Analyses of Ring of maximum Wind, Ring of Maximum Pressure Gradient, Inflow angle and RMW in Tropical Storm

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ABSTRACT

Value of Constant in Fletcher's equation for maximum wind has been analytically re-examined with the help of gradient wind equation. Suitable approximations lead us to the mathematical result that maximum angular velocity is inversely proportional to square root of the peripheral radius, provided central an ambient pressure and the ring of maximum wind (RMW) are same for any two different tropical storms. Mathematical consistency demands that the value of RMW must be larger than the value of radius of maximum pressure gradient (r_{pmax}). Predominance of radial component of velocity over the angular component, at places, is also possible, close to RMW. Observations of Mukherjee et al(1981) over Bay of Bengal are the cumulative effects of asymmetry causing factors e.g. gradient in earth's vorticity, vertical shear, cold water tongue which induces overlying boundary layer modification, landfall and β-gyres. These could be responsible for large inflow angle of 60^0 to 70^0, at times, in preferred sectors. It is further noted that Hydromet pressure profile cannot truly represent the cyclone pressure field since there is a point of inflection at $r = r_{max}$ close to the centre of tropical storm.

Key Words: Gradient Wind, Tropical Cyclone, Ring of Maximum Wind, Radius of Tropical Cyclone, Inflow angle.

Introduction

1. First equation relating maximum wind in typhoons to the central pressure was developed by Takashi (1939). He used wind data from ships and island stations near or in Japan during late 1930's. Since central pressure was not available, he estimated these by interpolation from a statistical horizontal pressure distribution model for typhoons. Without making mathematical analysis of constant of proportionality he used the following form of cyclostrophic equation.

$$V_{max} = K^* (p_R - p_0)^{1/2}, \qquad (1)$$

where V_{max} is the maximum surface wind speed (kt), p_R the environmental pressure (hPa), p_0 the central pressure (hPa) and K* a constant. By observations over north-western Pacific he determined K* as 13.40; later he claimed K* = 11.50 as better fit for higher latitudes. The empirical equation developed by Fletcher [Published in 1955 though available earlier, Atkinson and Holliday (1977)] for the maximum wind , V_{max}, was based on the regression analysis and which was.

$$V_{max} = K^{*} (p_R – p_0)^{1/2} \qquad (2)$$

Fletcher had put K* = 16 for all practical purpose. The Typhoon Postanalysis Board (Mcknown et al 1952) at Gaum derived an equation based on 230 typhoon penetrations as during 1951 and 1952. Using Fletcher's eqation as starting point, they developed a family of curves for the best-fit reconnaissance data. Fletcher's equation was modified such that,

$$V_{max} = (20-\theta/5)\ (1010 – p_0)^{1/2}\ ; \qquad (3)$$

where θ is the latitude (deg). All the subsequent researches towards the estimation of V_{max} value were largely concentrating on either adjustment value of proportionality constant K* or the estimated central pressure; e.g.

Fortner (1958) $\quad Vmax = (20 – \theta /5)(372-h_7/8.54)^{1/2} \quad (4)$

And Sea(1964) $\quad Vmax = (19 – \theta /5)(372-h_7/8.54)^{1/2} \quad (5)$

Where h_7 = 700 hPa height value in meters.

Joint Typhoon Warning Centre (1965) adopted Seay's equation with slight modification for the height of 700 hPa term. i.e.

$$V_{max} = (19 – \theta /5)\ (364 – h_7/8.54)^{1/2} \qquad (6)$$

But despite these adjustments they noted that winds derived from Eqn. (6) exceeded the maximum wind observed at land stations by 23.40 kt on the average. Hence, they had to apply graphical correction, subsequently. In 1973, a new pressure-wind relationship developed by Fujita (1971) was adopted for operational use. Later Atkinson and Holliday (1977) found the nonlinear relation,

$$V_{max} = 6.70\ (1010 – p_0)^{0.644} \qquad (7)$$

Though Eqn. (7) showed lower departure than Eqn. (6) but their scatter data of point about the regression line remained quite large.

Eqn. (1) to (7) certainly indicated that at least the direct proportionality existed with the maximum surface wind and surface pressure drop ($p_R – p_0$) raised to fractional exponent, of the order of 0.5. Another common feature in all the previous approaches had been that they were all either based on statistical approach of regression method or curve fitting by graphical techniques.

