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A preliminary study about the prospects of extended range forecast of tropical cyclogenesis over the north Indian Ocean during 2010 post-monsoon season

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सार – वर्ष 2010 में मानसूनोत्तर ऋतु के दौरान दो चक्रवातीय तूफान निर्मित हुए थे। जैसे 'गिरी' नामक अति प्रचंड चक्रवातीय तूफान (वी.एस.सी.एस.) 19 अक्तूबर को निर्मित हुआ और यह 22 तारीख को म्यांमार समुद्र तट को पार कर गया और दूसरा 'जाल' नामक प्रचंड चक्रवातीय तूफान (एस.सी.एस.) 2 नवंबर को निर्मित हुआ और यह चेन्नै के उत्तरी भाग के समीप उत्तरी तमिलनाडु – दक्षिणी आंध्र प्रदेश के समुद्री तटों को 07 नवंबर को पार कर गया जिसकी वजह से तमिलनाडु और दक्षिणी आंध्र प्रदेश के समुद्र तटीय क्षेत्रों में न केवल तीव्र पवन से बल्कि उससे हुई भारी वर्षा से भारी क्षति हुई।

वास्तविक समय विस्तृत क्षेत्र पूर्वानुमान गत्यात्मक भिन्नताओं के साप्ताहिक औसत के आधार पर दो सप्ताह के लिए तैयार किए गए हैं जो. ई. सी. एम. डब्ल्यू. एफ., एन. ई. सी. पी. तथा दोनों के 2 मॉडल्स औसत (2 एम. ए. वी. ई.) के युग्मित मॉडल परिणाम पर आधारित हैं। साप्ताहिक औसत, पवन और सापेक्षिक भ्रमिलता के 5–11 दिनों के प्रचालनात्मक पूर्वानुमान 14 अक्तूबर 2010 के आरंभिक स्थिति पर आधारित हैं जिससे पता चला है कि 18–24 अक्तूबर की अवधि के दौरान मध्य बंगाल की खाड़ी के ऊपर निम्न दाब का चक्रवातीय सर्कुलेशन था जो अति प्रचंड चक्रवातीय तूफान 'गिरी' के समान था। 'जाल' नामक चक्रवात की उत्पत्ति का 2 एम. ए. वी. ई. में अच्छी तरह पता लगा लिया गया था। इसका पूर्वानुमान 12–18 दिनों के लिए वैध था और यह 21 अक्तूबर 2010 की आरंभिक स्थिति पर आधारित था। 2 एम. ए. वी. ई. पूर्वानुमान 1–7 नवंबर तक के लिए वैध था जो 28 एवं 21 अक्तूबर की आरंभिक स्थितियों पर आधारित था (इनके पूर्वानुमान की अवधि क्रमशः 5–11 दिनों तथा 12–18 दिनों की थी) जिसमें स्पष्ट रूप से दर्शाया गया है कि तमिलनाडु समुद्र तट और इससे लगे हुए आंध्र प्रदेश के क्षेत्र में प्रेक्षित की गई विसंगतियों से काफी अधिक घनात्मक वर्षा विसंगतियाँ देखी गई हैं। इस प्रारंभिक अध्ययन में आगे बताया गया है कि साप्ताहिक चक्रवातीय भ्रमिलता के मॉडल पूर्वानुमानों की अधिकतम विसंगति त्रुटि लगभग -0.8 से -1.0×10^{-5} प्रति सैकेण्ड को निम्न स्तरीय अभिसरण विसंगति लगभग -0.8 से -1.0×10^{-5} प्रति सैकेण्ड के साथ मिलने पर उष्णकटिबंधी चक्रवात बनने की संभावना बनती है। तथापि इस सिस्टम के चक्रवात के रूप में तीव्रीकरण हेतु थ्रेशहोल्ड वैल्यू की पहचान करने के लिए और अधिक मामलों के विश्लेषण करने की आवश्यकता है।

ABSTRACT. There were two cyclonic storms formed during the post monsoon season of 2010 *viz*., "Giri" a very severe cyclonic storm (VSCS) formed on 19th October and crossed the Myanmar coast on 22nd and the second system "Jal" a severe cyclonic storm (SCS) formed on 2nd November and crossed north Tamil Nadu-south Andhra Pradesh coasts, close to north of Chennai on 7th November, which caused lot of damage in Tamil Nadu and south Andhra Pradesh coast associated with not only strong wind but also due to associated heavy rainfall.

The real time extended range forecasts in terms of weekly mean of dynamical variables are prepared for two weeks based on the coupled model outputs from ECMWF, NECP and the 2 models average (2MAVE) of both. The operational forecast for days 5-11 of weekly mean wind and relative vorticity based on 14th October, 2010 initial condition indicates cyclonic circulation at low level over the central Bay of Bengal during the period from 18-24 October associated with the very severe cyclone "Giri". The genesis of the cyclone "Jal" was very much captured in the 2MAVE forecast valid for 12-18 days forecast based on the initial condition of 21st October, 2010. The 2MAVE forecast valid for 1-7 November based on 28 October and 21 October initial conditions (with forecast period of days 5-11 and days 12-18 respectively) also clearly indicated large positive rainfall anomalies over Tamil Nadu coast and adjoining coastal Andhra Pradesh region like that of observed rainfall anomalies. This preliminary study further indicates that the model forecasts anomaly of weekly cyclonic vorticity maximum of about 2.5×10^{-5} sec^{-1} combined with a low level convergence anomaly of about -0.8 to -1.0×10^{-5} sec^{-1} may lead to formation of a tropical cyclone. However, more number of cases required to be analysed for the proper identification of the threshold values for intensification of the system into a cyclone.

Key words – Extended range forecast, Bay of Bengal, Ensemble forecast, Cyclogenesis, Relative vorticity, Coupled model .

1. Introduction

Over the North Indian Ocean (NIO), the months of October-November are known to produce tropical cyclones (TCs) of severe intensity in the Bay of Bengal, which after crossing the coast cause damages to life and property over many countries surrounding the Bay of Bengal. 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. Rains (sometimes even more than 30 cm/24 hrs) associated with cyclones are another source of damage. TCs in the NIO have a profound impact on the littoral countries of the Arabian Sea and the Bay of Bengal. The combination of a shallow coastal plain along with a thermodynamically favorable 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 landfalling TCs becoming devastating natural disasters.

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; Singh and Saha, 1978 ; Mohanty and Gupta 1997; Prasad and Rama Rao, 2003; 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, while one with GP value greater than 45×10^{-12} at T. No. 2.0 has the potential to intensify into a very severe cyclonic storm over the Indian Sea. 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. Kotal and Bhattacharya (2011) tested the GPP in case of forecast field from ECMWF and found that Region with GPP value equal or greater

