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Operational tropical cyclone intensity prediction—an empirical technique

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Abstract One very specific operational requirement of the Tropical Cyclone (TC)Programme of the Regional Specialized Meteorological Centre, New Delhi is to provide 12-hourly forecasts valid up to 48 h (preferably 72 h) on the intensity of cyclones over the southern Indian Seas. In this paper, a simple empirical model for predicting the intensity of TCs occurring in the Bay of Bengal is proposed. The model parameter has been determined from a database assembled on 30 recent cyclones, and the model itself is based on the assumption that a TC intensifies exponentially. A method for correcting the forecast during subsequent observation hours (6- or 12-h intervals) is also presented. The results show that the forecast skill for forecasts of up to 48 h is reasonably good. The absolute mean errors are less than 12 knots for 48-h forecasts, with the forecast skill decreasing with time. With the incorporation of a correction procedure based on the latest observations, some improvement in the forecast skill can be obtained. The model is expected to be useful to operational forecasters.

Keywords Intensity prediction · Empirical model and tropical cyclone

1 Introduction

The Northern Hemisphere Analysis Centre (NHAC) at the headquarters of the India Meteorological Department (IMD) functions as a Regional Specialized Meteorological Centre (RSMC)for Tropical Cyclones (TCs), and is officially recognized as such by the World Meteorological Organization (WMO). According to WMO's Tropical Cyclone Programme (TCP), one of the major responsibilities of RSMC New Delhi is to provide TC Advisories to the WMO Economic and Social Commission for Asia and Pacific (ESCAP) member countries on cyclones over the southern Indian Seas, in addition to its national responsibilities of co-ordinating and

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supervising the totality of the cyclone warning program in India. The issuance of cyclone advisory for the member countries, which begins from the cyclone stage, includes information related to the present and forecast track of the cyclone and its intensity. Operational forecasting of TC intensity remains a challenging task. With the availability of recently developed sophisticated Numerical Weather Prediction (NWP) models, however, some progress has been made in the recent past in the area of TC track prediction, although the prediction of intensity remains problematic. Until the time when NWP models can be used with reasonable success, there is an imperative need in the operational scenario to derive a statistical or empirical model for predicting the intensity of a TC. Steps in this direction have been made with the development of a number of statistical models (DeMaria and Kaplan 1994, 1999; Baik and Hwang 1998) for the Atlantic and the North Pacific basins. However, to date no equivalent model for predicting the intensity of TCs over the Indian Seas is presently available.

In this paper, we propose a simple empirical model for predicting the intensity of a TC (valid up to 72 h) using a database assembled on 30 recent cyclones over the Bay of Bengal. Roy Bhowmik et al. (2005) very recently used a similar empirical technique for predicting the decay of the wind speed of a TC over the Indian region after the latter had reached landfall.

2 Data and analysis

For the present study, we compiled a random sample of 30 severe (wind speed of more than 48 knots) TCs that had formed over the Bay of Bengal during the period 1981–2002. The data used to derive the empirical equation consists of intensity estimates (maximum sustained surface wind) obtained from post-cyclone reports of the IMD (such as the Annual Reports of RSMC, Annual Cyclone Review and Mausam). IMD utilizes all of the available ships/buoy observations, satellite estimates and radar reports for preparing the post-cyclone reports and, as such, these are considered to be authentic and reliable reports. The 30 cyclones considered for this study are given in Table 1.

3 Formulation of the technique

One very specific operational requirement of RSMC, New Delhi-TCP is to provide 6 or 12 hourly intensity forecasts that are valid for up to 48–72 h for GTS (Global Telecommunication System) transmission in the case of cyclones over the southern Indian Seas. In order to develop the empirical model for predicting the intensity from the stage of the TC, we first considered the initial intensity of the system to be 30 knots.