Adopting the similar technique Natarajan and Ramamurthy (1975) found that K* = 13.60; while studying hurricanes and typhoons in the Atlantic Ocean and East Pacific Ocean. Gupta and Sud (1974) and Mishra and Gupta (1976) claimed the best-fit relationship for K* was equal to 15 and 14.20 respectively on the basis of their study on the Indian Ocean. Gupta and Sud (1974) took p_R = 1008 taking the mean of observed lowest and highest values of p_R i.e. 1005 and 1011 hPa respectively. Without the constraints of gradient wind balance, Stephen & Franklin (1987) had attempted the least square fitting algorithm of Ooyama (1987) to simulate the hurricane wind field in Pacific. They found single level deviation of the range of 5-10 ms^{-1} near RMW. Studies by Hawkins and Rubsam (1968), Jorgensen (1984) and Willoughby (1988, 1990) noted that above the boundary layer, in azimuths mean sense, hurricane winds are in approximate gradients and were thermal wind balance. But none of these past studies were based on mathematical analysis and largely they remained observation based, only.

2. In the present paper starting from the first principals, a mathematical reexamination of the value of K* from the gradient wind equation, has been made per-se, with the finite differences approximation to the pressure gradient. Analysis will explain that why so much variation are coming in the value of K* for different workers and at different places of latitudes. It then leads to an important result from this analysis, in section 2, that $r_{max} > r_{pmax}$; where r_{max} is RMW and r_{pmax} is the ring of maximum pressure gradient. Section 3 derives Fletcher's equation by gradient wind equation and points-out the limited application possibility of Hydromet pressure profile formula. In section 4 it is established that the V_{max} is inversely proportional to the square root of the radius of the maximum dimension of the storm, when r_{max}, pressure deficit i.e. $(p_R - p_0)$ and density (ρ) are constants. In section 5, theoretical result of present work and observational evidences of other workers are presented in support of the fact of dominances of radial component in the ring of maximum wind. The meteorological reasons for abnormally strong inflow angle of the order of 60^0 to 70^0 have also been discussed by quoting other authors.

Velocity equation

3. Ring of maximum wind from gradient wind equation.

We know from gradient wind equation.

$$V = -\frac{fr}{2} + \sqrt{\frac{f^2 r^2}{4} + \frac{r}{\rho}k} \qquad (8)$$

Where V is the tangential velocity f is the coriolis parameter, ρ the density, k is the pressure (∂p/∂r).

Radius of maximum wind (RMW i.e. r_{max}) can be obtained from Eqn. (8) by the condition ∂V/∂r = 0,

$$i.e., r_{max} = \frac{-k\frac{\partial k}{\partial r} \pm \sqrt{k^2 f^2\left(-\rho\frac{\partial k}{\partial r}\right)}}{\left[\left(\frac{\partial k}{\partial r}\right)^2 + \left(f^2\rho\frac{\partial k}{\partial r}\right)\right]} \qquad (9)$$

Eqn. 9 show that r_{max} will be real if $\partial k/\partial r$ is less than zero. Fig. 1 shown the profiles of p,k and $\partial k/\partial r$ close to the center of storm.

