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Estimation of maximum wind speeds in tropical cyclones occurring in Indian Seas

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ABSTRACT. From dynamical considerations, the maximum wind speed in a tropical cyclone depends upon the pressure gradient, the range with respect to the storm centre, and the air density at the spot at which the maximum wind occurs inside the storm. It is nearly impossible to obtain direct measurements of these parameters in the cyclones because of their violent nature. A more practical approach is provided by the relation between the maximum winds and the central pressures in the storms. In the present paper the relationship between maximum wind speed and the minimum sea level pressure in cyclonic storms occurring in the Bay of Bengal and Arabian Sea has been studied with the help of the available observations from ships, reconnaissance aircraft and the coastal stations. On the basis of these data, best fit equation for the maximum wind speeds applicable for the Indian Seas has been empirically derived.

1. Introduction

The damage caused by the tropical cyclones is predominantly due to the associated strong winds and coastal inundation by the wind-generated tidal waves. Winds occurring in severe cyclonic storms are among the most violent ever encountered. Maximum wind speeds reaching even 200 kt have been experienced in severe storms of the northwest Pacific Ocean. Generally, winds in these storm field are either derived from observations of reconnaissance aircraft, dropsondes, and ships which are caught in the storms, or estimated from the damage caused by the storm in the coastal regions. Direct wind measurements are not always possible because anemometers often break or are blown off as wind gusts exceed 100 kt. The low level wind field of moving storms is asymmetrical. The strongest wind speeds occur in the right quadrants (in northern hemisphere) of the storm relative to the direction of its motion, in the region of wall clouds and the adjoining rain bands. The distance of the band of maximum winds from the storm centre is highly variable, ranging from 10 to 150 km (about 5 to 75 n. miles).

The two parameters taken as measures of tropical cyclone intensity are, (*i*) maximum sustained winds speed (MWS), and (*ii*) minimum sea level pressure (MSLP) at the storm centre. Several workers have investigated into the relationship between the two and have given formulae for eastimation of maximum wind speed from central pressure. From dynamical considerations, Fletcher (1955) concluded that the relationship between P_0, the sea level pressure in mb at the storm centre, and V_{max} the maximum sustained wind speed in kt in the storm, is of the form :

$$V_{max}=K.\sqrt{P_n-P_0} \quad (1)$$

where, K is constant and P_n, the pressure in mb at the outer edge of the storm. Flecther empirically derived $K=16$, on the basis of pressure and wind data of coastal and island stations for northwest Atlantic hurricanes.

Various formulae for deriving V_{max}, given by different workers on the basis of data of the Pacific and the Atlantic storms, are as follows :

(*i*) $V_{max}=16.\sqrt{P_n-P_0}$ (Fletcher 1955) (2)

(*ii*) $V_{max}=13.4\sqrt{1010-P_0}$ (Takahashai) (3)

(*iii*) $V_{max}=\left(20-\frac{\phi}{5}\right)\sqrt{1010-P_0}$ (JTWC 1952) (4)

where ϕ is the latitude of the storm centre.

(*iv*) $V_{max}=11\sqrt{1010-P_0}$ (Myers 1957) (5)

(*v*) $V_{max}=14\sqrt{1013-P_0}$ (Kraft 1961) (6)

Erickson (1972) has found that in the Atlantic, Eq. (6) best fits the data in the middle range of

