Meteorol. Atmos. Phys. 47, 117–126 (1992)

Meteorology and Atmospheric Physics

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Printed in Austria

551.515.23

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Vortex Initialization for Typhoon Track Prediction

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With 8 Figures

Received September 29, 1991
Revised October 30, 1991

Summary

A shallow water single level primitive equation model is ideally suited for studying the motion of a tropical cyclone. Three factors seem to be important in the initialization, i.e. the size, intensity and the initial speed and direction of motion of the storm. This study presents the results of sensitivity studies on the above parameters in the definition of a synthetic idealized vortex. The sensitivity studies include results of experimental forecasts for typhoons Betty of 1987 and Dan of 1989. The results of these studies show that the initial size, intensity and direction and speed of motion show considerable sensitivity to the predicted track. Finally a summary of the track forecast errors through 72 hours are presented for these storms.

1. Introduction

In several models of numerical prediction of typhoon tracks the typhoon was considered as a vortex imbedded in a steering flow of its environment. The steering flow was determined from the removal of vortex circulation from the environmental circulation (Kasahara, 1957). This method was faced with considerable uncertainty since the steering flow was hard to isolate (Dong and Neumann, 1986). Another method advanced by Birchfield (1986) considered the typhoon circulation as an inseparable part of atmospheric circulations, in that study for its detailed description and forecast, the use of fine grid was proposed. During the last decade with the rapid development of super computers a number of high resolution models have been developed for predicting typhoon tracks (Krishnamurti and Oosterhof, 1989; Hitsuma, 1990, etc.). Mathur (1991) developed a procedure to insert an idealized vortex into the initial analysis of NMC's operational hurricane prediction model, QLM (Quasi-Lagrangian model). The input parameters for the vortex are the storm's central surface pressure (Pc), the pressure of the outermost closed isobar (Pb) and its distance (R) from the center.

The surface pressure Psfc(r) of the the idealized symmetric vortex is determined by:

$$\mathrm{Psfc}(r) = P\max - [\Delta p \exp(-x^2)]/(1 + ax^2)^{1/2}; \quad r < R$$

$$\mathrm{Psfc}(r) = Pb; \quad r \geqslant R \text{ (where } x = r/R)$$

The wind at the 1000 hpa level ($Vg(r)$) was obtained from the gradient wind law. Then the wind at any radial distance (r) and at any standard pressure level (p) was obtained from $Vg(r)$ and a set empirical functions related to p and r, i.e. an empirical vertical structure function.

The vortex data were merged with the gridded data by the relation:

$$X = wX_v + (1 - w)X_a$$

where $w = \cos\left(\frac{\pi}{2}\frac{r}{R}\right); \quad r < R;$

X_a = gridded data

X_v = vortex data

In a recent study, Demaria et al. (1990) examined the mean track forecast errors for a 6-year period, 1983–1988, for 4 models: CLIPER (CLImatology and PERsistence), NHC83 (National Hurricane Center's statistical model developed in 1983), MFM (Movable Fine Mesh model) and SANBAR (SANders BARotropic model).

The model NHC83 had the smallest mean errors and this was the only model which proved to be better than CLIPER for at all forecast periods from 12 to 72 hours. MFM had the largest errors at 12 and 24 h although it had a significant skill at 36 and 48 hr for the northern storms. For the southern storms (i.e. south of 25 °N) MFM had no skill at any forecast period.

In 1988, MFM was replaced by QLM (Quasi-Lagrangian model) and BAM (the beta and advection "barotropic-dynamical" model) for operational forecasts at NHC (National Hurricane Center). The mean forecast errors during the 1988 season showed that the performance of the QLM and MFM were similar, BAM was comparative with NHC83 and proved to be a useful guidance model. For the southern storms, SANBAR appeared to provide useful forecasts for 36–48 h. The track forecast errors were studied using a barotropic-dynamical model with slightly different initial position and motion of the storms. The results showed that initial position errors had a very small effect on the track forecasts except at 12 h. The initial storm motion had a significant effect on the average forecast error out to 72 h; several individual cases showed significant sensitivity to the initial motion. For the low latitudes (south of 20°), the statistical skill scores reviewed recently by Hitsuma (1990) and Neumann and Plissier (1981) suggest that sophisticated models have so far not proved superior to simple extrapolation or climatology-persistence methods for short range forecasts. In low latitude, with lack of observational data, the barotropic or equivalent barotropic models can be used for typhoon track forecast (Sanders et al., 1975). A deep-layer single level primitive equation model was developed and tested at the Florida State University for this problem. The novel feature of this study are that it includes a scheme for vortex initialization. For experimental forecasts, the initial observation data for wind components (u, v) and geopotential height (z) at 7 pressure levels 1000, 850, 700, 500, 300, 200 and 100 hpa are taken from the ECMWF's (European Center for Medium Range Weather Forecasts) final analysis. The input parameters for the typhoon track and intensity are included in our analysis. These are based on the annual tropical cyclone reports of GUAM-Joint typhoon warning center (1987, 1989).

2. Vortex Initialization

2.1 Equations of Vortex Tangential Wind and Geopotential Height

According to Milne-Thompson (1968), Andersson and Hollingsworth (1988) the tangential wind velocity (c) of a Rankine vortex can be described by a function of radial distance (r) as follows:

$$c = c_m \frac{r}{R_m}; \quad r \leqslant R_m \tag{1.1}$$

$$c = c_m \left(\frac{r}{R_m}\right)^{-\alpha}; \quad r > R_m \tag{1.2}$$

where c_m is the maximum tangential wind at the radial distance R_m; α is an empirical parameter with the value from 0.5 to 1.0. In this work, α equals 0.6. From Eqs. (1.1) and (1.2) we can compute the zonal and meridional components of vortex tangential wind.