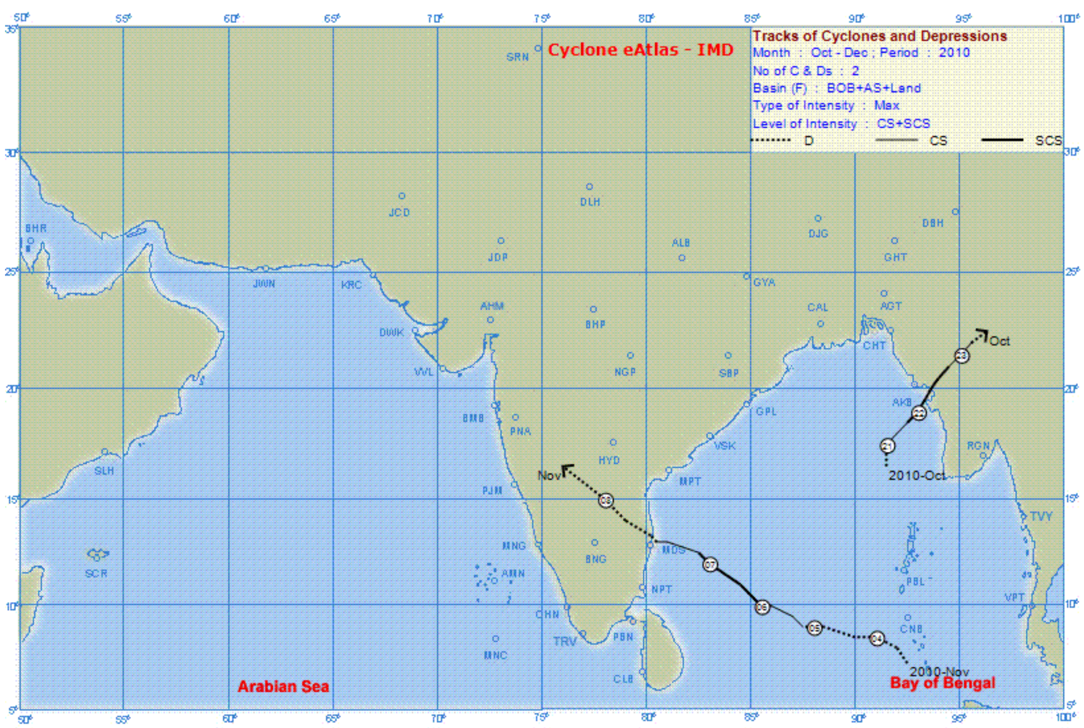
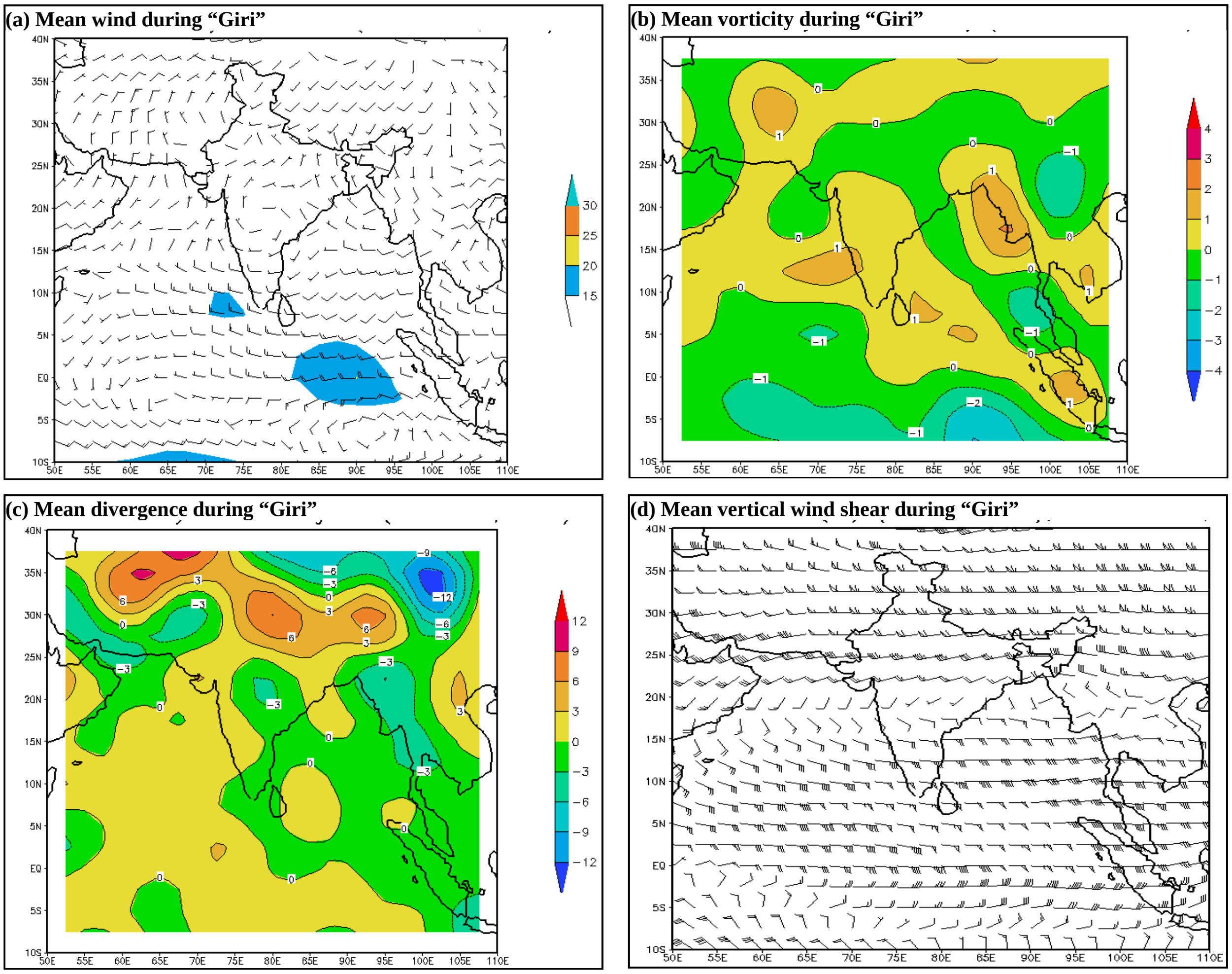
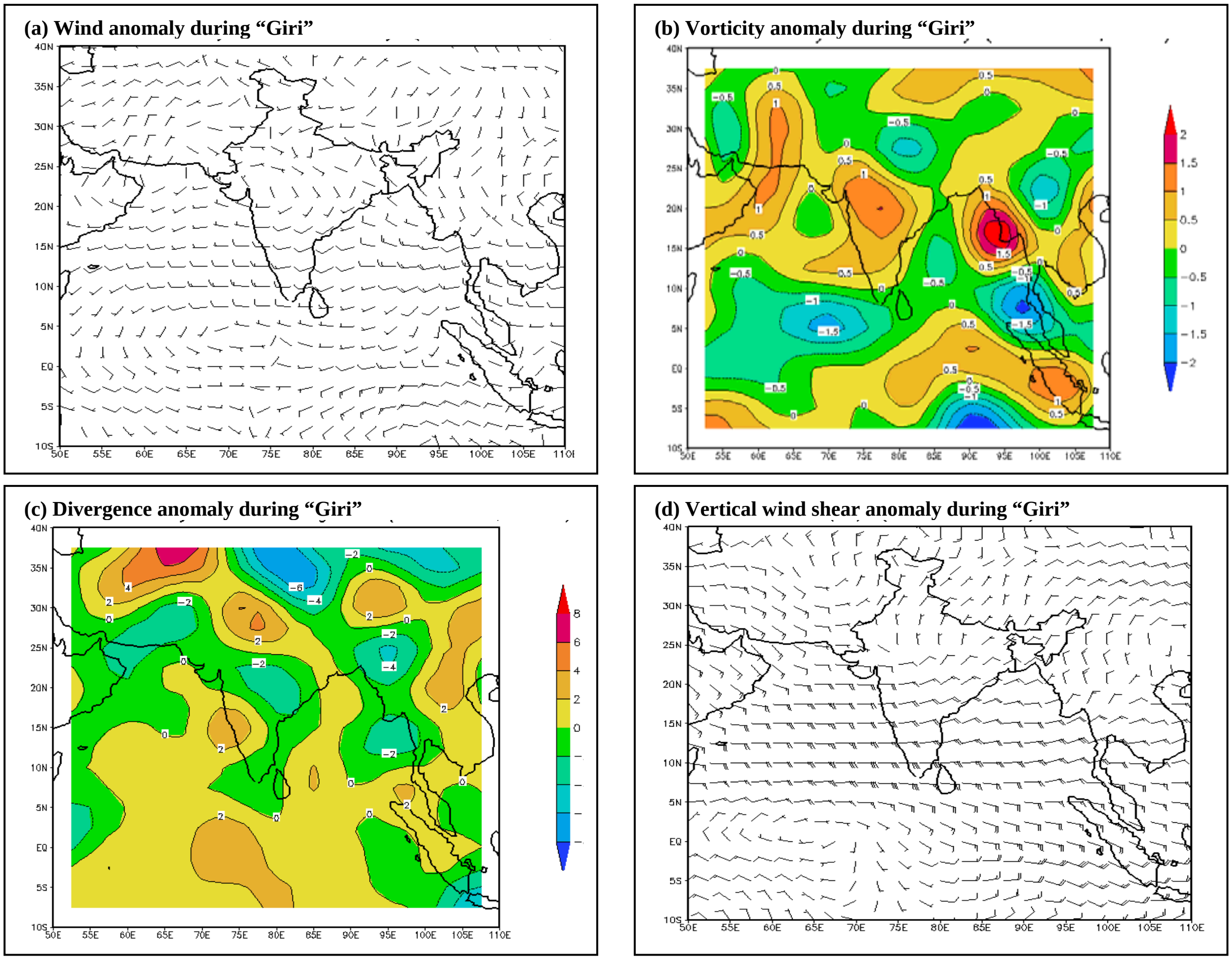


Fig. 1. Cyclonic storms of post monsoon season from October-December, 2010. The dark black lines indicate two severe cyclones "Jal" and "Giri"



Figs. 2 (a-d). (a) Observed 850 hPa mean wind during VSCS "Giri" (18-24 Oct 2010). (b) Same as 'a' but for mean relative vorticity (1×10^{-5} sec^{-1}) (c) Same as 'a' but for mean divergence (1×10^{-6} sec^{-1}) and (d) Same as 'a' but for mean vertical wind shear (W200-W850) in kts

than 30 is found to be high potential zone for cyclogenesis. 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. In addition, 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. From the 51 members ensemble for two seasons of 2008 and 2009 over North Atlantic Ocean 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 at the time of model initialization. Fu 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. They also showed that a realistic MJO/Intra-Seasonal Variability (ISV) prediction will make the extended- range forecasting of tropical cyclogenesis possible and also call for improved representation of the MJO/ISV in contemporary weather and climate forecast models. 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



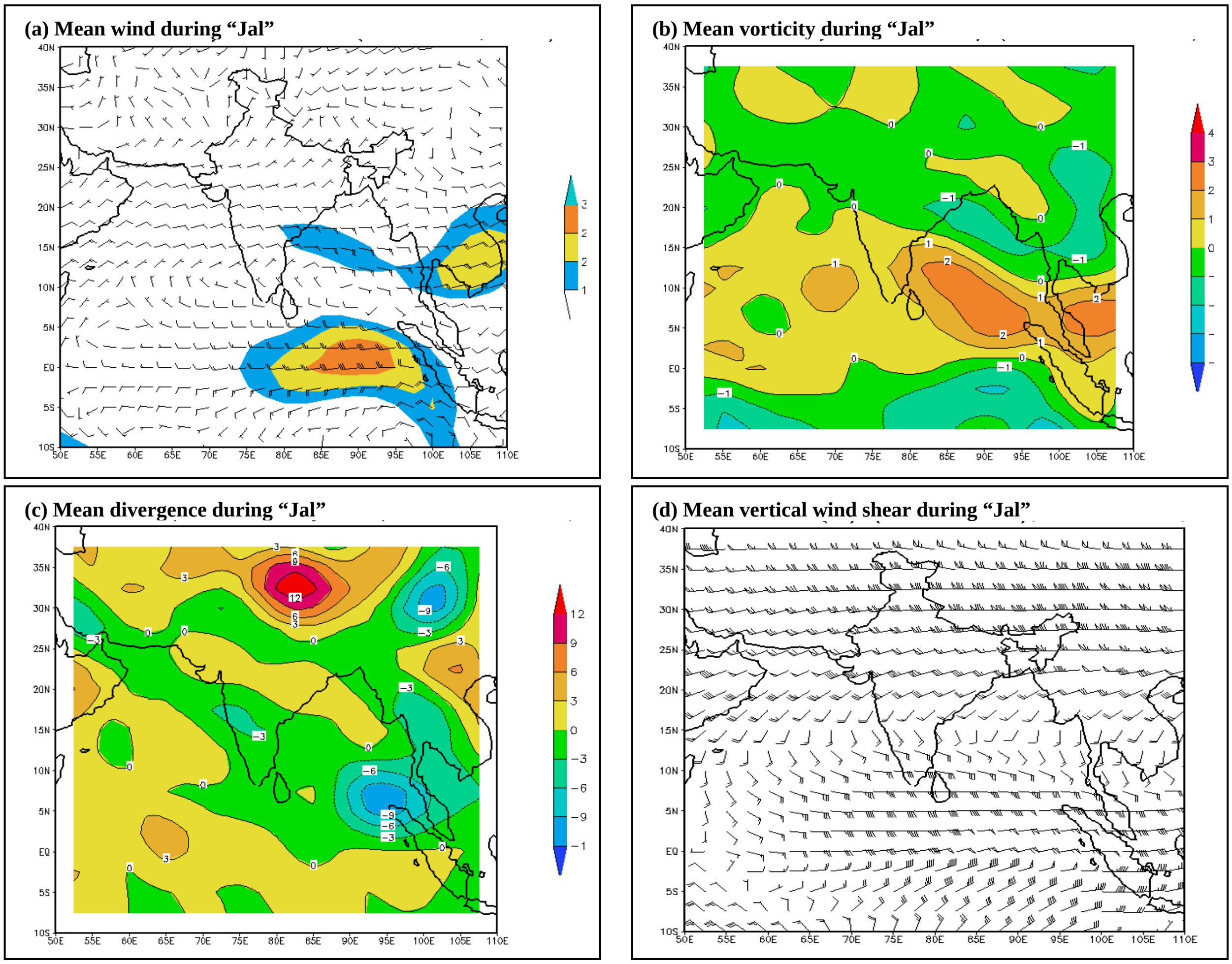
Figs. 3 (a-d). (a) Observed 850 hPa wind anomaly during VSCS "Giri" (18-24 Oct 2010). (b) Same as 'a' but for relative vorticity anomaly (1×10^{-5} sec^{-1}) (c) Same as 'a' but for divergence anomaly (1×10^{-6} sec^{-1}) and (d) Same as 'a' but for vertical wind shear anomaly (W200-W850) in kts

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 in during October-December. The probability of intensification and duration in cyclone stage and hence life period of cyclone is higher with MJO in phase 3 and 4 and less with MJO in phase 1 and 7. There is no relationship, when the MJO lies in 2, 5 and 6. The probability of intensification increases with increase in amplitude of MJO in the favourable phase.

