# Parametric Typhoon Models for Determining Sea Level Pressure and Surface Wind Fields

Yueh-Jiuan G. Hsu

Marine Meteorology Center, Central Weather Bureau

## Abstract

**Pressure and wind fields, determined by an adequate parametric typhoon model based on predictive typhoon tracks, sizes and intensities, are very important for supplying the required meteorological forcing for a typhoon surge model. In this paper, nine parametric typhoon models, some of which are still in use on coastal engineering or on planting bogus vortices in numerical typhoon models, are reviewed. In summary, two different approaches are used in parametric typhoon models. One approach uses a standard wind profile, and then determines wind and pressure fields. They are Li(1979), SLOTH(1992), and Rankene vortex. Another approach uses a standard pressure profile, which includes Holland(1980), Liu(1985), FEMA(1988) and Lai(1995). Nevertheless, all above methods require good estimate of the radius of maximum wind, the maximum wind speed and the central pressure depression. A proposed parametric typhoon model for determining the sea level pressure and surface wind fields is presented, which includes a newly developed method for determining the radius of maximum wind. Three typhoons that crossed Taiwan, Herb in 1996, Winnie and Amber in 1997, are examined to verify the proposed parametric typhoon model. The results are very encouraging because the new method makes possible the determination of wind profile from readily available typhoon data incorporating all aspects of typhoon size and their corresponding wind speed.**

## 1. Introduction

Typhoon surges occur when a typhoon approaches a coastal area. These surges are mainly induced by the suction of sea water due to the central pressure depression and the piling up of sea water to the upstream side of the coast due to continuous blowing of strong winds. Therefore, the precision of dynamic forcing calculated from sea level pressure and surface wind fields of a typhoon model is very important for typhoon surge prediction. At present, those fields from numerical typhoon models are not available because most numerical typhoon modelers focus their attention on the predictive abilities of typhoon tracks instead of the accuracy on the pressure and wind fields in the lowest model layer. In addition, the grid resolution of a numerical typhoon model in tens of kilometers is too coarse to meet the need of a surge model and the predictive typhoon tracks contain uncertainties. In practice, pressure and wind fields determined by an adequate parametric typhoon model based on predictive typhoon tracks and intensities might be the best way to supply the required meteorological forcing for a typhoon surge model.

In Section 2, nine parametric typhoon models, some of which are still in use on coastal engineering or on planting bogus vortices in numerical typhoon models, will be reviewed. In Section 3, a proposed parametric typhoon model for determining the sea level pressure and surface wind fields will be presented, which includes a newly developed method for determining the radius of maximum wind. In Section 4, three typhoons that crossed Taiwan, Herb in 1996, Winnie and Amber in 1997, are examined to verify the proposed parametric typhoon model. Section 5 is the conclusions.

## 2. Review of some parametric typhoon models

Different typhoon types are shown in satellite pictures. For the same central pressure, the cloud bands of some typhoons are shrunken in size with a small, distinct eye, while those of other typhoons extend widely from a larger, less distinct eye or, in some cases, no discernible eye at all. It seems that typhoons in the West Pacific ocean are larger than hurricanes in the West Atlantic ocean. Probably the ocean environments cause this size difference. Typhoon is generally described as a circularly symmetric storm on an open ocean. However, the wind is not purely circumferential but has an inward radial component due to the surface friction. This inflow angle (or the ingress angle, the cross-isobar angle) should be considered in the wind field. In addition, forward motion of the storm center causes the wind field to be asymmetrical. This background flow field (or the basic flow field) should also be superimposed on the wind field, thus stronger winds appear on the right rear quadrant of the moving direction. Nine parametric models for wind and pressure profiles near typhoon centers and associated two-dimensional fields derived from those profiles are reviewed.

## 2.1 Li (1979)

Li (1979) developed a numerical prediction model of typhoon surges for the Taiwan Strait, and Li and Su (1987) designed a numerical model to study typhoon surges and tides in the seas adjacent to Taiwan. Li's approach defined the wind profile first, and then determined the pressure profile depending on that.