The geopotential height (z) is assumed to be related with the wind by the formula of gradient wind:

$$\frac{\partial z}{\partial r} = fc + \frac{c^2}{r} \tag{2.1}$$

Replacing c from Eqs. (1.1), (1.2) into (2.1), after integration of (2.1), we have:

$$z(r) = \frac{c_m}{2}(fR_m + c_m)\left(\frac{r}{R_m}\right)^2 + c_1; \quad r \leqslant R_m \tag{2.2}$$

$$z(r) = \frac{fR_m c_m}{1-\alpha}\left(\frac{r}{R_m}\right)^{1-\alpha} - \frac{c_m{}^2}{2\alpha}\left(\frac{r}{R_m}\right)^{-2\alpha} + c_2; \quad r > R_m \tag{2.3}$$

R denotes the maximum radius of the bogus vortex (also signifies its size). In the hurricane track forecasting literature, a synthetic vortex, such as the one described in this sector is usually called a 'bogus' storm. We shall use this terminology to describe the Rankine like vortex in the rest of this paper. It is used as an input parameter for the vortex initialization in the

present study. Under the assumption of the continuity of the geopotential height at the radius R_m, we can eliminate c_1, c_2 in Eqs. (2.2), (2.3) and obtain the following equations:
with $r \leqslant R_m$:

$$z(r) = z(R) - \left[\frac{fR_m c_m}{2(1-\alpha)} \left\{ 2\left(\frac{R}{R_m}\right)^{1-\alpha} - (1+\alpha) - (1-\alpha)\left(\frac{r}{R_m}\right)^2 \right\} - \frac{c_m{}^2}{2\alpha} \left\{ \left(\frac{R}{R_m}\right)^{-2\alpha} - (1+\alpha) + \alpha\left(\frac{r}{R_m}\right)^2 \right\} \right] \tag{2.4}$$

with $r > R_m$:

$$z(r) = z(R) - \left[\frac{fR_m c_m}{1-\alpha} \left\{ \left(\frac{R}{R_m}\right)^{1-\alpha} - \left(\frac{r}{R_m}\right)^{1-\alpha} \right\} - \frac{c_m{}^2}{2\alpha} \left\{ \left(\frac{R}{R_m}\right)^{-2\alpha} - \left(\frac{r}{R_m}\right)^{-2\alpha} \right\} \right] \tag{2.5}$$

These equations allow us to compute $z(r)$ within as well as outside of the radius R_m, given the input parameters c_m, R_m, R and $z(R)$.

2.2 Expressions for Computing Typhoon Initial Movement

In the prediction of typhoon tracks over the low latitudes most statistical and synoptical methods have used the past 12 or 24 hours movement of typhoon as a predictor (Trinh, 1982, etc). Because of the lack of surface and upper air observations over the low latitude oceanic areas the typhoon's initial movement can be incorporated in the initialization to provide additional information. For this purpose the 3-hourly past positions, the position at time zero and the position 3 hours ahead of initial forecast time have been used to fit a polynomial of second order as follows:

$$x = a_1 t^2 + a_2 t + a_3 \tag{3.1}$$

$$y = b_1 t^2 + b_2 t + b_3 \tag{3.2}$$

here x, y are the latitudinal and longitudinal components of the typhoon track; t denotes time.

From Eqs. (3.1) and (3.2) the latitudinal and longitudinal velocities (u_0, v_0) of the typhoon's movement at initial forecast time can be easily obtained by differentiation with respect to t and setting $t = 0$ in the resulting expression, i.e.

$$u_0 = a_2; \quad (t = 0) \tag{4.1}$$

$$v_0 = b_2; \quad (t = 0) \tag{4.2}$$

2.3 The Merging of Vortex Bogus Data into the Initial Data Fields

Given u, v, z – the vertically integrated data at the grid locations of a single level primitive equation model; and U_b, V_b, Z_b – the bogus data computed from Eqs. (1.1), (1.2) and (2.4), (2.5). The initial movement of typhoon (U_0, V_0) can be added to U_b, V_b respectively. We shall denote by u^*, v^*, z^* as the data that is obtained from merging U_b, V_b, Z_b and u, v, z respectively;

The merging is carried out only for an inner vortex local grid which is shown in Fig. 1 a and Fig. 1 b. This local grid is determined by giving coordinates of the typhoon center and its maximum radius or size R. The formulae for the merging are as follows:

a) $0 \leqslant r \leqslant R_m$ (inside R_m region)

$$u^*(r) = U_b(r); \quad v^*(r) = V_b(r); \quad z^*(r) = Z_b(r); \tag{5.1}$$

b) $R_m < r \leqslant R$ (outside R_m region)

$$u^*(r) = U_b(r) \cdot rR/RR_m + u(r) \cdot rR_m/RR_m; \tag{5.2}$$

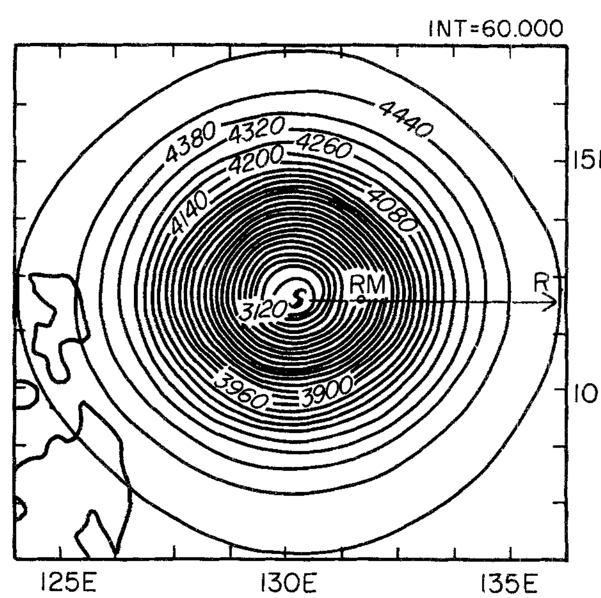

Fig. 1 a. Height of the free surface of the shallow water. This shows the analysis of the bogus vortex with the radius of maximum wind at 150 km and size of vortex equal to 650 km. Interval of analysis is 60 m. Date: August 10, 1987, 12UTC. Super Typhoon Betty is modeled here

