GEOFIZIKA VOL. 25 No. 2 2008

Short communication
UDC 551.509.21

Application of statistical – dynamical scheme for real time forecasting of the Bay of Bengal very severe cyclonic storm »SIDR« of November 2007

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Received 9 May 2008, in final form 20 October 2008

There is an operational requirement to formulate an objective procedure to handle operational cyclone forecasting work in a more efficient and effective way. In this paper we propose a four-step statistical-dynamical scheme for the real time application in cyclone forecasting work. The four-step scheme consists of (a) Analysis of Genesis Potential Parameter (GPP), (b) Estimation of Maximum Potential Intensity (MPI), (c) 72 hours Intensity Prediction and (d) Prediction of decaying intensity after the landfall. In November 2007, a very severe cyclonic storm 'SIDR' formed over the Bay of Bengal and hit the Bangladesh coast. In this paper, a four-step procedure is demonstrated for real time forecasting this cyclone. The results show that the GPP analysis at early stages of development can strongly indicate that the cyclone »SIDR« had enough potential to reach its cyclone stage. The MPI of the cyclone based on the SST (Sea Surface Temperature) values along the cyclone track is estimated to be 146 knots. The observed maximum intensity of the cyclone is found to be 79 % of its MPI. The 72 hours intensity prediction based on 00 UTC on 12 November could reproduce the intensity value of 109 knots, an underestimation of 6 knots. The subsequent updated forecasts are found to be realistic and useful. The 6-hourly decaying intensity forecast after the landfall shows an underestimation of 10 knots at 12 hours forecast and a significant improvement is noticed with the incorporation of correction factor. The study has documented the potentiality of the procedure for operational application.

Keywords: Tropical cyclone, Statistical-Dynamical Scheme, Genesis Potential Parameter (GPP), Maximum Potential Intensity (MPI), Intensity Prediction (IP), Decay after Landfall (DAL), Bay of Bengal.

1. Introduction

Operational forecasting of a tropical cyclone remains a challenging task. The most outstanding problems in tropical cyclone prediction are to adequately understand the mechanism leading to the genesis of the tropical cyclone and the process of intensification. By contrast movement of an already formed cyclone is better understood.

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 genesis and intensity of tropical cyclones (Elsberry et al., 2007; Houze et al., 2007). Until the time when a NWP model can be used with reasonable success, there is an imperative need in the operational scenario to use statistical and empirical models in conjuntion with the dynamical models in order to take advantage of each of these procedures.

In recent studies, efforts are being made (Kalsi et al., 2003; Roy Bhowmik, 2003; Roy Bhowmik et al., 2005, 2007; Kotal et al., 2008a, 2008b, 2008c) towards the development of empirical and statistical methods to aid operational cyclone forecasting work over the Bay of Bengal. During November 2007, a very severe cyclonic storm žSIDR' formed over the Bay of Bengal and hit Bangladesh coast. This has provided an opportunity to examine the potential of these methods for real time application. The objective of this paper is to examine the performance of these methods for the real time forecasting of the cyclone SIDR and thereby to formulate a multi-step objective scheme for operational forcasting of cyclones over the Bay of Bengal.

The source of the data is described in Section 2. The observational characteristics of the very severe cyclonic storm »SIDR« are discussed in Section 3. Performance of different NWP models used for the track prediction of this Cyclone »SIDR« is presented in Section 4. Description of different components of the proposed multi-step scheme and discussions on their performance are given in Section 5. Finally, concluding remarks are given in Section 6.

2. Data sources

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 cyclone warning for the neighbouring member countries. The data table includes date and 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. As per

Table 1. »T.No.« Classification of Cyclonic Systems and corresponding wind speed.

Weather System	T.No.	Wind criteria (knots)
Low (L)	1.0	< 17
Depression (D)	1.5	17–27
Deep Depression (DD)	2.0	28–33
Cyclonic Storm (CS)	2.5	34–47
Cyclonic storm (CS)	3.0	34–47
Severe cyclonic storm (SCS)	3.5	48–63
Very severe cyclonic storm (VSCS)	4.0–6.0	64–119
Super Cyclonic Storm (SUCS)	6.5	120

the convention of India Meteorological Department, classifications of tropical disturbances based on intensity are given in Table 1.

Various thermo-dynamical parameters, which are used in analyzing Genesis Potential Parameter (GPP), are derived from NCEP (National Centre for Environmental Prediction) re-analysis data (Fnl) at 1 latitude-longitude grid freely available on the Internet.

To evaluate the Maximum Potential Intensity (MPI) of cyclone »SIDR« during its lifetime, the forecast storm tracks from MM5 model operational at India Meteorological Department (IMD) and the corresponding NCEP Sea Surface Temperature (SST) analysis at 1° latitude-longitude grid interval are used.

The thermodynamic parameters used as predictors for the Statistical Cyclone Intensity Prediction (SCIP) model (the third step of the four-step scheme; Section 5.3) are derived from the forecast fields of MM5 model operational at India Meteorological Department (IMD), New Delhi.