TABLE 1

Maximum wind speed observed in tropical cyclonic storms in the Indian Seas

Cyclone period	Date of obser-vation	Time (GMT)	Max. wind (kt)	Periph-eral pressure P_n (mb)	Central pressure P_0 (mb)	Place of observation: Type/Station	Place of observation: Position Lat. (°N)	Place of observation: Position Long. (°E)	Location of storm centre Lat. (°N)	Location of storm centre Long. (°E)
27-30 May 61	29 May	1200	60	996	983·4	Ship	20·7	91·4	20·6	91·0
11-17 Sep 61	12 Sep	0400	45	1000	989·7	Ship	21·0	91·2	20·8	91·2
26-29 Nov 62	29 Nov	0300	50	1010	997·3	Ship	14·0	81·8	14·0	81·6
18-29 May 63	22 May	0630	60	1007	984	Reconn. Aircraft (RFF)	11·3	66·1	11·3	66·1
18-29 May 63	24 May	0813	104	1006	947	Do.	14·7	60·1	14·7	60·1
18-29 May 63	24 May	1200	70	1006	988·3	Ship	14·8	59·6	14·9	59·8
9-13 Jun 64	11 Jun	1030	60	1000	978·6	Ship	22·0	68·9	21·8	68·9
9-13 Jun 64	12 Jun	0400	80	1002	969·5	Naliya	23·3	68·8	23·3 (10 km from Obsy.)	68·8
16-28 Nov 64	21 Nov	2130	80	1010	983	Ship	12·2	81·7	12·3	81·7
17-24 Dec 64	21 Dec	0130	60	1010	986·4	Ship	5·4 7·0	87·7(wind) 87·5(pressure)	5·8	87·6
17-24 Dec 64	22 Dec	0830	50	1008	994·3	Ship	8·2	82·0	7·8	82·9
7-15 Dec 65	13 Dec	1200	50	1006	984·2	Ship	16·1	86·8	16·0	86·5
1-4 Nov 66	3 Nov	0910	115	1010	961·0	Ship	12·5	80·2	12·5	80·2
1-11 Nov 66	10 Nov	0500	70	1008	965·1	Ship	16·0	61·2	15·8	61·0
1-11 Nov 66	11 Nov	1200	60	1006	971·5	Ship	15·6	57·1	16·3	57·0
25-30 Nov 66	28 Nov	0330	50	1008	984·5	Ship	13·2	80·7	12·8	80·2
12-18 Aug 69	13 Aug	1200	50	1000	991·0	Sandheads	20·9	88·3	21·2	88·3
4-8 Nov 69	6 Nov	2000	75	1012	975·2	Ship	16·0	85·2	15·4	85·0
18-24 Oct 70	23 Oct	0130	50	1004	991·3	Ship	21·4	88·3	21·2	88·8
8-13 Nov 70	12 Nov	2200	80	1008	982·6	Ship	22·3	91·7	22·7	91·0
3-8 Jun 71	5 Jun	0001	50	994	978·8	Sandheads	20·9	88·3	21·5	88·3
3-8 Jun 71	5 Jun	0300	46	997	983·9	Sandheads	20·9	88·3	21·5	88·3
27 Sep to 1 Oct 71	29 Sep	1200	55	998 (Sandheads)	978·5 Alipur	Sandheads Alipore	20·9	88·3	22·3	88·0
26-31 Oct 71	29 Oct	2230	100	1006	966	Ship	20·3 (Paradeep Port)	86·7	20·3 (Paradeep Port)	86·7
7-11 Apr 72	9 Apr	1300	80	1008	983	Reconn. Aircraft (USAF)	13·9	91·2	13·9	91·2
7-14 Sep 72	10 Sep	0600	110	1004	969	Gopalpur	19·3	84·9	1 Gopalpur	
20-25 Sep 72	20 Sep	0730	45	1004	994	Reconn. Aircraft (USAF)	17·6	90·9	17·6	90·9
20-25 Sep 72	21 Sep	0830	65	1002	978	Do.	18·5	87·5	18·5	87·5
20-25 Sep 72	21 Sep	1730	100	1004	975	Ship	19·4	87·2	19·0	87·0
19-25 Oct 72	24 Oct	0001	65	1008	995·7	Ship	12·0	55·2	12·5	55·0
15-23 Nov 72	21 Nov	1530	80	1008	983·0	Ship	12·7	84·2	12·5	85·0
1-8 Dec 72	5 Dec	2300	75	1006	984	Cuddalore	11·8	79·8	Close to Cuddalore	
6-12 Oct 73	11 Oct	0600	45	1006	996·0	Sandheads	20·9 (Sandheads)	88·3	21·0	87·5
3-9 Nov 73	5 Nov	0600	74	1008	982·5	Ship	10·0	88·2	10·5	88·0
5-9 Dec 73	8 Dec	1200	55	1006	991·0	Ship	16·8	87·0	16·5	86·0

wind speeds (30 to 100 kt). In the western Pacific he found that Eq. (3) was the best fit for intense storms and Eq. (5) for weaker storms.