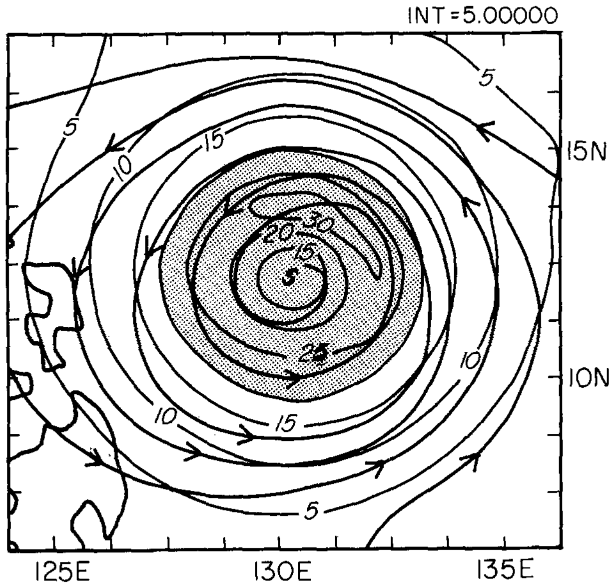

Fig. 1 b. Same as Fig. 1 a except it illustrates the streamlines and isotachs (ms^{-1}) at the free surface

where rR, rR_m, RR_m are the distances from r to R, from r to R_m and from R to R_m.

The formulae for $v^*(r)$ and $z^*(r)$ are similar to those given in Eq. (5.2). Equations (5.1) and (5.2) imply that inside R_m, the merged data contain the bogus storm; outside R_m the interpolated data uses the distance based on the ratio of rR and rR_m. At $r = R_m$ the merged data is set equal to the bogus data; where as $r = R$ the merged data is set equal to the observational data. Figures 1 a, b illustrate the merged initial data for the geopotential field, streamlines and isotachs at the free surface for Super Typhoon Betty, 1987 August 10, 12 UTC. The coordinates of typhoon center are 130.7 °E, 12 °N; Here $R = 650$ km; $R_m = 150$ km; $C_m = 85$ kt.

3. The Results of Experimental Forecasts

3.1 *The Forecast Model*

The deep layer mean primitive equation forecast model is based on the following equations:

$$\frac{Du}{Dt} = -g\frac{\partial z}{\partial x} + fv \tag{6.1}$$

$$\frac{Dv}{Dt} = -g\frac{\partial z}{\partial y} - fu \tag{6.2}$$

$$\frac{Dz}{Dt} = -z\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{6.3}$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y};$$

u, v, z – are the initial input data, vertically integrated from 7 pressure levels: 1000, 850, 700, 500, 300, 200 and 100 hpa. The weight for the vertical integration for u, v are 75/700; 150/700; 175/700, 150/700; 75/700; 50/700; 25/700 respectively for the above-mentioned pressure levels. The geo-potential is obtained from a dynamic normal mode initialization. A grid of 65 × 49 points with a resolution of 1.25 degrees in the latitude and longitude is used. The details of the model will not be presented here since it is described in detail previously in Krishnamurti et al. (1987), Yap (1987).

3.2 *The Effect of the Vortex Size Upon its Movement*

The effect of tropical cyclone structure on the vortex motion have been studied by numerous authors in recent years (Chan and Gray 1982, Holland 1983, Fiorino and Elsberry 1989, etc.). In these studies it is shown that the nonlinear advection terms in the barotropic vorticity equation contribute to the displacement of the vortex. In a number of these studies the difference between "steering" flow vector and the storm motion vector was noted to be a function of the vortex size and intensity. These studies gave us some estimates on the optimal size for the vortex initialization for 3 day forecasts of typhoon tracks. The sizes of the bogus vortex was varied from 550 km to 650 km and 750 km. The results from the first and the second experimental forecasts are presented in Figs. 2 a, b. These refer to Super Typhoon Betty of August, 1987. In these forecasts the radius of maximum wind (R_m) was assigned a value 150 km. The maximum wind (C_m) at the initial time was taken from the data described in the 1987 annual tropical cyclone report of the Joint Typhoon Warning Center. For the first experiment it was assigned a value of 43 ms^{-1} and for the second experiment it was set to 50 ms^{-1}. The maximum wind data were multiplied by a factor (equal to 0.9) in order to derive a maximum wind data for the deep-layer mean. In these experiments the vortex initialization does not include the initial movement of the

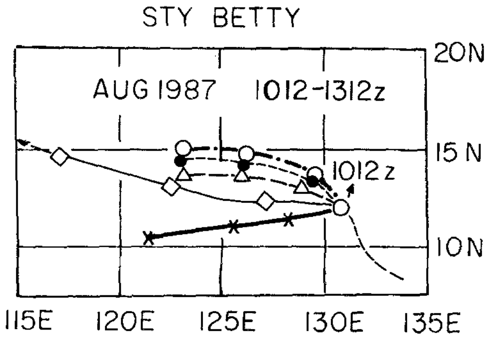

Fig. 2 a. Track of Super Typhoon Betty between August 10, 1987 12 UTC to August 13, 1987 12 UTC. Diamond denotes 24 hourly positions for the best track. Here we have experimented with different sizes S of the bogus storm. The open circles denote the track for $S = 750$ km; the closed circles denote the track for $S = 650$ km; triangle $S = 550$ km. The crosses denote position of storm where no bogus storm was used initially

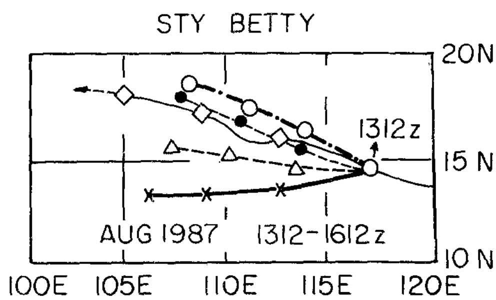

Fig. 2 b. Same as Fig. 2 a except for a different initial start date, i.e. August, 13, 1987, 12 UTC