Table 2 presents 12-hourly changes in intensity (until landfall or near landfall) in the 30 cyclones considered for the formulation of this model. The intensity curve (Fig. 1) is constructed taking the mean intensity of these cyclones at consecutive intervals of 12 h. It can be seen from the curve that intensity (MSSW) increases exponentially and that intensity at time *t* can be written as

$$V_t = V_0 * \exp(bt) \qquad (1)$$

Table 1 The 30 cyclones considered for the study

Cyclone no.	Period	Year	Maximum wind speed (knots)	Landfall
1	25–31 October	1999	140	Paradip
2	24–30 April	1991	127	Bangaladesh
3	1–9 November	1989	127	Kavali
4	29 April–2 May	1994	115	Bangaladesh
5	23–30 November	1988	115	Bangaladesh
6	9–14 November	1984	115	Sriharikota
7	26–30 November	2000	102	Cuddalore
8	21–25 November	1995	102	Bangaladesh
9	23–28 December	2000	90	Trincomalee
10	15–19 October	1999	90	Gopalpur
11	15–20 May	1997	90	Sitakundu
12	1–4 December	1993	90	Karikal
13	13–16 November	1998	77	Vizag
14	5–7 November	1996	77	Kakinada
15	7–10 November	1995	77	North Andhara Coast
16	4–11 December	1981	75	Sagar Island
17	19–23 November	1998	65	Sagar Island
18	28 November–6 December	1996	65	Machilipatnam
19	23–27 May	1989	65	Balasore
20	21–25 May	1985	65	Bangaladesh
21	16–21 October	1982	65	Sriharikota
22	31 May–5 June	1982	65	Paradip
23	16–20 November	1981	65	Weakened
24	17–20 May	1998	60	Bangladesh
25	29–31 October	1994	60	Madras
26	10–12 November	2002	55	Sagar Island
27	17–20 May	1998	60	Bangladesh
28	15–18 November	1988	55	Weakened
29	13–17 October	1985	55	Balasore
30	27 November–2 December	1984	55	Karikal

where b is the intensity parameter. V_0 is the initial intensity (30 knots) and V_t is the intensity at time t. From Eq. 1, the intensity parameter b at any time t can be written as

$$b = [\ln(V_t + \Delta V_{12})/V_t)]/12 \tag{2}$$

The corresponding 12-hourly intensification factors is defined as

$$I = \exp(b * 12.0) \tag{3}$$

Now, from Eq. 1, the intensity equation for 12-hourly forecasts valid for up to 72 h can be written as

$$V_{t+12} = V_t * I, \text{for } \ t = 0, 12, 24, 48, 60 \tag{4}$$

Figure 2 presents the frequency distribution of the changes in intensity (ΔV_{12}) of the 30 cyclones considered in this study for each 12-h interval. A frequency distribution is made for each intensity class; namely, tropical depression (here we consider the cases when wind speed is between 30 and 33 knots), cyclone (wind speed between 34 and 47 knots), severe cyclonic storm (wind speed between 48 and 63 knots)

Table 2 Twelve-hourly intensity changes (knots) of 30 cyclones

00 h	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h
30.00	45.00	45.00	55.00	65.00	102.0	127.0	Landfall	
30.00	35.00	55.00	55.00	77.00	77.00	102.0	115.0	127.0
30.00	30.00	35.00	55.00	65.00	90.00	90.00	102.0	90.00
30.00	45.00	45.00	55.00	60.00	90.00	102.0	Landfall	
30.00	35.00	55.00	55.00	65.00	65.00	65.00	77.00	90.00
30.00	30.00	30.00	30.00	45.00	65.00	90.00	90.00	115.0
30.00	30.00	45.00	65.00	102.0	Landfall			
30.00	45.00	55.00	65.00	90.00	Landfall			
30.00	30.00	30.00	55.00	65.00	90.00	Landfall		
30.00	45.00	65.00	80.00	Landfall				
30.00	30.00	35.00	35.00	55.00	55.00	65.00	90.00	90.00
30.00	30.00	45.00	45.00	65.00	77.00	Landfall		
30.00	55.00	77.00	Landfall					
30.00	45.00	65.00	Landfall					
30.00	35.00	55.00	65.00	Landfall				
30.00	30.00	35.00	35.00	45.00	55.00	65.00	65.00	75.00
30.00	30.00	45.00	45.00	65.00	65.00	Landfall		
30.00	30.00	30.00	25.00	25.00	35.00	35.00	45.00	65.00
30.00	30.00	45.00	55.00	65.00	Landfall			
30.00	35.00	45.00	45.00	45.00	55.00	Landfall		
30.00	55.00	65.00	65.00	Landfall				
30.00	35.00	45.00	55.00	65.00	65.00	Landfall		
30.00	35.00	45.00	55.00	65.00	Landfall			
30.00	35.00	55.00	60.00	Landfall				
30.00	30.00	55.00	60.00	Landfall				
30.00	30.00	45.00	45.00	Landfall				
30.00	30.00	35.00	35.00	35.00	35.00	45.00	Landfall	
30.00	30.00	45.00	45.00	Landfall				
30.00	35.00	35.00	55.00	Landfall				
30.00	35.00	45.00	45.00	55.00	55.00	Landfall		
Mean								
30.0	35.70	46.90	51.40	61.00	67.30	78.60	83.40	93.10