As a part of the daily operational mandate, the 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, the IMD begins issuing forecast advisories (IMD 2003) valid for 72 hrs A guidance of TC genesis with longer lead time is also useful. Hence, the IMD is issuing the guidance on cyclogenesis on experimental basis since 2010 on extended range scale (up to two weeks) over the NIO based on European Centre for Medium Range Weather Forecasting (ECMWF) coupled model and the National Centre for Environmental Prediction (NCEP) Climate Forecast System (CFS) coupled model. In the present study an attempt is made to evaluate the real time forecast from these two coupled models for the tropical cyclogenesis and associated rainfall activity in the extended range time scale (up to two weeks) over the north Indian Ocean during post monsoon seasons of 2010.

2. Coupled models output considered for preparing the extended range forecast

In recent years, it is found that the forecast errors from numerical models in different temporal scales can be reduced with ensemble prediction techniques and secondly through the combination of the forecasts from



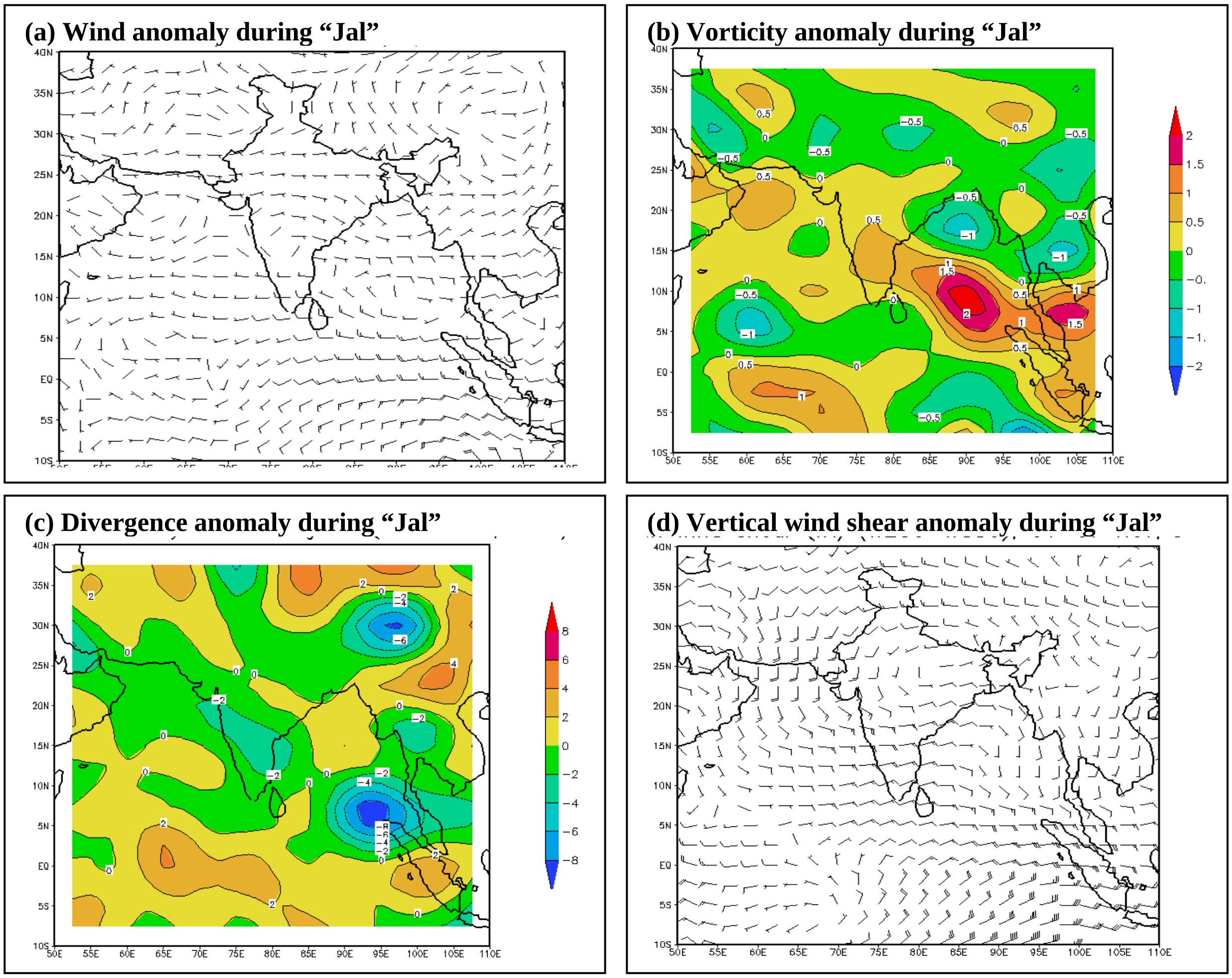
Figs. 4 (a-d). (a) Observed 850 hPa mean wind during SCS "Jal" (01-07 Nov 2010). (b) Same as 'a' but for mean relative vorticity (1×10^{-5} sec^{-1}) (c) Same as 'a' but for mean divergence (1×10^{-6} sec^{-1}) and (d) Same as 'a' but for mean vertical wind shear (W200-W850) in kts

multiple models (Krishnamurti *et al.*, 1999; Wang *et al.*, 2004). For providing the outlook for cyclogenssis potential IMD utilizes products from two well known coupled models *viz*., the monthly forecasting system of ECMWF coupled model and the National Centre for Environmental Prediction (NCEP) Climate Forecast System (CFS) coupled model. The details of these models forecasts, and the methodology of multi-model ensembles, are discussed.

2.1. *ECMWF monthly forecast system*

The ECMWF monthly forecasting system (Vitart 2004) used here is based on 32-day coupled ocean–atmosphere integrations set up at ECMWF. This system has run routinely since March 2002. The atmospheric component of the model used in this study has horizontal and vertical resolution of T159 L40 (1.125° × 1.125°) with 40 levels in the vertical. The ECMWF monthly forecasting system is based on fully coupled ocean–atmosphere integrations forced by persisted SSTs. The oceanic component is the same as that for the current ECMWF seasonal forecasting system. It is the Hamburg Ocean Primitive Equation (HOPE) model (Wolff *et al.* 1997). The coupling between atmosphere and ocean is done through the Ocean Atmosphere Sea Ice Soil (OASIS) coupler (Terray *et al.*, 1995). The atmospheric fluxes of momentum, heat, and freshwater are passed to the Ocean every hour. The atmospheric and land surface initial conditions are obtained from the ECMWF operational atmospheric analysis/reanalysis system, whereas the oceanic initial conditions originate from the oceanic data assimilation system used to produce the initial conditions of the ECMWF seasonal forecasting system.

The ECMWF monthly forecasting system has an ensemble size of 51 members. One forecast, called the control, is run from the operational ocean and atmosphere ECMWF analyses. The 50 additional integrations, the