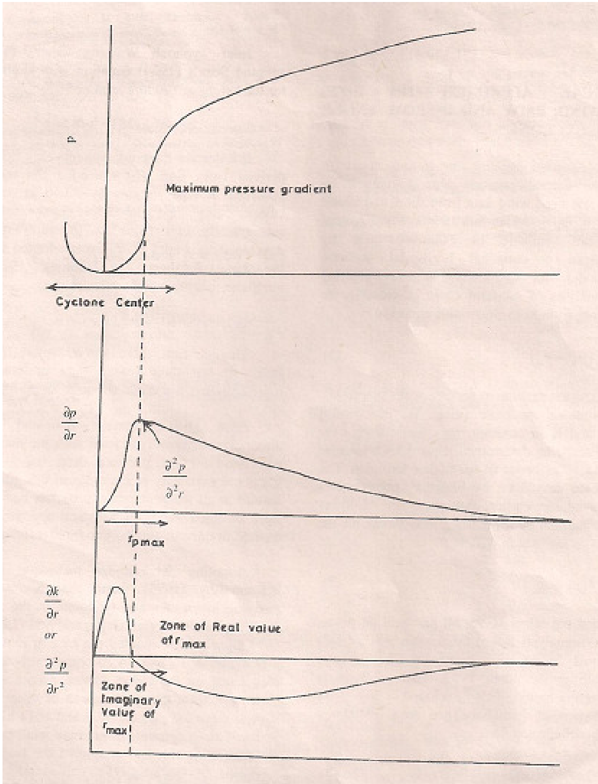

Fig. 1. Graphical presentation of profiles of p, k and $\partial k/\partial r$. Note the location of r_{pmax} at the point of inflexion and domain in which r_{max} is possible

It is obvious that mathematical validity of the existences of r_{max} is inherent in the types of pressure profile which has point of inflexion i.e. $\partial k/\partial r = 0$ at a radial distance $r = r_{max}$ (say) where pressure gradient is maximum. Further, the domain in which r_{max} may exist occurs outside the ring of radius $r = r_{max}$; where $\partial k/\partial r < 0$. In side the ring of $r = r_{pmax}$ where value of $\partial k/\partial r > 0$, r_{max} cannot exist. This is general case.

In particular can be easily seen that if coriolis term is neglected (cyclostrophic balance) then $r_{max} = k/\ \partial k/\partial r$. On the other hand if centrigugal term is neglected (geostrophic balance), r_{max} must occur at the r_{max} of inflexion where $\partial k/\partial r = 0$. In general therefore r_{max} must lie between r_{pmax} (i.e. point of inflexion) and $k/\ \partial k/\partial r$. The root provided by the negative sign in equation 9 has this property. Positive sign indicates that for $\partial k/\partial r > \rho f^2$, $r_{max} > k/\ \partial k/\partial r$ which is out of the valid region for the existences of r_{max} and for $\partial k/\partial r > \rho f^2$; $r_{max} < 0$ which is absurd. Hence positive sign in equation 9 must be ignored. It may be noted that root provided by minus sign is continuous everywhere except possibly $\partial k/\partial r = \rho f^2$. At this point numerator and denominator go to zero simultaneously which is indeterminate form. But using D-Hospital's rule it can be shown that $r_{max} = k/2*\{\ \partial k/\partial r\}$. Thus the profile of p for varying r is well behaved and continuous near the center of the storm.

4. Validation of Theoretical result $r_{max} > r_{max}$ through the work of previous researchers

Holland (1980) has compared the radius of the ring of maximum wind (RMW) r_{max} and the ring of maximum pressure gradient r_{max} on his simulated profiles.

$$\text{If } X = \frac{r_{pmax}}{r_{max}} = \left\{ \frac{B}{1+B} \right\}^{1/B} \quad \text{where B is a constant.}$$

Then $1 \leq B \leq 3$; when surface e friction is ignored and $1 \leq B \leq 2.5$; when surface friction is also accounted .

This implies that;

$$0.5 \leq X \leq 0.908 \quad \text{(for non-friction case)}$$

$$0.5 \leq X \leq 0.874 \quad \text{(for friction case)}$$

This validates the present theoretical finding of the paper that the quotient $X = (r_{pmax/} r_{max})$ is always less than one and is never equal to one. The result negates the validity of Schloemers (1954) relation, which puts the ratio equal to one. Same, therefore, needs adjustment in the engineering and storm surge modeling attempted by Myers (1954), Graham and Hudson (1960), Marinas and Woodwar (1954) and Das (1972). This could be a contributing factor to large errors in simulating the actual profile based on Wang's (1978) model, which was based on Schlomers (1954) relation. Note the larges departures in the computed wind through Wang (1978) and Schlomer (1954) with the actually observed wind in Fig. 2, within enclosed region with thick line, less than 10 km from the centre.