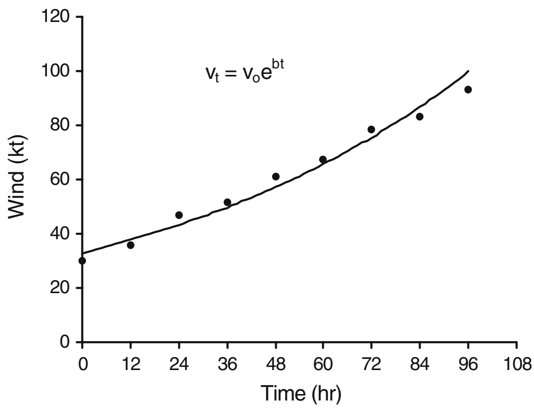

Fig. 1 The mean intensity curve

and very severe cyclonic storm (wind speed more than 63 knots). Figure 2 also shows that for a tropical depression, ΔV_{12} is 0–5 knots in 70% of the cases, 10–15 knots in 25% and 20–25 knots in 8%. The change ΔV_{12} for a tropical cyclone

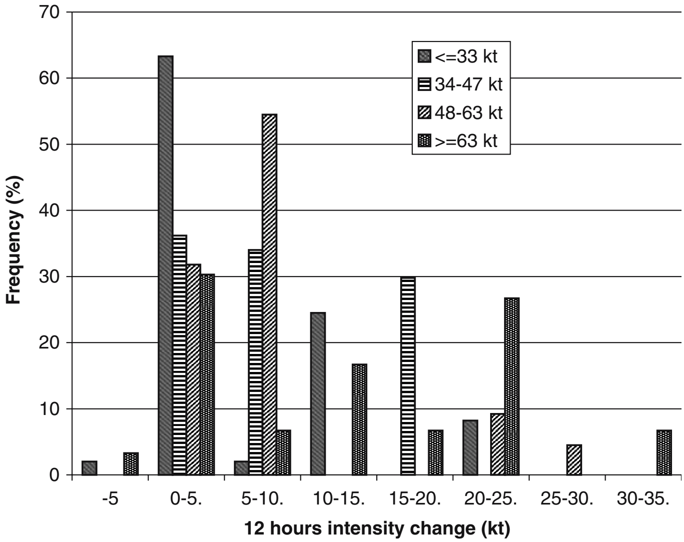

Fig. 2 The frequency distribution (%) of the changes in intensity for each 12-h interval (ΔV_{12}) of the 30 cyclones considered in this study

becomes 0–5 knots in 37% of the cases, 10–15 knots in 35% and 15–20 knots in 30%. In the case of a severe cyclonic storm, ΔV_{12} is 0–5 knots in 31%, 5–10 knots in 55 and 20–25 knots in 9%. For a very severe cyclonic storm and above, ΔV_{12} becomes 0–5 knots in 30% of the cases, 10–15 knots in 18%, 20–25 knots in 28% and more than 30–35 knots in 5%. The mean ΔV_{12} (Table 3) becomes 7, 9, 10 and 13 knots, respectively, for a depression, cyclonic storm, severe cyclonic storm and very severe cyclonic storm and above. The intensity parameter b (in Eq. 2) can be computed from ΔV_{12} using Table 3.

4 Correction procedure

The 12-hourly forecasts (valid for up to 72 h) issued with the initial intensity of 30 knots can be corrected and updated at 6 or 12 h intervals based on the latest available observations. In order to apply this method in operational forecasting and to be able to update the forecast at each 12-h interval, the following steps are suggested:

1. At the time when intensity reaches 30 knots, employ the observed initial intensity V_0 (30 knots) and intensity parameter b that is obtained based upon the sample average of ΔV_{12} (Table 3) and use these to make the 12-hourly prediction for V_t using Eqs. 2, 3 and 4.

Table 3 The average 12-h changes in intensity (in knots; ΔV_{12})

V	30–33	34–47	48–63	>63
ΔV_{12}	7	9	10	13

2. Twelve hours after the first forecast, use the observed V_{12} as the initial intensity and then revise the forecast for later times.
3. Repeat procedure (2) to update the forecast during subsequent observation hours.

