exceeding 70% in week 1 forecast based on IC of 18 November as shown in Fig. 15(a). The Fig. 15(a) also indicated active cyclogenesis probability (exceeding 60%) over the southern BoB in week 1 forecast valid for the period 20-

26 November, which coincides with the period of VSCS 'Nivar'. The IGPP forecast for two weeks based on IC of 25 November [Fig. 15(b)] also captured the genesis of 'Nivar' with high probability (> 60%) in week 1 forecast valid for the period from 27 November to 3 December. At the same time the week 2 forecast valid for 4-10 December indicated moderate probability (about 40%) over the Bay of Bengal for the cyclone 'Burehi' as shown in Fig. 15(b). But the probability of cyclogenesis increases to more than 60% in its week 1 forecast during the period 4-10 December (period of cyclone 'Burehi' as shown in Fig. 15(c)). Thus, it indicated that the IGPP performed very well with regard to the genesis of both the cyclonic



Figs. 17. Extended Range forecast of MJO phase and intensity for 4 weeks based on the initial condition of 18 November, 2020

storms as well as depression over land region and the Ocean region. However, the probability and intensity of the systems are not having very uniform relationship.

5. Operational ERF of cyclogenesis for two weeks

As discussed in earlier sections the operational ERF based on coupled models are able to capture the cyclogenesis potential probability over the north Indian Ocean for two weeks with reasonable accuracy, although the IGPP probability varies from 40% to 80% and is not very linear with respect to the intensity of the system. Further the IGPP is only based on the dynamical and thermodynamical variables from the model and the cyclogenesis probability even depends on many other physical parameters of which, MJO is most relevant. Mohapatra and Adhikary (2011) have examined the relationship of MJO with the cyclogenesis and further intensification over the NIO and found that the MJO index in phase 3 and 4 (east equatorial Indian Ocean and adjoining maritime continent as defined by Wheeler and Hendon, 2004) is significantly linked with cyclogenesis (formation of depression) in about 37% of the cases in the NIO during October-December. There is no relationship between genesis and MJO index in other phases. The frequency of genesis is negligible (about 10%) when the MJO with amplitude of < 0.5 lies in the favourable phase of 3 and 4 during October-December. The probability of intensification increases with increase in amplitude of MJO in the favourable phase. A comprehensive paper by Bhardwaj *et al.* (2019) discussed extensively the association of MJO with TC over Bay of Bengal during

the two peak TC periods, *i.e.*, April-June (AMJ) and October-December (OND) by using the data from 1974 to 2015. They have shown that the TC activity is significantly enhanced (suppressed) over the BoB when the convectively active MJO phase is positioned over the Indian Ocean and the Maritime Continents (Western Hemisphere & Africa). The genesis locations and tracks are also modulated by the MJO. These modulations in TC activity are mainly triggered by the MJO-driven alterations of large-scale oceanic and atmospheric conditions. Overall, the combination of more convective activity, higher relative humidity (RH), lower sea level pressure (SLP), increased cyclonic vorticity, upper-level easterly winds and reduced vertical wind shear (VWS) provide favorable conditions for TC formation and intensification in the BoB in P2-P5. Conversely, in phases P7-P8, reduced convective activity, lower RH, higher SLP, anomalous upper-level westerly winds and higher VWS suppress TC activity over the BoB. As shown by them normalized accumulation cyclone energy (ACE) and Probability Dissipation Index (PDI) values are significantly higher in P2-P4 and lower in P7-P8. The MJO does not show a significant modulation of TC formation in OND; however, it does significantly modulate the duration of TCs and their ACE and PDI values. ACE and PDI values during OND are significantly enhanced in P2, P4-P5 and suppressed in P1, P7-P8.

The phase amplitude diagram constructed with the RMM1 and RMM2 indices of MJO during AMJ and OND season has been prepared for the period from 1974 to 2019 (excluding 1978) and is shown in Figs. 16(a&b) respectively. The black dots represent the cyclogenesis days. The circle in the center with amplitude 0.75 represents days with weak MJO activity. As it is seen from Fig. 16(a) during AMJ, TC formation is significantly enhanced and suppressed over the BoB in P3-P4 (47%) and P8, respectively with 13% of TC formed even during weak MJO conditions (Magnitude, 0.75). Further the Fig. 16(c) indicates that during AMJ 67% of TC genesis occurred in MJO phases from P2 to P5 (Indian Ocean and maritime continent). Slightly different pattern is seen during OND season with relatively weaker influence of MJO on TC genesis with 28% of TC formed even during weak MJO conditions followed by 27% in P4-P5 and 24% in P2-P3 constituting 51% from P2-P5 (Indian Ocean and maritime continent). Thus, MJO plays a major role in TC genesis over the BoB. Considering this the operational ERF forecast of cyclogenesis is issued by IMD for two weeks on every Thursday based on the cyclogenesis probability forecast along with MJO forecast and other parameters. The MJO forecast based on 18th November, 2020 is shown in Fig. 17, which indicates MJO is on P2 (eastern Indian ocean) and subsequent forecasts for two weeks indicated it to enter into P3 and P4, which has the