Recently, Natarajan and Ramamurthy (1975) have derived a relationship (Eq. 7) based on data of 42 hurricanes and typhoons in the east Pacific and Atlantic Oceans during 1970-73 :

$$V_{max} = 13 \cdot 6 \sqrt{P_n - P_0} \quad (7)$$

They have tested Eq. (7) with (8) observations of cyclonic storms in the Bay of Bengal and the Arabian Sea, and found that it yields better results for Indian Seas than Eq. (2).

The present paper attempts to derive a relationship between MWS and MSLP based on the tropical cyclone data of the Bay of Bengal and the Arabian Sea, in order to obtain the most suitable relationship for the Indian Seas. Such a relationship will be operationally useful for deriving the central pressure from the storm pictures taken by weather satellites. It will also be useful for deriving MWS from aircraft reconnaissance data of MSLP, when such flights are organised over Indian Seas in future.

2. Data used

The main difficulty in storm studies lies in obtaining adequate volume of sufficiently reliable observations from the storm field. There are few direct observations of the central pressure and the maximum wind speed available. Therefore, data obtained from reconnaissance aircraft, which make several storm penetrations across different parts of the storm at different levels, and simultaneous dropsonde observations are best suited for obtaining the central pressure and maximum wind values. In absence of any organised aircraft reconnaissance, adequate data are not available for Indian Seas. Consequently, available observations from ships, coastal stations and reconnaissance aircraft for the cyclonic storms which occurred in the Bay of Bengal and the Arabian Sea during 1961-73 were scrutinised for the purpose of this study. At any particular time of observation, the values of maximum wind speed and the corresponding minimum sea level pressure were selected on the basis of all the available observations from the storm field. On occasions when several wind and pressure values were available from the storm field within a few hours of each other and the time of the lowest pressure did not coincide with that of the maximum wind speed, the lowest pressure and the highest wind values were taken; the time of such values refers to the time of pressure observation. In this way, 35 observations of minimum sea level pressure and the corresponding maximun wind speed pertaining to 29 cyclonic storms were selected as basic data (Table 1). In the table 'peripheral pressure' and 'location of storm centre' have been taken from the past sea level charts and the verified storm tracks. Out of the 35 observations, 27 were taken by ships, 5 by reconnaissance aircraft and 3 by coastal observatories. Intensity-wise, the data set consists of 4 cases of cyclonic storms, 14 cases of severe cyclonic storms and 17 cases of severe cyclonic storms with core of hurricane winds at the time of observations.

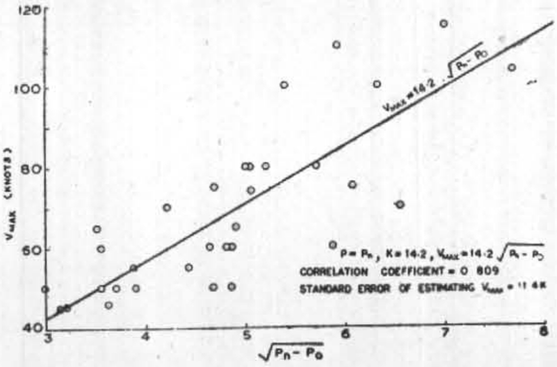

Fig. 1. Scatter diagram of max. wind speed (kt) V_{max} *versus* $\sqrt{Pn-Po}$ showing the best fit linear relationship

3. Discussions

In Eq. (1) several workers have taken fixed values of 1010 or 1013 mb instead of P_n. Hence the general formula (putting P for P_n) for V_{max} would be —

$$V_{max} = K. \sqrt{P - P_0} \quad (8)$$

The derivation of a MWS-MSLP relationship for storms occurring in Indian Seas, therefore involves the computation of the most suitable values of K and P in Eq. (8), utilising the data of Table 1. For this purpose P was given different values from 1000 to 1030 mb as also the actual peripheral pressure P_n. For each value of P, with the data of Table 1, the best-fit relationship between V_{max} and $\sqrt{P-P_0}$ was computed using least square method. Also coefficient of correlation between V_{max} and $\sqrt{P-P_0}$ and its standard error, were computed. Different sets of computation, corresponding to the specific values of P, were carried out on the IBM 360/44 computer available at the Meteorological Office, New Delhi