Li (1979) used a circular typhoon model proposed by Jelesnianski (1965) which used a standard wind profile to compute wind stress and to derive the associated air pressure distribution. The ingress angle across the circular isobars were assumed to be a constant of $30^\circ$. The wind velocity also modified by the velocity of a moving typhoon center depends on a weighting function of a distance from the center. The pressure distribution is determined by using the cyclostrophic wind balance in the typhoon domain. The air density is taken to be 1.173 $\times 10^{-3} gcm^{-3}$ and the surface wind is assumed to be proportional to the cyclostrophic wind by a factor, which determined by the maximum wind and the central pressure depression. Assuming the maximum wind and the radius of the maximum wind can be empirically estimated, the wind and pressure distributions are thus determined.

## 2.2 Holland (1980)

Holland (1980) presented an analytic model of the wind and pressure profiles in hurricanes. He followed Schloemer (1954)'s idea and then generalized it. The pressure profile is written as

$$p = p_c + (p_\infty - p_c)\exp\left(-\frac{A}{r^B}\right). \qquad (2.1)$$

Here $p_c$ is the central pressure and $p_\infty$ is the ambient pressure at great distance; $A$ and $B$ are scaling parameters. The associated gradient wind profile is

$$V_g = \sqrt{\frac{AB(p_\infty - p_c)\exp\left(-\frac{A}{r^B}\right)}{\rho_a r^B} + \frac{r^2 f^2}{4}} - \frac{rf}{2}. \qquad (2.2)$$

Here $\rho_a$ is the air density which is taken to be $1.15 \times 10^{-3} gcm^{-3}$. While in the region of maximum winds, the Coriolis force is small in comparison with the pressure gradient and centrifugal forces and the air is in cyclostrophic balance. The cyclostrophic wind profile is then given by

$$V_c = \sqrt{\frac{AB(p_\infty - p_c)\exp\left(-\frac{A}{r^B}\right)}{\rho_a r^B}} \qquad (2.3)$$

By setting $dV_c/dr = 0$, the radius of maximum wind $R_w$ is obtained,

$$R_w = A^{1/B}. \qquad (2.4)$$

Note that here $R_w$ is independent of the central pressure deficit $(p_\infty - p_c)$. The maximum cyclostrophic wind speed is obtained by setting $r = R_w$ in (2.3),

$$V_{cm} = C\sqrt{(p_\infty - p_c)}, \qquad (2.5)$$

where

$$C = \sqrt{\frac{B}{\rho_a e}}, \qquad (2.6)$$

and $e$ is the base of natural logarithms. Note that here $V_{cm}$ is independent of $R_w$, but depends on the parameter $B$. Holland (1980) introduced the parameter $B$ to define the shape of the pressure profile and the parameter $A$ to determine its location relative to the center. Physical reasoning indicated that B should be between 1 and 2.5. If there are sufficient observations in a typhoon domain, then $A$ and $B$ can be best determined by directly applying these data in Holland's model. In Schloemer's original relation, $A = R_w$ and $B$=1. Being constrained by a single profile of $B$ equal to 1, Schloemer's relation markedly underestimates the maximum winds and overestimates the radial extent of destructive winds in most hurricanes. Holland (1980) introduced the additional parameter $B$ to stand for the intensity measure of a storm. This has proved to be superior to the former method.

## 2.3 Liu (1985)

Liu (1985) developed a numerical model for tide and typhoon surge prediction in the Taiwan area. He used a similar radial pressure profile as in Holland (1980). He assumed the parameter $B$ linearly decreases from a central pressure 940 hPa to both two ends. He used the monthly area-mean sea level pressure as the ambient pressure, and estimated the radius of maximum wind as a function of the central pressure (while in Holland's result, the radius of maximum wind is independent of the central pressure deficit). He follows Holland's approach to obtain the gradient wind profile, which depends on the air pressure distribution. The air density is taken to be $1.226 \times 10^{-3} gcm^{-3}$. In estimating the surface wind, the moving velocity of a typhoon center is added to the gradient wind and the cross-isobar angle is considered under stable, neutral or unstable vertical temperature gradient. The cross-isobar angle has a maximum value when the air temperature is lower than the surface water temperature by $0.7^0 C$; the cross-isobar angle decreases when a typhoon moves toward the higher latitudes.