3. The Very Severe Cyclonic Storm »SIDR«

The system was located as a low pressure area over the southeast Bay of Bengal at 00 UTC of 11 November 2007. The low pressure system concentrated into a depression at 09 UTC of 11 November and lay centered at latitude10.0° N, longitude 92.0° E about 200 km south-southwest of Port Blair and intensified into deep depression at 18 UTC of the same day. Moving in a northwesterly direction, the system intensified into cyclonic storm at 03 UTC of 12 November. Thereafter, the system rapidly intensified into severe cyclonic storm at 12 UTC and into a very severe cyclonic storm (90 knots) at 18 UTC on 12 November. The system continued to move in a northwesterly direction till 00 UTC of 13 November. Afterwards the system moved in a northerly direction up to 12 UTC on 15 November and then started to move north-northeastwards. It maintained the same intensity (90 knots) from 18

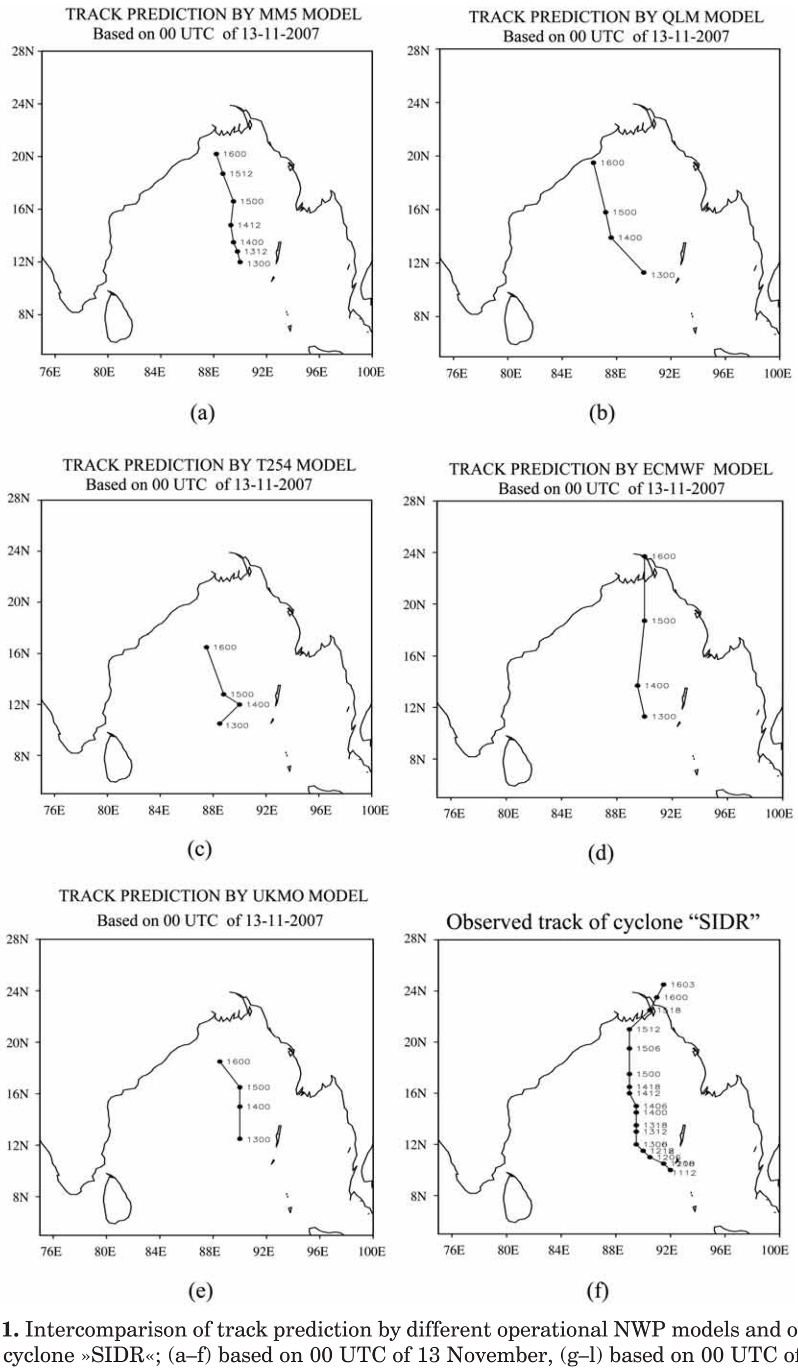

Figure 1. Intercomparison of track prediction by different operational NWP models and observed track of cyclone »SIDR«; (a–f) based on 00 UTC of 13 November, (g–l) based on 00 UTC of 14 November; and (m–r) based on 00 UTC of 15 November.