TABLE 2

Comparison between values of K giving best fit with Indian data for different values of peripheral pressure (P)

Number of observations = 35

P (mb)	K	Correlation coefficient between V_{max} and $\sqrt{P-P_0}$	Standard error of correlation	Standard error of estimating V_{max} (kt)
1000	15·9	0·718	0·0819	13·5
1010	12·9	0·731	0·0786	13·2
1013	12·3	0·733	0·0783	13·2
1015	11·9	0.733	0.0781	13·2
1020	11·1	0·735	0·0778	13·2
1030	9·8	0·736	0· 774	13·1
$^*P_n$	14·2	0·809	0·0585	11·4

$^*P_n$ is the actual peripheral pressure at the time of observation.

A comparison between different sets of values of P and K is provided by the coefficient of correlation between V_{max} and $\sqrt{P-P_0}$ and the standard error of estimation of V_{max}, as given in Table 2. It will be seen that the coefficient of correlation is highest, *i.e.*, 0·809, corresponding to $P=P_n$, when $K=14{\cdot}2$. Fig. 1 shows the scatter diagram of V_{max} and $\sqrt{P_n-P_0}$ and the best fit relationship corresponding to $K=14{\cdot}2$.

From physical considerations also it may be expected that in Eq. (8) the actual values of P_n will give better fit for the Bay of Bengal and the Arabian Sea storms than the fixed values of P. There are considerable seasonal as well as space variations of sea level pressure over the Indian Seas, so that the normal pressure varies from 998 mb in July (1200 GMT normal) to more than 1016 mb in January (0300 GMT normal) over the northwest Bay as well as north Arabian Sea. In the actual data (Table 1) the peripheral pressures for storms have ranged from 994 mb to 1012 mb. Such large variations do not occur in the Pacific and the Atlantic Oceans, for which Eqns. (3) to (6) have been worked out and are presently in operational use. This difference according to the present authors, is mainly due to the fact that the Bay of Bengal and Arabian Sea are surrounded by the vast Asian landmass on three sides — they are open only towards the south and are porfoundly influenced by the seasonal temperature and pressure changes over the land area. On the contrary, the tropical regions of the Pacific and the Atlantic are open on both sides towards the poles, and are subjected to such large seasonal influences. Thus, the best fit formula for the maximum wind speed for Indian Seas is :

$$V_{max} = 14.2\sqrt{P_n-P_0} \qquad (9)$$

The above relation arrived at was applied to 35 observations given in Table 1. Fig. 2 shows the scatter diagram of the actual values of maximum wind speed $(V_{max})_a$ from the data set of Table 1 *versus* the expected values $(V_{max})_e$ computed from Eq. (9). The equation of linear regression of $(V_{max})_a$ on $(V_{max})_e$ works out to be

$$(V_{max})_a = 0.9599.(V_{max})_e + 2.9 \qquad (10)$$

and the standard error of estimating V_{max} for the sample is 11·4 kt. It is seen from Table 2 that the standard error is the least for Eq. (9).

It is noted that V_{max} computed from Eq. (9) is intended to represent only the storm scale motion and on occasions this may vary widely from the spot measurements of wind speed. Sheets and Grieman (1975) have observed that MWS variations as large as 20 to 30 per cent of total wind speed occur over a few minutes, without any apparent change in the actual intensity of the storm. They have explained that these large sudden fluctuations are contributions from individual thunderstorm cells, as illustrated in Fig. 3. Here V_{max} represents the hurricane scale flow at the location of a *Cb* cell A, while small vectors around A represent a superimposed *Cb* scale flow at any typical inflow level. In an aircraft and wind measurement to the north of the cell, the two components would act in opposite

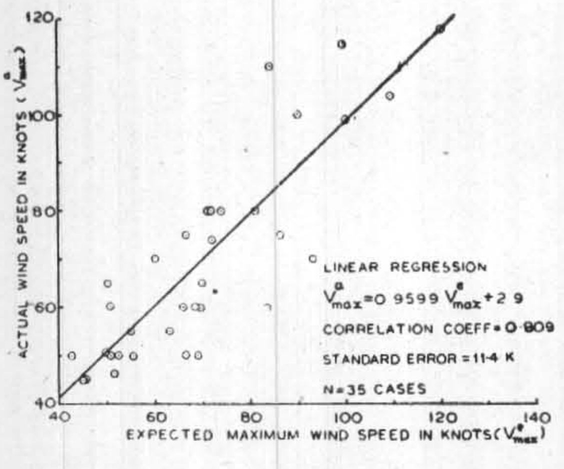

Fig. 2. Scatter diagram of expected max. wind speed (kt) computed from Eq. (9) and the actual max. wind speed (kt) storms in Indian Seas

