

Real time forecasting of the Bay of Bengal cyclonic storm “RASHMI” of October 2008 – A statistical-dynamical approach

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(Received 24 December 2008, Modified 15 September 2009)

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सार – अक्टूबर, 2008 में बंगाल की खाड़ी में चक्रवाती तूफान ‘रश्मि’ के आने के वास्तविक समय का पूर्वानुमान करने के लिए चार चरणीय सांख्यिकीय गतिकीय पद्धति का उपयोग किया गया है। यह चक्रवात 26 अक्टूबर 2008 को 2200 यू. टी. सी. के लगभग खेपूपाड़ा (बांगलादेश) के निकट तट से टकराया था। इस चार चरणीय पद्धति में (क) चक्रवात के उत्पन्न होने के विभव प्राचल (जी. पी. पी.) का विश्लेषण (ख) चक्रवात के मार्ग का पूर्वानुमान (ग) सांख्यिकीय चक्रवात तीव्रता पूर्वानुमान निदर्श द्वारा तीव्रता पूर्वानुमान और (घ) चक्रवात के तट से टकराने के बाद तूफान के कमजोर पड़ने की तीव्रता का पूर्वानुमान समाहित किया गया है। तूफान के विकसित होने की आरंभिक अवस्थाओं में चक्रवात के उत्पन्न होने के विभव प्राचल के विश्लेषण से यह संकेत प्रबल रूप से मिलते हैं कि चक्रवात ‘रश्मि’ के चक्रवातीय तूफान की अवस्था में पहुँचने की क्षमता काफी अधिक थी। 25 अक्टूबर को 0000 यू. टी. सी. पर विभिन्न सांख्यिकीय निदर्शों (एन. डब्ल्यू. पी.) द्वारा तूफान के तट से टकराने के स्थान का पूर्वानुमान करने में लगभग 10 कि. मी. से 95 कि. मी तक की त्रुटि का और तूफान के तट से टकराने के समय के पूर्वानुमान में तूफान के 12 घंटे पहले आने से लेकर 23 घंटे बाद तक आने की त्रुटि का पता चला है। इन संख्यात्मक मौसम पूर्वानुमान निदर्शों के आधार पर सर्वसम्मति से जारी किए गए पूर्वानुमान से तूफान के तट से टकराने वाले स्थान के पूर्वानुमान में लगभग 10 कि. मी. के लगभग की त्रुटि का पता चला है और तूफान के तट से टकराने के समय में लगभग दो घंटों के विलंब की त्रुटि का पता चला है। 26 अक्टूबर को 0000 यू. टी. सी. के आधार पर 24 घंटे के अधतन पूर्वानुमान में सुधार का पता चला है। इन निदर्शों के आधार पर जारी किए गए पूर्वानुमान के अनुसार तूफान के तट से टकराने के स्थान में 10 कि. मी. से 55 कि. मी. और तूफान के तट से टकराने के समय के पूर्वानुमान में 6 घंटे पहले से लेकर 3 घंटे विलंब तक की त्रुटि का पता चला है। सर्वसम्मति से जारी किए गए पूर्वानुमान से तूफान के तट से टकराने का स्थान प्रेक्षित किए गए तट से टकराने वाले स्थान के केन्द्र बिन्दु के समीप होने और तूफान के तट से टकराने के समय के पूर्वानुमान से दो घंटे पहले तूफान के आने का पता चला है। जे. एम. ए. (जापान मौसम विज्ञान अभिकरण) और सर्वसम्मति से जारी किए गए पूर्वानुमान तूफान के तट से टकराने के स्थान के संबंध में 24 घंटेवार पूर्वानुमान, उस स्थान के केन्द्र बिन्दु एवं तूफान के तट से टकराने के समय दोनों ही अनुकूल पाए गए। 26 अक्टूबर, को 0000 यू. टी. सी. पर 24 घंटे के पूर्वानुमान तक तूफान की प्रचंडता की 12 घंटेवार प्रागुक्ति से यह पता चलता है कि निदर्श (एस. सी. आई. पी.) चक्रवात की प्रचंडता का अनुमान लगा सकता है। तूफान के तट से टकराने के स्थान के केन्द्र बिन्दु तक निदर्श के पूर्वानुमान से यह पता चलता कि 12 घंटे और 24 घंटे के पूर्वानुमान में तूफान की तीव्रता क्रमशः 2 नॉट्स और 8 नॉट्स कम आँकी गई है। तूफान के तट से टकराने के बाद उसके 6 घंटे बाद कमजोर पड़ जाने की तीव्रता 6 नॉट्स आँकी गई है और 6 घंटे और 12 घंटे के पूर्वानुमान क्रमशः 6 नॉट्स और 10 नॉट्स अधिक आँके गए हैं। यह पद्धति चक्रवात के वास्तविक समय का पूर्वानुमान देने में पूर्वानुमानकर्ताओं का उपयोगी मागदर्शन करती है।