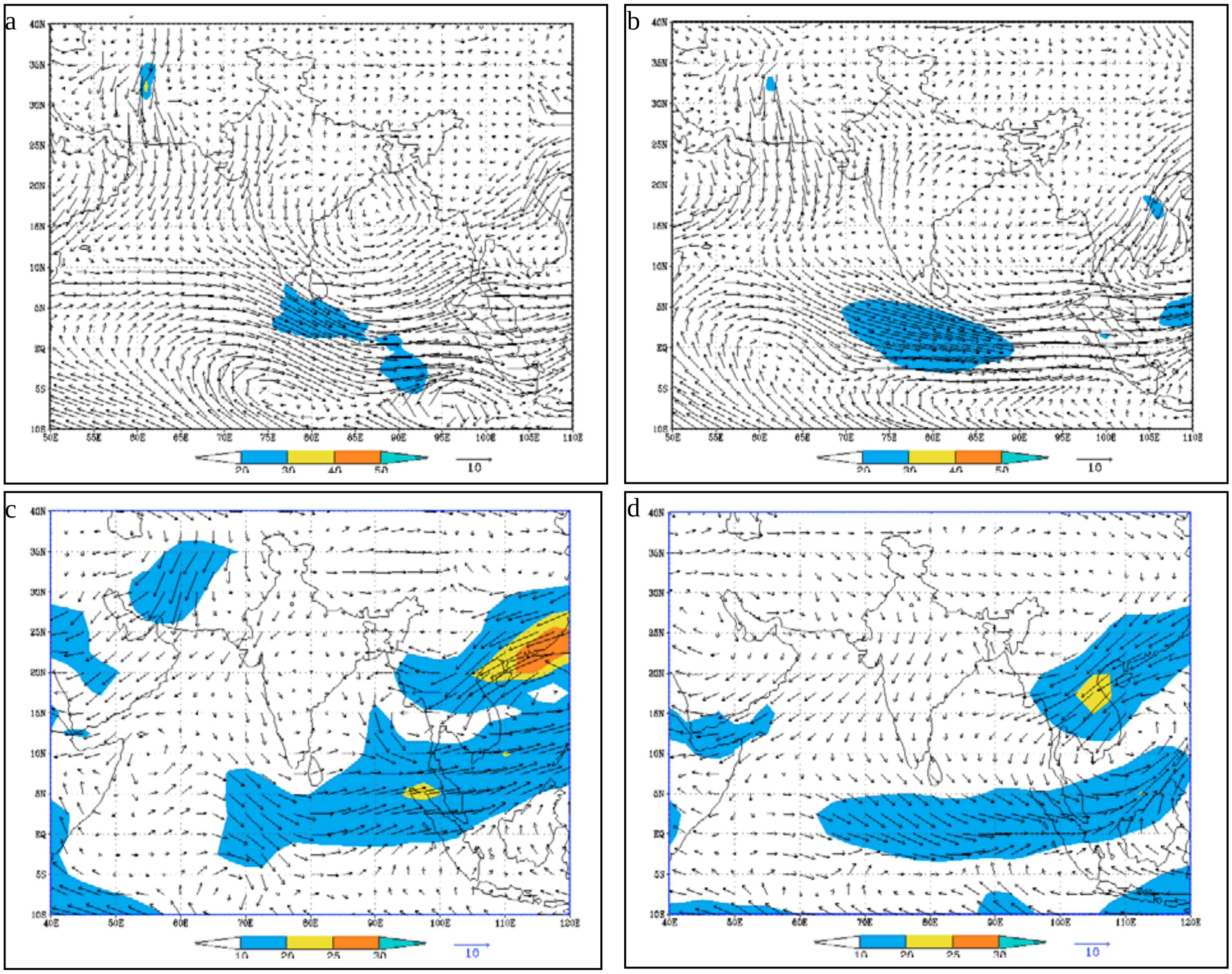


Figs. 5. (a-d) (a) Observed 850 hPa wind anomaly during SCS "Jal" (01-07 Nov 2010). (b) Same as 'a' but for relative vorticity anomaly (1×10^{-5} sec^{-1}) (c) Same as 'a' but for divergence anomaly (1×10^{-6} sec^{-1}) and (d) Same as 'a' but for vertical wind shear anomaly (W200-W850) in kts

perturbed members, are made from slightly different initial atmospheric and oceanic conditions, which are designed to represent the uncertainties inherent in the operational analyses. The details about the ECMWF monthly forecast system along with its skill over the different geographical regions have been discussed in Vitart (2004) and Vitart *et al*. (2008). As it will be shown the model displays some useful skill up to 18 days over some geographical regions including Asia. It is also seen from the study of Vitart (2004) that for days 12–18, probabilistic scores indicate that the monthly forecasting system performs generally better than both climatology and the persistence of the previous weekly probabilities, suggesting that forecasts at that time range could be useful. There is also a possibility that false signals about tropical cyclogenesis may be present but there could be advanced forecast on several occasions, which could be tested by implementing the technique on experimental basis.

2.2. *NCEP's Climate Forecast System (CFS)*

Extended-range prediction is also carried out at Climate Prediction Centre, National Centre for Environmental Prediction by using the dynamical model outputs from Climate Forecast System (CFS-version 1) as discussed in Jon *et al*., (2008). The details about the operational CFS are discussed in Saha *et al.*, (2006). The operational CFS (T62L64) – is initialized 4 times daily from 0000UTC, 0600 UTC, 1200 UTC and 1800 UTC with one day delay (because of the availability of the ocean analysis). The atmospheric component of the CFS is the NCEP atmospheric GFS model. The oceanic component is the GFDL Modular Ocean Model V.3 (MOM3). The ocean-atmosphere coupling is nearly global (64°N-74°S) and no flux correction applied. Thus, the CFS is a fully 'tier-1' forecast system. The skill of the seasonal and monthly monsoon rainfall forecast is found to be reasonable in the CFS (Pattanaik and Kumar, 2010).



Figs. 6(a-d). Forecast 850 weekly mean wind for VSCS "Giri" during the period 18-24 October, 2010. (a) ECMWF, days - 11 forecast (IC=14 Oct) (b) ECMWF, days 12-18 forecast (IC=07 Oct) (c) NCEP CFS, days 5-11 forecast (IC=14 Oct) and (d) NCEP CFS, days 12-18 forecast (IC=07 Oct)

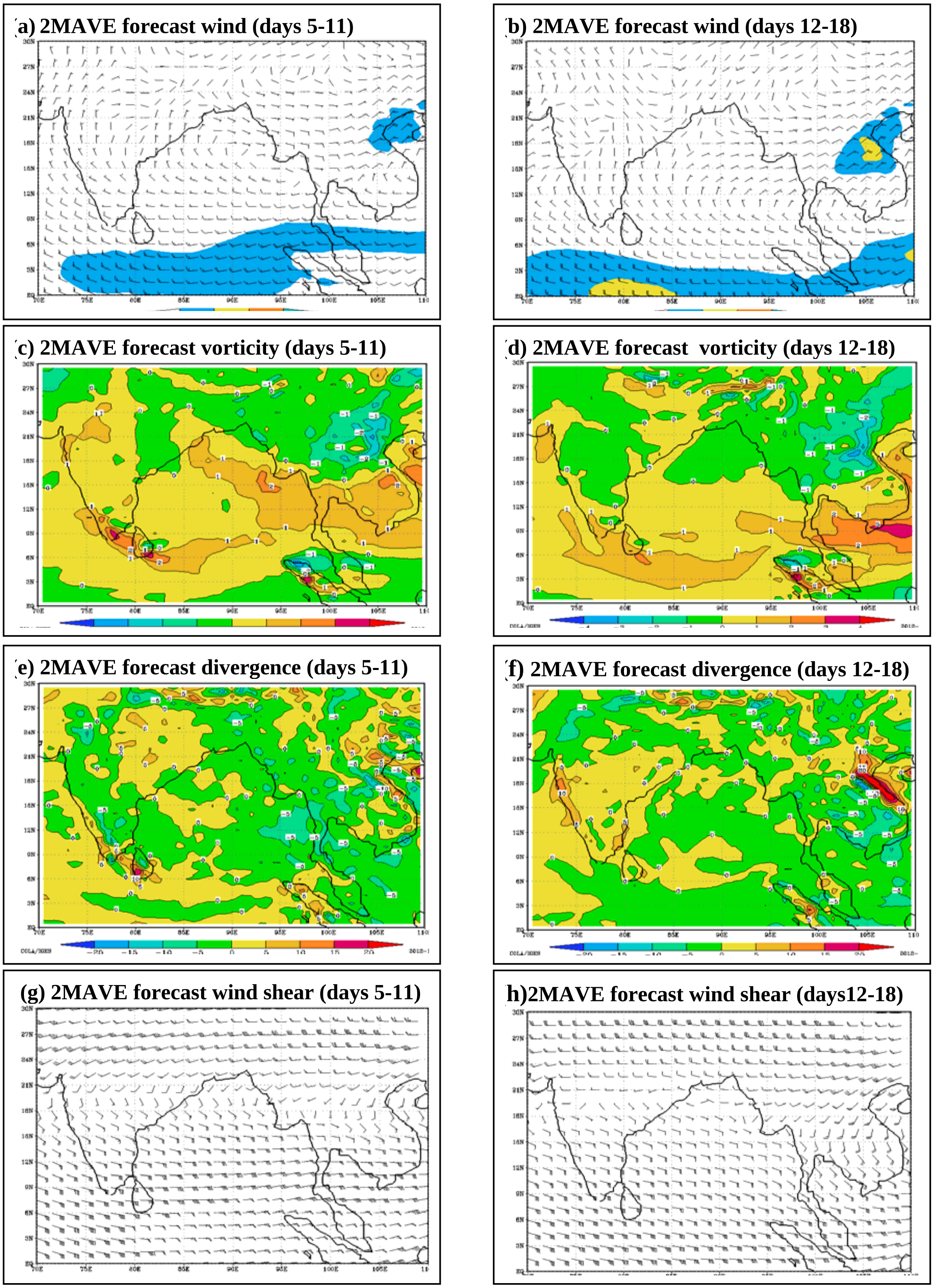
2.3. *Two Models Average (2MAVE) forecast*

As discussed above, the ECMWF and the NCEP are routinely generating the forecast from their coupled models. The products of the ECMWF monthly forecasting system used here are based on weekly forecasts for 2 weeks which updates on every Thursday and valid for week 1 (days 5-11) and week 2 (days 12-18). For the CFS there are four forecasts every day. The outputs from these two models are used for generating the equal weighted average (2 MAVE) forecast based on following steps: The ensemble means (51 members) from ECMWF forecast is considered with forecast period for days 5-11 and days 12-18. Similarly, the ensemble mean forecast from 4 members NCEP CFS valid for the same period as that of ECMWF are used. The corresponding hindcast mean is calculated both from ECMWF (18 years climatology) and the NCEP CFS (25 years climatology) and interpolated into uniform grid of 0.5 degrees. The corresponding hindcast climatology is subtracted and the weekly anomaly for three weeks is calculated both from ECMWF and the NCEP CFS. The anomaly for week 1 to week 2 is calculated by giving equal weight to ECMWF and NCEP CFS model. The product is generated on real time basis on every Friday with forecast for week 1 (Monday to Sunday ; days 5-11) and week 2 (subsequent Monday to Sunday ; days 12-18).

3. Two Models Average (2MAVE) forecast of Cyclogenesis during 2010 post monsoon season

3.1. *Observed cyclonic storm during 2010 post monsoon season*

There are two very severe cyclonic storms, which formed during the post monsoon season of 2010 (Fig. 1) over the Bay of Bengal. The first one "Giri" initially seen as a low pressure area on 19^{th} October over the east



Figs. 7 (a-h). 2MAVE 850 hPa forecast based on 14 Oct (days 5-11 forecast) mean winds during VSCS "Giri" (18-24 Oct 2010). (c), (e) and (g) same as 'a' but for mean relative vorticity (1×10^{-5} sec^{-1}), mean divergence (1×10^{-6} 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 07 Oct, 2012 central Bay of Bengal and neighbourhood, intensified into a cyclonic storm (maximum sustained wind speed of 34-47 knots) with centred near 17.5ºN and 91.5ºE at 0600 UTC of 21st, became a severe cyclonic storm (SCS) at 0000 UTC of 22nd with centred near 18.5ºN and 92.5ºE and became a very severe cyclonic storm (VSCS) at 0300 UTC of 22nd and crossed the Myanmar coast near Kayapkyu. The second cyclonic storm of the season "Jal" as shown in Fig. 1 was first observed as a low pressure area over the south Andaman Sea and neighbourhood on 2nd November, intensified into a cyclonic storm at 0600 UTC of 5th November centred near 9.0ºN, 87.5ºE, which further intensified into a severe cyclonic storm (SCS) at 2100 UTC of 5th centred near 10.0ºN, 86.0ºE. However, it weakened gradually over the sea and crossed north Tamil Nadu-south Andhra Pradesh coasts, close to north of Chennai between 1700 & 1800 UTC of 7th November and caused lot of damage in Tamilnadu and south Andhra Pradesh coast associated with not only strong wind but also due to heavy rainfall associated with the cyclone. In addition to the above 2 cyclones the post monsoon season of 2010 also witnessed three depressions over the Bay of Bengal during the period from 7-8 October, 13-16 October and 7-8 December, 2010.

