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Computation of surface winds in tropical cyclones

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ABSTRACT. At present, the formula $V_{max}=K\sqrt{(p_r-p_0)}$ developed by Fletcher (1955) is in use with some modification for the values of the constant K, for estimating the maximum wind speed in tropical cyclones. But no formula is now available for estimating the wind speeds in different areas in the storm field. A formula for computing windspeeds at any point on the radius of the storm and for computing maximum windspeed is presented here. This formula will also enable checking doubtful wind and pressure observations, either due to wrong coding or due to mutilations during transmissions, received at the cyclone warning centres during critical moments and will help in correct assessment of the intensity of the cyclones

The wind speeds computed with this formula, have been verified with the actual observed winds during recent cyclones in the Indian seas. It is seen that the computed values fit in exceedingly well with the observed values.

1. Introduction

Computation of surface winds in tropical cyclones is one of the most important problems confronting the weather forecasters working in Cyclone Warning Centres. For estimating maximum windspeed in tropical cyclones Fletcher (1955) developed an empirical relationship which is as follows :

$$V_{max} = K\sqrt{p_r-p_0} \quad (1)$$

where V_{max} is the maximum sustained windspeed in knots in the storm, p_0 is the sea level pressure in mb at the centre of the storm, p_r is the pressure in mb at the outer edge of the storm and K is a constant (taken as 16 by Fletcher).

Various formulae for deriving V_{max} had further been developed by different authors which are basically same as that derived by Fletcher. These formulae differ only in respect of the values of the constant K and p_r. Based on data of 42 hurricanes and typhoons in the east Pacific and Atlantic Oceans during 1970—73, Natarajan and Ramamurthy (1975) had given the relationship as :

$$V_{max}=13.6\sqrt{p_r-p_0} \quad (2)$$

Whereas Mishra and Gupta (1976) claimed that the best fit relationship between the minimum sea level pressure (p_0) and the maximum sustained windspeed (V_{max}) in storms occurring in Indian seas is found to be

$$V_{max}=14.2\sqrt{p_r-p_0} \quad (3)$$

All the above formulae give the value of maximum windspeed in tropical cyclones provided the central pressure is known. But, at present, there is no formula which gives windspeed at various points on the radius of the storm as one proceeds from the periphery of the storm to its centre. Computation of gradient or cyclostrophic winds on the basis of surface synoptic charts is usually subject to considerable error because, with current techniques and data, the analyst is unable to draw isobars with sufficiently accurate spacing especially in the areas around the centre of cyclone.

The author derived a formula which gives a method of computing windspeed at any point on the radius of a storm, provided the pressure at that point is known, say, from any ship's observation. This formula also can be utilised to compute the maximum wind in a cyclonic storm.

Forecasters working in cyclone warning centres receive some ship's observation occasionally from depression field reporting abnormally high windspeed due to either coding mistakes or errors creeping in during transmission. Such windspeeds appear incompatible with surface pressure observations. But, as there is no method at present to check the veracity of such wind observations, forecasters are tempted to upgrade the system in the absence of any other observation. This is because the storm warning procedures in many countries stress maximum weightage to windspeed reports from ships for classification of systems. The formula derived by the author can be used to check the veracity of such abnormal windspeed reports.

2. Derivation of wind field in a tropical storm

Although tropical storms never remain in a precisely steady state, the essential features of the wind and temperature fields are always maintained. Therefore, the question of evaluation of the wind field on the basis of steady state maintenance is quite legitimate.

The equations of motion in a steady state in polar co-ordinates can be written as :

$$v_r \frac{\partial v_r}{\partial r} + v_\theta \frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} = f v_\theta - \frac{1}{\rho}\frac{\partial p}{\partial r} \tag{4}$$

and

$$v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{\partial v_\theta}{r\partial \theta} + \frac{v_\theta v_r}{r} = -f v_r - \frac{1}{\rho}\frac{\partial p}{r\partial \theta} \tag{5}$$

When the windspeed along the radius is v_r (radial velocity) and the windspeed perpendicular to the radius is v_θ (tangential velocity). The total velocity V is given by :

$$V^2 = u^2 + v^2 = v_r^2 + v_\theta^2 \tag{6}$$

If we now consider circular concentric isobars with their centres at $r=0$, $\partial p/\partial\theta = 0$. If we also assume that the velocity distributions have circular symmetry then :

$$\frac{\partial v_r}{\partial \theta} = \frac{\partial v_\theta}{\partial \theta} = 0$$