## 2.4 FEMA (1988)

The USA's Federal Emergency Management

Agency (FEMA) has developed a coastal flooding hurricane storm surge model, which is referred to as the FEMA model, for use in Flood Insurance Studies. The FEMA model is composed of a hydrostatic model and a hurricane storm model.

The pressure distribution in its hurricane storm model is described by (2.1) with $B$=1, which is the same as in Schloemer's relation. The ambient pressure is set to be 1,013hPa. FEMA model uses the maximum gradient wind to determine the hurricane wind field. The gradient wind usually applies at the top of the atmospheric frictional boundary layer, thus let the maximum 10-meter, 10-minute wind speed be related to he maximum gradient wind by a constant of 0.91. The hurricane wind distribution is given by an azimuthally symmetric part of wind field produced by the symmetric surface pressure field, and an asymmetrical part of the wind field produced by the forward motion of the storm by using empirical curve fitting coefficients vary with the radius of maximum wind. The inflow angle is also empirically variant with the radius of maximum wind and the radial distance from the center. When the eye of the storm moves over land, the storm weakens and the wind velocities reduce. The FEMA model includes this filling effect by specifying the time of landfall and the hourly reduction coefficients. Wind stresses are affected differentially by various land covers. Separate wind stress reduction factors are used for 5 general categories: wooded areas, marshland, open water, developed areas, and open land. As the wind passes from rough areas to areas with reduced roughness, the wind velocity, and hence the wind stress must build for several miles before reaching its open ocean value. This downwind sheltering effect is also considered.

## 2.5 SLOTH (1992)

The National Weather Service (NWS) has developed a tropical storm surge model called SLOSH, for Sea, Lake and Overland Surges from Hurricanes, to make real-time operational forecasts of storm surge heights.

The wind model used in SLOTH computes pressure and wind direction for a stationary, circularly symmetric storm. The equations are based on a balance of forces (Jelesnianski and Taylor, 1973; Myers and Malkin, 1961) containing two empirical friction constants. The wind speed profile is defined based on an undetermined maximum wind speed. Under iterative process, with an estimated maximum wind speed, a specified central pressure deficit and $R_w$, the equations are solved for pressure and inflow angle profiles. The maximum wind is adjusted in the process by matching the pressure gradients to the empirical friction and centrifugal terms. In the equations, stronger friction gives weaker winds but larger inflow angle, in other words, more convergence in the wind field. This compensated effect make the surge generated by the surge model is not so sensitive to the friction coefficients as the computed wind speed does. The wind vector is then corrected by the storm's forward motion vector where the local wind vector has been modified by the inflow angle. For inland water bodies, stronger friction is used and an additional correction for pressure distortion is included.

## 2.6 Lai (1995)

Lai (1995) constructed a dynamic and statistical algorithm for a probabilistic forecasting of storm surge. He used the same pressure profile as (2.8), while $p_\infty$ is taken to be 1,013hPa. For the wind distribution, Lai (1995) used an axis-symmetric cyclostrophic vortex superimposed on a basic flow. The empirical constant used in the maximum cyclostrophic wind speed implies that $\rho_a$ is equivalent to $1.1185\times10^{-3}gcm^{-3}$. A pair of simultaneously observed central pressure and maximum wind speed is necessary to determine the parameter $B$ as follows

$$B=\frac{1}{p_\infty-p_c}\left(\frac{V_m}{5.735}\right)^2 \qquad (2.7)$$

The radial profile of wind speed is therefore determined. When time series of these data are available, the evolution of the structure of the typhoon is well described.