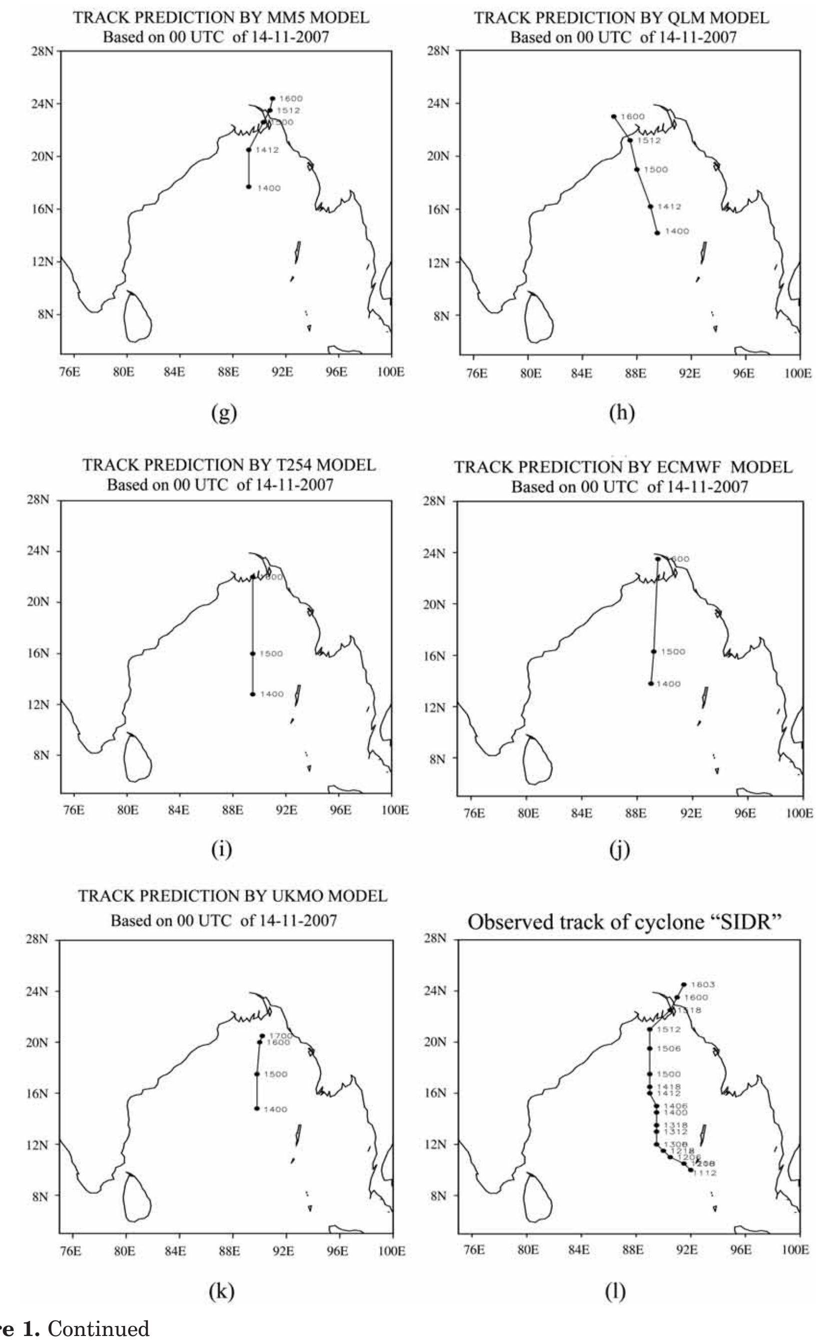

Figure 1. Continued

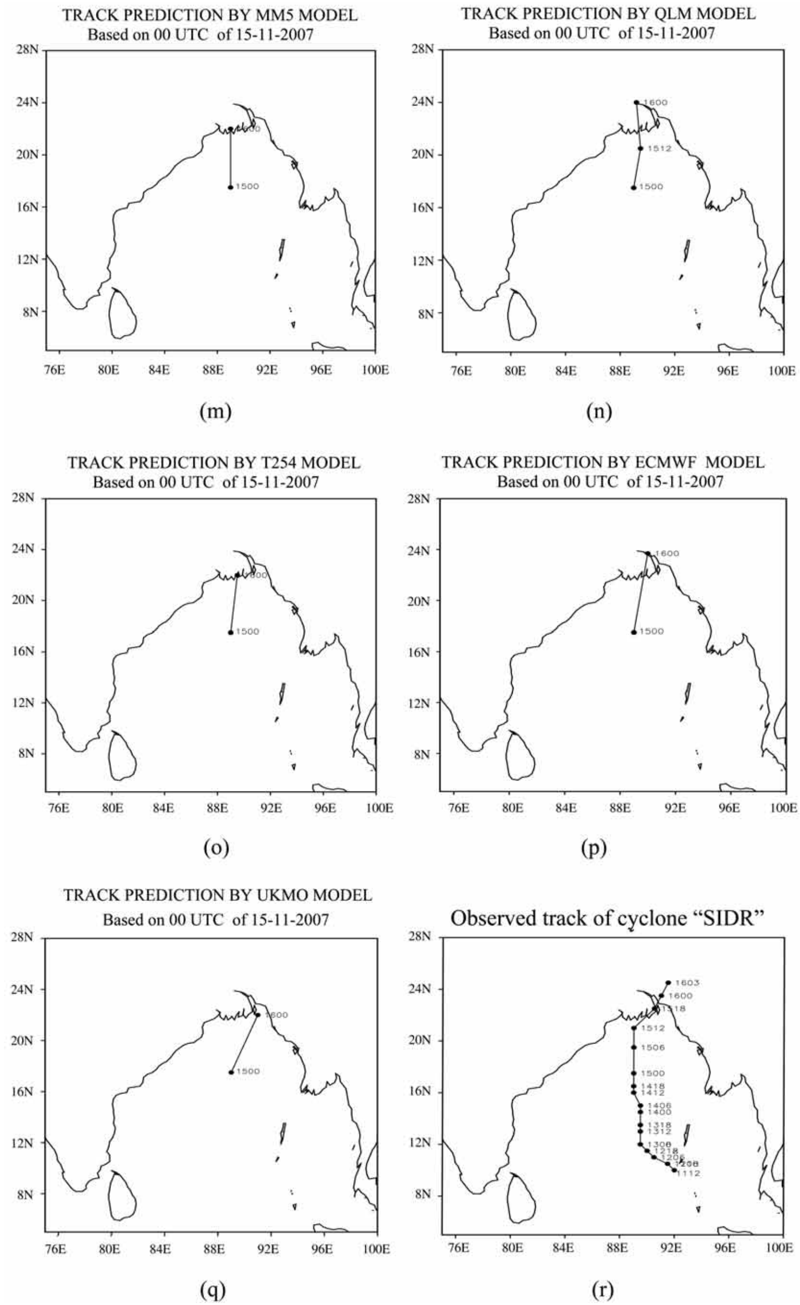

Figure 1. Continued

UTC on 12 November to 00 UTC on 15 November. The system further intensified to 115 knots at 03 UTC on the same day and crossed the west Bangladesh coast around 17 UTC near latitude 21.7° N, longitude 89.8° E with same intensity. After landfall the system weakened into cyclonic storm at 21 UTC of 15 November. The system further weakened into depression at 03 UTC and remained depression until 06 UTC on 16 November. The observed track of the system is presented in Figure 1 along with model forecast tracks.