Eqn. (4) may then be written as :

$$\frac{v_\theta^2}{r} + f v_\theta - v_r \frac{\partial v_r}{\partial r} - \frac{1}{\rho}\frac{\partial p}{\partial r} = 0 \tag{7}$$

Similarly Eqn. (5) may be written as :

$$\frac{v_\theta}{r} + \frac{\partial v_\theta}{\partial r} + f = 0 \tag{8}$$

or

$$\frac{v_\theta^2}{r} + v_\theta \frac{\partial v_\theta}{\partial r} + f v_\theta = 0 \tag{9}$$

Now subtracting Eqn. (7) from Eqn. (9) we get :

$$v_\theta \frac{\partial v_\theta}{\partial r} + v_r \frac{\partial v_r}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0 \tag{10}$$

or

$$\frac{\partial}{\partial r}(v_\theta^2) + \frac{\partial}{\partial r}(v_r^2) + \frac{2}{\rho}\frac{\partial p}{\partial r} = 0 \tag{11}$$

Now integrating Eqn. (11) with respect to r from $r=r_1$ to $r=r_2$ $[r_1<r_2]$, we get

$$\left[v^2_{\theta,r1} + v^2_{r,r1}\right] - \left[v^2_{\theta,r2} + v^2_{r,r2}\right] = \frac{2}{\rho}\left[p_{r2} - p_{r1}\right] \tag{12}$$

where $v_{\theta,r1}$ and $v_{\theta,r2}$ are the tangential velocities, $v_{r,r1}$ and $v_{r,r2}$ are the radial velocities and p_{r1} and p_{r2} are the pressures at radii r_1 and r_2 respectively.

In the above integration ρ had been considered as constant. In terms of total velocity V, the above equation can be written as :

$$V_{r1}^2 - V_{r2}^2 = \frac{2}{\rho}(p_{r2} - p_{r1}) \tag{13}$$

where V_{r1} and V_{r2} are the total velocities at radii r_1 and r_2. If the windspeed and pressure at any point (say the periphery) of the storm is known, the wind speed at any point on the radius of the storm can be calculated provided the pressure at that point is known or is estimated.

3. Actual computation of wind field at surface level

In a mature storm, maximum windspeed occurs very close to the centre of the cyclone. If we denote the maximum near-centre windspeed by V_0 with corresponding central pressure of the storm as p_0 and V_n and p_n represent the peripheral windspeed and pressure respectively, Eqn. (13) becomes :

$$V_0^2 = V_n^2 = \frac{2}{\rho}(p_n - p_0) \tag{14}$$

The above equation reduces to the form of the semi-empirical relation put forward by Fletcher if the peripheral windspeed is equated to zero. If near the surface $\rho = 1.13\times10^{-3}$gm cm^{-3} and p_n and p_0 are expressed in millibars and windspeed is expressed in knots and peripheral windspeed is assumed as zero, Eqn. (14) reduces to

$$V_0^2 = 697\,(p_n - p_0) \tag{15}$$

whereas Fletcher's formula on taking square becomes :

$$V^2_{max} = 256\,(p_n - p_0) \tag{16}$$

Thus it is seen that V_0^2 is about 2.72 times greater than V^2_{max}, *i.e.*, V_0 is about 1.65 times greater than V_{max}. This implies that Eqn. (13) will give higher values than those given by Fletcher's formula for windspeeds.

It may be mentioned that Eqn. (8) is a component equation on which the derivation of Eqn. (13) is based. Now Eqn. (8) implies that the absolute vorticity about the vertical is zero. Actual computations, on the basis of average wind field in the lower troposphere, indicate that the relative vorticity and certainly the absolute vorticity remain positive everywhere in the cyclonic storm field. The second term in Eqn. (8) which represents anticyclonic shear in case of tropical cyclones, is the only negative contributory factor towards absolute vorticity. This implies that the anticyclonic shear (increase in windspeed with decrease in radius) in cyclonic storms does not attain so high a value as will be required strictly by Eqn. (13). Eqn. (13), perhaps, gives the maximum possible limit to which windspeed can reach in a tropical cyclone corresponding to a particular pressure depth $(p_n - p_0)$ provided all the retarding forces like frictional force, viscous drag of air etc are absent. It is, therefore, necessary to reduce the value of the constant $2/\rho$ by a suitable factor so that the computed values of windspeed as per the modified equation are in agreement with windspeeds actually observed in storm fields.