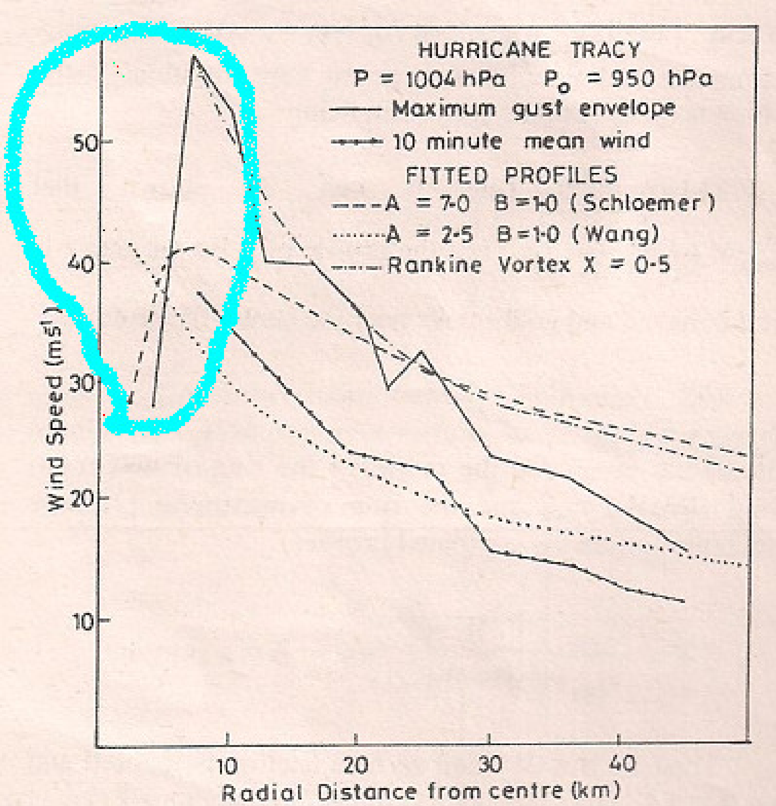

Fig. 2. Application of the models of Schlomer (1954), Wang (1978) and the modified Rankine vortex to the actual wind profile Hurricane Tracy

5. Sensitivity of Depperman model with r_{max}

Depperman (1947) proposed the modified Rankine Vortex. He could explain the profiles better in vicinity of RMW, since it was based on the empirically obtained relation $VR^x = D$, (or $V = D/R^x$) where $0.4 < x < 0.6$ (Hughes 1952; Riehl 1963; Gray and Shea 1972). D is empirically determined by the observation of RMW. It has been noted by Holland (1980), though without giving any reason that modified rankine vortex model of Depperman (1947) is highly sensitive to the small errors in estimating the RMW. The causes of this sensitivity of Depperman (1947) relation and the validity of the same will be examined in per 4, through para 3.

Pressure gradient approximation

6. In Eqn. (8) it may be noted that, $f^2 \approx O(10)^{-10}$ and $\rho^{-1} = O(800)$ gm^{-1} cm^3. r_{max} represent the radius of dimension of the eye, that is of the order of 10 to 25 kilometer and k is the radial rate of fall of pressure and is of the order of 20 to 40 hPa, between the r_{max} and the center of the storm. This is equivalent to 0.008 to 0.004 dynes/cm^2. Hence we can simplify equation (8) after applying finite difference approximation as,

$$V_{max} = \left[\frac{r_{max}}{\rho}\right]^{1/2}\left[\frac{p_R - p_o}{R}\right]^{1/2} \quad (10)$$

Where p_R = peripheral pressure or ambient pressure (theoretically at infinite radius, in practice the value of the first anti-cyclonically curved isobar may be used). It is normally ranging between 1005 to 1011 hPa over the Indian Seas [Srinivasan and Ramamurthy (1973)]

$P0$ = Central pressure

R = Radius of the periphery of the tropical storm.

Although Eqn. (10) is not very good approximation to k since most of the pressure drop occurs near the center but the equation can be fairly well used in developing regression equation for maximum wind speed from the practical point of view. Nevertheless the simplification applied in deriving Eqn. (10) from Eqn. (8) gives insight into the Fletcher's equation which is based on the same approximation i.e.

$$V_{max} = \left[\frac{r_{max}}{\rho R}\right]^{1/2}(p_R - p_o)^{1/2}$$

$$= K^*(p_R - p_o)^{1/2} \quad (11)$$

Questionable derivation of Eqn. has been presented in NOAA technical report, Hallgren (1979) (henceforth referred as NT) where it equates the value of

$K^* = (\rho e)^{-1/2}$. NT derivation is based on hydromet pressure profile formula.