ABSTRACT. A four-step statistical-dynamical approach is applied for real time forecasting of the Bay of Bengal cyclonic storm “RASHMI” of October 2008 which made landfall near Khepupara (Bangladesh) around 2200 UTC of 26 October 2008. The four-step approach consists of (a) Analysis of Genesis Potential Parameter (GPP), (b) Track prediction, (c) Intensity Prediction by Statistical Cyclone Intensity Prediction (SCIP) model and (d) Prediction of decaying intensity after the landfall. The results show that the analysis of Genesis Potential Parameter (GPP) at early stages of development strongly indicated that the cyclone “RASHMI” had enough potential to reach its cyclone stage. The 48 hours landfall forecast position error based on 0000 UTC on 25 October shows that the error varies from around 10 km to 95 km and landfall time error varies from 12 hours early to 23 hours delay by different numerical models (NWP). The consensus forecast (ensemble) based on these NWP models shows that landfall forecast position error is around 10 km and landfall time error is around 2 hours delay. The updated 24 hours forecast based on 0000 UTC of 26 October shows improvement in the forecast. The model predicted landfall position error varies from around 10 km to 55 km with landfall time 6 hours early to 3 hours delay. The Multiple Model Ensemble (MME) forecast shows that the landfall forecast position is close to observed landfall point and the landfall time is early by 2 hours. The JMA (Japan

Meteorological Agency) and ensemble forecasts are found to be consistent both in terms of 24-hourly forecasts position, landfall point and landfall time. The 12-hourly intensity prediction up to 24 hours forecasts based on 0000 UTC on 26 October show that the model (SCIP) could pick up the intensification of the cyclone. The model forecasts till the landfall point show that there is an underestimation of intensity by 2 knots and 8 knots at 12 hour and 24 hour forecasts respectively. The 6-hourly decaying intensity forecast after the landfall shows an overestimation of 6 knots and 10 knots at 6-hour and 12-hour forecasts respectively. The approach provided useful guidance to the forecasters for real time forecasting of the cyclone.

Key words – Tropical cyclone, Genesis Potential Parameter (GPP), Track prediction, Multi-model ensemble forecast, Intensity Prediction and Decay after Landfall.

1. Introduction

Tropical Cyclones (TCs) are well known for their destructive character and impact on human activities. Operational forecasting of a tropical cyclone remains a challenging task to the Meteorologists. Three outstanding problems in tropical cyclone forecasting are: cyclogenesis, track prediction, and the intensity prediction.

During the last two decades, weather forecasting all over the world has greatly benefited from the guidance provided by the Numerical Weather Prediction (NWP). Significant improvement in accuracy and reliability of NWP products has been driven by sophisticated numerical techniques and by the phenomenal increase in satellite based soundings. However, limitations remain, particularly in the prediction of intensity of tropical cyclones (Elsberry *et al.* 2007; Houze *et al.* 2007).

In recent studies, efforts are being made (Kalsi *et al.* 2003; Roy Bhowmik, 2003; Roy Bhowmik *et al.* 2005, 2007; Kotal *et al.* 2009, 2008) towards the development of empirical and statistical methods to aid operational cyclone forecasting work over the Bay of Bengal. During October 2008, a cyclonic storm 'RASHMI' formed over the Bay of Bengal and crossed Bangladesh coast. The objective of this paper is to examine the performance of genesis analysis (Kotal *et al.* 2009), intensity prediction model (Kotal *et al.* 2008; Roy Bhowmik *et al.* 2005) and the performance of various numerical models for the real time forecasting of the cyclone RASHMI and thereby to apply a simple consensus objective scheme (ensemble) for operational forecasting of cyclone.

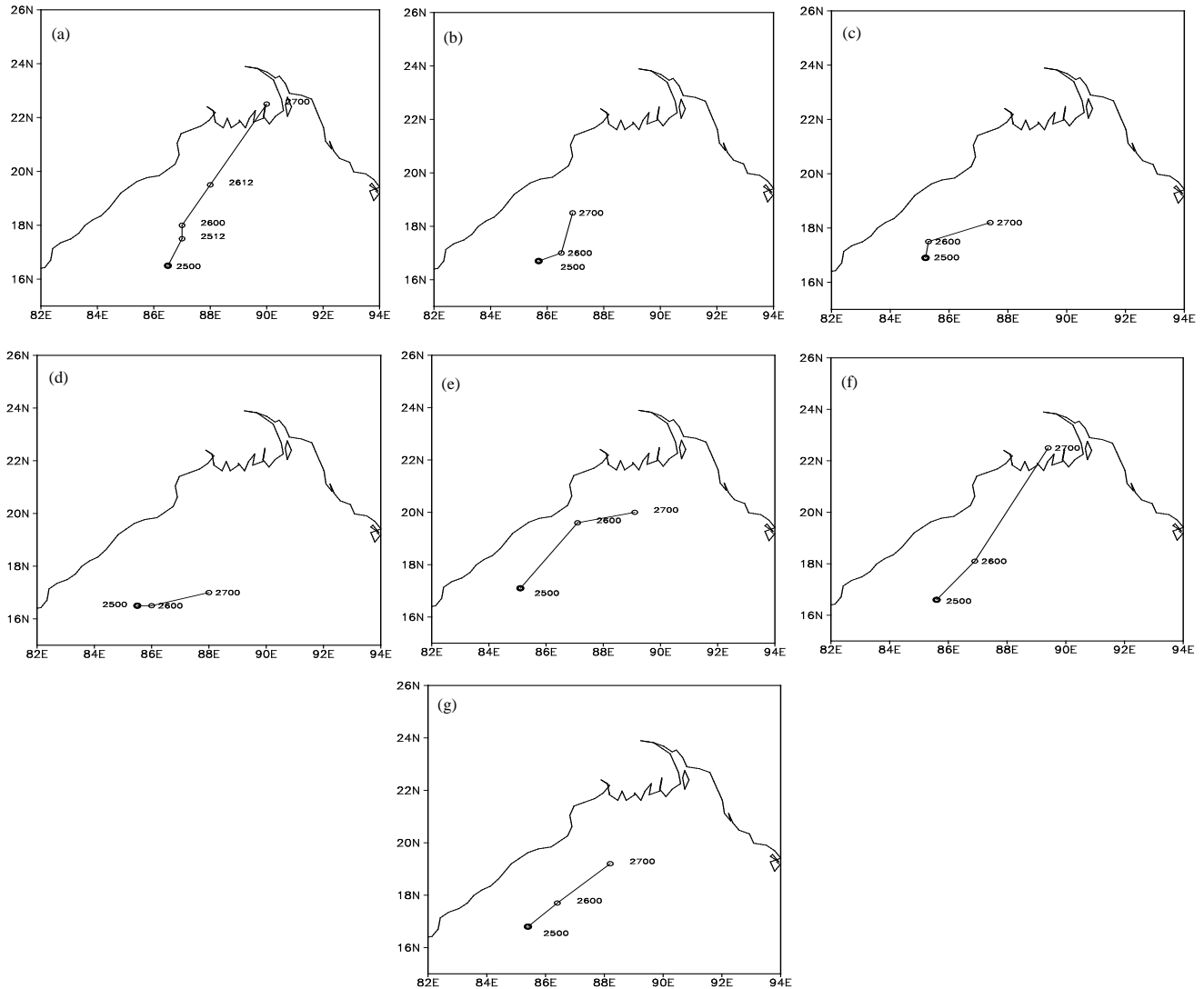
The source of the data is described in Section 2. The observational characteristics of the cyclonic storm "RASHMI" are discussed in Section 3. Analysis of genesis is described in Section 4. Performance of different NWP models used for the track prediction of this Cyclone "RASHMI" is presented in Section 5. Performance of intensity prediction and decay after landfall is presented in Section 6 and Section 7 respectively. Finally, concluding remarks are given in Section 8.