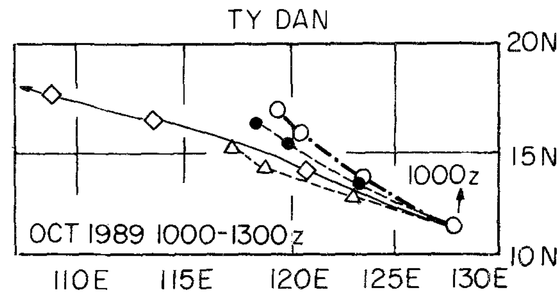

Fig. 3 a. Track of Typhoon Dan between October 10 to Octrober 13, 1989, 00 UTC. The diamond denotes 24 hourly position for the best track of storm. The sensitivity to the maximum wind Cm of the bogus storm is illustrated here. Diamond denotes observed positions of best track. Open circles denote Cm = 40 ms^{-1}; closed circle Cm = 30 ms^{-1}; triangle Cm = 20 ms^{-1}

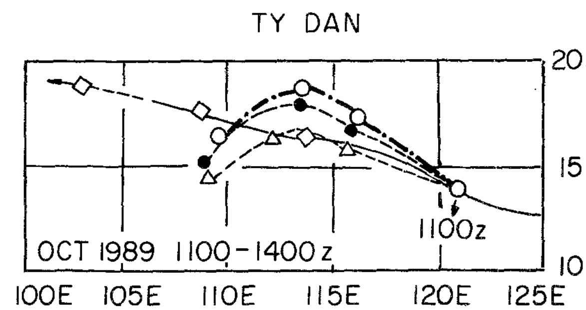

Fig. 3 b. Same as a Fig. 3 a expect for a different starting date, i.e. October 11, 1989 , 00 UTC. Here the best track is denoted by the diamond, whereas the open circle has Cm = 42.5 ms^{-1}; closed circle Cm = 32.5 ms^{-1} and triangle Cm = 22.5 ms^{-1}

vortex. The results of these forecasts show that the larger size of the bogus vortex contributes to a more northwestward movement of the typhoon center. A 650 km size for the bogus vortex yielded the best typhoon track forecasts. Furthermore we noted a slowdown of typhoon movement with the inclusion of the bogus vortex as contrasted with its exclusion. This slowdown appears to be in accordance with the storm's motions.

3.3 The Effect of Vortex Intensity upon its Movement

The effect of the initial intensity of the vortex upon its movement was studied from two experimental forecasts for Typhoon Dan in October 1989. In these forecasts we set $R_m = 150$ km, $R = 650$ km and C_m is varied by minus and plus 10 ms^{-1} from the best estimates based on the observational values. In these experiments the initial movement of Typhoon Dan was not invoked. The results of 3-day forecasts of the typhoon track are presented in Figs. 3 a, b. In the first case the observed maximum wind was 30 ms^{-1} while for the second case – it was 33 ms^{-1}. The forecast results show that the addition (or subtraction) to the maximum wind from its observed value by 10 ms^{-1} had a considerable influence on the typhoon's predicted track. The typhoon had a more northwestward motion when the maximum wind was increased by 10 ms^{-1}.

3.4 The Effect of Typhoon's Past Movement on the Track Forecast

The initial movement of the typhoon computed from Eqs. (4.1) and (4.2) were added to the tangential wind of the bogus vortex. The input parameters of bogus vortex are: $R_m = 150$ km; $R = 650$ km, $C_m =$ observed maximum wind. In Figs. 4 a, 4 b, 4 c and 4 d we present the results for the Super Typhoon Betty, 1987 and Typhoon

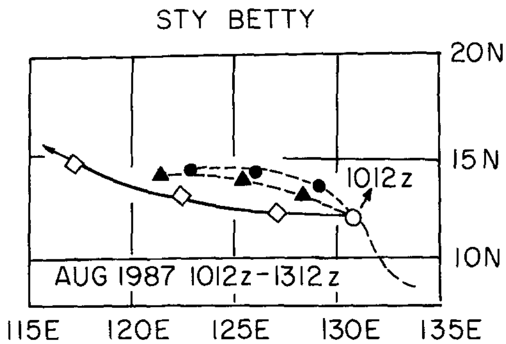

Fig. 4a. A comparison of the best track (diamond), is made with (triangle) and without (closed circle) the initial movement of the bogus vortex for Super Typhoon Betty between August 10 to August 13, 1987, 12 UTC. Here the intial movement is given by $U_0 = -2.59\,\mathrm{ms}^{-1}$; $V_0 = 1.21\,\mathrm{ms}^{-1}$

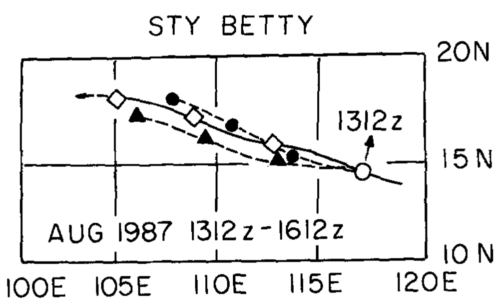

Fig. 4b. Same as Fig. 4a except for a different initial date, i.e. August 13, 1987 12 UTC, here $U_0 = -6.00\,\mathrm{ms}^{-1}$, $V_0 = 3.06\,\mathrm{ms}^{-1}$

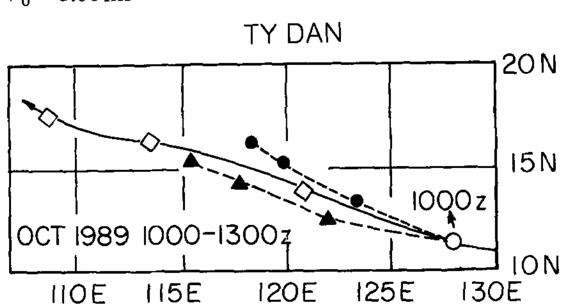

Fig. 4c. Same as Fig. 4a except for Typhoon Dan starting on October 10, 1989 00 UTC; here $U_0 = -11.68\,\mathrm{ms}^{-1}$, $V_0 = 3.31\,\mathrm{ms}^{-1}$