$$(p - p_0) = (p_R - p_0)\, e^{-R/r} \quad (12)$$

Where R is the outer radius of tropical storm. This equation gives pressure gradients as

$$\frac{\partial p}{\partial r} = k = \frac{(p_R - p_o)R}{r^2} e^{-R/r} \quad (13)$$

Eqn.(13) will give the value of radius of ring of maximum pressure gradient as

$$\frac{\partial k}{\partial r} = (p_R - p_o)\ R\left[\frac{Re^{-R/r}}{r^4} - 2\frac{e^{-R/r}}{r^3}\right] = 0$$

Or

$$r_{p\,max} = R/2 \qquad (14)$$

Had Eqn. (14) been true, ring of maximum wind has to be greater than half of the outer radius of radius of tropical storm since $r_{pmax} < r_{max}$ [as has been proved in section 2 (a) of this paper] then this would mean that a storm having outer radius of 300 – 400 km can never have radius of eye less than 150 – 200 km. This result is against the observed facts, since it is common observation that RMW of the cyclonic storm is normally an order less than outer radius R i.e. r_{max} /R < O (0.1) (approximately). Obviously, therefore, hydromet pressure profile formula does not truly represent the cyclonic storm radial pressure drop; it can only approximate it.

Based on Eqn. (11) we can mathematically conceive all those parameters which may possibly cause the variation o K*. We will see it in next section.

Relation between V_{max} and R

8. Correlation of V_{max} with tropical storm dimension, as per Eqn. (11) suggests following relation.

V_{max} α (r_{max}) (if p_0, p_r and R are constants) (15)

V_{max} α $(p_R - p_0)^{1/2}$ (If r_{max} and R are constants) (16)

V_{max} α $1/(\rho R)^{1/2}$ (If r_{max}, p_R and p_0 are Constants) (17)

Eqn. (15) suggests the sensitivity of Depperman's models with respect to the RMW (r_{max}), as discussed in section 2(c) above. Eqn(16) indisputably relates the pressure gradient with the wind and Eqn(17) relates the total radius of the storm with the maximum wind field. Since surface air density (p) may be assumed to be nearly invariant for the storm fields over Indian Ocean, Atlantic or Pacific (Colone et al, 1970)it implies.

V_{max} α $1/R^{1/2}$ (18)

Or in other words we may say that more compact the storm the higher the absolute wind if other variables are kept constant.

Dominance of radial wind component over the angular component near RMW

9. If the mathematical expression provided by $(r_{max} /R\rho)^{1/2}$ for K* is true then we should get reasonably good approximation in the computation of absolute wind. But absolute value of K* theoretically calculated by Mishra (1981) after neglecting the vertical velocity and frictional effect of surface equals to $(2/\rho)^{1/2}$. Holland (1980) simulated the pressure profile with a rectangular hyperbola based on this assumption founds the value of K* equal to $(B/\rho e)^{1/2}$ where B is a constant whose value varies between 1 to 3 when surface friction is neglected (e is a base of the natural logarithm). Thus in Holland's model also K* lies between $(1/p)^{1/2}$ to (1.103/p) ½. Both in Mishra's case and in Holland case the numerator under the square root is much large than (r_{max} /R) (as par Eqn. (11) – which may be taken to be of the order of = 01). High value of K* in Mishra's (1981) case can be understood since he neglects the friction and vertical velocity. But high value of Holland (1980), which is based on actual observation, can be explained by acyclostrophicity, at times, near the center. Though it is normally known that cross isobaric angle does not exceed 35^0 (NT page 262) it has been observed as high as 60^0 to 70^0 over bay of Bengal. Derivation of K* in the present paper is based on cyclostrophic balance. Close to the center of a tropical cyclones sometimes a cyclostrophic flow inducing extra ordinary large radial component of velocity plays a stronger contributory role to the absolute velocity, giving cross isobaric winds. Observational evidence to this effect over Bay of Bengal was Provided by Mukherjee et. al (1981). Refer Fig. 3 and also table 1.