The observed weekly mean wind, mean vorticity, mean divergence at 850 hPa and the vertical wind shear (W200-W850) during the period of the VSCS "Giri" from 18-24 October are shown in Figs. 2 (a-d). The corresponding anomaly of all the parameters during the same period from 18-24 October, 2010 is shown in Figs. 3 (a-d). As seen from Figs. 2 in case of the VSCS "Giri" clearly show the cyclonic circulation over the Bay of Bengal along Myanmar coast associated with positive cyclonic vorticity of the order of 1 to 2 $\times$ 10^{-5} sec^{-1} and low-level convergence of the order of -3 $\times$ 10^{-6} sec^{-1} (Figs. 2(b & c). The weekly mean patterns valid for 18-24 October in case of "Giri" also shows a anomaly of cyclonic vorticity of the order of 1.5 $\times$ 10^{-5} sec^{-1} and low level divergence anomaly of the order of -2 $\times$ 10^{-5} sec^{-1} [Figs. 3 (b &c)]. In case of the SCS "Jal" the weekly mean [Figs. 4 (a-d)] and weekly anomaly [Figs. 5 (a-d)] variables during the period from 01-07 November, 2010 shows very prominent low level cyclonic circulation over the southern Bay of Bengal both in the mean [Fig. 4 (a)] and anomaly field [Fig. 5(a)] associated with cyclonic vorticity [Fig. (4b)] more than 2 $\times$ 10^{-5} sec^{-1} both in the mean and anomaly field [Fig. 4(b) & Fig. 5(b)]. The horizontal convergence at 850 is also found to be around 8 to 9 $\times$ 10^{-6} sec^{-1} in the mean and anomaly field [Fig. 4(c) & Fig. 5(c)]. The lower vertical wind shear favour formation of TC. The anomalous shear over the region of TC is found to be of the order of 10 to 15 kts easterly in case of "Giri" and "Jal" [Fig. 3(d)& Fig. 5(d)].

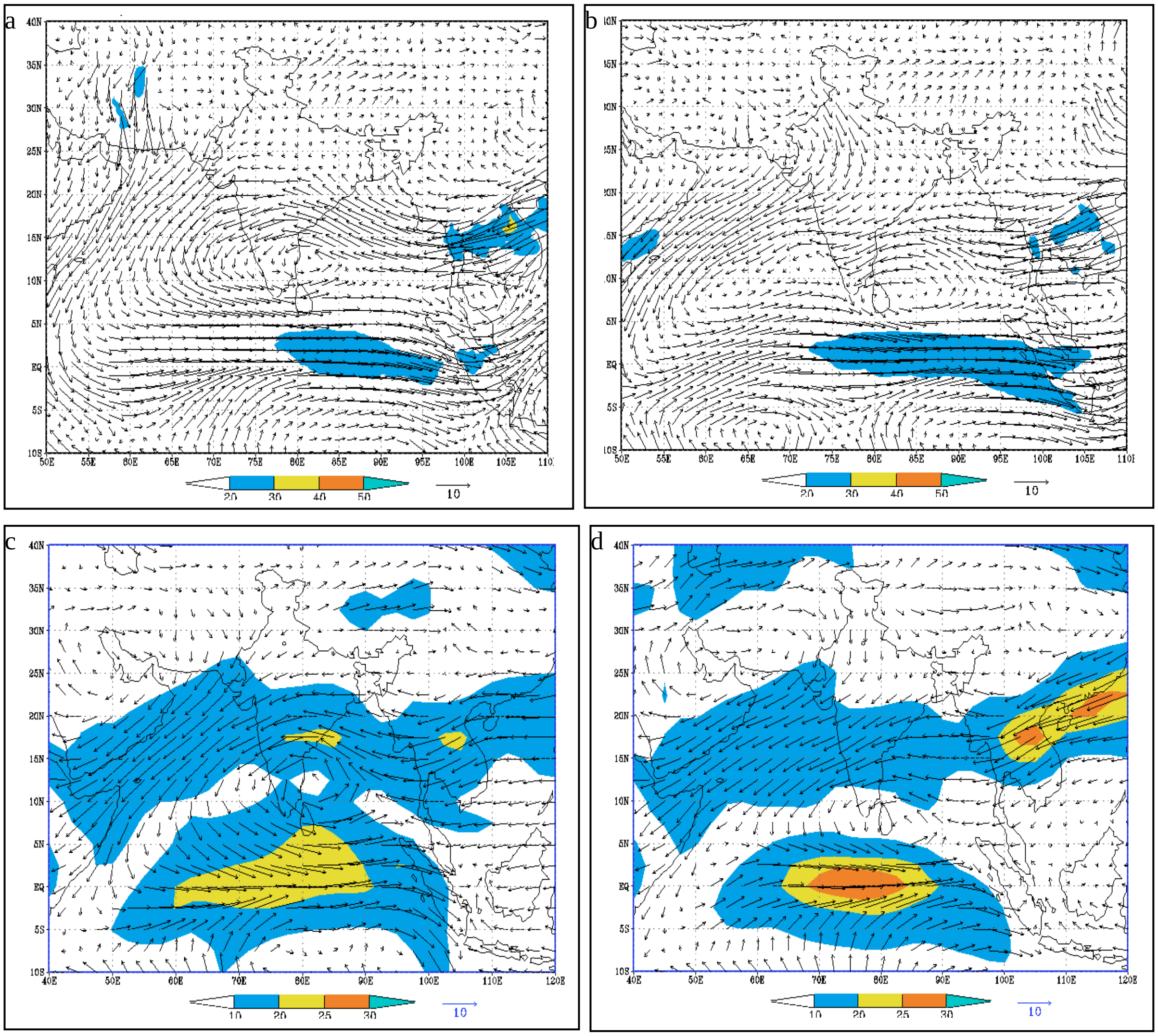
3.2. *Two Models Average (2MAVE) forecast of cyclonic storms during 2010 post monsoon season*

The low level relative vorticity, low level convergence, wind shear and the rainfall forecasts based on 2 MAVE extended range forecasts as discussed in previous sections are analysed to consider the genesis of tropical cyclone and associated rainfall.

(*i*) *Genesis of "VSCS" Giri during 18-24 October, 2010*

Before we analyse the ensemble mean from both the models it is useful to see the performance of individual model. Thus, the operational weekly mean forecast wind for week 1 (days 5-11) and week 2 (days 12-18) valid for the period of "VSCS" Giri from ECMWF and NCEP CFS models are shown in Fig. 6. Like in the observed field shown in Fig. 2(a) the forecast field from the ECMWF and NCEP CFS models also indicated closed cyclonic circulation associated with the system "Giri" in the forecast valid for days 5-11 [Fig. 6(a) & 6(c) respectively]. However, the position of the cyclonic circulation is seems to be much closer to the observation in NCEP CFS model compared to that of ECMWF. In case of week 2 (days 12-18) forecast both the models [Figs. 6(c) & 6(d)] show cyclonic circulation located south-east off the actual location. Since the individual models on some occasions, may perform differently from one another, it is always better to see the multi-model ensembles, which can reduce the forecast uncertainty. Since 2 coupled models are used in the present case with equal weight the multi-model ensemble is called as 2 models average (2MAVE) forecast in the present study.

The operational weekly mean 2MAVE forecast for wind, vorticity, divergence and wind shear for week 1 (days 05-11) and week 2 (days 12-18) forecasts based on 14th October and 7th October, 2010 initial conditions and valid for the VSCS period "Giri" (18-24 October, 2010) are shown in Figs. 7(a-h). The 2MAVE forecast mean wind [Fig. 7(a)] is found to be closer to the observed patterns shown in Fig. 2(a) and also seems to be better from the individual model in terms of capturing location of the system. But like as in the case of individual model the 2MAVE forecast for 12-18 days valid for 18-24 October, 2010 also indicate cyclonic circulation southeast off actual position associated with an east-west trough [Fig. 7(b)]. The 2MAVE forecast for week 1 (days 5-11) for other parameters like mean vorticity, negative divergence (convergence) valid for the period 18-24 October, 2010 also shows the cyclonic vorticity and convergence near the Myanmar coast [Figs. 7(c) & 7(e), whereas, the forecast for 12-18 days based on the initial

