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

S. D. KOTAL, S. K. ROY BHOWMKI and B. MUKHPADHYAY

India Meteorological Department, New Delhi - 110003, India

(Received 24 December 2008, Modified 15 September 2009)

email: sdkotal.imd@gmail.com

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 position and the landfall time is early by 2 hours. The JMA (Japan
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 (Elsherry 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 concensus 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° x 1° 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° × 1° 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° × 0.5° Latitude/Longitude). UKMO data is available at the resolution 1° × 1°, ECMWF at 0.25° × 0.25° and JMA at 1.25° × 1.25° 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

| T No. | Developing | Non-Developing | Cyclone “RASHMI” |
|-------|------------|---------------|------------------|
|       | GPP (x10^{-5}) |              |                  |
| 1.0   | 11.1       | 3.4           | 10.9             |
| 1.5   | 12.3       | 4.2           | 15.8             |
| 2.0   | 13.3       | 4.6           | 10.6             |

ports 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:

\[
GPP = \frac{\xi_{850} \times M \times I}{S} \quad \text{if} \quad \xi_{850} > 0, \ M > 0 \ \text{and} \ I > 0
\]

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

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}\)]

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

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

\[I = (T_{850} - T_{950})^\circ C = \text{Middle-tropospheric instability (Temperature difference between 850 hPa and 500 hPa)}\]
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. ≤ 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
“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.
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 × 4440 km² 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 forecast position 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 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:

\[
dV_t = a_0 + a_1 IC12 + a_2 SMS + a_3 VWS + a_4 D200 + a_5 V850 + a_6 ISL + a_7 SST + a_8 ISI
\]

(2)

for \( t = \) forecast hour 12, 24, 36, 48, 60 and 72

Where \( a_0 \) is a constant term and \( a_1, a_2, \ldots, a_8 \) 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,
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.

References

Dvorak, V. F., 1975, “Tropical cyclone intensity analysis and forecasting from satellite imagery”, Mon. Wea. Rev., 103, 420-430.

Elsberry, R. L., Lambert, T. D. B. and Boothe, M. A., 2007, “Accuracy of Atlantic and eastern North Pacific tropical cyclone intensity forecast guidance”, Wea. Forecasting, 22, 747-762.

Houze, R. A., Chen, S. S., Smull, B. F., Lee, W. C. and Bell, M. M., 2007, “Hurricane intensity and eyewall replacement”, Science, 315, 1235-1238.

Kalsi, S. R., Kotal, S. D. and Roy Bhowmik, S. K., 2003, “Decaying nature of super cyclone of Orissa after landfall”, Mausam, 54, 393-396.

Kotal, S. D., Kundu, P. K. and Roy Bhowmik, S. K., 2009, “Analysis of cyclogenesis parameter for developing and non-developing low pressure systems over the Indian Sea”, Natural Hazards, 50, 389-402.

Kotal, S. D., Roy Bhowmik, S. K. and Kundu, P. K. and Das, A. K., 2008, “A Statistical Cyclone Intensity Prediction (SCIP) Model for Bay of Bengal”, J. Earth. Sys. Sci., 117, 157-168.

McBride, J. L. and Zehr, R. M., 1981, “Observational analysis of tropical cyclone formation. Part II: Comparison of non-developing versus developing systems”, J. Atmos. Sci., 38, 1132-1151.

Roy Bhowmik, S. K., 2003, “An evaluation of cyclone genesis parameter over the Bay of Bengal using model analysis”, Mausam, 54, 351-358.

Roy Bhowmik, S. K., Kotal, S. D. and Kalsi, S. R., 2005, “An empirical model for predicting decaying rate of tropical cyclone wind speed after landfall over Indian region”, J. Appl. Meteor., 44, 179-185.

Roy Bhowmik, S. K., Kotal, S. D. and Kalsi, S. R., 2007, “Operational tropical cyclone intensity prediction - an empirical technique”, Naturals Hazards, 41, 447-455.

Zehr, R. M., 1992, “Tropical cyclogenesis in the western north Pacific”, NOAA Tech. Rep. NESDIS 61:181pp.