It had already been mentioned that V_0^2 in Eqn. (15) is about 2.72 times greater than V^2_{max} in Eqn. (15). If the r.h.s. of Eqn. (13) is reduced by a factor of 2.72, the modified equation becomes,

$$V_{r1}^2 - V_{r2}^2 = (0.74/\rho)\,(p_{r2} - p_{r1})$$

or

$$V_{r1}^2 - V_{r2}^2 \approx \frac{1}{\rho}\,(p_{r2} - p_{r1}) \qquad (17)$$

It will be seen from Table 2, that corresponding to a particular pressure depth $\triangle p$, there are reports of windspeeds varying over a large scale. As for instance the table shows that corresponding to a pressure depth of 10 mb, there are reports of winds varying from 35 kt to 55 kt. Thus it will be quite justifying to round off the fraction 0.74 into 1.

If density of air is taken as 1.13×10^{-3} gm cm^{-3} windspeed is expressed in metres per second, p_{r2} and p_{r1} are expressed in millibars, Eqn. (17) reduces to :

$$V_{r1}^2 - V_{r2}^2 = 88\,(p_{r2} - p_{r1}) \qquad (18)$$

4. Comparison between computed windspeeds and recorded windspeeds in tropical cyclones

Windspeeds at land stations are mostly measured by three cup anemometers. The accuracy of these anemometers decrease rapidly with increasing wind velocity. Thus it becomes necessary to apply large corrections to the indicated readings in order to obtain true wind velocity. Moreover, these anemometers are slow to respond to rapid fluctuations in windspeed and as a result they cannot record the peak guests in tropical cyclones. But it is these powerful gusts in tropical cyclones that make their winds so destructive. Dines' P.T. anemographs installed at coastal stations are capable of recording the peak gusts. But the number of such 'gust recorders' are so few and they are so widely spaced along the coasts that only rarely such records are available.

An occasion to observe the wide disparity between the readings of three-cup anemometers and Dines' P.T. anemographs arose during the Porbandar cyclone of 22 October 1975. According to newspaper reports the area worst hit by the cyclone were Porbandar and its neighbouring places in Gujarat State. Eighteen people lost their lives in Porbandar and its surroundings. The loss of property and crops due to the cyclone and rain in Junagadh district (comprising of Porbandar) had been put at 20 crores by official agencies. More than 1500 houses had collapsed and 35,000 houses were damaged in Junagadh district. There was not a single house in Porbandar town which had not suffered any damage in the cyclone. The newspapers had published a number of photographs of toppled and severely damaged pucca buildings, factories and mosques at Porbandar. But the maximum windspeed recorded by the three-cup anemometer at Porbandar was only 58 kt.

Jamnagar city which is much inland and is located about 100 km northnortheast of Porbandar was hit by the cyclone after about six hours. The devastation caused at Jamnagar city was much less compared to that of Porbandar. Though a number of houses had collapsed at Jamnagar also, there are very few reports of damage to pucca buildings. The only photograph published in the newspapers showing the destructive features of the cyclone at Jamnagar was that of a damaged mental hospital, the tiled roof of which was blown off by the fury of the wind. The maximum pressure depth $\triangle p$ (difference between the pressure at the periphery of the storm and the minimum pressure recorded at the station) at Porbandar was 36 mb whereas the maximum pressure depth at Jamnagar was 28 mb. Thus it can be easily concluded that the severity of the cyclone over Porbandar was much more compared to its severity over Jamnagar. The Dines' P.T. anemograph at Jamnagar recorded maximum windspeed at 98 kt, whereas the maximum windspeed recorded by three-cup anemometer at Porbandar was only 58 kt. Maximum windspeed of 70 kt recorded subsequently by Dines' P.T. anemograph at Port Kandla which is located about 65 km north of Jamnagar confirms the veracity of Jamnagar wind observation.