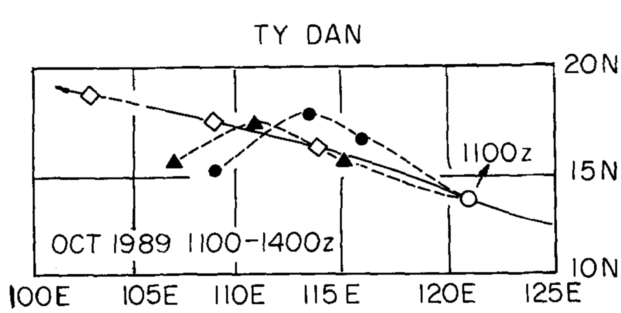

Fig. 4d. Same as Fig. 4a except for Typhoon Dan starting on October 11, 1989 00 UTC; here $U_0 = -10.06\,\mathrm{ms}^{-1}$, $V_0 = 4.04\,\mathrm{ms}^{-1}$

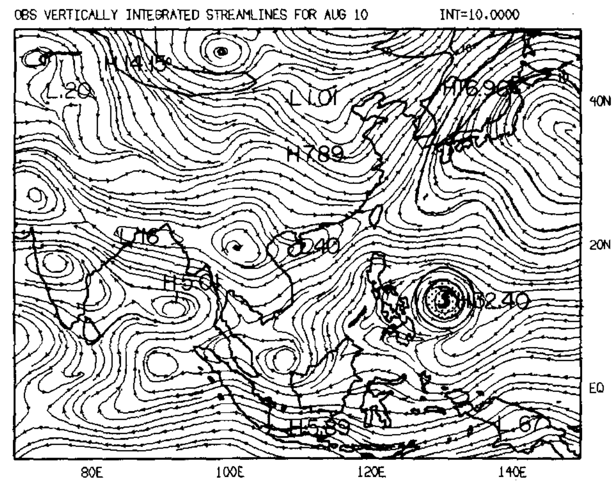

Fig. 5a. Initial streamline field for Super Typhoon Betty, August 10, 1987 12 UTC (with bogus vortex plus typhoon's initial movement). The figures indicate the wind speed in ms^{-1}

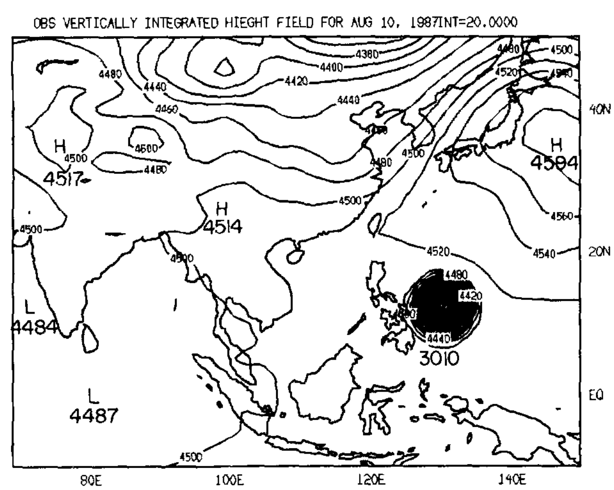

Fig. 5b. Initial geopotential height field for Super Typhoon Betty, August 10, 1987, 12 UTC (with bogus vortex). Interval of analysis 10 m

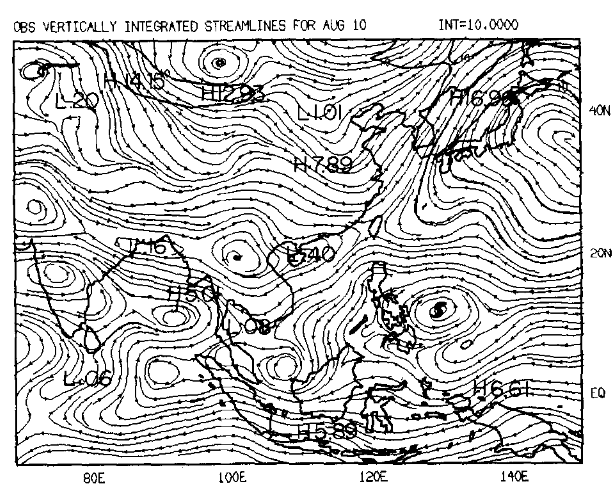

Fig. 5c. Initial streamline field for Super Typhoon Betty, August 10, 1987, 12 UTC (without bogus vortex). The figures indicate the wind speed in ms^{-1}

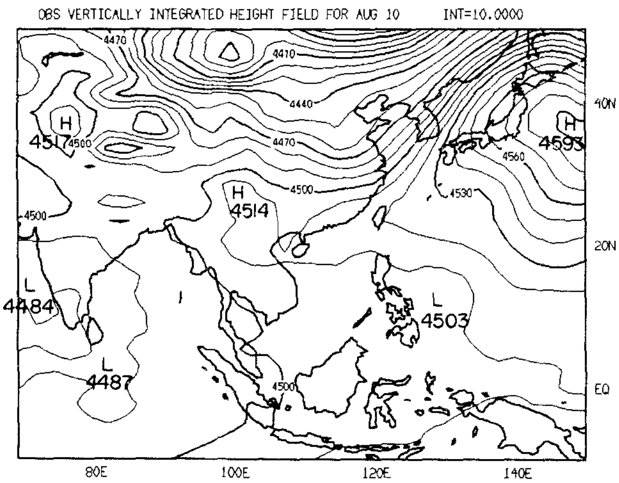

Fig. 5 d. Initial geopotential height field for Super Typhoon Betty, August 10, 1987, 12 UTC (without bogus vortex). Interval of analysis 10 m