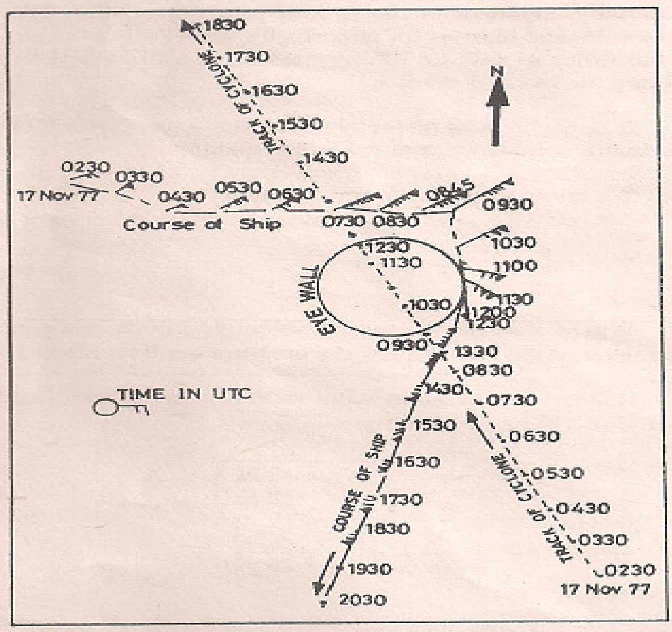

Fig. 3. Hourly track of the cyclone over Bay of Bengal on 17 November 1977 from 0230 UTC to 2030 UTC. Special wind observations were taken at 0845, 1100 and 1200 UTC due to close proximity of the eye of the cyclone. Note the predominance of the radial component of the actual wind close to the eye wall

TABLE 1

Actual observation of surface wind by the ship as shown in Fig. 3. Note the predominance of radial component over the tangential component close to the eye wall at 1100 UTC (column 5)

S. No.	Time of observation 17 Nov 1977 (UTC)	Distance of the ship from cyclone centre (n.m. Approx.)	Wind direction (Deg. from north)	Speed (kt)	Inflow angle (Degree)	Radial wind (kt)	Tangential wind (kt)
1	0230	92.4	060	020	-10	-003.47	19.70
2	0330	90.8	045	050	6	5.23	49.73
3	0430	70.2	060	070	8	-009.74	69.32
4	0530	58.0	050	075	4.5	6.10	74.71
5	0630	49.8	060	085	-1	-001.43	84.99
6	0730	38.2	060	090	5	7.84	89.66
7	0830	28.8	050	095	27	43.12	84.65
8	0845	26.4	030	095	53	75.87	57.17
9	0930	22.4	060	095	52	074.86	58.49
10	1030	11.3	060	105	60	90.93	52.50
11	1100	09.0	100	110	80	108.42	19.10
12	1130	11.0	120	110	68	101.99	41.21
13	1200	14.4	195	105	67	096.65	41.03
14	1230	19.2	190	105	49	079.24	68.89
15	1330	30.2	190	095	35	054.49	77.82
16	1430	41.2	195	085	35	048.75	69.63
17	1530	53.0	195	085	31	043.78	72.86
18	1630	65.0	195	080	29	038.78	69.97
19	1730	76.8	195	080	27	036.32	71.28
20	1830	80.2	195	075	27	034.05	66.83

Although it is common awareness among the topical forecaster that estimation of accurate inflow angle from ship data is difficult (refer NT – page 260) but an approximate estimate of the same within permissible error of about $\pm 10^0$ or so (due to observation from the moving ship) readers can refer table1 column 5. Observe that as the moving ship's distance decreases the inflow angle increases and it becomes maximum when at 1100 UTC the distance from the ship and the center of the storm is least. This table is presented to highlight the phenomenal increase in the radial component (acyclostrophic flow) close to r_{max}. Thus cyclostrophic wind balances, is at times, certainly greatly disbalanced when $r = r_{max}$ Hence computation of absolute maximum wind just by value of $K^* = (r_{max} / R\rho)^{1/2}$ would be certainly an underestimate with the increased inflow angle. Usually inflow angle is of the order of 15^0 to 30^0 but it is strongly influenced by the structural asymmetry of the cyclone. The departure from the normal value could be quite large and at places inflow angle may reach 60^0 to 70^0 as in Table 1. Reasons of such a strong radial flow has been attributed to frictionally and diabatically induced convergence beneath the eyewall – Willoughby (1990). Which also, therefore finally influences value of K* in Fletcher's equation. Hence the effect of sum of the balance vortex and frictional effect, is inherent in the actual value of K*in the computation of absolute maximum wind for operational purpose. Black & Holland (1995) attributed structural asymmetry of tropical cyclone to primarily three factors. Firstly gradients distortion from cyclone rotation across a gradients of earth vorticity, secondly to environmental vertical shear, which produces forced ascent/subsidence in preferred sectors and thirdly to boundary layer modification due to tongue of cold water in storm regime which develops in preferred sectors presumably from stress induced mixing. Land fall process (Powell and Houston – 1996) may also cause RMW to tilt more outward as the decreases. Also, though, effect of β-gyres (De Maria 1985) has not yet been documented in nature but it may effect asymmetry. Cumulative effect of all these causes would explain the strong variation in the observed value of inflow (i.e. 15^0 to 30^0 on an average) which is preferred sectors may reach even 60^0 to 70^0 at time.