2. Data sources and methodology

Cyclone data such as intensity, track and other synoptic information are taken from the records of the Cyclone Warning Division of the Regional Specialized Meteorological Centre (RSMC), New Delhi operating in Head Quarters office of the India Meteorological Department (IMD). World Meteorological Organization (WMO) recognizes this office as the Regional Specialized Meteorological Centre (RSMC) for providing cyclone warning advisories over the region. The data table includes date, time, position in latitude and longitude and intensity (maximum surface winds in knots). Primarily the Dvorak technique (Dvorak, 1975) is used to estimate tropical cyclone intensity. The Dvorak technique is based on the analysis of cloud patterns in visible and infrared imagery from geostationary satellites (INSAT Kalpana-I). The estimated tropical cyclone intensity is rounded to the nearest 5 knots.

Various thermo dynamical parameters, which are used in analyzing Genesis Potential Parameter (GPP), are derived from the operational model analysis of the limited area model (LAM) of India Meteorological Department (IMD), New Delhi. In the operational practice LAM analysis (resolution of $1^\circ \times 1^\circ$ latitude/longitude) is done applying bogusing from the stage 'low' (T.No.1.0). As LAM data is available at greater lead-time (around 3 hour) than ECMWF (European Center for Medium Range Weather Forecast) data, GPP is calculated using LAM data to provide the information for operational forecasting. The MM5 model and Quasi-Lagrangian Model (QLM) are also run for short-range prediction. The MM5 model is run at the horizontal resolution of 45 km. The Quasi-Lagrangian Model (QLM) is run at a horizontal resolution of 40 km for tropical cyclone track prediction.

For the day-to-day weather forecasting, IMD also makes use of NWP products prepared by some other operational NWP Centres like, National Centre for Medium Range Weather Forecasting (NCMRWF), European Center for Medium Range Weather Forecasts (ECMWF), United Kingdom Meteorological Office (UKMO), Global Forecast System (GFS) at NCEP



Figs. 1(a-g). Intercomparison of observed track of cyclone “RASHMI” and track predicted by different operational NWP models based on the initial condition of 0000 UTC of 24 October 2008. (a) Observed, (b) ECMWF, (c) MM5, (d) T254, (e) GFS, (f) JMA and (g) MME

(National Center for Environmental Prediction) and Japan Meteorological Agency (JMA). The NCEP GFS is freely available in the internet on real time at the resolution of $1^{\circ} \times 1^{\circ}$ latitude/longitude. NCMRWF, UKMO, ECMWF and JMA model data are received on real time through a special arrangement. The resolution of the NCMRWF model is T254L64 ($0.5^{\circ} \times 0.5^{\circ}$ Latitude/Longitude). UKMO data is available at the resolution $1^{\circ} \times 1^{\circ}$, ECMWF at $0.25^{\circ} \times 0.25^{\circ}$ and JMA at $1.25^{\circ} \times 1.25^{\circ}$ Latitude/Longitude.

Performance of these NWP models and corresponding consensus forecasts is examined. Consensus forecasts are taken as the simple Mean Multi-Model Ensemble (MME) based on these individual

models to predict the track of this system. The forecast positions of the cyclone are picked up through computer algorithm for QLM model. Where as for other models the forecast positions of the cyclone are determined on the basis of corresponding 850 hPa winds in the forecast fields. The co-ordinate (x,y) of the storm centres have been picked up by putting the computer cursor (manual visualization) at the centre of the storm (cyclonic circulation) at 850 hPa wind plot using GrADS software. Then the co-ordinate (x,y) is converted in to its latitude and longitude using a simple FORTRAN program. The MME forecast positions (at 24 hours, 48 hours, 72 hours) are determined by taking the mean of forecast latitude and mean longitude positions of the centre of the system as depicted by these NWP models at 24-hourly forecast

TABLE 1

Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone "RASHMI"			
GPP($\times 10^{-5}$) \rightarrow			
T No. \rightarrow	1.0	1.5	2.0
Developing	11.1	12.3	13.3
Non-Developing	3.4	4.2	4.6
Cyclone "RASHMI"	10.9 (0000 UTC/24 Oct 2008)	15.8 (0000 UTC/25 Oct 2008)	10.6 (0000 UTC/26 Oct 2008)

positions up to 72 hours. Forecasts landfall point and time by NWP models are computed by interpolation of forecasts positions before landfall and after landfall.

