Improvement of Numerical Prediction of Typhoon Tracks in the Western North Pacific Basin near Taiwan

MELINDA S. PENG,* DER-SONG CHEN, SIMON W. CHANG,† C.-P. CHANG,* AND B.-F. JENG

Central Weather Bureau, Taipei, Taiwan, Republic of China

(Manuscript received 28 February 1994, in final form 7 December 1994)

ABSTRACT

In an effort to improve the tropical cyclone track forecast, two preprocessing procedures are applied to an operational baroclinic forecast system at the Central Weather Bureau (CWB) in Taipei. The first replaces the environmental wind field near the storm by the previous 6-h movement vector of the storm. The second incorporates a wavenumber-1 asymmetry constructed by matching the flow at the center of the asymmetry with the previous 6-h storm movement. Applying both processes to the 32 typhoon cases archived at the CWB in 1990 reduces the averaged 48-h forecast distance error from 474 to 351 km.

Multiexisting typhoons may have interactions among themselves that depend on relative intensity. Proper representation of the intensities in the initial bogus is important for the track forecast. Experiments with different initial bogus intensities are conducted on a case of dual typhoons—Nat and Mireille in 1991. The forecast using different bogus vortices according to the estimated intensities of each typhoon gives substantially smaller errors than that using identical bogus vortices. The impact of initial bogus vortex intensity on the track forecast for single typhoon cases is also illustrated.

1. Introduction

Due to the lack of sufficient observations over open oceans, tropical cyclone circulations and surrounding environmental flows are usually not well analyzed in numerical forecast models. This problem is especially serious over the western North Pacific where observation stations are sparse and typhoon reconnaissance flights have been terminated since 1987. Therefore, the bogus of an initial vortex circulation in numerical typhoon forecast models becomes more critical without information from the flights. There are basically three approaches to bogus initial vortices (Peng et al. 1993). The first is to bogus synthetic observation data around the cyclone before analysis. The second is to include in the analysis fields a prescribed vortex in a gradient balance. The third is to bogus into the initial analysis a complete vortex circulation that includes the thermodynamic structure generated in a spinup procedure. In this study, we present the results of applying two preprocessing procedures for improving the initial conditions and the forecasts. The procedures involve adjusting the environmental flow and adding asymmetry to the bogus vortex.

Based on the fact that climatology and persistence models usually outperform other dynamical models in the first 12-h forecast, DeMaria (1987) proposed that past storm movement may provide a better environmental steering flow than what can be realized from the analyzed initial field. With a barotropic model and testing hurricanes in the Atlantic Ocean, DeMaria demonstrated that incorporating the past storm movement improved the 12-h track forecast by 30% and the 48-h forecast by 10%. Since there are even less observation data in the analysis to define the initial condition in the western North Pacific basin, DeMaria's suggestion provides a promising alternative. The effect of adjusting the environmental flow following DeMaria (1987) will be tested in this study.

The vortex structure bogussed into a dynamical model is usually axisymmetric so that it does not contain a wavenumber-1 asymmetry due to planetary vorticity variation (Fiorino and Elsberry 1989). When a vortex without this wavenumber-1 asymmetry is used in a dynamical model, it takes some time (typically 12 h) to generate the asymmetry with nonuniform planetary vorticity in the model (Carr and Elsberry 1992). During this period, the initial vortex undergoes an adjustment process and the forecast track may deviate from the observed track due solely to this adjustment. One way of introducing this asymmetry is to spin up a vortex on a β plane with zero-mean flow. This vortex contains a wavenumber-1 asymmetry that produces a

---

* Permanent affiliation: Department of Meteorology, Naval Postgraduate School, Monterey, California.

† Permanent affiliation: Naval Research Laboratory, Monterey, California.

Corresponding author address: Melinda S. Peng, Department of Meteorology, Code MR/pg, Naval Postgraduate School, Monterey, CA 93943-5114.

net acceleration toward the northwest (Chan and Williams 1987; Fiorino and Elsberry 1989; Peng and Williams 1990). Note that the spunup vortex also contains asymmetric structure generated by diabatic processes during the spinup period. When this vortex is used for bogussing, an initial northwest track bias is introduced (Peng et al. 1993). In this study, the effect of using a wavenumber-1 asymmetry constructed by matching the flow at the center of the asymmetry with the typhoon's previous movement will be tested. Similar to the incorporation of a wavenumber-1 asymmetry in our study, a dipole structure has been adopted in the Quasi-Lagrangian Model (QLM) for hurricane forecasts at the National Meteorological Center (Mathur 1991). Two types of dipoles were used in the QLM. The first type is constructed with a westerly steering flow so that the dipole is always oriented westward (westerly dipole). This is to correct the general northward bias of the forecast track due to a north-oriented asymmetry by the westward displacement of the initial storm center in the analysis. The second one is a generalized dipole constructed with previous 12-h storm movement. Incorporating either led to improvement of the storm track forecast for the QLM.