## 2.7 Bogus Rankine vortex in CWB's TFM

Planting bogus typhoons in the Central Weather Bureau's Typhoon Forecast Model is necessary. The typhoon is approximated by a Rankine vortex, where the wind distribution implies that the typhoon is in solid body rotation inside the $R_w$, and is approximated to conserve relative angular momentum outside the $R_w$ because the air may loses momentum due to frictional dissipation. A coefficient $\chi$ in wind distribution is used to match the wind profile such that $V=V_m$ for $r=R_w$ and $V=V_7$ for $r=R_7$, where $V_7$ is the seventh Beaufort scale wind speed and $R_7$ is the radius of $V_7$. The parameter $\chi$ lies between 0.4 and 0.6 (Holland 1980). In CWB's TFM, $R_w$ is taken to be 45 km, which is one grid size of this model. In addition, the bogus vortex is blended with the three dimensional environmental flow, including a vertical weighting factor and a horizontal blending factor.

In summary, two different approaches are used in parametric typhoon models. One approach uses a standard wind profile, and then determines wind and pressure fields. They are Li (1979), SLOTH (1992), and Rankene vortex. Compare Li (1979) with Rankene vortex, and we see that Li uses fix $\chi$ but that is adjustable in Rankene vortex. The latter can give a good approximation to the wind profile if it had a very accurate estimate of $V_m$ and $R_w$. In SLOTH model, maximum wind speed, inflow angle and pressure distribution are adjusted by the balance of forces, so that the surge generation by surge model is not very sensitive to the friction coefficients due to the compensated effect. However, the SLOTH model needs a good estimate of $R_w$. Another approach uses a standard pressure profile, which includes Holland (1980), Liu (1985), FEMA (1988) and Lai (1995). The parameter $B$ calculated in Liu (1985) usually has larger value than other methods, while the parameter $B$ equal to 1 in FEMA (1988). For the same $R_w$ and $p_\infty - p_c$, the greater $B$ gives the steeper pressure profile and the larger maximum wind speed. Therefore, typhoons are shrunken in size in Liu's results, while typhoons extended widely in FEMA model results. In Lai (1995), $B$ is determined by a specified $V_m$ and $p_\infty - p_c$, and seems to have a reasonable value. For the same $B$, the smaller $R_w$ gives steeper pressure profile. The corresponding wind profile is derived by the gradient wind equation in Liu (1985), but by cyclostophic balance in Lai (1995). The calculated gradient wind speed decelerates which is lower than the maximum wind speed near $R_w$. However, the small gradient wind speed at great distance is more reasonable. In FEMA model, the wind profile is obtained by using the maximum gradient wind and curve fitting coefficients a and b. Nevertheless, all above methods require good estimate of the radius of the maximum wind, $R_w$, the maximum wind speed, $V_m$, and the central pressure depression, $p_\infty - p_c$.

## 3. A proposed parametric typhoon model

The typhoon track, intensity and size crucially affect the generated surge. In the operational use, track, intensity and some aspects of size can be determined by readily available typhoon data, such as locations of typhoon centers (latitudes and longitudes), the corresponding central pressure ($p_c$), the maximum wind speed ($V_m$), the radius of the seventh Beaufort scale wind ($R_7$), and the radius of the tenth Beaufort scale wind ($R_{10}$). All of these can be provided by the Weather Forecast Center of the Central Weather Bureau. However, one critical aspect of size, the radius of maximum wind ($R_w$), is not readily available. In fact, its accurate determination is extremely elusive. In my research, I determine the radius of maximum wind in the following way:

I match a gradient wind profile by using the known $p_\infty - p_c$, $V_m$, $R_7$ and $R_{10}$ to determine $R_w$ such that $V \cong V_m$ for $r = R_w$, $V \cong V_7$ for $r = R_7$ and $V \cong V_{10}$ for $r = R_{10}$. First, the parameter $B$ is determined by using (2.5-6),

$$B = \frac{V_m^{\ 2} \rho_a e}{p_\infty - p_c} \ . \tag{3.1}$$

Here the ambient pressure $p_\infty$ can be obtained by the first unenclosed isobar from a surface weather map, $\rho_a$ is taken to be $1.15 \times 10^{-3} gcm^{-3}$. Second, applying the gradient wind equation (2.2) to the seventh Beaufort scale wind,

$$V_7 = \sqrt{\left(\frac{R_w}{R_7}\right)^B \frac{B}{\rho_a}(p_\infty - p_c)\exp\left[-\left(\frac{R_w}{R_7}\right)^B\right] + \frac{R_7^2 f^2}{4}} - \frac{R_7 f}{2} \tag{3.2}$$