10. Findings of the paper are summarize as under

(i) Ring of maximum wind (r_{max}) is always larger than the ring of maximum pressure gradient. Hence Schlomer;s (1954) relation which is based on assumption that $r_{pmax} = r_{max}$ has inherent error. This could be one reason of larges departure in wind computation near the RMW. Refer enclosed region with thick line in Fig. 2.

(ii) Deppereman's relation can also be derived gradient wind equation but the sensitivity of value of constant would not only depend on accurate measurement of r_{max} – as noticed by Holland – but also on the accurate measurement of pressure deficit and air density, since proportionately constant 'D' in Depperman's model is function of the term $[r_{max} (p_R\text{-}p_0)/ \rho]^{1/2}$.

(iii) Fletcher's equation is based on coarse finite difference approximation.

(iv) Hydromet pressure profile formula cannot truly represent the cyclonic radial pressure drop.

(v) The proportionality constant in Fletcher's equation is based on eyes dimension (r_{max}), storm size (R) and the air density (p) and different factors which induce asymmetry [refer(vi) below].this explain the reason of wide variation of its value given by different workers over different part of the world.

(vi) The radial component often dominants the wind close to the RMW. It's value, however, is strongly influenced in different sectors (Black and Holland, 1995; Powell and Houston. 1996; De Maria 1985) by the gradient in earth's vorticity, vertical shear, cold water tongue which induces overlying boundary layers modification, landfall and β-gyres. The cumulative effect of this might contribute to abnormally large inflow angle in preferred sectors which could, at places reach to as much as 60^0 to 70^0 at times.

References

Atkinson, Gray D and Holland, Charles R. 1977, Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for western North Pacific; Mon Wea. Rev. 105.

Black peter. G and Holland Grag .J 1995, The boundary layers of tropical cyclone Kery (1979) Mon, Wea. Rev. 123.

Colone J. A. Raman C. R. V. and srinvasan V. 1970. on some aspects of the tropical cyclone of 20 – 29 may over the Arabian sec. Indian J. Met. & Geophys.

Das, P. K. 1972. ‘ Predication model for storm surges in the Bay of Bengal’ Nature 139, 211 – 213.
Depperman C. E. 1947 Not. To the origin and structure of Philippine typhoon’s. Bull Amer. Met. Soc. 28. 399 – 404.

DeMaira. M. 1985. Tropical cyclone in a non – divergent berotropic model. Mon. Wes. Rwv. 113. 1199 – 1210.

Fletcher’ s R. D. 1955, Bull Amer Met. Soc. 36. 6247 – 6250.

Fortner. L. E. Jr. 1958. ‘Typhoon Sarah 1956. Bull. Amer Met. Soc. 39.636 – 639.

Fujita T. T. 1971, Propsed characterization of tormadoes and hurricanes by aera intersity ‘SMRP Res. Pep 91 deptt. Of Geophys. Sci. The University of Chicago P42.

Graham H. E. and Hudson G. N. 1960Surface winds nears the center of hurricanes (and other cyclone) NHRD Rep. 39, 200 (Govt. Printing Offices No. C30. 44;39)

Gary W. M. and Shea D. J. 1973 The Hurricances inners core region II Thermal stability and dynamic characterisrics J Atmos. Sci. 30. 1565 – 1576.