TABLE 1

Windspeed recorded by three-cup anemometer and Dines P.T. anemograph

Observed common pressure depth=26 mb

Station	Wind speed as recorded by: Three-cup anemometer (kt)	Wind speed as recorded by: Dines P.T. anemograph (kt)	Remarks
Porbandar	44	—	Correction to be applied to three-cup anemometer records=72%
Do.	53	—	
Rajkot	48	—	
Jamnagar	—	80	—
Do.	—	86	—
Mean	48	83	

On 22 October 1975, the peak storm intensity derived from satellite picture at 0405 GMT was T-6 which corresponds to a maximum windspeed of 115 kt (Mishra and Gupta 1976). The lowest pressure of 972.2 mb was recorded at Porbandar at 1000 GMT about six hours after the satellite observation. According to Eqn. (18), the computed maximum windspeed at Porbandar was 109 kt corresponding to the observed pressure depth of 36 mb. This value compares very well with the satellite derived windspeed of 115 kt. The computed maximum windspeed at Jamnagar corresponding to the observed pressure depth of 28 mb is 96 kt, which compares excellently with the observed windspeed of 98 kt by Dines' P.T. anemograph.

The satellite derived windspeed of 115 kt will correspond according to Mishra and Gupta (1976) to a sea level pressure of 944 mb whereas the minimum pressure recorded at Porbandar was 972 mb. Eqn. (18) on the other hand gives a sea-level pressure of 968 mb, a difference of only 4 mb which may be accounted for due to a certain amount of filling up of the storm during the interval of 6 hours between satellite and actual pressure observations.

Similarly the Dines' P.T. observation of 98 kt at Jamnagar will correspond according to Mishra and Gupta (1976) to a sea-level pressure of 960 mb whereas the minimum sea-level pressure recorded at Jamnagar was 979 mb, a difference of 19 mb. Eqn. (18) on the other hand gives the identical pressure value of 979 mb. It will be evident from the wind records at Porbandar and Jamnagar that large corrections are to be applied to the three-cup anemometer wind records to get the true windspeed. Table 1 indicates the amount of correction to be applied to the three-cup anemometer records to bring them at par with Dines' P.T. anemograph wind records during the Porbandar cyclone of 22 October 1975.

Ships are generally the only source of wind observation from high seas as reconnaissance flights are confined to limited sea areas. But many ships are not equipped with anemometers and they estimate windspeed from sea surface conditions based on the criteria of Beaufort scale. Beaufort scale on the other hand cannot differentiate sea-conditions beyond hurricane stage (64 to 71 kt corresponding to B.F. No. 12). Consequently the ships when they encounter even mountainous waves report windspeed of the order of 100 kt only. On 19 November 1977 an Indian ship *Jagatswamini* which was caught in the eye of a hurricane around 1130 GMT reported a central pressure of 941 mb (uncorrected). But the ship reported maximum windspeed of B.F. No. 15 equivalent to 90-99 kt only. The peak storm intensity derived from NOAA-5 cloud pictures at 1430 GMT of 17 November and 0305 GMT of 18 November was T-6.5 and T-7 respectively which correspond to maximum windspeed of 127 kt and 140 kt respectively. Corresponding to the observed pressure depth of 69 mb $p_0=941$ mb and $p_n = 1010$ mb) Eqn. (18) gives the maximum value of windspeed as 148 kt. According to Mishra and Gupta (1976), the sea level pressure corresponding to T-6.5 is 930 mb, 11 mb lower than the observed pressure of 941 mb. According to NOAA-5 cloud pictures, peak intensity of the hurricane thereafter remained practically constant at T-7 till it crossed Andhra coast towards the afternoon of 19 November. This hurricane claimed a heavy toll of lives and caused unprecedented devastation. It will be most reasonable to assume that the maximum windspeed in this hurricane might had crossed 150 kt.

Thus it is clear that certain amount of corrections are to be applied to the wind observations reported by ships on the basis of Beaufort scale especially beyond the hurricane stage. Wind observations made by three-cup anemometers on board the ships will also require correction. But the extent of correction to be applied over high seas is smaller compared to land stations because of smaller ground friction over sea surface.

Thus the value of K as computed by most authors on the basis of reported windspeeds from land and sea stations, without giving due weightage to the type of instrument used for such measurements, is smaller than its actual magnitude. Windspeed computed on the basis of these best fit formulae will give lower values than are actually encountered in cyclones corresponding to certain pressure depth.