4. Track predictions by different operational NWP models

IMD 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 T–254 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 km^2 domain that is centered on the initial position of the cyclone. 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 SIDR, the model is run with the initial fields and lateral boundary conditions from NCEP GFS.

For the day-to-day weather forecasting, IMD also makes use of NWP products prepared by some other operational NWP Centers like, NCMRWF, European centre for medium range weather forecast (ECMWF), United Kingdom Meteorological Office (UKMO).

We examine the performance of these NWP models to predict the track of this system. The forecast position of the cyclone is determined on the basis of corresponding 850 hPa winds in the forecast fields.

Figure 1 (a–f) displays the forecast track of the cyclone by the operational models up to 72 hours. Figure 1 (g–l) displays the forecast and observed tracks up to 48 hours and Figure 1 (m–r) displays the forecast and observed tracks up to 24 hours before landfall, respectively. Observed track of SIDR is included in the diagrams to visualize the performance of the models. The corresponding landfall errors are summarized in Table 2. The 72 hours forecasts based on 00 UTC initial conditions on 13 November depicted large landfall error by all these models except the ECMWF. Similar error with lesser magnitude persisted in the 48 hours forecasts based on 00 UTC initial conditions of 14 November. All the models showed reasonably good performance in the 24 hours forecasts based on the initial conditions of 00 UTC on 15 November, when some convergence in the forecasts by these models are noted. Forecasts produced by ECMWF model are found to be superior both in terms of landfall point and landfall time. All the forecasts (72 hours, 48 hours, 24 hours) by ECMWF were found to be consistent. Landfall position errors were around 55 for a 72 hour forecast and 25 km for a 24 hour forecast. The landfall time error was within 2 hours of observed landfall time in the 72 hours, 48 hours and 24 hours. QLM showed landfall position errors of 650 km, 270 km and 45 km respectively in the 72 hours, 48 hours and 24 hours forecasts. The landfall time was close to the observed landfall time. MM5 landfall position errors of around 385 km, 90 km and 35 km in the 72 hours, 48 hours and 24 hours forecast respectively are observed. The landfall time was delayed by around 7 hours in the 48 hours and close to the observed landfall time at 24 hours forecasts. T–254 (NCMRWF) showed landfall position errors of around 720 km in the 72 hours forecast and 115 – 120 km in the 48 hours to 24 hours forecasts. The landfall time was delayed by around 25 hours in the 72 hour forecast and by 12 hours in the 48 hour forecasts. UKMO showed landfall position errors of around 605 km, 30 km and 190 km in the 72 hours, 48 hours and 24 hours forecasts respectively. The landfall time was delayed by 20 hours at all the forecast times.

All the models show reasonably good performance in the 24 hours forecasts prepared based on the initial conditions of 00 UTC on 15 November, when some convergence in the forecasts by these models are noted. Forecasts prepared by ECMWF model are found to be superior both in terms of landfall point and landfall time. All the forecasts (72 hours, 48 hours, 24 hours) by ECMWF were found to be consistent.

5. Proposed multi-step scheme and its application

Different statistical models are available for the Atlantic, Eastern North Pacific and Western North Pacific basins, but no such model is presently available for the Indian Seas for predicting intensity of Tropical Cyclone. Due to non-availability of such objective methods, in the operational scenario a subjective approach combining the inputs of persistency, climatology, synoptic

Table 2. Performance of Different Models for Track Prediction of Cyclone »SIDR«.

Numerical Models	Initial Date (Based on)	Landfall forecast point Latitude/ Longitude	Landfall forecast time Date/Time (IST)	Landfall forecast position Error (Km)	Landfall forecast time error (hrs)
ECMWF	13/ 00 UTC	22.4/89.4	16/0030	55	2 hrs delay
	14/ 00 UTC	22.1/89.5	15/2130	55	1 hr early
	15/ 00 UTC	21.9/89.7	15/2030	25	2 hrs early
MM5 (IMD)	13/ 00 UTC	14.3/87.6 (At 72hr)	–	385	No land fall
	14/ 00 UTC	22.5/89.6	16/0530	90	7 hrs delay
	15/ 00 UTC	22.0/89.9	16/0130	35	3 hrs delay
QLM (IMD)	13/ 00 UTC	19.5/86.3 (At 72hr)	–	660	No land fall
	14/ 00 UTC	21.4/87.2	15/1830	270	5 hrs early
	15/ 00 UTC	21.9/89.4	15/2130	45	1 hr early
T–254 (NCMRWF)	13/ 00 UTC	18.2/84.0	17/0030	720	25 hrs delay
	14/ 00 UTC	21.8/88.7	16/1130	115	12 hrs delay
	15/ 00 UTC	22.0/88.7	15/2330	120	1 hr delay
UKMO	13/ 00 UTC	23.5/91.0 (At 72hr)	–	605	No landfall till day 5
	14/ 00 UTC	21.5/90.0	17/0730	30	30 hrs delay
	15/ 00 UTC	22.4/91.5	16/1730	190	20 hrs delay

and satellite technique is the primary aid for the forecast of tropical cyclone intensity over the north Indian Sea.