The thermodynamic parameters except Sea Surface Temperature (SST) used as predictors for the Statistical Cyclone Intensity Prediction (SCIP) model are derived from the forecast fields of ECMWF model. SST analysis at 1° latitude-longitude grid interval from NCEP is used in this study.

3. The cyclonic storm "Rashmi"

The initial disturbance was located as a low pressure area over the west-central Bay of Bengal at 0000 UTC of 24 October 2008. The low pressure area concentrated into a depression at 0300 UTC of 25 October and lay centered at latitude 16.5° N, longitude 86.5° E. Moving in a north-north-easterly direction, the system intensified into a deep depression at 0000 UTC of 26 October over west-central and adjoining north Bay of Bengal near Latitude 18.0° N and Longitude 87.0° E about 500 km southwest of Kolkata. The system further moved in a north-northeasterly direction and intensified into a cyclonic storm designated as "Rashmi" (T.No. 2.5) over Northwest Bay of Bengal at 1200 UTC of same day and lay centered at latitude 19.5° N, longitude 88.0° E. Thereafter the storm moved fast in a north-northeasterly direction and intensified into a T.No 3.0 system at 2100 UTC and crossed Bangladesh Coast near latitude 21.8° N and longitude 89.5° E between 2200 & 2300 UTC of 26 October. The system further moved in a north-northeasterly direction, weakened rapidly into a deep depression at 0300 UTC of 27 October over northern part of Bangladesh and adjoining Meghalaya. The system continued moving in a north-northeasterly direction and weakened rapidly into a well marked low pressure area over Meghalaya and neighbourhood at 0900 UTC of same day, which became further less marked on 28 October. The observed track of the system is presented in Fig. 1(a).

4. Analysis of Genesis Potential Parameter (GPP)

The process of initiation of a cyclonic circulation in the atmosphere is called cyclogenesis. To quantify the cyclogenesis, McBride and Zehr (1981) proposed a Daily Genesis Potential parameter (DGP) on the basis of model analysis fields over the Atlantic and Pacific Ocean basin. In their study, DGP is defined as the difference of vorticity between 900 hPa and 200 hPa. The study showed that DGP is three times greater for developing systems than that of non-developing systems at early development stages. Following Zehr (1992), analysis of Cyclone Genesis Parameter for the Bay of Bengal, conducted by Roy Bhowmik (2003), showed that the procedure is capable of providing useful predictive signal. Kotal *et al.* (2009) extended the work further by defining Genesis Potential Parameter (GPP) as :

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

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

Where,

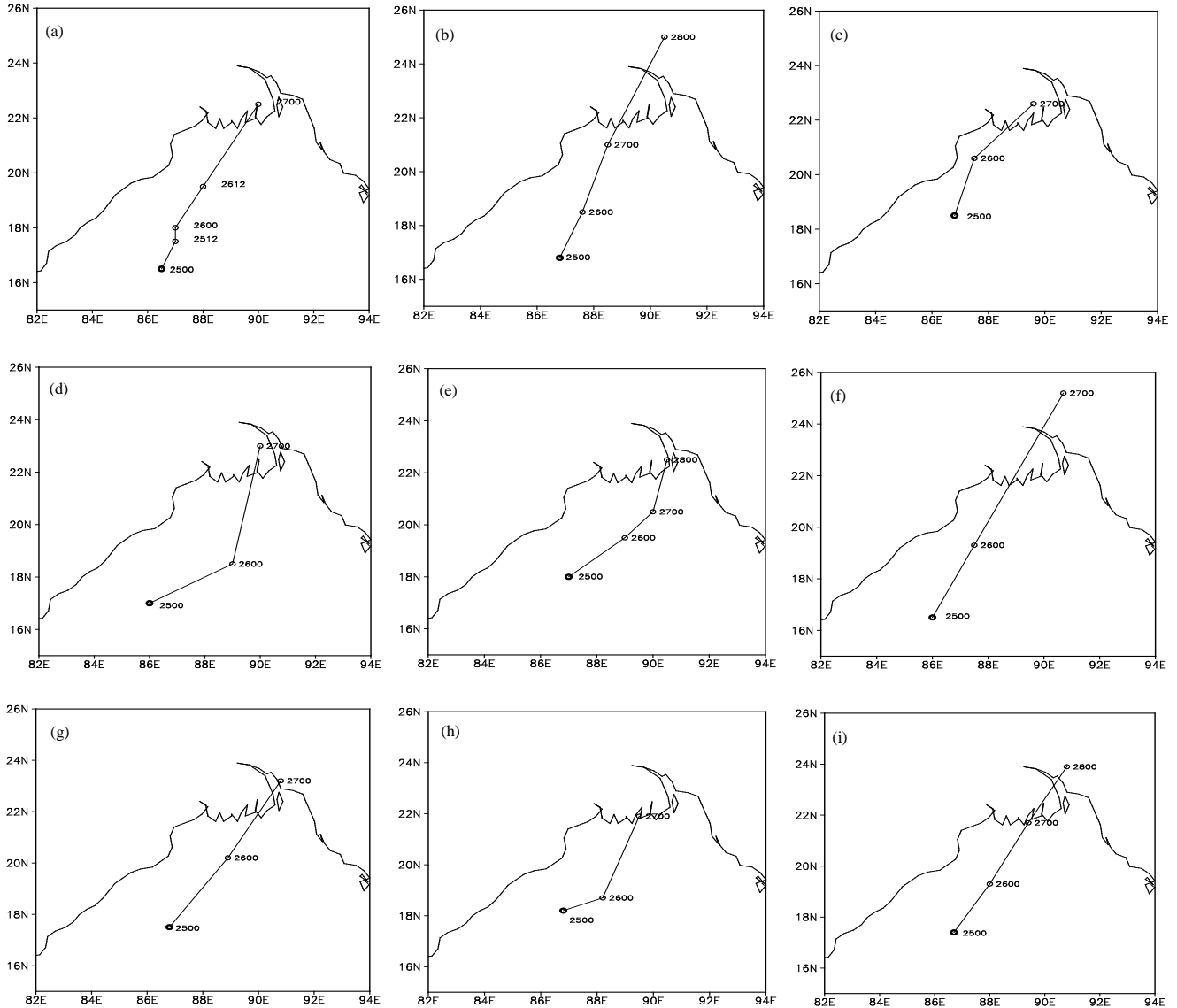
$$\xi_{850} = \text{Low level relative vorticity (at 850 hPa) in } 10^{-5} \text{ s}^{-1}$$