Writing a simple FORTRAN programme; the entire procedure (steps 1–3) can be automated to apply it operationally.

5 Performance and limitation of the technique

In order to verify the method, we applied the technique to the development database of 30 cyclones.

The results of 12-hourly forecasts for the 30 TCs tested, both without the correction procedure and with the correction procedure based on subsequent observations, are shown in Table 4. This table shows that, in general, there is a good agreement between the predicted and observed values for the forecasts up to 48 h. Table 5 shows the error statistics for the model with and without the use of the correction procedure. For the latter case, absolute mean error (AE) ranges from 6.6 to 11.2 knots for forecasts up to 48 h. The absolute mean error increases with time and becomes 21.3 knots at the 72-h forecast. The root mean square error (RMSE) is less than 12 knots for the forecasts up to 36 h and increases to 25.6 knots at 72 h. With the incorporation of the correction procedure based on current observations, some improvement in the forecast skill is achieved when the technique is tested using the dependent sample. The method can be also used for 6-hourly forecasts by replacing the 12 with a 6 in Eqs. 2, 3 and 4. As the correction procedure is very sensitive to the availability of real time estimates, real time tests with independent data would be necessary to confirm the skill score obtained from the dependent evaluation.

The importance of ocean, inner core process and environmental interactions on changes in the TC intensity has been discussed by many authors (Fitzpatrick 1997; Schade and Emanuel 1999; Kaplan and DeMaria 2003; among others). A major limitation of an empirical model is that it does not include the impact of the physical and dynamical processes involved. The success of this empirical technique depends on how accurately the intensity parameter b (which depends on ΔV_{12}) is derived. In the present example, b is derived based on climatology. Therefore, before the technique is used, synoptic evaluation based on the latest synoptic inputs and NWP model outputs is a pre-requisite. The statistical model SHIPS (DeMaria and Kaplan 1994, 1999) combines climatology, persistence and synoptic predictors (such as information related to sea surface temperature, vertical wind shear, upper tropospheric trough, etc.) using the multiple regression equation. In the updated version (DeMaria and Kaplan 1999), analysis and forecast fields from a NWP model are used for deriving synoptic predictors.

6 Concluding remarks

There has been growing national and international demand for accurate predictions of TC intensity. The present paper describes a simple method for predicting the intensity of TCs at 12-hourly intervals that is valid up to 72 h. A correction

Table 4 Comparison of 12-hourly forecast intensity[a] (knots) for the 30 cyclones

Cyclone no.	12 h	24 h	36 h	48 h	60 h	72 h
1	45.0	45.0	55.0	65.0	102.0	127.0 a
	37.0	46.0	55.0	65.0	78.0	91.0 b
		54.0	63.0	73.0	86.0	99.0 c
2	35.0	55.0	55.0	77.0	77.0	102.0 a
	37.0	46.0	56.0	66.0	79.0	92.0 b
		44.0	54.0	64.0	77.0	90.0 c
3	30.0	35.0	55.0	65.0	90.0	90.0 a
	37.0	46.0	55.0	65.0	78.0	91.0 b
		37.0	46.0	56.0	69.0	82.0 c
4	45.0	45.0	55.0	60.0	90.0	102.0 a
	37.0	46.0	55.0	65.0	75.0	88.0 b
		54.0	63.0	73.0	83.0	96.0 c
5	35.0	55.0	55.0	65.0	65.0	65.0 a
	37.0	46.0	56.0	66.0	79.0	92.0 b
		44.0	54.0	64.0	77.0	90.0 c
6	30.0	30.0	30.0	45.0	65.0	90.0 a
	37.0	46.0	55.0	64.0	73.0	86.0 b
		37.0	46.0	55.0	64.0	77.0 c
7	30.0	45.0	65.0	102.0 a		
	37.0	46.0	55.0	68.0 b		
		37.0	46.0	59.0 c		
8	45.0	55.0	65.0	90.0 a		
	37.0	46.0	56.0	69.0 b		
		54.0	64.0	77.0 c		
9	30.0	30.0	55.0	65.0	90.0 a	
	37.0	46.0	55.0	65.0	78.0 b	
		37.0	46.0	56.0	69.0 c	
10	45.0	65.0	80.0 a			
	37.0	46.0	59.0 b			
		54.0	67.0 c			
11	30.0	35.0	35.0	55.0	55.0	65.0 a
	37.0	46.0	55.0	64.0	74.0	84.0 b
		37.0	46.0	55.0	65.0	75.0 c
12	30.0	45.0	45.0	65.0	77.0 a	
	37.0	46.0	55.0	64.0	77.0 b	
		37.0	46.0	55.0	68.0 c	
13	55.0	77.0 a				
	37.0	47.0 b				
		65.0 c				
14	45.0	65.0 a				
	37.0	46.0 b				
		54.0 c				
15	35.0	55.0	65.0 a			
	37.0	46.0	56.0 b			
		44.0	54.0 c			
16	30.0	35.0	35.0	45.0	55.0	65.0 a
	37.0	46.0	55.0	64.0	73.0	83.0 b
		37.0	46.0	55.0	64.0	74.0 c
17	30.0	45.0	45.0	65.0	65.0 a	
	37.0	46.0	55.0	64.0	77.0 b	
		37.0	46.0	55.0	68.0 c	
18	30.0	30.0	25.0	25.0	35.0	35.0 a
	37.0	46.0	55.0	64.0	73.0	82.0 b
		37.0	46.0	55.0	64.0	73.0 c