Then substituting (3.1) into (3.2), after some manipulations, I obtain

$$R_w^B = \left(\frac{R_7^B}{V_m^2 e}\right)\left[\left(V_7 + \frac{R_7 f}{2}\right)^2 - \frac{R_7^2 f^2}{4}\right]\exp\left(\frac{R_w^B}{R_7^B}\right) \tag{3.3}$$

The above equation can be rewritten as

$$x = C_1 \exp\left(\frac{x}{C_2}\right) , \tag{3.4}$$

where

$$x = R_w^B , \tag{3.5}$$

$$C_2 = R_7^B \tag{3.6}$$

and

$$C_1 = \left(\frac{C_2}{V_m^2 e}\right)\left[\left(V_7 + \frac{R_7 f}{2}\right)^2 - \frac{R_7^2 f^2}{4}\right] . \tag{3.7}$$

For solving (3.4), I use the ZREAL subroutine in IMSL Fortran Numerical Libraries to find the real zeroes of a real function

$$g(x) = C_1 \exp\left(\frac{x}{C_2}\right) - x = 0 \ . \tag{3.8}$$

There are two roots in (3.8) and only the smaller one fits the physical meaning in solution of (3.5). Note that $V_7$ and $R_7$ in (3.2) can be replaced by $V_{10}$ and $R_{10}$, so that two corresponding solutions of the radius of maximum wind ($R_{w\_7}$ and $R_{w\_10}$) can be obtained separately. The equivalent wind speed of Beaufort number 7 ($V_7$) is from 13.9 to 17.1 $ms^{-1}$, and that of Beaufort number 10 ($V_{10}$) is from 24.5 to 28.4 $ms^{-1}$. In my study, I found that $R_7$ provided by CWB has an overestimated bias and $R_{10}$ an underestimated bias. I recommend the use of $V_7$=13.9 $ms^{-1}$ and $V_{10}$=28.4 $ms^{-1}$; then the corresponding $R_{w\_7}$ and $R_{w\_10}$ are very close.

When $B$ and $R_w$ are determined, the gradient wind and the cyclostrophic wind profiles are then determined by (2.2) and (2.3) respectively. I present the following wind profile such that the wind speed near the typhoon center is the cyclostrophic wind speed but approaches the gradient wind speed in proportional to the distance from the typhoon center:

$$\begin{cases} V = V_c \quad \text{for} \quad r \le R_w \\ V = V_c\left(\frac{R_w}{r}\right) + V_g\left(1 - \frac{R_w}{r}\right) \quad \text{for} \quad r > R_w \end{cases} \quad (3.9)$$

The corresponding pressure profile is determined by (2.1), using of the same calculated $B$ and $R_w$ as in the wind profile.

## 4. Results and discussions

Three typhoons that crossed Taiwan, Herb in 1996, Winnie and Amber in 1997 (Fig. 1), are examined to verify the proposed parametric typhoon model. The corresponding typhoon data provided by CWB and the calculated $B$, $R_{w\_7}$ and $R_{w\_10}$ are shown in Table 1. The sea level pressure (solid lines) and surface wind profiles calculated by using $R_{w\_7}$ in Table 1 are shown in Fig. 1. The abscissa shows the radial distance in Km from the center. The right ordinate shows the central pressure difference in hPa. The left ordinate shows the wind speed in $ms^{-1}$. The upper broken lines represent the cyclostrophic wind profiles, in which the wind speed is equal to the maximum wind at $R_w$. The lower broken lines represent the gradient wind profiles. The calculated gradient wind speed decelerates, resulting in it being lower than the maximum wind speed near $R_w$. The dotted lines between two broken lines represent my proposed wind profiles calculated by (3.9), in which the wind speed near the typhoon center is the cyclostrophic wind speed but approaches the gradient wind speed in proportional to the distance from the typhoon center. The radius of the seventh Beaufort scale wind ($R_7$), and that of the tenth scale ($R_{10}$) provided by CWB and their corresponding wind speed $V_7$ ($13.9 ms^{-1}$) and $V_{10}$ ($28.4 ms^{-1}$) are also marked out in these figures. The results show that the new method makes possible the determination of wind profile from readily available typhoon data incorporating all aspects of typhoon size and their corresponding wind speed.