In view of this, we propose here a multi-step statistical-dynamical scheme comprising of four components, namely (i) Analysis of Genesis Potential Parameter (GPP), (ii) Evaluation of Maximum Potential Intensity (MPI), (iii) Six hourly Intensity Prediction up to 72 hours (IP72) and (iv) Prediction of decaying intensity after the Landfall (DAL). In the following sub-sections a brief description of each of the components and their performance for the cyclone SIDR are discussed.

5.1. 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 et al. (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. An 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. (2008a) extended the work further by defining Genesis Potential Parameter (GPP) as:

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

$$= 0 \qquad \text{if } \xi_{850} \le 0,\ M \le 0 \text{ or } I \le 0$$

Where, ξ_{850} = Low level relative vorticity (at 850 hPa) in 10^{-5} s^{-1}

S = Vertical wind shear between 200 and 850 hPa (knots)

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

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

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

All the four variables are averaged over an area of radius 2.5° around the storm center for the computation of GPP values. The study showed that GPP for the developing system is 3 to 5 times higher than that of non-developing system and is useful in differentiating between developing and non-developing systems at their early stages of development. GPP values for developing and non-developing systems as reported by Kotal et al. (2008a) are shown in Table 3.

5.1.1. GPP analysis for cyclone »SIDR«

GPP values are computed for this cyclone on the basis of real time model analysis fields are shown in Table 3. The GPP values at early stages of development (T.No. 1.0, 1.5, 2.0) comparing with that of developing and non-developing systems have clearly indicated that the cyclone »SIDR« has enough potential to reach the stage of cyclonic storm.

Table 3. Genesis potential parameter (GPP) for Developing System, Non-Developing System and Cyclone »SIDR«; Numbers within bracket in the Developing and Non-Developing rows indicate the number of cases.

	GPP($\times 10^{-5}$)				
T.No. →	1.0	1.5	2.0	2.5	3.0
Developing	11.1 (21)	12.3 (32)	13.3 (28)	13.5 (25)	13.6 (19)
Non-Developing	3.4 (22)	4.2 (79)	4.6 (67)	2.7 (18)	–
Cyclone »SIDR«	10.9	15.5	12.7	13.1	13.5

5.2. Estimation of Maximum Potential Intensity (MPI)

The MPI of a cyclonic storm is defined as the expected highest intensity of a cyclone against a particular Sea Surface Temperature (SST) value (on the basis of a large sample of data) where the cyclone intensity is defined in terms of maximum sustained surface winds.

Kotal et al. (2008b) found an empirical relationship between SST (°C) and MPI (knots) for a Bay of Bengal cyclone as:

$$MPI = 35.714 \times \mathrm{SST} - 889.64 \qquad (2)$$

The study (Kotal et al 2008b) showed that for the Bay of Bengal, 38 % of the cyclones reach 50 % of their MPI and only 18 % of the cyclones exceed 80 % of their MPI. On an average storms over the Bay of Bengal are found to reach 51% of their MPI.

Daily global analysis of SST prepared by NCEP is freely available on the Internet. This analysis could be used to determine the SST value at the particular location of a basin where the cyclone is formed or likely to move. As day-to-day variation of the SST value is negligible, this SST value could be used to determine the MPI at the forecast positions of the storms from the SST–MPI relationship. The MPI could provide useful information to a forecaster about the possible extreme intensity of tropical cyclones.

5.2.1. Maximum Potential Intensity (MPI) of cyclone »SIDR«

The MPI of cyclone »SIDR« is calculated on the basis of SST value of 12 and 13 November (Figure 2 (a, b)) around the forecast cyclone centre. The MPI for this cyclone is found to be 146 knots (using equation (2)). The observed maximum intensity of the cyclone is 115 knots. The observed maximum intensity of the cyclone is found to be 79 % of its MPI.

5.3. Intensity Prediction (IP72)

Recently, Roy Bhowmik et al. (2007) proposed a simple empirical model for predicting cyclone intensity over the Bay of Bengal. The study is based on the assumption that tropical cyclone intensifies exponentially, where the intensification factor is determined using past 12 hours intensity changes. A major limitation of this empirical model (Roy Bhowmik et al 2007) is that it does not include parameters to take into account the physical and dynamical processes involved. The study warranted further investigation in a more general manner incorporating other synoptic and thermodynamical factors, which play important role for intensification of storms. In order to over come these shortcomings, Kotal et al. (2008c) 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