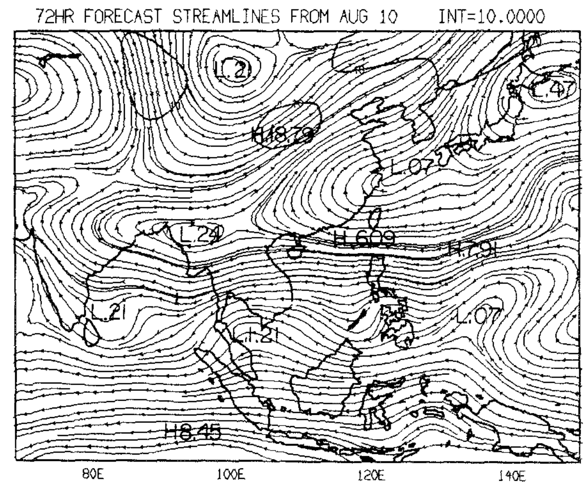

Fig. 6 c. 72-h forecast of streamline field for Super Typhoon Betty, August 13, 1987 12 UTC (without bogus vortex). The figures indicate the wind speed in ms^{-1}

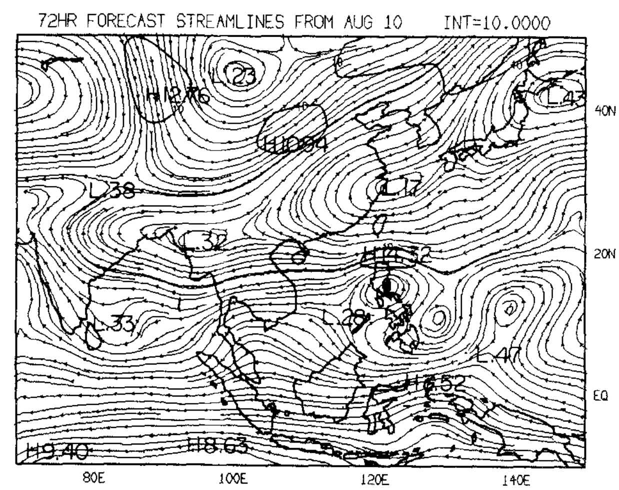

Fig. 6 a. 72-h forecast of streamline field for Super Typhoon Betty, August 13, 1987, 12 UTC (with bogus vortex plus typhoon's initial movement). The figures indicate the wind speed in ms^{-1}

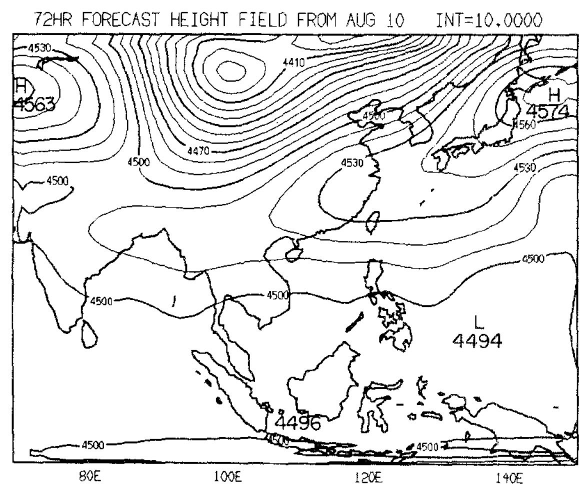

Fig. 6 d. 72-h forecast of geopotential height field for Super Typhoon Betty, August 13. 1987 12 UTC (without bogus vortex). Interval of a analysis 10 m

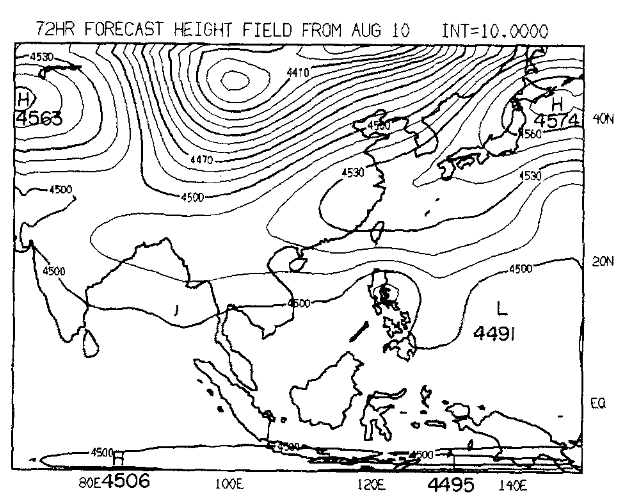

Fig. 6 b. 72-h forecast of geopotential height field for Super Typhoon Betty, August 13, 1987, 12 UTC (with bogus vortex). Interval of analysis 10 m

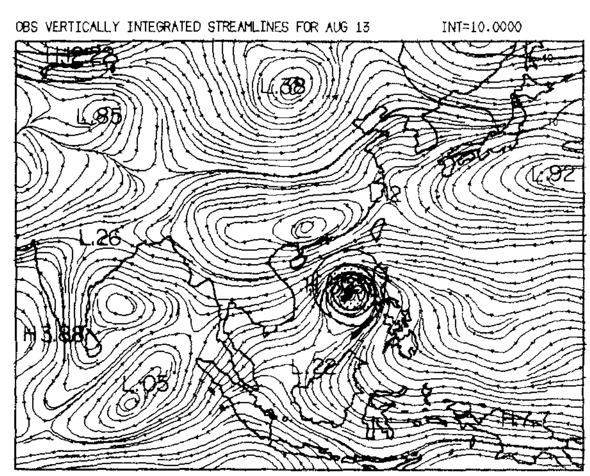

Fig. 7 a. Initial streamline field for Super Typhoon Betty; August 13, 1987 12 UTC (with bogus vortex plus typhoon's initial movement). The figures indicate the wind speed in ms^{-1}