## 5.Conclusions

In this paper, nine parametric typhoon models, some of which are still in use on coastal engineering or on planting bogus vortices in numerical typhoon models, are reviewed. All methods require good estimate of the radius of maximum wind, the maximum wind speed and the central pressure depression. However, the critical aspect of size, the radius of maximum wind, is not readily available. In fact, its accurate determination is extremely elusive. A proposed parametric typhoon model for determining the sea level pressure and surface wind fields is presented, which includes a newly developed method for determining the radius of maximum wind. Three typhoons that crossed Taiwan, Herb in 1996, Winnie and Amber in 1997, are examined to verify the proposed parametric typhoon model. The results show that the new method for determining wind profiles is more efficient because its successfully demonstrates the relationship between typhoon size and corresponding wind speed. Nevertheless, this parametric typhoon model like others is still only suitable for the open sea area because it does not include a terrain effect. When a typhoon approaches Taiwan, the meso-scale phenomenon occurs due to the steep topography. More research is required on including this terrain effect to improve the typhoon pressure and wind field estimation.

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## References

Federal Emergency Management Agency (FEMA), Federal Insurance Administration, 1988: Coastal flooding hurricane storm surge model. Methodology, **1**, Washington, D.C.

Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.*, **108**, 1212-1218.

Jelesnianski, C. P.,1965: A numerical calculation of storm tides induced by a tropical storm impinging on a continental shelf. *Mon. Wea. Rev.*, **93**, 343-358.

Jelesnianski, C. P. and A. D. Taylor, 1973: A preliminary view of storm surges before and after storm modifications, NOAA Tech. Mem. ERL WMPO-3, NOAA, Dept. of Commerce, 33pp.

Jelesnianski, C. P., J. Chen and W. A. Shaffer, 1992: SLOTH: Sea, lake, and overland surges from hurricanes. NOAA Technical Report NWS 48, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 71pp.

Lai, C.-C. A., 1995: Probabilistic forecast of tropical cyclone-generated storm surge with a dynamic-statistical approach. *MTS Journal*, **26**, No. 2, 33-43.

Li, H.-W., 1979: Numerical prediction of typhoon surges along the coast area of Taiwan Strait. *Acta Oceanographica Taiwanica*, Science reports of the National Taiwan University, **10**, 50-66.

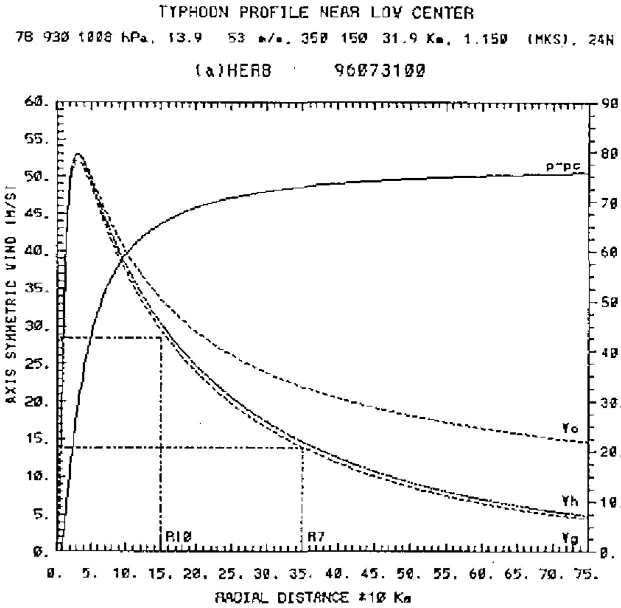
Li, H.-W. and K.-H. Su, 1987: A numerical model of typhoon surges and tides in the seas adjacent to Taiwan, *Acta Oceanographica Taiwanica*, **18**, 39-48.