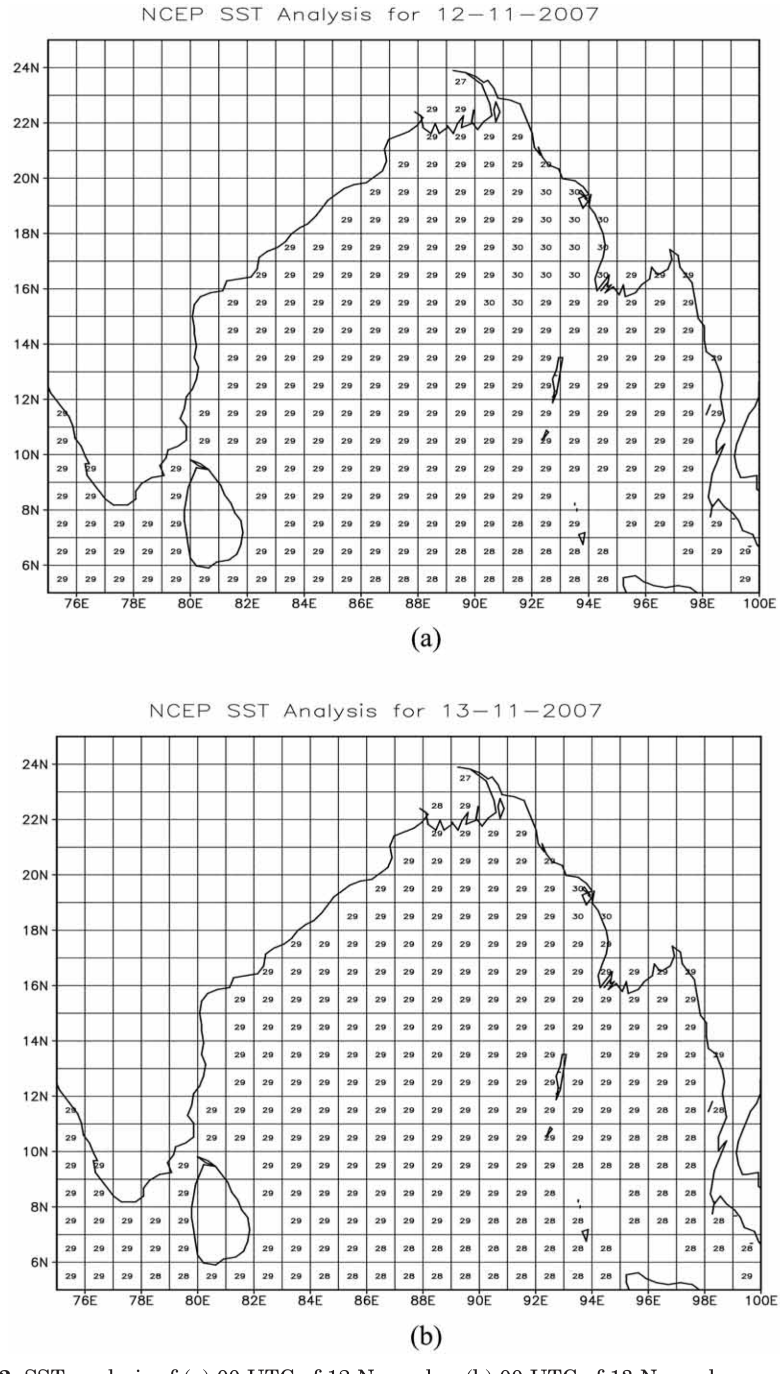

Figure 2. SST analysis of (a) 00 UTC of 12 November (b) 00 UTC of 13 November.

various dynamical and physical parameters as predictors. The dynamical parameters of model SCIP are derived from forecast fields of MM5 model. The model equation (Kotal et al., 2008c) is given as:

$$\mathrm{d}v_t = a_0 + a_1\, IC12 + a_2\, SMS + a_3\, VWS + a_4\, D200 + a_5\, V850 + a_6\, ISL + a_7\, SST + a_8\, ISI \quad (3)$$

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

The detailed of model predictors are given in Table 4. The constant term a_0 and coefficients $a_1, a_2, \ldots, a_8$ for a 12 hourly forecast interval are given in table 5. Positive regression coefficient of the 12-hour intensity change variable (IC12) suggests that intensity change during past 12 hour can indicate the future rate of intensification (Kotal et al., 2008c). But an error could arise, if the rate of intensity change increases or decreases significantly. However, subsequent updates of the previous forecasts based on the current observations (modified IC12) could improve the forecast error.

Table 4. Model parameters.

S.No.	Predictors	Symbol of Predictors	Unit
1.	Intensity change during last 12 hours	IC12	knots
2.	Vorticity at 850 hPa	V850	$\times 10^5\ s^{-1}$
3.	Storm motion speed	SMS	$m\ s^{-1}$
4.	Divergence at 200 hPa	D200	$\times 10^5\ s^{-1}$
5.	Initial Storm intensity	ISI	knots
6.	Initial Storm latitude position	ISL	°N
7.	Sea surface temperature	SST	°C
8.	Vertical wind shear	VWS	knots

Table 5. Regression coefficients for different forecasts hours.

Forecast hours	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
12	–9.54983	0.31517	0.6749	–0.18668	0.865	0.75918	0.16853	0.24186	0.04103
24	–14.66671	0.58485	1.42963	–0.54507	1.58903	1.46658	0.5017	0.36094	0.14683
36	–7.61006	0.57747	3.03779	–0.8867	2.51223	2.28032	1.02698	–0.072297	0.22346
48	4.4943	0.54152	5.0484	–1.18528	3.29409	2.63681	1.66914	–0.71783	0.3127
60	18.75396	0.37624	6.66114	–1.33578	3.14652	2.85734	1.95777	–1.08646	0.1684
72	24.58879	0.19425	7.87951	–1.31717	5.09006	2.49177	2.22359	–1.30808	0.10789

5.3.1. Intensity forecast for cyclone »SIDR«:

Based on 00 UTC of 12 November:

The cyclone »SIDR« intensified rapidly during the period 00UTC on 12 November to 00 UTC on 13 November (by 60 knots in 24 hours). The 12 hourly intensity forecast valid up to 72 hours (Table 6) shows that during the initial forecast hours the model could not predict rapid intensification. However, as the forecast hour increases, the model could pick up the gradual intensity increase and at the 72 hours forecast (valid for 00 UTC on 15 November) the predicted intensity becomes very close to the observed intensity with an underestimation of 6 knots.

Updated forecast based on 00 UTC of 13 November:

The cyclone »SIDR« shows no intensification during the 48 hours period (00UTC on 13 November to 00 UTC on 15 November). Thereafter it intensified to 115 knots during next 12 hours. The model shows intensification (Ta-

Table 6. Model performance based on 00 UTC of 12 November 2007.