Gupta M. G. and std. A.M. 1974. use of satellites prictures for the estimate of central pressure maximum wind speed and storm surface height associated with tropical storm Pre. Pub. Sci. Rep. no. 212 India Met. Dept. India

Hallgren R. E. 1979 Meteorology criteria for standred project hurricane and probable maximum hurricane wind fields Gulf and seat of the United States. NOAA Tech. Rep. NWS-23.

Hawkins H. F. and Rubsam D.T. 1968. Hurricane Hilda 1964 II structures and budgets of the Hurricane of 1 October 1964. Mon Wea. Rev. 96.617-636.

Holland Greg J 1980 An analysis of wind and pressures profile in hurricane Mon. Wea. Rev. 108,8,1212-1218.

Hughes L. A. 1952 on the low-level wind structure of tropical cyclones J Meteo. 9,422-428.

Joint Typhoon warning centre (JTWC) 1965. " Annual Typhoon Report. 1964. Fleet Weather Central/Joint – Typhoon Warning Centre Guam M. I. 26-27 (NTIS Ref. AD 786209).

Jorgenes D. P. 1984. Mesoscale and convective-scale charactertics of nature hurricance part. II Inner cone structure of hurricnce Allen J Atmos. Sci. 41, 1287-1311.

Marinas D. and Woodward J. W. 1968. Estimation of hurricane surges hydrographs. ASCE. Waterway Harborts WW2, 189-216.

Mcknown R and Collaborators 1952. 5th Annual report of the Typhoon post Analysis Board Andesen AFB, Guam. M.I.

Mishra D. K. and Gupta G. R. 1976. Estimation of max wind speed in tropical cyclone occurring in India Seas. Indian J Met. Hydro. & Geophys. 27, 3, 285-290.

Mishra D. K. 1981, Computation of surface winds in tropical cyclone Mausam 32, 4, 357-361.
Mukherjee A. K. Gurunadham G. and Rozoria R. V. D. 1981, Crossing eye of the cyclone by ship Vayumadal 11 3841-3846.

Myers V. A. 1954, Characteristices of United states Hurricances pertinent to level for lake Okchobbe' Fl Hydroment Rep. 32, 126 (Govt. Printing office No. C 30.7.:32).

Natrajan R. and Ramamurthy K. M. 1975, Estimation of central Pressures of cyclonic storm in the seas. Indian J Met. Hydro.& Geophys. 26, 1, 65 – 66.

Ooyama K. V. 1987, Scic storm controlled objectives analysis men. Was. Rev. 115. 2479 – 2506.

Powell Marks D. and Samuel H. Houston 1996 ' Hurricences Anderw;s Landfall in south Florida Part. I : Standardzing measurements for documenetion of surface wind fields. Weasth. And for 11, 304 – 328.

Reihl H. 1963. ' some relations between and thermal structure of steady stte hurricences J Atmos. Sci. 20, 276 – 287.

Schlomer R.W. 1954. ' Analysis and synthesis of hurricane and wind pattern over the lake Okechobbe Fl. Hydroment Rep. 31, 49 (Govt. Printing Offices No. C 30, 70:31).

Seay D. N. 1964, " Annual Typhoon Report 1963 Fleet Weather Centra/Joint Typhoon Warning centre Guam M.1 6-7 10-11 NTIS Ref. 786208.

Srinivasan V, and Ramamurth 1973 Wwather over the Indian seas during post-monsoon season India Meteorological Deptt. FMU, report. No. 41.

Stephen J Lord and James 1987, The environment of Hurricance Debby (1982) Part. I Winds Mon Was Rev. 115. 2760-2780.

Takashi K. 1939. Destribution of pressure and wind in a typhoon J Meteor. Soc. Japan- 2 17, 417 421.

Wang G. C. 1978 Sec. Level Pressure profile and gusts within a typhoon circulation Mon. Was. 106, 954-960.

Willoughby H. E. 1988. The dynamic of the tropical core aust. Meteor. Mag. 183-191.

Willoughby H. E. 1990 Temproal changes of the primary circulation in tropical cyclone. J atmos Sci. 47, 242-264.

Willoughby H. E. 1990 Gradients balance in tropical cyclone J. Atmos. Sci. 47, 2, 265-274.