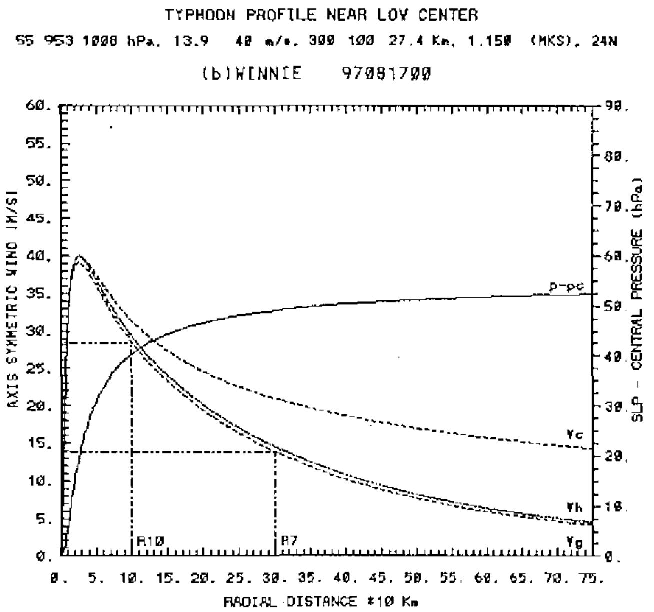
Liu, S.-K., 1985: A numerical typhoon surge model for Taiwan. Technical Reports of the Central Weather Bureau, TR-181, 107pp.

Myers, V. A., 1954: Characteristics of United States hurricanes pertinent to levee design for Lake Okechobee, FL. Hydromet. Rep., **32**, 126pp.

Myers, V. A. and W. Malkin, 1961: Some properties of hurricane wind fields, as deduced from trajectories. National Hurricane Research Report No. 49, U. S. Weather Bureau, Washington, D. C., 45pp.

Schloemer, R. W., 1954: Analysis and synthesis of hurricane wind patterns over Lake Okechobee. *FL. Hydromet Rep.*, **31**, 49pp.



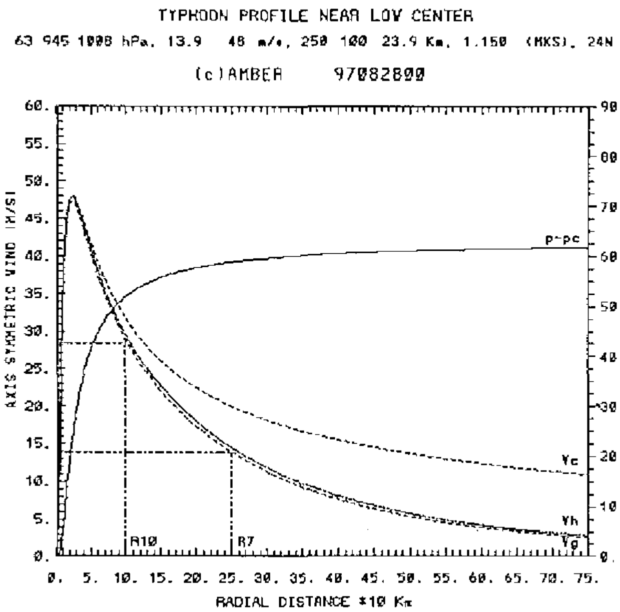




Fig. 1. The calculated sea level pressure and surface wind profiles for typhoon (a)Herb (b)Winnie (c) Amber

**Table 1. Typhoon data and the calculated parameter B and radii of maximum wind**

| Typhoon Name | Date yymmddhh | Lat degN | Lon degE | pc hPa | Vm Knots | R7 Km | R10 Km | pinf hPa | dp hPa | B | Rw_7 Km | Rw_10 Km |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Herb | 96073100 | 24.0 | 124.6 | 930 | 53 | 350 | 150 | 1008 | 78 | 1.12577 | 31.9 | 30.0 |
| Winnie | 97081700 | 24.5 | 128.3 | 953 | 40 | 300 | 100 | 1008 | 55 | 0.90939 | 27.4 | 27.0 |
| Amber | 97082800 | 20.7 | 123.7 | 945 | 48 | 250 | 100 | 1008 | 63 | 1.14323 | 23.9 | 23.2 |