A more complicated bogussing procedure is used in the GFDL Multiply nested Movable Mesh (MMM) hurricane model (Kurihara et al. 1993; Bender et al. 1993). A spinup procedure is carried out first using the axisymmetric version of the model where the tangential wind is forced to a target wind profile determined from available observations and empirical knowledge. During the spinup time, all the model physics are retained. The resultant symmetric flow is then used in a barotropic model (Ross and Kurihara 1992) to generate the asymmetry on a β plane. The symmetric and asymmetric flow are then bogussed into a smoothed environmental field. The results from the MMM using this initialization procedure are very promising. The major difference between the asymmetry constructed by Kurihara et al. (1993) and the one constructed in our study (or the one in Mathur 1991) is that the former one does not use the information of the previous storm movement whereas the latter does.

The model used to examine the effect of the aforementioned two preprocessing procedures in this study is the operational Typhoon track Forecast System (TFS) at the Central Weather Bureau (CWB) in Taipei, Taiwan. The TFS, which became operational in January 1990, is a limited-area 3D primitive equation model dedicated to the forecast of typhoon tracks in the western North Pacific. The model has a 70-km horizontal resolution with a domain of 8400 km × 6160 km centered near Taiwan, and nine σ levels in the vertical. The system contains its own objective analysis and initialization procedure with the first guess fields from the Global Forecast System (GFS) (Liou et al. 1989), which also provides the boundary values for the TFS. Due to computer constraints and operational scheduling requirements, the TFS is run before the GFS at each watch and thus uses 12-h-old forecasts from the GFS as boundary conditions. This schedule degrades the forecast of the TFS but is unavoidable under current available resources. The system is run only when there is at least a typhoon in the western North Pacific that posts potential threat to Taiwan and its vicinity. Detailed description of the TFS can be found in Peng et al. (1993).

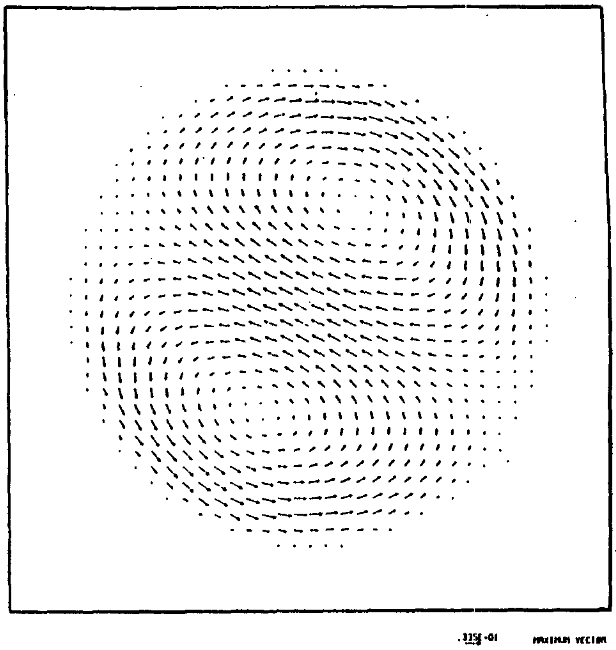


FIG. 1. Wind vector of the wavenumber-1 asymmetry constructed by matching the central flow of it to a northwest storm movement. The distance between centers of the two vortices is the half wavelength $r_{\max}$ in Eq. (3).

The TFS uses a spinup procedure to generate a model-balanced vortex for bogussing and has an artificial heating enhancement to supplement the Kuo cumulus parameterization in order to maintain the vortex intensity during forecast integration. In the spinup procedure, an initial Rankine-like vortex is specified on an f plane in a typical tropical sounding without a mean flow. The vortex is spun up in a 96-h integration of the TFS, with all the physics retained to obtain a model-balanced quasi-steady vortex. Instead of carrying out the spinup procedure every time, three vortices of different intensity and size are spun up and saved, using different sea surface temperatures and initial maximum winds. One of these three spunup vortices is chosen for bogussing according to the estimated intensity and size of the typhoon. When the estimated minimum sea level pressure is less than or equal to 985 hPa, only one spunup vortex will be used for bogussing. When the estimated minimum sea level pressure is greater than 985 hPa, two spunup vortices can be chosen depending on the estimated radius of gale-force wind (Table 1 in Peng et al. 1993). A hyperbolic tangent weighting function is applied in bogussing, such that all the data fields from the spunup vortex within 630-km radial distance from the typhoon center are added to the analysis. Between 630 and 840 km, the weighting of the bogus vortex is decreased from one at the distance of 630 km to zero at 840 km. The artificial heating is designed to maintain the mean radial gradient of the temperature of the vortex in the forecast model to be no less than 50% of that in the initial spunup vortex.