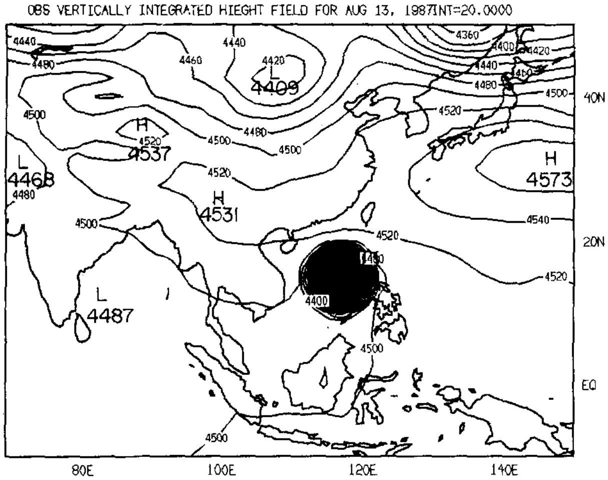

Fig. 7 b. Initial geopotential height field for Super Typhoon Betty, August 13, 1987 12 UTC (with bogus vortex). Interval of analysis 10 m

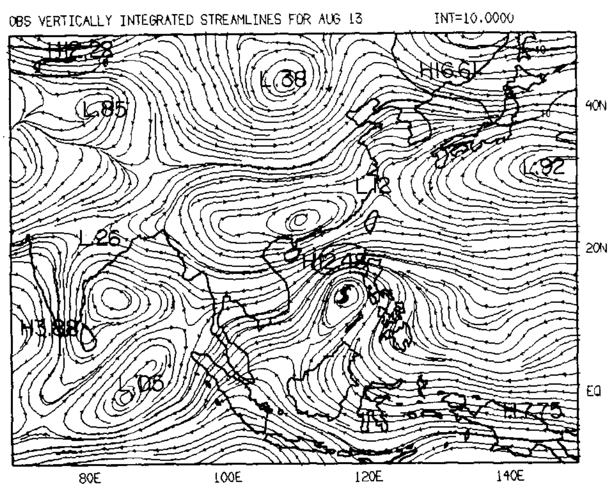

Fig. 7 c. Initial streamline field for Super Typhoon Betty, August 13, 1987 12 UTC (without bogus vortex). The figures indicate the wind speed in ms^{-1}

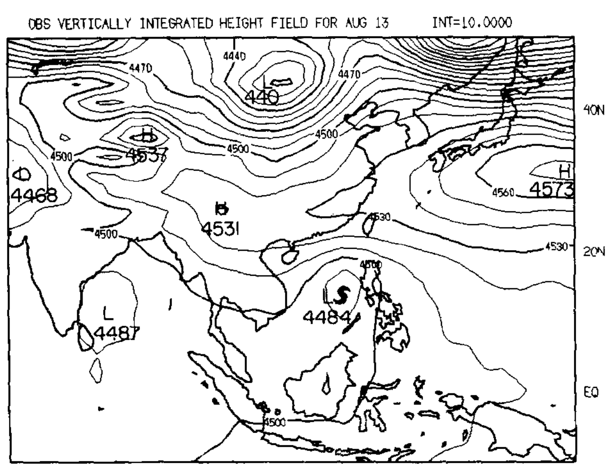

Fig. 7 d. Initial geopotential height field for Super Typhoon Betty, August 13, 1987 12 UTC (without bogus vortex). Interval of analysis 10 m

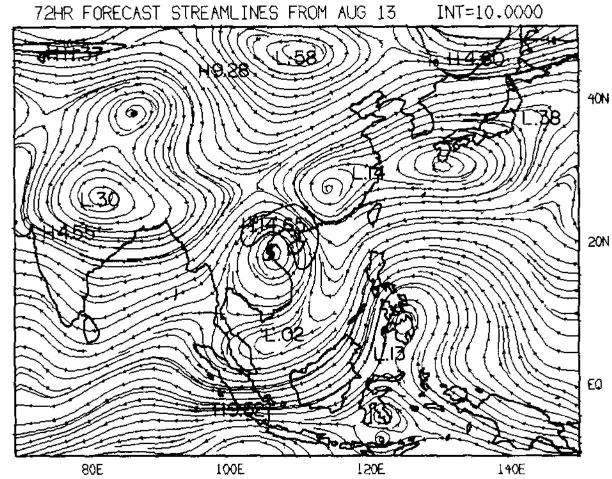

Fig. 8 a. 72-h forecast of streamline field for Super Typhoon Betty, August 16, 1987 12 UTC (with bogus vortex plus typhoon's initial movement). The figures indicate the wind speed in ms^{-1}

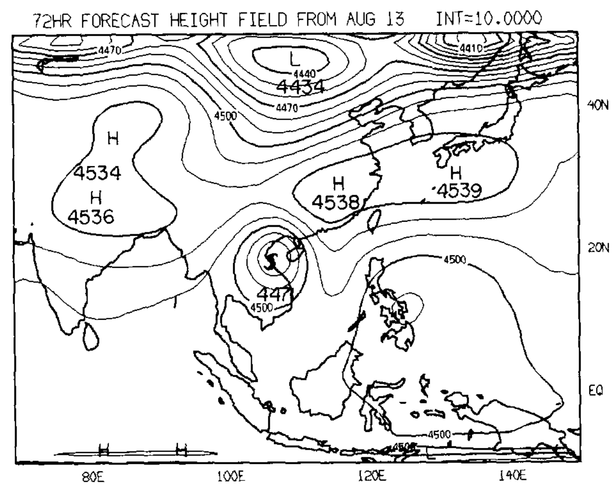

Fig. 8 b. 72-h forecast of geopotential height field for Super Typhoon Betty, August 16, 1987 12 UTC (with bogus vortex). Interval of analysis 10 m