$$S = \text{Vertical wind shear between 200 and 850 hPa (ms}^{-1}\text{)}$$

$$M = \frac{[RH - 40]}{30} = \text{Middle troposphere relative humidity}$$

Where, RH is the mean relative humidity between 700 and 500 hPa

$$I = (T_{850} - T_{500})^\circ\text{C} = \text{Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa)}$$



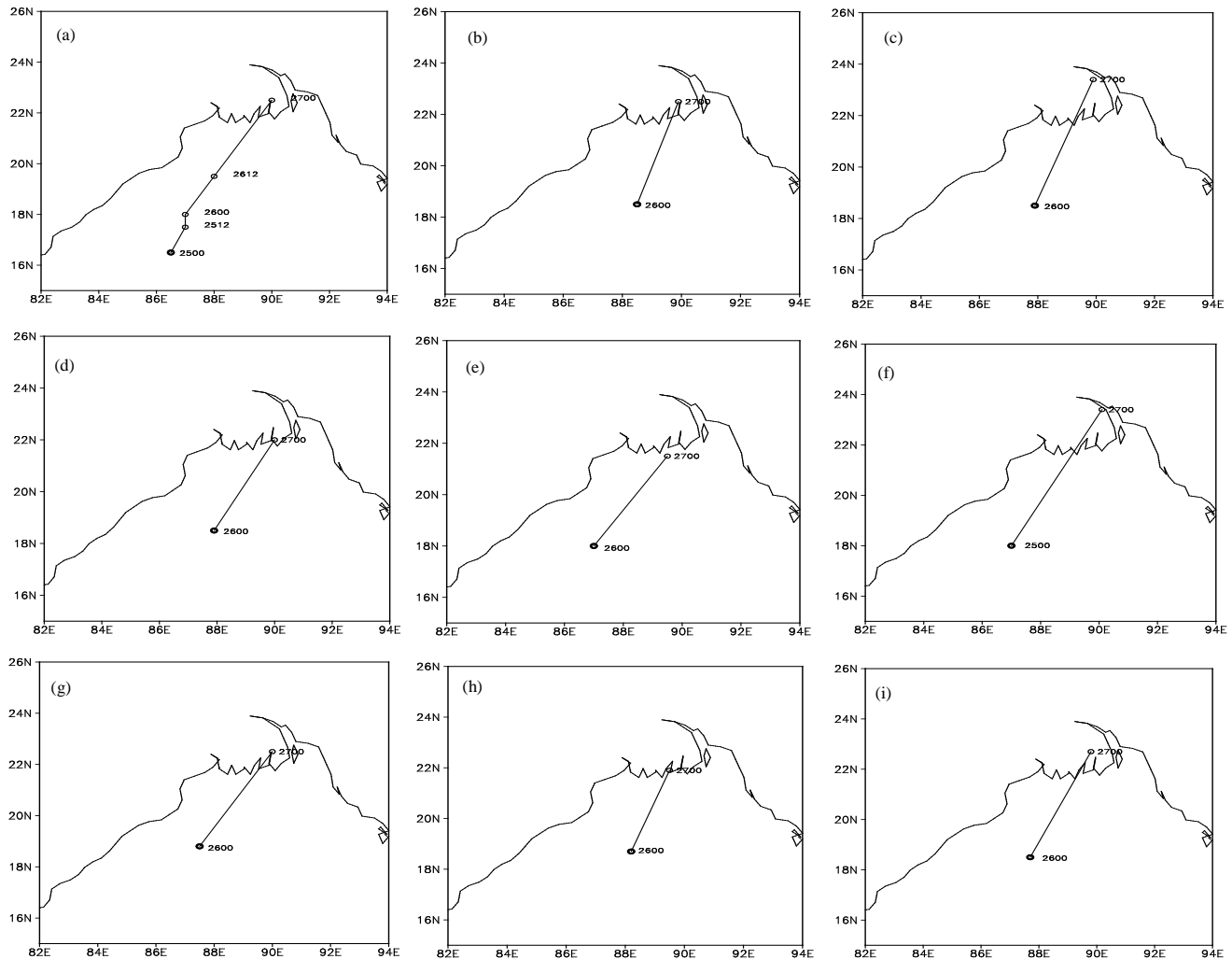
Figs. 2(a-i). Intercomparison of observed track of cyclone “RASHMI” and track predicted by different operational NWP models based on the initial condition of 0000 UTC of 25 October 2008. (a) Observed, (b) ECMWF, (c) MM5, (d) UKMO, (e) T254, (f) QLM, (g) GFS, (h) JMA and (i) MME