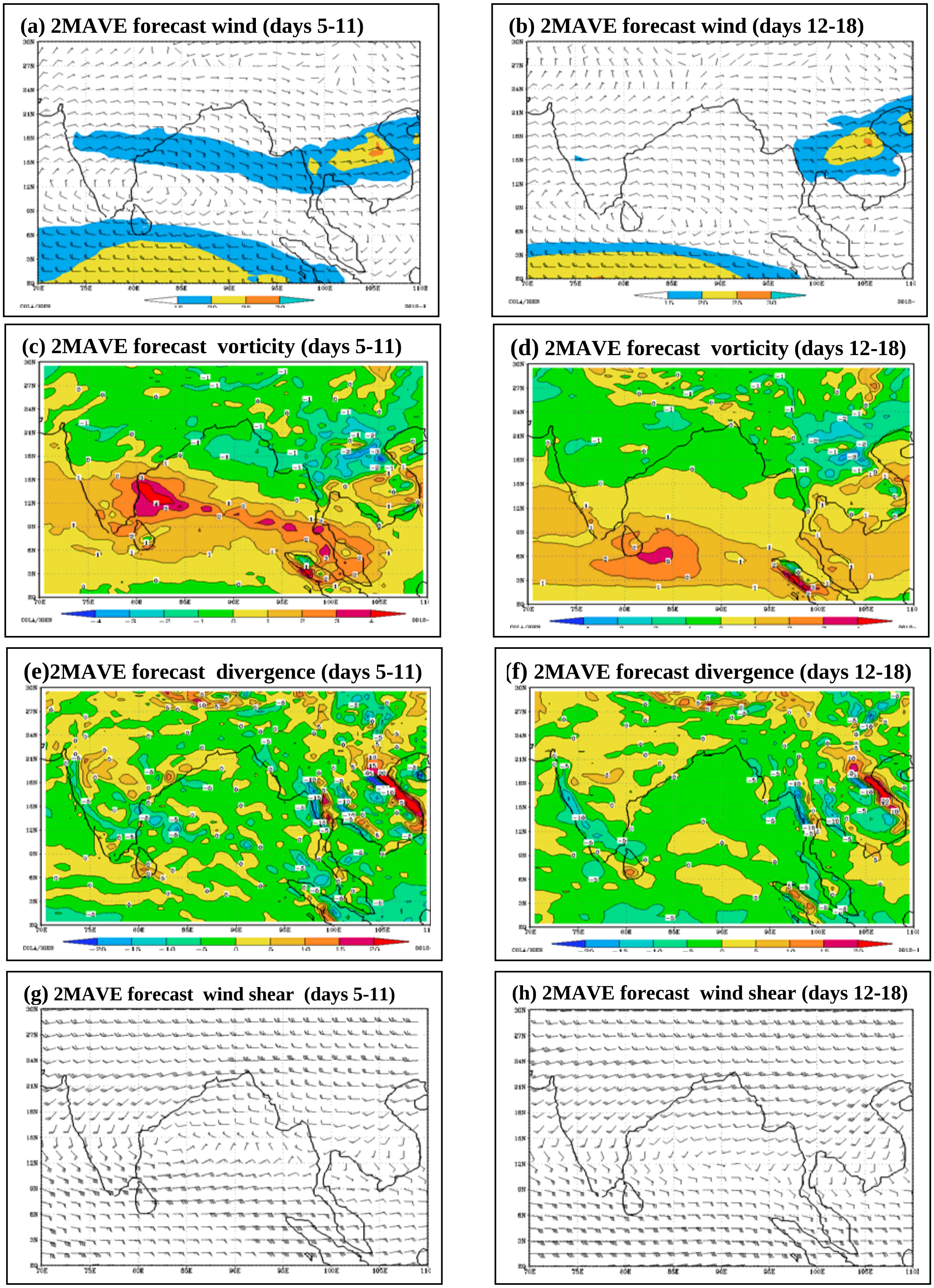


Figs. 8(a-d). Forecast 850 weekly mean wind for SCS "Jal" during the period 01-07 November, 2010. (a) ECMWF, days -11 forecast (IC=28 Oct.) (b) ECMWF, days 12-18 forecast (IC=21 Oct) (c) NCEP CFS, days 5-11 forecast (IC=28 Oct) and (d) NCEP CFS, days 12-18 forecast (IC=21 Oct)

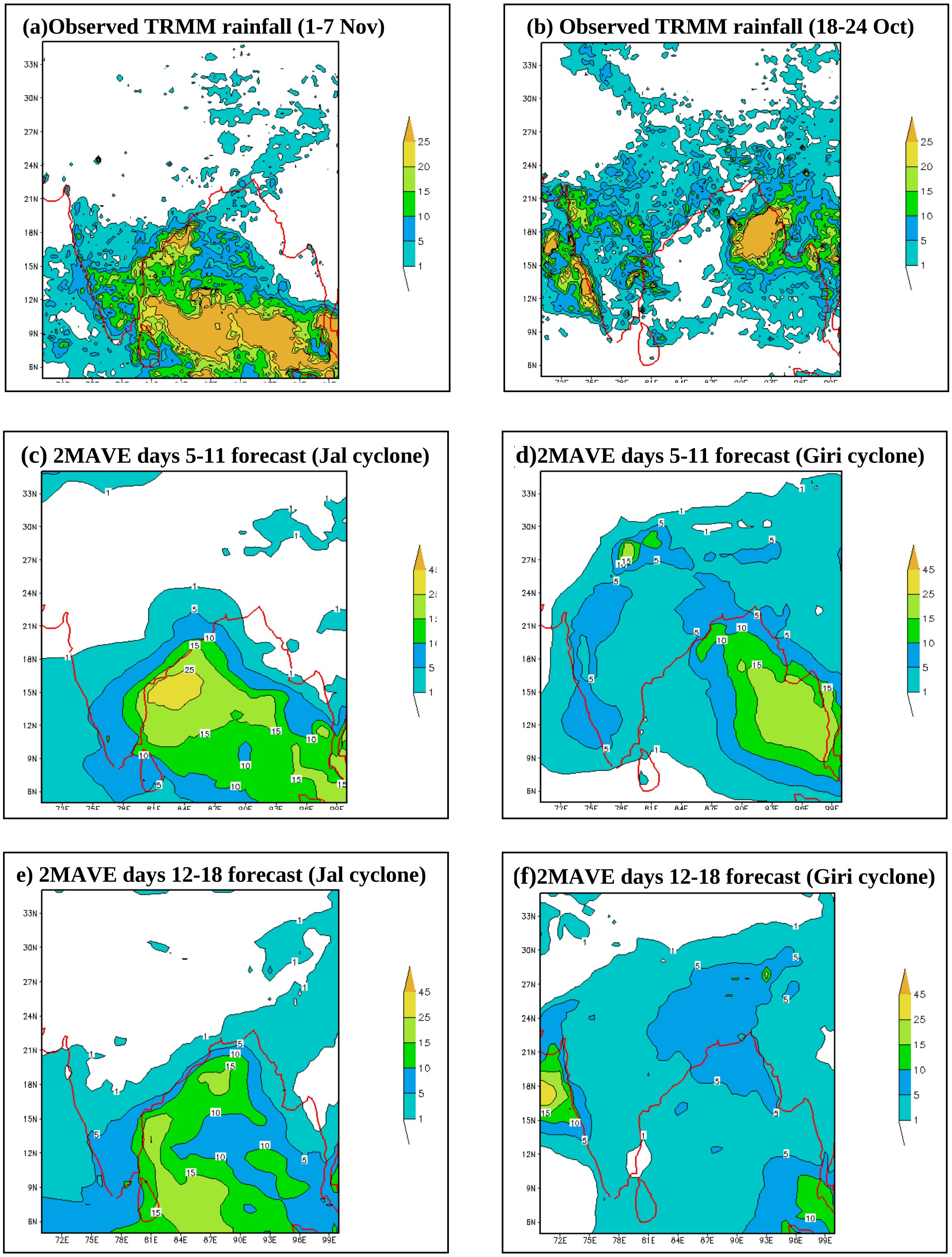
condition of 07 October, 2010 and valid for the same period of 18-24 October did not indicate the system very clearly [Fig. 7(d) & 7(f)]. The 2MAVE forecast weekly mean vertical wind shear during the "VSCS" "Giri" indicates easterly shear like in the observation [Fig. 2(d)] mainly to the south of the cyclone position [Fig. 7(g) &7(h)]. Thus, the genesis of "Giri" on the possibility of formation of a tropical cyclone is well captured particularly in days 5-11 forecast. However, the model is unable to capture properly the intensity in 12-18 days forecast.

(*ii*) *Genesis of "SCS" Jal during 01-07 November, 2010*

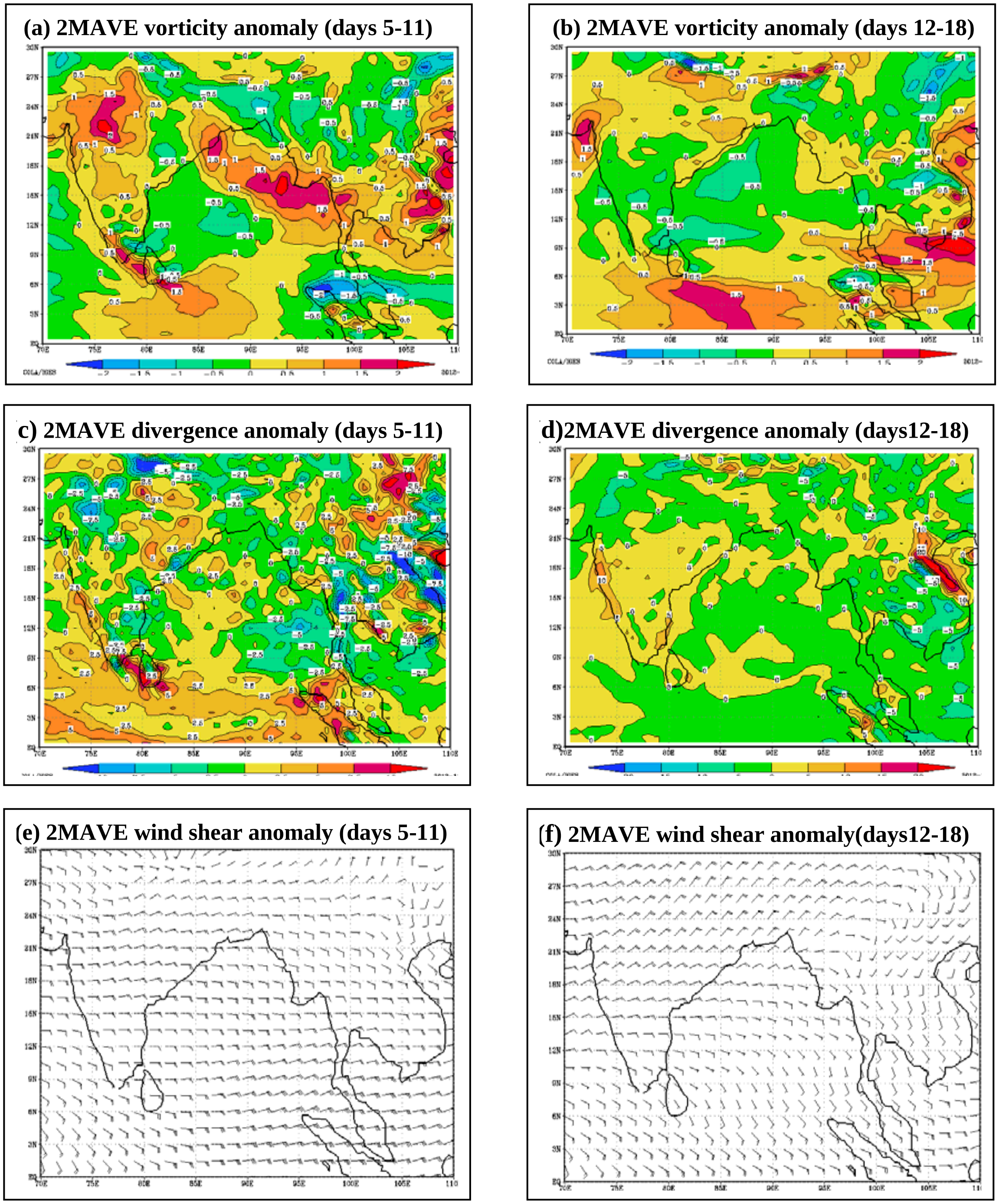
The genesis of the cyclone "Jal" was very much captured in both the coupled models [Figs. 8(a) & 8(d)] even in the forecast valid for 12-18 days based on the initial condition of 21 October, 2010 and for days 5-11 forecast based on 28 October indicated by cyclonic circulation over the Tamil Nadu coast during 01-07 November. The 2MAVE forecast valid for 01-07 November based on 28 and 21 October initial conditions (with forecast period of days 05-11 and days 12-18 respectively) also clearly indicated the cyclonic circulation at lower level over Tamil Nadu coast and adjoining coastal Andhra Pradesh region [Fig. 9(a) & 9(b)] like that of observed patterns shown in [Fig. 4(a)]. The associated low level vorticity at 850 hPa based on 2MAVE also indicated cyclonic vorticity of the order of 4 $\times 10^{-5}$ sec^{-1} near Tamilnadu coast in its forecast for days 5-11 [Fig. 9(c)] based on 28th October 2010. The mean vorticity in case of "Jal" cyclone for days 12-18 forecast