Forecast hour →	12hr	24hr	36hr	48hr	60hr	72hr
Observed Wind speed (knots)	55	90	90	90	90	90
Forecast (knots)	34.6	41.7	49.5	56.4	59.0	83.9
Error (knots)	–20.4	–48.3	–40.5	–33.6	–31.0	–6.1

Table 7. Model performance based on 00 UTC of 13 November 2007.

Forecast hour →	12hr	24hr	36hr	48hr	60hr
Observed Wind speed (knots)	90	90	90	90	115
Forecast (knots)	105.8	130.7	143.1	150.3	138.4
Error (knots)	18.5	40.7	53.1	60.3	23.4

Table 8. Model performance based on 00 UTC of 14 November 2007.

Forecast hour →	12hr	24hr	36hr
Observed Wind speed (knots)	90	90	115
Forecast (knots)	98.5	111.5	130.5
Error (knots)	8.5	21.5	15.5

Table 9. Model performance based on 00 UTC of 15 November 2007.

Forecast hour →	12hr
Observed Wind speed (knots)	115
Forecast (knots)	108.3
Error (knots)	–6.7

ble 7) and the forecast intensity at 60 hours (valid for 12 UTC on 15 November near the land fall time) is found to be 138 knots, an overestimation of 23 knots.

Updated forecast based on 00 UTC of 14 November:

It is very encouraging to note that all the12 hourly forecasts valid up to 36 hours (Table 8) are considerably improved. The model could capture the observed constant intensity during initial 12 hours and rapid intensification from 24 hours to 36 hours.

Updated forecast based on 00 UTC of 15 November:

The 12 hours forecast intensity (Table 9) valid for 12 UTC on 15 November is found to be 108 knots, an underestimation of 7 knots.

The updated forecasts valid for 12 UTC on 15 November (when the system was very close to the coast), issued based on observations of 00 UTC on 13 November, 14 November and 15 November indicated forecast intensity as 138 knots (over estimation of 23 knots), 130 knots (over estimation of 15 knots) and 108 knots (under estimation of 7 knots) respectively. This shows that the updated forecast could provide improved forecast values.

5.4. Prediction of the decaying intensity after the Landfall (DAL)

The forecast of inland wind after the landfall of a cyclone is of great concern to disaster management agencies. To address this problem, Roy Bhowmik et al. (2005) proposed an empirical model for predicting 6 hourly maximum sustained surface winds (intensity) that is valid till the system becomes a weak low pressure area after the landfall over the Indian region, using the decay equation of Kaplan and DeMaria (1995, 2001) in a different way. In the model of Kaplan and DeMaria (1995, 2001), the reduction factor is applied right at the landfall point and then the winds decay exponentially with time at the same decay constant. The decay constant is determined from a sample of U.S. land falling cyclones. In the version of Roy Bhowmik et al. (2005), the decay constant is determined at each time interval. According to the decay equation (Roy Bhowmik et al 2005), the maximum sustained surface wind speed (MSSW) after the landfall at time t is given by:

$$V_{t+6} = V_b + (V_t - V_b) \times R_1, \qquad \text{for } t = 0$$

$$= V_b + (V_t - V_b) \times R_2, \qquad \text{for } t = 6, 12, 18 \text{ and } 24 \tag{4}$$

Where, reduction factors

$$R_1 = \exp(-a_1 \times 6.0) \tag{5}$$

$$\text{and, } R_2 = \exp(-a_2 \times 6.0) \tag{6}$$

Decay constant α_1 for the first six hours after the landfall (for $t = 0$ to 6) is given by:

$$a_1 = [\ln \{(V_0 - V_b)/(V_6 - V_b))\}] / 6 \tag{7}$$

The decay constant a_2 for the remaining 12 hours (for $t = 6$ to 18 hours) is taken as:

$$a_2 = [\ln \{(V_6 - V_b)/(V_{18} - V_b))\}] / 12 \tag{8}$$

Regression equation relating R_1 and R_2 as given below:

$$R_2 = 0.982 \times R_1 - 0.081 \tag{9}$$

Where, V_0 is the maximum sustained surface wind speed at the time of landfall, V_t is the wind speed at time t after the landfall and V_b is the background wind speed. After landfall, tropical cyclone decays to some background wind speed. The background wind speed V_b and the reduction factors R_1 and R_2 as determined (Table 10) in the decay model (Roy Bhowmik et al., 2005) are used in this study.

The steps suggested by Roy Bhowmik et al. (2005) for the operational forecasting are:

(i) At the time of landfall (at $t = 0$), employ the observed landfall intensity V_0 and the values of R_1, R_2 and V_b, that are obtained based upon the sample average decay rate (Table 10), to make a six hourly prediction of V_t using equation (4).

(ii) Six hours after the landfall (at $t = 6$), use V_0 and V_6 from observation and V_b from table 10 to compute actual R_1 from equations 5 and 7. Then get

Table 10. Decay parameters of mean curve.

MSSW (knots)	a_1 (h^{-1})	R_1 (6 h)$^{-1}$	a_2 (h^{-1})	R_2 (6 h)$^{-1}$	V_b (knots)
< 65	0.099	0.552	0.149	0.408	19.0
≥ 65	0.154	0.339	0.194	0.311	21.0

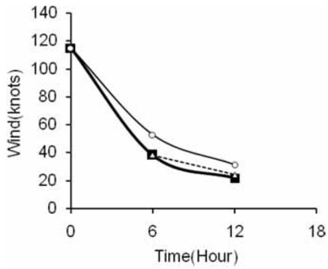

Figure 3. Comparision of intensity forecast of cyclone »SIDR« with observed intensity after landfall.

new R_2 from equation 9 and use equation 4 to revise the forecast for 12 hours after the landfall and later times.