The study showed that GPP for a developing system is 3 to 5 times higher than that for a non-developing system and is useful in differentiating between developing and non-developing systems at their early stages of development. They showed that GPP values are equal and above 8.0 for developing systems ($T.No. > 2.5$) and below 8.0 for non-developing systems ($T.No. \leq 2.5$) in more than 85% cases at early development stages.

4.1. GPP analysis for cyclone “RASHMI”

GPP values computed (using equation 1) for this cyclone on the basis of real time model analysis fields are

shown in Table 1 along with the GPP values for developing systems and non-developing systems for comparisons. As GPP analysis is useful to understand the potential of a low pressure system for intensification at its early development stage (McBride and Zehr, 1981; Roy Bhowmik, 2003; Kotal *et al.*, 2009), GPP is calculated up to the deep depression stage ($T.No. 2.0$) of this cyclone. The GPP values (as discussed in the above section) are equal and above 8.0 for developing systems and below 8.0 for non-developing systems. The higher GPP values (greater than the threshold value 8.0; shown in Table 1) of the cyclone “RASHMI” at early stages of development ($T.No. 1.0, 1.5, 2.0$) clearly indicate that the cyclone



Figs. 3(a-i). Same as Figs. 2(a-i) except based on the initial condition of 0000 UTC of 26 October 2008

“RASHMI” had enough potential to intensify into a developing system. Although GPP showed decreasing trend from stage T.No. 1.5 to 2.0 (15.8 to 10.6), the magnitude remained above the threshold value (8.0 to intensify in to a developing system). GPP calculated from model forecast fields can provide better lead time, but it has the disadvantage due to uncertainties in the model forecast fields. More over, GPP is calibrated (Kotal *et al.*, 2009) based on model analysis fields for a good number of developing and non-developing systems to derive the threshold value. In future we intend to carry out similar work with ECMWF forecast field.

5. Track predictions by different operational NWP models

India Meteorological Department operates three regional models, Limited Area Model (LAM), MM5

model and Quasi-Lagrangian Model (QLM) for short-range prediction. The MM5 model is run at the horizontal resolution of 45 km with 23 sigma levels in the vertical and the integration is carried up to 72 hours over a single domain covering the area between latitude 30° S to 45° N and longitude 25° E to 125° E. Initial and boundary conditions are obtained from the NCEP Global Forecast System (NCEP GFS) readily available on the Internet at the resolution of 1° × 1° latitude/longitude. The boundary conditions are updated every six hours. The LAM is integrated up to 48 hours at the horizontal resolution of 0.75° × 0.75° latitude/longitude with 16 sigma levels in the vertical over the same domain using the initial and boundary conditions provided by the T254 Global operational model run at NCMRWF (National Center for Medium Range Weather Forecast). The model is also made flexible to run with NCEP GFS outputs as initial and boundary conditions.

TABLE 2

Track forecasts error of NWP models

Based on →	0000 UTC of 24 Oct 2008				0000 UTC of 25 Oct 2008			0000 UTC of 26 Oct 2008	
	Models	00 hr (km)	24 hr (km)	48 hr (km)	72 hr (km)	00 hr (km)	24 hr (km)	48 hr (km)	00 hr (km)
ECMWF	NA	39	123	549	63	84	227	168	10
MM5	NA	91	188	549	228	294	43	110	100
UKMO	-	-	-	-	56	218	56	77	55
T254	NA	107	198	646	77	119	541	0	151
QLM	-	-	-	-	0	154	308	0	100
GFS	NA	117	178	293	123	315	113	103	0
JMA	NA	44	15	61	207	148	84	160	68
MME	NA	72	72	411	119	177	88	84	20

TABLE 3

Landfall forecasts error of NWP models

Based on →	0000 UTC of 24 Oct 2008		0000 UTC of 25 Oct 2008		0000 UTC of 26 Oct 2008	
	Models	Landfall Position Error (km)	Landfall time error	Landfall Position Error (km)	Landfall time error	Landfall Position Error (km)
ECMWF	No landfall	-	76	5 hrs delay	30	2 hrs delay
MM5	No landfall	-	95	10 hrs early	10	6 hrs early
UKMO	-	-	31	2 hrs delay	56	2 hrs delay
T254	No landfall	-	41	23 hrs delay	20	3 hrs delay
QLM	-	-	20	12 hrs early	25	1 hr early
GFS	No landfall	-	66	8 hrs early	0	2 hrs early
JMA	56	5 hrs early	10	1 hr delay	46	1 hr early
MME	No landfall	-	10	2 hrs delay	0	2 hrs early

The Quasi-Lagrangian Model (QLM), a multilevel fine-mesh primitive equation model with a horizontal resolution of 40 km and 16 sigma levels in the vertical, has been in operation for tropical cyclone track prediction. The integration domain consists of 111×111 grid points in a $4440 \times 4440 \text{ km}^2$ domain that is centered on the initial position of the cyclone and the integration is carried up to 72 hours. The model includes parameterization of basic physical and dynamical processes associated with the development and movement of a tropical cyclone. The two special attributes of the QLM are: (i) merging of an idealized vortex into the initial analysis to represent a storm in the QLM initial state; and (ii) imposition of a steering current over the vortex area with the use of a dipole. For the track prediction of cyclone RASHMI, the

model is run with the initial fields and lateral boundary conditions from NCEP GFS.