Figs. 9 (a-h). (a) 2MAVE 850 hPa forecast based on 28 Oct (days 5-11 forecast) mean winds during SCS "Jal" (01-07 Nov, 2010). (c), (e) and (g) same as 'a' but for mean relative vorticity (1×10^{-5} sec^{-1}), mean divergence (1×10^{-6} 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 Oct, 2012



Figs. 10 (a-f). Observed TRMM (mm/day) weekly mean rainfall during JAL cyclone (01-07 Nov, 2010), (c) and (e) 2MAVE forecast rainfall for same period (valid for days 5-11 forecast) based on 28 Oct 2010 and valid for the forecast period 12-18 days based on 21 Oct, 2010. (b) Observed TRMM rainfall during Giri cyclone (18-24 Oct, 2010), (d) and (f) corresponding 2MAVE forecasts rainfall for days 5-11 and days 12-18 respectively



Figs. 11(a-f). 2MAVE 850 hPa forecast vorticity anomaly (1×10^{-5} sec^{-1}). during VSCS "Giri" (18-24 Oct, 2010) (a) based on 14 Oct (days 5-11 forecast) and (b) based on 07 Oct (days 12-18 forecast). (c) & (d) same as 'a' and 'b' but for divergence anomaly (1×10^{-6} sec^{-1}). (e) and (f) same as 'a' and 'b' but for wind shear anomaly (kt)

[Fig. 9(d)] based on 21 October valid for November 1-7, although indicated the vorticity patterns close to observation, it is slightly located to the south of the actual. The positive cyclonic vorticity in the 2MAVE forecast field is also associated with negative divergence as shown in [Figs. 9(e) & 9(f). The 2MAVE forecast vertical wind shear during days 5-11 and days 12-18 forecast valid for the period "SCS" "Jal" (01-07 Nov) as shown in [Fig. 9(g & h) is almost matching with the observed vertical wind shear shown in Fig. 4(d).

(*iii*) *Rainfall due to "SCS" Jal during 01-07 November and due to the "VSCS" Giri during 14-18 October, 2010*

Associated with the SCS "Jal" heavy rainfall occurred over coastal parts of Andhra Pradesh, Tamilnadu and also on Sri Lanka. Heavy rains occurred to the south and west of landfall point of "Jal". This is reflected from the observed weekly mean rainfall from TRMM [(Fig. 10(a)] during the "Jal" cyclone period from 1-7 November. Rainfall of the order of 45 mm/day reported over parts of Tamil Nadu and coastal Andhra Pradesh in the weekly mean rainfall during the period from 1-7 November, which caused severe loss of property and life over these two coastal states. With respect to "Giri" the rainfall mainly occurred over the Ocean near Myanmar coast as seen from the observed rainfall from TRMM during the period from 18-24 October, 2010 [Fig. 10(b)].

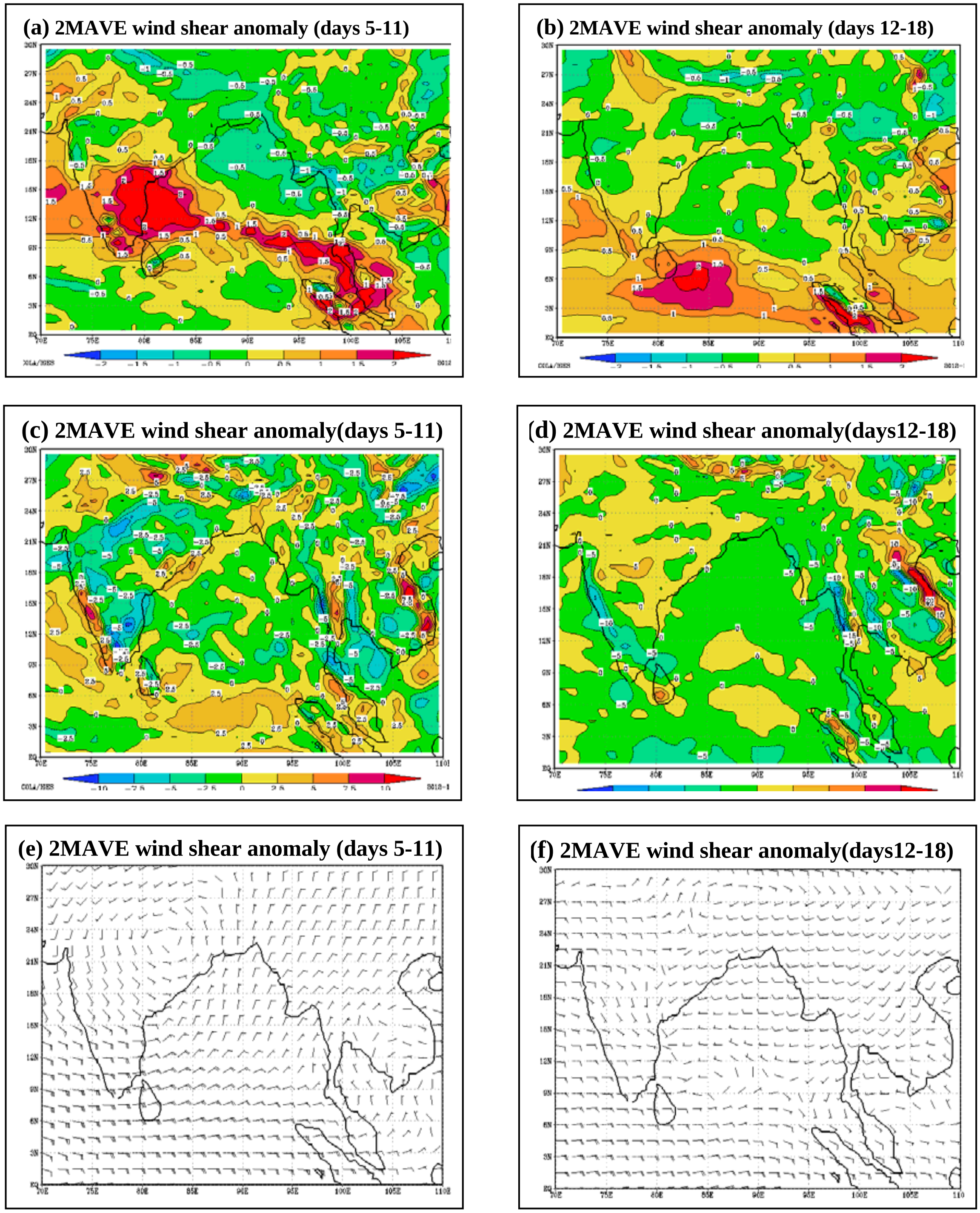
The 2 MAVE forecast based on the initial conditions of 28th October and 21st October, 2010 valid for days 5-11 (1-7 November) and days 12-18 (1-7 November) clearly showed the heavy rainfall associated with the system, although slightly away from the actual position [Fig. 10(b) &10(c)]. Thus, the genesis of the cyclone "Jal" was very much captured in both the coupled models even in the forecast valid for 12-18 days based on the initial condition of 21 October, 2010. The 2MAVE forecast valid for 01-07 November based on 28 October and 21 October initial conditions also clearly indicated large positive rainfall anomalies over the Tamil Nadu coast and adjoining coastal Andhra Pradesh region like that of observed rainfall anomalies. In case of days 5-11 forecast rainfall from 2MAVE for the "Giri" cyclone [Fig. 10 (d)] did indicate increase in rainfall over the eastern parts of Bay of Bengal, although, its location is slightly to the south of the exact observed rainfall. Like the forecast of mean wind field the 12-18 forecast of rainfall during Giri cyclone is also not very well captured by the models [Fig. 10 (f). Thus, it is found that the rainfall associated with "Jal" cyclone which formed associated with stronger north –monsoon flow was better captured in the 2MAVE forecast compared to that of "Giri" cyclone, which formed relatively at northern location and further moved in northeasterly direction.

(iv) Correct forecast of cyclogenesis versus false alarms

As shown above the coupled models have captured the genesis of two cyclones formed in the Bay of Bengal during the post-monsoon season of 2010. However, there is a possibility that on many occasions models might have given false signals about tropical cyclogenesis. In order to assess the comparison between the success rate and false alarm rate the coupled models forecasts over the Bay of Bengal are analysed for the entire post monsoon season from October to December 2010. During this season five cyclonic disturbances formed over the Bay of Bengal including the cyclone, Giri and Jal (RSMC, New Delhi, 2011). Other three cyclonic disturbances attaining maximum intensity of depressions occurred during 7-8 October, 13-16 October and 7-8 December, 2010. It is found that there were 6 cases of possible cyclogenesis indicated in the coupled model forecasts, out of which the genesis of two cyclones ("Giri" and "Jal") and 3 depressions as mentioned above were well captured in the model forecast. The models captured the genesis of three depressions in its forecasts for days 5-11 and days 12-18 valid for 4-10 October, 11-17 October and 6-12 December, 2010 (Figs. not shown in case of depressions). The models had indicated one false alarm during the period 20-26 December, 2010 with an indication of cyclonic centre close to around 5ºN in the ECMWF forecast for days 12-18 based on 9th December, 2010 initial condition and also in the NCEP CFS forecast for days 5-11 based on 16th December, 2010 initial condition (Fig. not shown). Thus, the extended range forecasts gave prospects for genesis of 6 systems out of which only 2 systems intensified into tropical cyclone intensity and 3 remained only as depression and one was a false alarm.