TABLE 2

Δp	V_F	V_0	Vc	$\overline{V_0}$	Date of obsn.	Type of obsn.
4	28	30	37	45	11 Nov '78	Land station in Coastal Tamil nadu
		35			2 Jun '76	Rig *Sagar Samrat* in A. Sea
		40			18 Jun '79	Ship in A. Sea
		45			2 Jun '76	Rig *Sagar Samrat* in A. Sea
		50			22 Sep '79	Ship in A. Sea
		55			Sep '79	Do.
		60			2 Jun '76	Rig *Hakon Magnus* in A. Sea
5	31	35	41	45	7 Nov '78	Ship GZJD in A. Sea
		35			6 Nov '78	Ship GKFE in A. Sea
		35			22 Oct '75	Land stn. Okha
		35			22 Oct '75	Land stn. Veraval
		40			18 Jun '79	Ship JJSU in A. Sea
		40			22 Oct '75	Land stn. Veraval
		45			22 Oct '75	Do.
		50			2 Jun '76	Rig *Sagar Samrat* in A. Sea
		70			2 Jun '76	Rig *Hakon Magnus* in A. Sea
		75			2 Jun '76	Rig *Shenon Doha* in A. Sea
6	35	30	45	46	13 May '79	Land stn. Ongole
		35			18 Nov '77	Ship ATJZ in the Bay
		40			22 Oct '75	Land stn. Okha
		45			22 Oct '75	Land stn. Veraval
		45			11 Nov '77	Ship A8LX in Bay
		80			2 Jun '76	Rig *Shenon Doah*
7	38	40	48	48	22 Oct '75	Land stn. Veraval
		45			8 Nov '78	Ship GZJD in A. Sea
		50			17 Nov '77	Ship *Srikailosh* in Bay
		55				Rig *Sagar Samrat* in A. Sea
8	40	30	51	49	11 Nov '78	Ship *HOYL* in A. Sea
		35			13 May '79	Land stn. Ongole
		40			22 Oct '75	Land stn. Veraval
		45			22 Oct '75	Land stn. Okha
		50			22 Oct '75	Do.
		50			22 Oct '75	Do.
		55			22 Oct '75	Do.
		55				Rig *Sagar Samrat* in A. Sea
		80				Rig *Shenon Doah* in A. Sea
9	43	40	54	46	7 Nov '78	Ship GFJD in A. Sea
		45			19 Jun '79	Ship PJKI in A. Sea
		50			13 Aug '69	Sand Heads
		50			2 Jun '76	Rig *Sagar Samrat* in A. Sea
10	44	35	57	46	13 May '79	Land stn. Nellore
		40			13 May '79	Land stn. Ongole
		45			12 Sep '61	Ship in the Bay
		45			20 Sep '72	Reconn. aircraft (USAF)