Table 4 continued

Cyclone no.	12 h	24 h	36 h	48 h	60 h	72 h
19	30.0	45.0	55.0	65.0 a		
	37.0	46.0	55.0	65.0 b		
		37.0	46.0	56.0 c		
20	35.0	45.0	45.0	45.0	55.0 a	
	37.0	46.0	55.0	64.0	73.0 b	
		44.0	53.0	62.0	71.0 c	
21	55.0	65.0	65.0 a			
	37.0	47.0	60.0 b			
		65.0	78.0 c			
22	35.0	45.0	55.0	65.0	65.0 a	
	44.0	53.0	62.0	72.0	85.0 b	
		44.0	53.0	63.0	76.0 c	
23	35.0	45.0	55.0	65.0 a		
	37.0	46.0	55.0	65.0 b		
		44.0	53.0	63.0 c		
24	35.0	55.0	60.0 a			
	37.0	46.0	56.0 b			
		44.0	54.0 c			
25	30.0	55.0	60.0 a			
	37.0	46.0	56.0 b			
		37.0	47.0 c			
26	30.0	45.0	45.0 a			
	37.0	46.0	55.0 b			
		37.0	46.0 c			
27	30.0	35.0	35.0	35.0	35.0	45.0 a
	37.0	46.0	55.0	64.0	73.0	82.0 b
		37.0	46.0	55.0	64.0	73.0 c
28	30.0	45.0	45.0 a			
	37.0	46.0	55.0 b			
		37.0	46.0 c			
29	35.0	35.0	55.0 a			
	37.0	46.0	55.0 b			
		44.0	53.0 c			
30	35.0	45.0	45.0	55.0	55.0 a	
	37.0	46.0	55.0	64.0	74.0 b	
		44.0	53.0	62.0	72.0 c	

[a] An 'a' after a values indicates observation (estimation); a 'b' indicates forecast without correction procedure; a 'c' indicates forecast with correction procedure

Table 5 Skill scores (AE and RMSE in knots)[a] of 12-hourly forecasts made for the 30 cyclones

Skill	12 h	24 h	36 h	48 h	60 h	72 h
AE (without correction)	6.6	8.7	8.8	11.2	16.8	21.3
AE (with correction)	–	6.8	7.7	11.3	13.1	17.7
RMSE (without correction)	7.6	11.3	12.1	16.4	19.6	25.6
RMSE (with correction)	–	8.1	9.6	15.3	15.7	20.5

[a] AE, Absolute mean error; RMSE, root mean square error

procedure is introduced to update the forecast at each 12-h interval that takes into account current observations. The method is expected to be useful for operational application. By applying a similar technique, it would be possible to develop a separate model for the Arabian Sea.

Further research is required to refine the model with a larger data set that would take into account the latitude/season of formation. The success of this empirical technique depends on how accurately the intensity parameter *b* is derived. While results are encouraging with the climatological value of *b*, future work needs to aim at whether synoptic predictors based on analysis and forecast fields of the Limited Area Model of the IMD can be employed to improve the accuracy through the use of some sophisticated statistical techniques (e.g. neural networks).

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