4. Quantitative analysis of dynamical parameters for the genesis of the system

Though the model forecast discussed above has shown useful skill about the genesis potential of TC in 10 to 15 days in advance, there is a need to quantify the threshold values to determine possible genesis of TC. In order to defined a threshold value for the genesis of tropical cyclone the dynamical parameters like low level vorticity, low level convergence and vertical wind shear are discussed and the mean and anomaly fields of these variables are analysed. The 2MAVE forecast field of 850 hPa vorticity anomaly valid for the period of "VSCS" "Giri" during 18-24 October based on initial condition of 14th October (days 5-11 forecast) and 7th October (days 12-18 forecast) are shown in [Fig. 11(a) & 11(b)] respectively. The corresponding forecast field of low level divergence anomaly and vertical wind shear anomaly for the "Giri" cyclone is also shown in [Figs. 11(c) to 11(f)]. The 2Mave forecast fields of all the three parameters for the "SCS" "Jal" cyclone during the period from 01-07 November, 2010 is shown in [Figs. 12(a-f)]. Since both the systems have formed at separate location a separate bounded area of 10° × 10° latitude-longitude box is considered for both the system to calculate the dynamical



Figs. 12 (a-f). 2MAVE 850 hPa forecast vorticity anomaly (1×10^{-5} sec^{-1}). during VSCS "Jal" (01-07 Nov 2010) (a) based on 28 Oct (days 5-11 forecast) and (b) based on 21 Oct (days 12-18 forecast). (c) & (d) same as 'a' and 'b' but for divergence anomaly (1×10^{-6} sec^{-1}). (e) & (f) same as 'a' and 'b' but for wind shear anomaly (kt)

variables. The area bounded by 90°E-100°E, 15°N-25°N is considered for the "VSCS" Giri for calculation of maximum low-level vorticity (highest positive value for cyclonic vorticity; max_vor) and minimum low level convergence (highest convergence; min_div). The area is chosen just to cover the life cycle of the system in that box. Table 1 provides the values of max_vor and min_div for the individual model from ECMWF and NCEP along

TABLE 1

Dynamical parameters like vorticity and divergence from the forecast fields in case of VSCS "Giri"

Dynamical Parameters	Mean and Anomaly	Week 1 (days 5-11) forecast Based on 14 Oct and valid for 18-24 October, 2010 (Area : 90ºE-100ºE,15ºN-25ºN)			Week 2 (days 12-18) forecast Based on 07 Oct and valid for 18-24 October, 2010 (Area : 90ºE-100ºE,15ºN-25ºN)		
		ECMWF	NCEP	2MAVE	ECMWF	NCEP	2MAVE
850 hPa max_vor (1×10^{-5} sec^{-1})	Mean	2.93	3.23	2.36	2.87	0.39	1.08
	Anomaly	2.71	3.15	2.56	2.29	0.43	0.73
850 hPa min_div (1×10^{-5} sec^{-1})	Mean	-1.39	-0.80	-0.83	-1.50	-0.47	-0.73
	Anomaly	-2.06	-0.62	-1.19	-1.29	-0.26	-0.59

TABLE 2

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 Oct and valid for 01-07 November, 2010 (Area : 80ºE-90ºE, 05-15ºN)			Week 2 forecast (days 12-18) Based on 21 Oct and valid for 01-07 November, 2010 (Area : 80ºE-90ºE, 05-15ºN)		
		ECMWF	NCEP	2MAVE	ECMWF	NCEP	2MAVE
850 hPa max_vor (1×10^{-5} 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 (1×10^{-5} 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

with the ensemble average (2MAVE). Similarly, in case of the "SCS" Jal the area bounded by 80°E-90°E, 5°N-15^{0}N is considered for the calculation of max_vor and min_div from the individual model and 2MAVE. Table 1 provides the 2MAVE forecast along with the forecasts from individual model for days 5-11 and days 12-18 valid for 18-24 October, 2010 of max_vor and min_div both for mean and anomaly obtained from Fig. 7 and Fig. 11 respectively. Similarly, Table 2 gives the corresponding forecast of max_vor and min_div for the "Jal" cyclone valid for the period 01-07 November, 2010 both for the mean and anomaly as shown in Fig. 9 and Fig. 12 respectively.

As seen from Table 1 for VSCS "Giri" the weekly mean max_vor is found to be about 2 to 3×10^{-5} Sec^{-1} and the anomaly max_vor is found to be in the range of 2.5 to 3.0×10^{-5} Sec^{-1} in individual model forecast and 2MAVE forecast. Both ECMWF and NCEP CFS along with 2MAVE have captured the enhancement of cyclone vorticity (genesis) properly in its forecast for days 5-11. In addition to the positive vorticity the magnitude of min_div for week 1 (days 5-11) forecast is found to be more than 0.8×10^{-5} sec^{-1} from the individual as well as 2MAVE forecast with ECMWF is showing higher value (-1.39×10^{-5} sec^{-1}). The magnitude in anomaly of min_div is also found to be more than 1×10^{-5} sec^{-1} in case of 2MAVE with ECMWF showing slightly higher and the NCEP is showing much smaller. With respect to the vertical wind shear anomaly the 2MAVE forecast wind shear anomaly indicates light easterly shear around 10 kts near the system as shown in Fig. 11(e), which is close to the observed shear anomaly shown in Fig. 7(g). As seen from Table 1 in case of week 2 (days 12-18) forecast for "Giri" only the ECMWF indicates the values for max_vor, min_div along with its anomaly exceeding the threshold values defined above. It is also seen from above that the week 2 forecast for 'Giri' was not very well captured in terms of its location particularly with NCEP CFS forecast as a result it was also not accurately captured in the 2MAVE forecast as well.

Compared to the system "Giri" the system "Jal" was intensified into a "SCS" and also was having relatively longer life span over the Ocean. The forecast from individual model and 2MAVE shows a value of max_vor and its anomaly of the order of 4 $\times 10^{-5}$ sec^{-1} associated with min_div and its anomaly exceeding -1.5 $\times$ 10^{-5} sec^{-1} in the 2MAVE forecast. However, the min_div and its anomaly with ECMWF model forecast is indicating a value close to -3 $\times 10^{-5}$ sec^{-1} and the NCEP CFS indicating a much lower value. The wind shear anomalies from 2MAVE forecast also indicates easterly shear as shown in [Fig. 12(e) & 12(f)], which is much close to the value of observed wind shear anomaly shown in Fig. 5 (d). As seen from Table 2 the week 2 (days 12-18) forecast from individual model and 2MAVE indicates max_vor exceeding 2 $\times$ 10^{-5} sec^{-1}. It may be mentioned here that the week 2 (days 12-18) forecast in case of "SCS" Jal in NCEP CFS is indicating slightly better compared to the ECMWF forecast in terms of the magnitude of the max_vor. The min_div for week 2 forecast in case of "Jal" is found to be of the order of -0.8 $\times$ 10^{-5} sec^{-1} in the 2MAVE forecast with ECMWF indicating stronger convergence and NCEP CFS indicating weaker convergence.

Thus, in general the present study indicates a forecast value of the order of 2.5 $\times$ 10^{-5} sec^{-1} both for max_vor and anomaly in max_vor can lead to the formation of a cyclone like "Giri". However, the threshold value is higher (4 $\times 10^{-5}$ sec^{-1}) in case of cyclone "Jal" which formed at southern latitude with more residence time over the Ocean. Similarly the min_div and its anomaly is found to be of the order of -0.8 to -1.0 $\times$ 10^{-5} sec^{-1} in case of "Giri", which, increases to about -1.5 $\times$ 10^{-5} sec^{-1} in case of "Jal" cyclone. In both the cases anomalous easterly shear is associated with the cyclogenesis. Though, the present study indicates some skill in predicting the genesis of the system 1 to 2 weeks in advance the quantitative analysis will need more number of cases to analyse the performance of individual models and also the ensemble forecast. Although, the ECMWF model is seems to be slightly better in case of "Giri" with respect to week 2 forecast the NCEP CFS model is seems to be better in case of "Jal" cyclone with respect to week 2 forecast. The mean of the two model forecast appears to be better option in order to reduce the uncertainty. Since the NCEP CFS model is also upgraded from 2012 onwards and additional coupled model from Japan Meteorological Agency is available it will be further necessary to analyse these models separately along with multi model ensemble to quantify the values, which will be investigated in a separate study.

5. Summary and conclusions

The extended range forecast (about two to three weeks in advance) based on combination of coupled models indicates satisfactorily the genesis of the tropical systems and also associated rainfall distribution based on this limited study of tropical cyclogenesis in the Bay of Bengal during post monsoon seasons of the year 2010. The forecast for days 5-11 of dynamical parameters like the low-level vorticity, low level circulation and the model rainfall clearly demonstrated the genesis of the system "Giri" over the Bay of Bengal during 18-24 October, 2010. The genesis of the cyclone "Jal" during the period from 01-07 November, 2010 was very much captured in the forecast in terms of closed cyclonic circulation and high relative vorticity valid for days 12-18 and days 5-11 based on 28 October and 21 October initial conditions respectively. The coupled models forecast valid for 01-07 November with forecast period of days 05-11 and days 12-18 respectively also clearly indicated large positive rainfall anomalies over the Tamil Nadu coast and adjoining coastal Andhra Pradesh region associated with "Jal" cyclone like that of observed rainfall anomalies.

The present generation coupled models are capable of providing useful guidance in the extended range for the tropical cyclogenesis potential for about 15 to 18 days in advance. Though the forecast had false alarm on one occasion, probability of cyclogenesis was indicated correctly on 5 occasions (3 depressions and 2 cyclones "Giri" and "Jal") during 2010 post-monsoon cyclone season. The study has shown that the two coupled models and their average forecast on extended range scale (one to two week in advance) have the potential to provide advance information for the prospects of a genesis of a tropical system of depression or tropical cyclone intensity. This can be tested profitably in operational setup. However, more work is needed to define an appropriate forecast genesis potential index. With respect to the threshold values the present study indicates an anomaly of weekly average cyclonic vorticity maximum of 2.5 $\times 10^{-5}$ sec^{-1} and anomaly of convergence of about -0.8 to -1.0 $\times 10^{-5}$ sec^{-1} at 850 hPa level may indicate a formation of depression/cyclone. However, more number of cases required to be investigated for the proper identification of the threshold values.

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