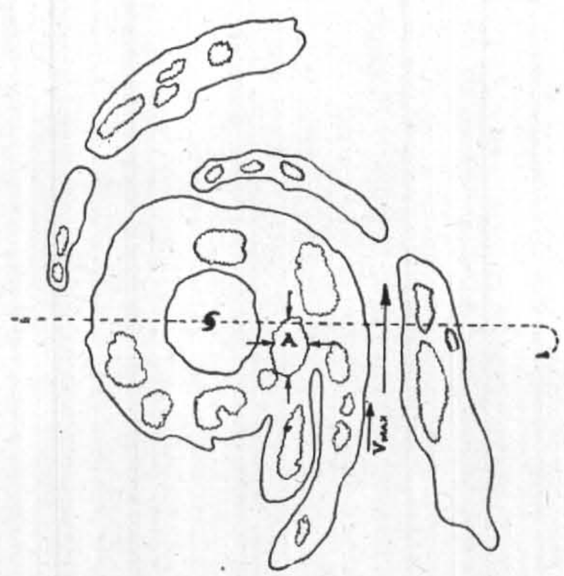

Fig. 3. Schematic drawing of a hurricane illustrating probabe sources of errors in measuring hurricane scale motions (winds) (After Sheets *et al.* 1975)

TABLE 3

Relationship between T-number and minimum sea level pressure (MSLP) or pressure depth

T-number	MSLP (Atlantic) (mb)	MSLP (NW Pacific) (mb)	Pressure depth $(P_n - Po)$ (Arabian Sea & Bay of Bengal) (mb)
2	1009	1003	4·5
2·5	1005	999	6·1
3	1000	994	10·0
3·5	994	988	15·0
4	987	981	20·9
4·5	979	973	29·4
5	970	964	40·2
5·5	960	954	51·6
6	948	942	65·6
6·5	935	929	80·0
7	921	915	97·2
7·5	906	900	119·1
8	890	884	143·3

(Adopted from Dvorak 1975 and extended for Indian Seas)

directions so that the measured wind will be the difference of the two vectors. In a similar measurement to the south of the cell, the two components would reinforce each other. These two measurements could even be observed at the same location relative to the storm centre, separated by an interval of a few minutes, since convective cells often circulate or form and dissipate around the storm centre. Hence, the spot wind measurements are often dominated by small scale contributions from individual thunderstorm cells, rather than by the storm scale circulation. This has to be kept in view while applying Eq. (9).

4. T-number-pressure depth relationship

Dvorak (1975) has developed a technique for deriving tropical cyclone intensities from satellite cloud imagery in terms of T-number and current-intensity (CI) number. He has empirically derived CI-MWS and T-number-MSLP relationships on the basis of past data for tropical cyclones in the Pacific and the Atlantic Oceans. His T-number-MSLP relationship for the Atlantic and the Pacific Oceans is given in Table 3.

In the Arabian Sea and the Bay of Bengal the peripheral pressure (P_n) has a large range of variation, as explained in Sec. 3. Therefore, it is considered more appropriate to relate the pressure depth at the storm centre, *i.e.*, (P_n—P_0) with the T-number. Table 3 also gives the values of (P_n—P_0) as derived from Eq. (9). It will be possible to assess the utility of Table 3 in future with the progressive utilization of weather satellite data in the meteorological analysis over the Indian region.

5. Conclusion

The best fit relationship between the minimum sea level pressure (P_0) in mb and the maximum sustained wind speed (V_{max}) in kt, in storms occurring in Indian Seas is found to be :

$$V_{max} = 14\cdot2\sqrt{P_n - P_0}$$

This relationship holds for cyclonic storms and severe cyclonic storms (MWS $>33K$).

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