(iii) Twelve hours after the landfall (at 12), employ observed V_{12} to make a six hourly prediction using equation 4.

(iv) Eighteen hours after the landfall, employ observed values of V_0, V_{18} to calculate actual R_2 from equations 6 and 8 and revise the forecast for 24 hours and beyond using equation 4.

(v) Twenty four hours after the landfall, use observed V_{24} to make a final forecast for V_{30}

5.4.1. Decay intensity forecast for the cyclone »SIDR :

Figure 3 shows the decay curves on the basis of observations (thick line with solid squares), 6 hourly forecast intensity up to 12 hours after the landfall (thin line with open circles) and the updated forecast (dotted line with solid triangles). Forecast errors at 6 hour and 12 hour after the landfall (at $t = 0$, Intensity = 115 knots) are found to be around 14 knots and 10 knots respectively. The updated forecast at 6 hours after the landfall shows significant improvement when the error becomes only 3 knots.

6. Concluding remarks

Tropical cyclones are one of the most disastrous weather phenomena affecting a large population and of common interest to countries in the Indian Ocean area. Accurate forecasts of their formation, movement and intensity are crucial for the early warning systems in the maritime countries of the region. There has been an operational requirement to formulate an objective procedure to handle operational cyclone forecasting work in a more efficient and effective way. Though a considerable improvement in accuracy and reliability of NWP products for cyclone track prediction is achieved, its limitations prevail in the prediction of genesis and intensity of tropical cyclone. In this paper we propose a four-step scheme for the real time application in cyclone forecasting work. The four-step statistical-dynamical scheme consists of analysis of Genesis Potential Parameter, estimation of Maximum Potential Intensity, 72 hours Intensity Prediction and prediction of decaying intensity after the landfall. The procedure is demonstrated for real time forecasting of the Bay of Bengal very recent severe cyclonic storm SIDR of November 2007. The results show that the GPP analysis at early stages of development (T.No. 1.0, 1.5, 2.0) have strongly indicated that the cyclone »SIDR« has enough potential to reach its cyclone stage. The MPI of the cyclone, estimated based on SST along the forecast track is found to be 146 knots. The maximum intensity (115 knots) of cyclone »SIDR« reached around 79 % of its MPI. The 72 hours intensity prediction based on 00 UTC of 12 November is found to be 109 knots, an underestimation of around 6 knots. The subsequent updated forecasts based on 00 UTC on 13, 14 and 15 November are found to be consistent and useful to the operational forecasters. The 6 hourly decaying intensity forecast after the landfall shows an underestimation of 10 knots at 12 hours forecast and a significant improvement is noticed with the incorporation of correction factor based on updated observations. The study not only documents the potentiality of the procedure for operational application, it also demonstrates the process of capacity building to transform research to operation. An ensemble technique based on individual numerical models could be developed for intensity prediction. Our future work will be in that direction.

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 NCEP data and products of NCMRWF, ECMWF and UKMO in this research work. Authors are grateful to the anonymous reviewers for their valuable comments to improve the quality of the paper.

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SAŽETAK

Statističko-dinamička shema za prognozu u stvarnom vremenu primjenjena na vrlo snažnu ciklonalnu oluju 'SIDR' nad Bengalskim zaljevom u studenom 2007.

S. D. Kotal, S. K. Roy Bhowmik i P. K. Kundu

U svrhu uspješnije prognoze ciklona potrebno je formulirati što objektivnije radne procedure kojima se prognoza određuje. U ovoj studiji je predložena statističko-dinamička shema u četiri koraka prognoze ciklona u stvarnom vremenu. Shema se sastoji od (a) analize potencijalnih parametara nastanka ciklone (GPP), (b) procijene maksimalnog potencijalnog intenziteta (MPI), (c) 72-satne prognoze intenziteta i (d) prognoze smanjivanja intenziteta nakon što se ciklona približila obali. U studenom 2007. godine oformila se vrlo snažna ciklonalna oluja "SIDR" nad Bengalskim zaljevom koja je pogodila obalu Bangladeša. U ovoj studiji je prikazan postupak u četiri koraka u slučaju prognoze ove ciklone u stvarnom vremenu. Rezultati pokazuju da GPP analiza u ranom stadiju razvoja može izrazito nagovijestiti da je ciklona »SIDR« imala dovoljan potencijal da dođe do svog ciklonalnog stupnja. MPI ciklone je procijenjen na 146 čvorova na bazi vrijednosti površinske temperature mora duž putanje ciklone. Opaženi maksimalni intenzitet ciklone je oko 79 % njenog MPI. Prognozirani 72-satni intenzitet na temelju podataka iz 00 UTC od 12 studenog može reproducirati intenzitet od 109 čvorova uz podcjenjivanje od 6 čvorova. Sljedeće ažurirane prognoze bile su realistične i korisne. Šest-satna prognoza zamiranja intenziteta nakon što se ciklona približila obali pokazuje podcjenjivanje od 10 čvorova u 12-satnoj prognozi te je uključivanjem faktora korekcije uočeno značajno poboljšanje. Studija je pokazala potencijal ovog postupka za operativnu primjenu.

Ključne riječi: Tropske ciklone, statistička-dinamička shema, parameter potencijalnog nastanka, maksimalni potencijalni intenzitet (MPI), intenzitet prognoze, Bengalski zaljev

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