The NWP products prepared by some other operational NWP Centers like, NCMRWF (T254), ECMWF, UKMO, NCEP (GFS) and JMA are also used for the day-to-day weather forecasting.

We examine the performance of these NWP models and corresponding consensus forecasts, simple Mean Multi-Model Ensemble (MME) based on these individual models to predict the track of this system.

Figs. 1 (a-g) displays the observed track and forecast tracks up to 72 hours of the cyclone by the operational

NWP models based on initial condition of 24 October 2008. The UKMO and QLM model tracks are not included in Fig. 1 as these products were not available on the day. Figs. 2 (a-i) and Figs. 3 (a-i) displays the observed track and forecast tracks based on initial condition of 25th and 26th October 2008 up to 48 hours and 24 hours (till the landfall) respectively. Observed track of RASHMI is included in the diagrams to visualize the performance of the models. The corresponding 24-hourly track prediction errors and landfall forecast errors of NWP models are summarized in Table 2 and Table 3 respectively. The 72 hours forecasts based on initial conditions of 0000 UTC of 24 October (Table 2) depicted large error by all these models except the JMA. The 48 hours forecast position error varies from around 15 km to 200 km with lowest error by JMA and largest error by T254 model. The 24 hours forecasts position error varies from around 40 km to 115 km with lowest error by ECMWF and largest error by GFS model. Corresponding MME as well as JMA forecasts showed reasonably good and consistent in the 24 hours and 48 hours forecasts with a position error around 70 km. The 48 hours forecasts based on initial conditions of 0000 UTC of 25 October depicted wide variation of errors. The 48 hours forecasts error varies from around 45 km to 540 km with lowest error by MM5 and largest error by T254 model. The 24 hours forecast position error varies from around 85 km to 315 km with lowest error by ECMWF and largest error by GFS model. Corresponding MME forecast position errors in the 24 hours and 48 hours are around 180 km and 90 km respectively. The 24 hours forecasts position error based on initial conditions of 0000 UTC of 26 October varies from near landfall to 150 km with lowest error by GFS and largest error by T254 model. Corresponding MME forecast position error is around 20 km only.

In the case of landfall errors (position and time), based on 0000 UTC of 24 October no model indicated landfall till 0000 UTC of 27 October except JMA which depicts landfall position error of around 55 km with 5 hours early (Table 3). Based on 0000 UTC of 25 October, the landfall position errors vary from around 10 km to 95 km and landfall time error varies from 12 hours early to 23 hours delay. The lowest error is found by the JMA model with a landfall position error of around 10 km with 1 hour delay. The largest landfall position error depicted by MM5 model of around 95 km and largest landfall time error by T254 model of around 23 hours delayed. Whereas, for the MME model the forecast landfall error is found to be around 10 km with a landfall time error of 2 hours delay. Updated forecast based on 0000 UTC of 26 October shows improvement of landfall forecast by all models. The maximum landfall error is found to be around 55 km by UKMO model. The landfall time error varies from 6 hours early to 3 hours delay. The lowest error is

TABLE 4

Model (SCIP) performance based on 0000 UTC of 26 October 2008

Forecast hour →	00 hr	12 hr	24 hr
Observed wind speed (knots)	30	35	45
Forecast (knots)	30	33	37
Error (knots)	-	-2	-8

found to be for the model QLM and JMA and largest error by MM5 model. The landfall forecast position is found to be close to observed landfall position with 2 hours early by the MME forecast.

The above analysis for the cyclone RASHMI shows that there is a variation of both positional errors and landfall time errors for different NWP models and improvement of forecasts is noticed after updating with time. Forecasts prepared by JMA and MME are found to be better for the cyclone 'RASHMI' both in terms of 24-hourly forecasts position, landfall point and landfall time. All the forecasts (48 hours, 24 hours) by JMA and MME are found to be consistent for this case. Further research is required to derive statistical properties of the various NWP models and MME with a larger data set.

6. Intensity prediction

Recently, Kotal *et al.* (2008) developed a Statistical Cyclone Intensity Prediction (SCIP) model for the Bay of Bengal for predicting 12 hourly cyclone intensity (up to 72 hours), applying multiple linear regression technique using various dynamical and physical parameters as predictors. Intensity change (dv_t) at t hour interval (Kotal *et al.*, 2008) is defined as:

$$dv_t = a_0 + a_1 \text{IC12} + a_2 \text{SMS} + a_3 \text{VWS} + a_4 \text{D200} + a_5 \text{V850} + a_6 \text{ISL} + a_7 \text{SST} + a_8 \text{ISI} \quad (2)$$

for $t =$ forecast hour 12, 24, 36, 48, 60 and 72

Where a_0 is a constant term and a_1, a_2, \dots, a_8 are coefficients for a 12 hourly forecast interval up to 72 hour.