Δp	V_P	V_0	Vc	$\overline{V_0}$	Date of obsn.	Type of obsn.
		45			11 Oct '73	Sand Heads
		45			2 Jun '76	Rig *Sagar Samrat* in A. Sea
		50			13 May '79	Land stn. Nellore
		55			2 Jun '76	Rig *Sagar Samrat* in A. Sea
		55			2 Jun '76	Rig *Sagar Samrat* in A. Sea
11	47	50	59	50	13 May '79	Land stn. Nellore
12	49	40	62	59	8 Nov '78	Ship GZJD in A. Sea
		45			22 Oct '75	Land stn. Porbandar
		65			24 Oct '72	Ship in A. Sea
		85			2 Jun '76	Rig *Hakon Magnus* in A. Sea
13	51	50	65	56	29 Nov '62	Ship in the Bay
		50			13 May '79	Land stn. Ongole
		50			13 May '79	Land stn. Nellore
		50			23 Oct '70	Ship in the Bay
		60			29 May '61	Ship in the Bay
		75			Jun '76	Rig *Shenon Doah* in A. Sea
14	53	45	67	54	5 Jun '71	Sand Heads
		50			22 Dec '64	Ship in the Bay
		50			2 Jun '76	Rig *Shenon Doah* in A. Sea
		55			2 Jun '76	Rig *Shenon Doah* in A. Sea
		55			13 May '79	Land stn. Nellore
		70			2 Jun '79	Rig *Hakon Magnus*
15	55	45	70		7 Nov '78	Ship *ESO Cambiria* in A. Sea
		50			5 Jun '71	Sand Heads
		55			8 Dec '73	Ship in the Bay
		55			17 Nov '77	Ship in A. Sea
		70			2 Jun '76	Rig *Shenon Doah* in A. Sea
16	57	45	72	51	13 May '79	Land stn. Ongole
		50			13 May '79	Land stn. Nellore
		50			13 May '79	Do.
		60			2 Jun '76	Rig *Hakon Magnus* in A. Sea
17	58	65	74	65	13 May '79	Land stn Nellore
		65			13 May '79	Do.
18	59	60	76	65	19 Nov '77	Land stn. Ongole
		70			24 May '63	Ship in A Sea
19	61	50	78	57	13 May '79	Land stn. Nellore
		60			13 May '79	Do.
		60			13 May '79	Do.
20	62	50	79	61	13 May '79	Land stn. Ongole
		55			29 Sep '71	Sand Heads
		60			2 Jun '76	Rig *Shenon Doah* in A. Sea
		60			2 Jun '76	Do.
		60			13 May '79	Land stn. Nellore
		60			13 May '79	Do.
		65			13 May '79	Do.
		75			22 Sep '79	Ship in A. Sea
21	65	45	82	63	2 Jun '76	Rig *Shenon Doah* in A. Sea
		60			11 Jun '64	Ship in A. Sea
		70			2 Jun '76	Rig *Hakon Magnus* in A. Sea
		75			2 Jun '76	Do.

TABLE 2 (*contd*)

Δp	V_F	V_0	Vc	$\overline{V}_0$		Date of obsn.	Type of obsn.
22	67	50	84	75	5625	13 Dec '65	Ship in the Bay
		50				2 Jun '76	Rig *Shenon Doah* in A. Sea
		75				5 Dec '72	Land stn. Cuddalore
		95				2 Jun '76	Rig *Hakon Magnus* in A. Sea
		97				2 Jun '76	Do.
23	69	50	86	67	4489	28 Nov '66	Ship in the Bay
		60				22 May '63	Reconn. aircraft (RFF)
		70				19 Nov '77	Land stn. Masulipatnam
24	70	60	88	63	3969	21 Dec '64	Ship in the Bay
		65				21 Sep '72	Ship in the Bay
25	71	80	89	80	6400	9 Apr '72	Reconn. aircraft. (USAF)
		80				21 Nov '72	Ship in the Bay
26	72	75	90	84	7056	5 Nov '73	Do.
		80				12 Nov '70	Do.
		80				22 Oct '75	Land stn. Jamnagar
		86				22 Oct '75	Do.
		100				7 Nov '78	Ship *ESO Cambiria* in A. Sea
27	73	80	93	80	6400	21 Nov '64	Ship in the Bay
28	75	98	95	98		22 Oct '75	Land stn. Jamnagar
29	76	70	96			17 Nov '77	Ship in the Bay
		100				21 Sep '72	Reconn. aircraft (USAF)
31	79	90	101			17 Nov '77	Ship in A. Sea
32	80	80	102			12 Jun '64	Land stn. Naliya

Δp	V_F	V_0	Vc	$\overline{V}_0$	Date of obsn.	Type of obsn.
34	82	125	104		1951	Reconn. aircraft. Obsn. at Puerto Rico
35	84	60	105		11 Nov '66	Ship in the Bay
		110			10 Sep '72	Land stn. Gopalpur
40	90	100	113		29 Oct '71	Land stn. Paradeep Port
42	92	>100	115		11 Nov '78	Ship *ESO Cambiria* in A. Sea
43	93	70	117		10 Nov '66	Ship in A. Sea
49	99		115 >150	125	3 Nov '66 8 Nov '78	Ship in the Bay Ship in A. Sea
59	109	104	137	104	24 May '63	Reconn. aircraft (RFF) in A. Sea
64	113	126 151 (in one isolated gust)	143		1975 1975	Land stn. supplied by Mauritius Met. Service
67	116	143	146		1960	Land stn. Carol Island near Mauritius. Max. wind speed in gust
69	117	135	148		1892	Land stn. supplied by Mauritius Met. Service
77	124	156	157		1972	Do. Max. windspeed in gust. Rodrigues Island
78	125	120	161		18 Sep '26	Land station Miami Beach, Florida
83	129	130	167		3-4 Sep '53	Reconn. aircraft. Wind speed recorded in hurricane *Carol*
99	141	>152	183		27-28 Sep '55	Land stn. Chetumal, Mexico.