higher climatological probability of TC genesis as shown in Figs. 16(b&c) in post monsoon season.

Considering the significant role of MJO in the north Indian Ocean in TC genesis, IMD uses the operational IGPP along with other parameters like current and forecast MJO, Tropical Cyclone Heat Potential etc and prepare value added cyclogenesis outlook for two weeks on every Thursday as its operational forecast.

6. Conclusions

The present generation coupled models are capable of providing useful guidance in the extended range for the tropical cyclogenesis potential for about two weeks' time in advance. The ERF of TC genesis and associated rainfall distribution associated with 'Jal' cyclone based on combination of coupled models' outputs had a modest beginning in IMD in 2010. The genesis of TC in terms of higher vorticity, higher convergence and lower vertical wind shear were well captured in the dynamical models (ECMWF and CFSv1) for week 1 and week 2 forecasts, which shows reasonable skill for week 1 and week 2 forecasts. Thus, the preliminary study indicated that the models have the potential to provide advance information for the prospects of a genesis of tropical cyclone. The 2015 cyclone season during Oct-Dec witnessed subdued cyclogenesis over the Bay of Bengal with only one deep depression and very active over the Arabian Sea. The ERF based on the CFSv2 coupled model could indicate useful guidance about the genesis of two extremely severe cyclonic storms "Chapala" and "Megh" over the Arabian Sea and depression over the Bay of Bengal with a lead time of about one to two weeks.

With the implementation of operational coupled modelling system in IMD, it started preparing the ERF of Genesis Potential Parameter (GPP) every week since 2017 by using the dynamical variables like vorticity, divergence, vertical wind shear and mid-level relative humidity and was tested for the 'Ockhi' cyclone of 24-30 November, 2017. The cyclogenesis probability over the Bay of Bengal off Sri Lanka coast during the 'Ockhi' period based on 22nd and 29th November initial conditions (ICs) were reasonably well captured in week 1 forecasts about its genesis near the Sri Lanka coast and also its re-curvature in the Arabian Sea towards western coastal state of India. However, the week 2 forecasts with both ICs were not very realistic leading to very short lead time.

In 2019 IMD used improved GPP (IGPP) based on (Ganesh *et al.*, 2020), which can be used both over the Ocean and land region. In the case of IGPP the vorticity and middle tropospheric humidity terms of GPP have been

retained but the thermodynamic term is modified as the scaled and averaged equivalent potential temperature (θ_e) between 1000 and 500 hPa so as to include the effect of sea surface temperatures, surface heat fluxes and also to include the effect of middle tropospheric warming due to latent heat release associated with conditional instabilities or positive feedbacks associated with cyclogenesis. The vertical shear between 850 and 200 hPa is scaled and averaged over an annular region between 100 and 200 km radii for each grid point. In case of Super cyclone "Amphan" of 16-21 May, 2020 it indicated the genesis of the system in "Week 1" and "Week 2" forecast and also its re-curvature northeastward like the observed track. The cyclone "Nisarga" over the Arabian Sea during first week of June and its track towards Maharashtra coast was also well captured in week 1 forecast. The IGPP also showed reasonable skill during the Post-monsoon season of 2020 in predicting the genesis of three cyclones VSCS 'Gati' during 21-24 November, VSCS 'Nivar' during 22-26 November and CS 'Burehi' during 30 November-5 December and the two depressions of October.

It is also seen that MJO phase and amplitude has a strong relationship with TC genesis over the BoB with TC formation is significantly enhanced during April-June (67%) and October-December (51%) in MJO phases from P2 to P5 (Indian Ocean and maritime continent). Considering the significant role of MJO in BoB TC genesis IMD uses the operational IGPP along with other parameters like current and forecast MJO, Tropical Cyclone Heat Potential etc. and prepared value added cyclogenesis probability for two weeks on every Thursday.

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