The dynamical parameters except Sea Surface Temperature (SST) of model SCIP are derived from forecast fields of ECMWF model valid at forecasts hour 12h, 24h, 36h, 48h, 60h, and 72h. Considering negligible day to day variation of Sea Surface Temperature (SST), current analysis field of SST from NCEP is used in this study for all ranges of forecast from 12 to 72 hour. IC12,

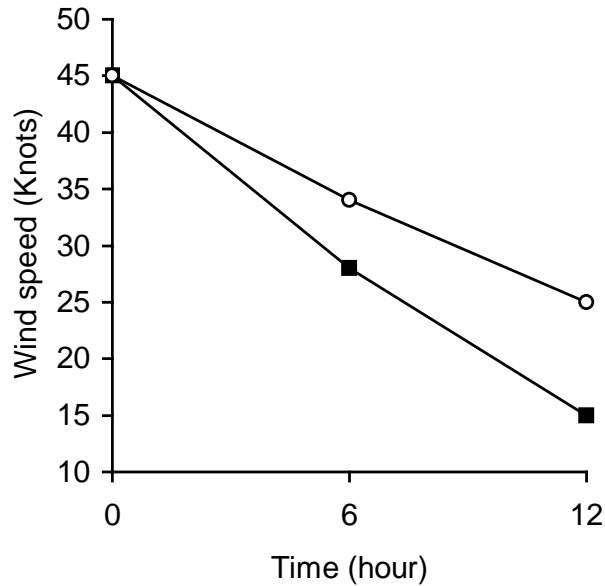


Fig. 4. Comparison of intensity forecast of cyclone “RASHMI” with observed intensity after the landfall

the intensity change (knots) during last 12 hour is available in cyclone division, IMD, New Delhi. Storm motion speed (SMS) in ms^{-1} is calculated from the initial position to the model forecast position at required forecast hour. Vertical wind shear (VWS) in knots is estimated by taking vector difference between 200 hPa and 850 hPa. D200 is the Divergence at 200 hPa and V850 is the Vorticity at 850 hPa in 10^{-5} s^{-1} . Initial storm intensity (ISI) at surface and Initial storm latitude position (ISL) is taken (at $t = 0$ hour) from cyclone division, IMD, New Delhi. Operationally the Dvorak technique (Dvorak, 1975) is used to estimate current tropical cyclone intensity.

6.1. Intensity forecast for cyclone “RASHMI”

The 12-hourly intensity forecasts (using equation 2) based on 0000 UTC of 26 October (from deep depression stage) valid up to 24 hours (Table 4) shows that the SCIP model could pick up intensification of the system. The model forecasts show that there is an underestimation of intensity by 2 knots and 8 knots at 12 hour and 24 hour respectively. Estimated cyclone intensity is rounded to nearest 5 knots. Therefore 12 hour forecast with an error of 2 knots suggests it is close to the observed (estimated) intensity. Performance of intensity forecast based on 24 October and 25 October using equation 2 could not be examined, as intensity change during last 12 hours (IC12) is not available. Cyclone intensity (knots) is available from 0300 UTC of 25 October in the RSMC report in cyclone division, IMD, New Delhi.

7. Prediction of the decaying intensity after the landfall

7.1. Decay intensity forecast for the cyclone “RASHMI”:

After landfall the cyclone RASHMI decayed rapidly. Following Roy Bhowmik *et al.* (2005) the decay intensity forecasts for “Rashmi” were attempted. Fig. 4 shows the decay curves on the basis of observations (line with solid squares) and 6-hourly forecast intensity (using Roy Bhowmik’s procedure) up to 12 hours after the landfall (line with open circles). Forecast errors at 6 hour and 12 hour after the landfall (at $t = 0$, Intensity = 45 knots) are found to be around 6 knots and 10 knots (over estimation) respectively.

8. Concluding remarks

In this paper performance of a four-step statistical-dynamical method for real time forecasting of the Bay of Bengal cyclone ‘RASHMI’ of October 2008 has been examined. The results show that the GPP analysis at early stages of development (T.No. 1.0, 1.5, 2.0) has strongly indicated that the cyclone “RASHMI” had enough potential to reach its cyclone stage. The track forecasts show that there is a large variation of both positional errors and landfall time errors of different NWP models. Forecasts prepared by JMA model and MME are found to be considerably good both in terms of landfall point and landfall time for this cyclone. All the forecasts (72 hours, 48 hours, 24 hours) by JMA and MME were found to be consistent. The 12-hourly intensity prediction based on 0000 UTC on 26 October shows that the SCIP model could pick up intensification of the system. The model forecasts show that there is an underestimation of intensity by 2 knots and 8 knots at 12 hour and 24 hour respectively. The 6-hourly decaying intensity forecast after the landfall shows an overestimation of 6 knots and 10 knots at 6 hours and 12 hours respectively. Under the circumstances of wide variation of forecasts (both position and time) of different NWP models, the proposed consensus technique (simple mean MME) based on individual numerical models for track prediction could provide useful guidance to the operational forecasters. However, ensemble technique by assigning weight factors on the basis of past performances of these NWP models at 12-hours forecast is expected to provide more accurate forecast track. Our future work will be in that direction. The four-step approach applied for forecasting of cyclone RASHMI is found to be promising for the real time application.

Acknowledgements

The authors are grateful to the Director General of Meteorology, India Meteorological Department, New Delhi for providing all the facilities to carry out this research work. Authors acknowledge the use of data and products of NCMRWF, NCEP, ECMWF, JMA and UKMO in this research work. Authors are grateful to the anonymous reviewer for his valuable comments to improve the quality of the paper.

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