$\Delta p=(p_n-p_0)$ where p_n is peripheral pressure and p_0 is the pressure corresponding to observed windspeed V_0.

V_F= Wind speed calculated on the basis of Eqn. (3) V_0=Observed windspeed.

$\overline{V}_0$=Mean of all observed windspeeds corresponding to pressure depth Δp

Vc=Windspeed calculated on the basis of Eqn. (18) deduced by the author. Peripheral windspeed is assumed as 5 mps (10 kt).

5. Scatter diagram of square of observed maximum wind versus pressure depth

In Fig. 1 square of observed maximum wind speed V_0^2 had been plotted against pressure depth $\Delta p=(p_n-p_0)$ where p_n was the peripheral pressure and p_0 was the observed pressure corresponding to the observed wind speed V_0. All the observations compiled by Mishra and Gupta (1976) from ships, coastal stations and reconnaisance aircraft for the cyclonic storms which occured in the Bay of Bengal and the Arabian Sea during the period 1961—73 had been utilised in this study. Apart from these data the unique observations recorded by stationary oil-drilling rigs belonging to Oil and Natural Gas Commission of India during the passage of June 1976 hurricane across Bombay High area had also been used. Also the observations recorded by ships and coastal observatories during the Andhra Pradesh hurricanes of November 1977 and May 1979 had been utilised in this study. A few observations with instrumental records of windspeed exceeding 100 kt supplied by Mauritius Met. Service and as compiled by Dunn and Miller (1960) had been plotted in the scatter diagram to supplement data coverage in higher ranges.

Table 2 gives all the observations utilised in the preparation of the scatter diagram. The data are arranged in such a way that for a particular pressure depth Δp, all the available windspeeds are grouped in increasing order of magnitude. Column 2 represents computed windspeed (V_F) as deduced from Eqn. (3) postulated by Mishra and Gupta (1976). In column 3, V_0 represents all observed windspeeds. Column 4 represents computed windspeed V_c calculated on the basis of Eqn. (18) deduced by the author now. Column 5 represents mean observed wind velocity, based on all the observations. Mean velocity had been calculated only when four or more observations were available for a particular pressure

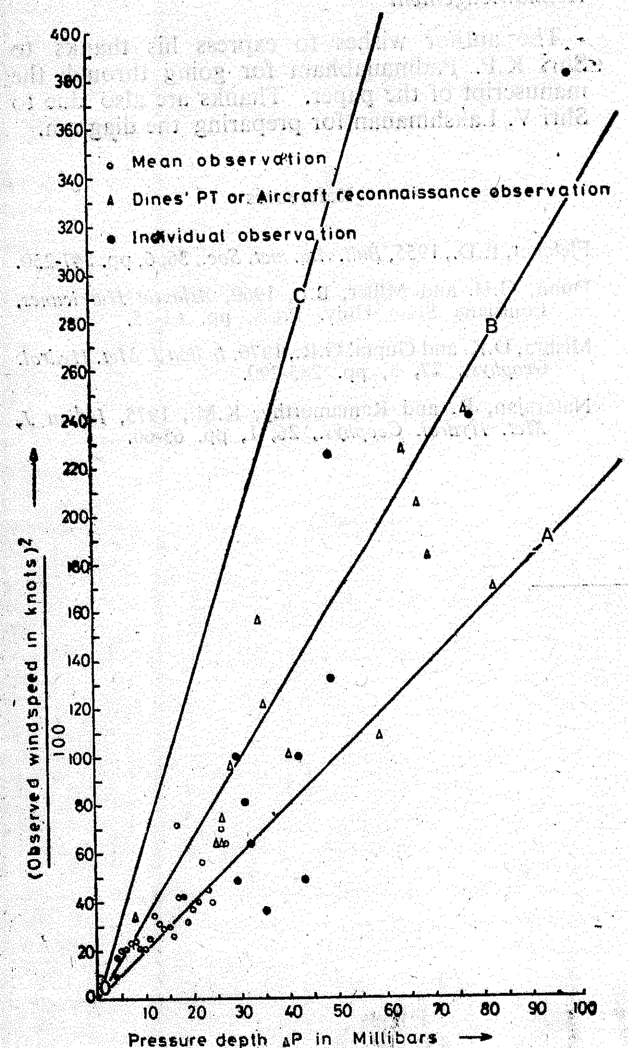

Fig. 1. Scatter diagram of square of observed windspeed (kt) *versus* pressure depth Δp (mb)

depth. Otherwise square of individual observations had been plotted against Δp.