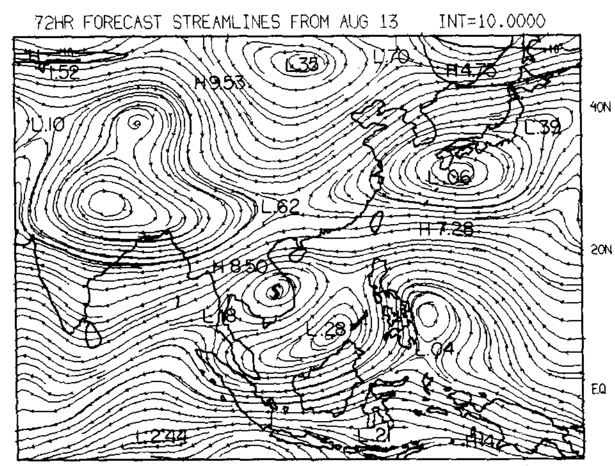

Fig. 8 c. 72-h forecast of streamline field for Super Typhoon Betty, August 16, 1987 12 UTC (without bogus vortex). The figures indicate the wind speed in ms^{-1}

Table 1. *The Errors of Typhoon Position Forecasts, ΔR (km)*

Typhoon	Init. Fcst Date	ΔR_{12}	ΔR_{24}	ΔR_{36}	ΔR_{48}	ΔR_{60}	ΔR_{72}
Betty	87 Aug 10	85	155	289	311	333	445
Betty	87 Aug 13	42	78	112	133	135	144
Dan	89 Oct 10	110	211	389	522	666	788
Dan	89 Oct 11	142	156	213	244	367	558
	Mean	95	150	251	303	375	484

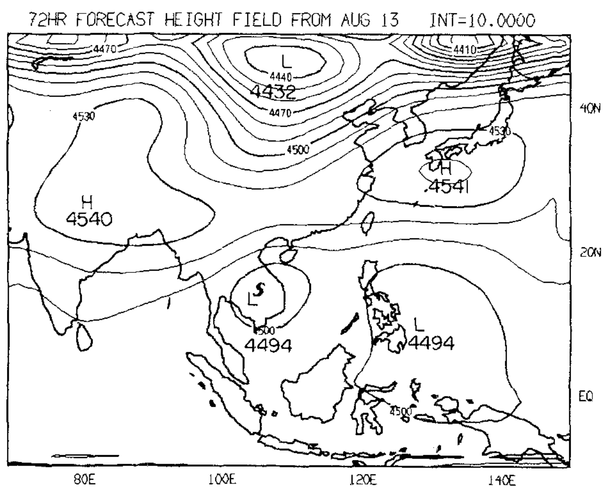

Fig. 8 d. 72-h forecast of geopotential height field for Super Typhoon Betty, August 16, 1987 12 UTC (without bogus vortex). Interval of analysis 10 m

Dan, 1989. Below each of these figures we indicate the initial movement vector (U_0, V_0) of each typhoon. Typhoon Dan moved twice as fast as Super Typhoon Betty with a speed about 40 km/hr. We find that in all of these forecasts the addition of the typhoon's initial movement resulted in a better forecast for both the direction and the speed of typhoon's motion; although the predicted movement of each typhoon was a noticeably slower, especially for Typhoon Dan of 1989.

The errors of typhoon position forecasts (with addition of typhoon initial movement into bogus vortex) are shown in Table 1 above.

In Table 1 ΔRj – denotes the distance errors between the predicted and the observed positions relative to 12, 24, 36, 48, 60 and 72-hour forecasts.

The forecast errors shown in Table 1 suggests that the forecasts based on the proposed scheme of bogus vortex initialization is promising.

For example, the initial fields of streamlines and geopotential heights with and without vortex initialization for Super Typhoon Betty in August 1987, 1012 UTC are shown in Figs. 5 a, 5 b and in Figs. 5 c, 5 d respectively. The 72-h forecasts of these fields are presented in Figs. 6 a, 6 b and in Figs. 6 c, 6 d respectively.

The same initial fields for this typhoon at 1312 UTC (with and without bogus vortex initialization) are shown in Figs. 7 a, 7 b, 7 c and 7 d. Their 72-h forecasts are shown in Figs. 8 a, 8 b, 8 c and 8 d respectively.

These figures demonstrate clearly an improvement in the typhoon track forecasts from the proposed bogus vortex initialization.

4. Conclusion

The results of some limited tests on typhoon motion with a shallow water single level primitive equation model are carried out in this study. The new areas of study are in the sensitivity of storm motion forecasts to three aspects of initialization. These include the variation in the initial intensity, size, direction and speed of initial motion of the typhoon. We find that a more northwestward motion is favored with increasing size of the vortex. The bogus storm is a Rankine – like vortex that was based on an analytical formulation. The optimal size of a bogus storm seems to be around 650 km. This is not surprising since the large size encounters a larger β drift. This optimal size may be more relevant to the large typhoons of the Western Pacific ocean. In specifying the intensity of the bogus storm we experimented with storm's intensities $\pm 10\,\mathrm{ms}^{-1}$ of the reported storm speed. We noted that the best results were obtained when the storm's intensity was at least $10\,\mathrm{ms}^{-1}$ larger than best estimate provided by the joint typhoon warning center at Guam. In order to incorporate the immediate past motion around the initial state we incorporated the past ($t_0 - 3h, t_0 - 6h, t_0 - 9h, t_0 - 12\,h$), initial ($t_0$) as well as the future ($t_0 + 3\,h$)

positions via a quadric interpolation scheme. The initial storm asymmetry was constructed from this motion. It was noted that this led to a significant improvement the typhoons investigated in this study. We have presented results of track forecast errors for two typhoons starting on different initial dates. Results of 4 experiments are summarized here. Further studies are being continued on a larger sample of storms.

Acknowledgements

This study is a part of training program of Trinh Van Thu, a WMO fellow at Florida State University. The authors deeply acknowledge the kind assistance of WMO, Meteorological Department of Florida State University for providing him with good conditions during his study.

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