In Fig. 1, OA represents relationship between square of windspeed computed as per Eqn. (3) and pressure depth. Similarly OB represents the relationship between square of windspeed computed as per Eqn. (18) postulated by the author and pressure depth. OC represents the relationship between square of maximum possible windspeed computed on the basis of Eqn. (13) and pressure depth.

This scatter diagram in Fig. 1, as well as the data given in Table 2 will show that the line OA generally represents the lower limit of windspeed that are observed in cyclonic storms. Especially this line greatly underestimates windspeed in case of hurricanes of severe intensity. In case of Porbandar cyclone of 1975, this line gives a windspeed of 72 kt corresponding to the recorded pressure depth of 26 mb, whereas the actual recorded windspeed was 86 kt by Dines' P.T. anemograph corresponding to the pressure depth of 26 mb.

The line OB on the other hand generally represents the upper limit of windspeed that is reached in gusts in a cyclonic storm. Especially in case of hurricanes of severe intensity this curve gives a better estimate of windspeed for a particular pressure depth. The computed windspeed for a pressure depth of 26 mb as observed over Jamnagar during Porbandar cyclone of 1975 is 90 kt. This compares very well with the recorded windspeed of 86 kt.

6. Discussion

In computing windspeeds which had been plotted in the scatter diagram the value of V_{r2} in Eqn. (18) had been given a constant value of 5 m.p.s. (*i.e.*, 10 kt). The value of V_{r1}, depends upon V_{r2}. V_{r1} will assume a larger magnitude if the value of V_{r2} is more than 5 m.p.s. It is a well known fact that in depressions, cyclones and hurricanes windspeeds are different in different sectors. Especially in case of monsoon depressions over the Bay of Bengal and the Arabian Sea, windspeed in the southern sector is much higher than the windspeed in the northern sector. It is believed by Indian meteorologists that the strong west to southwesterly winds prevailing over Indian seas during the monsoon months somehow enter into the depression circulation. Hence windspeed in the southern sector becomes stronger compared to the northern sector. Eqn. (18) explains the mechanism as to how the strong wind field in the southern sector representing V_{r2} influences the depression circulation to give a higher value of V_{r1} in the southern sector. Since the value of V_{r2} in the northern sector is much smaller, the value of V_{r1} in that sector is also smaller. Thus Eqn. (18) explains how different values of V_{r2} in different quadrants contribute to the existence of assymetric wind field in cyclones and hurricanes.

The formula postulated by Fletcher and modified subsequently by others gives only an estimation of maximum windspeed that can occur in cyclones and hurricanes. But it does not provide any method to calculate windspeed at different points on the radius of the storm as one proceeds from the outer periphery of the storm towards its centre even if the pressure configuration is known with fair degree of accuracy. But Eqn. (18) can be employed to calculate the windspeed at any point on the radius of the storm provided the surface pressure (p_0) at that point is known because all other parameters like p_n, V_{r2} can always be observed or estimated from weather charts. This equation can also be utilised to check the accuracy of any doubtful wind observation from ships which had reported corresponding surface pressure. When the pressure configuration in a storm is known with fair degree of accuracy it may be argued that the gradient wind equation can be used to estimate the windspeed at various points on the radius of the storm. But the gradient wind equation involves parameters like geostrophic wind V_g and coriolis parameter f.

Over the tropical region where cyclonic storms develop the applicability of geostrophic wind itself is not considered reliable. Also the coriolis parameter is likely to introduce considerable error in the estimation of gradient wind because of its small magnitude over the tropics. On the other hand Eqn. (18) is independent of geostrophic wind factor as well as coriolis parameter. Hence the equation can be used without any limitation over any part of the globe.

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