Performance of the TFS during 1989–1991 has been reported in Peng et al. (1993). The averaged 48-h forecast position error during the operational checkout period before 1990 is 415 km (62 cases). The 48-h forecast error for 1990, the first year of operation, is 395 km (64 cases). The model performance is comparable to the One-way interactive Tropical Cyclone Model (OTCM), one of the U.S. Navy's primary operational numerical track models in the western North Pacific. Continuing research and development for the TFS are carried out, and modification of the system is implemented each year prior to the typhoon season.

The two preprocessing procedures—the replacement of analyzed environmental flow in the typhoon's vicinity by previous storm movement and the incorporation of wavenumber-1 asymmetry—are tested on archived 1990 typhoon cases. The results are reported in section 2. In section 3, we will report the results of two experiments in studying the impact of intensity of the bogus vortex on the track forecast. The first is on a multityphoon case (Typhoons Nat, Mireille, and Tropical Storm Luke of 1991), and the second is on a single typhoon case (Typhoon Walt of 1991). The forecast errors of the TFS for 1991 and 1992 typhoons, and comparison with the Climatology and Persistence Model (CLIPER) and the OTCM are given in section 4. Summary of this study and future plans are given in section 5.

2. Preprocessing procedures with persistence and asymmetry

a. Persistence

Following DeMaria (1987), the analyzed wind within a large distance from the storm center (radius of 1000 to 1500 km) is replaced by the previous storm movement with a weighting function; that is,

$$\mathbf{V} = (1 - W)\mathbf{V}_a + W\mathbf{V}_s \tag{1}$$

$$W = e^{-(r/r_e)^2}, \tag{2}$$

where r is the radial distance from the storm center; r_e, the effective e-folding distance; $\mathbf{V}_a$, the analyzed environmental wind vector; and $\mathbf{V}_s$, the previous movement of the storm. The average of the previous 6-h typhoon movement estimated at the CWB as the working best track is used. After a number of tests, $r_e = 1000$ km is chosen for the TFS. The bogussing of a spunup vortex is then carried out after this process.

b. Wavenumber-1 asymmetry

The streamfunction of a wavenumber-1 asymmetry is specified as

$$\psi = A \sin(\theta) \sin\left(\frac{\pi r}{r_{\max}}\right), \quad 0 \leqslant r \leqslant r_{\max}, \tag{3}$$

where θ is the orientation of the asymmetry determined by the averaged direction of the storm movement in the previous 6 h and r is the distance from the storm center. The half-wavelength of the asymmetry, $r_{\max}$, is set to 1000 km after a sensitivity test. The amplitude A in (3) is determined by matching the radial wind speed at the center to the previous 6-h averaged storm speed. The radial and tangential velocities are computed from the streamfunction with the nondivergent wind relationship. The asymmetry thus constructed not only has a wavenumber-1 structure, but also carries the persistence concentrated near the center part of the vortex. This asymmetry is added to the spunup vortex throughout the vertical layers. The nondivergent wind vectors associated with a wavenumber-1 asymmetry for a 3.35 m s^{-1} northwestward movement are plotted in Fig. 1.

The effects of these two preprocessing procedures are tested on the 32 typhoon cases that were archived at the CWB in 1990. The number of archived cases is less than the total operational cases due to occasional computer system failure and human mistakes. Four forecast experiments are designed and tested for each case. Experiment 1 reruns the cases using the operational version of the TFS in 1990. This is the control run for a homogeneous comparison with other experiments, because the archived dataset contains data that came after the data cutoff time and may be slightly different from the operational dataset. In experiment 1, only a spunup vortex is included. The second set of experiments, experiment 2, includes the spunup vortex and a wavenumber-1 asymmetry. The third experiment, experiment 3, adjusts the environmental flow according to (1) before a spunup vortex is added. The fourth experiment, experiment 4, includes both preprocessing procedures contained in experiments 2 and 3. The names of the typhoons and the time of each watch are given in Table 1 and the average forecast errors for these four experiments are given in Table 2. A direction error with a negative sign indicates the forecast track has leftward bias and a negative sign before the speed error indicates a slow speed bias.

The averaged 48-h distance error is 474 km for experiment 1, and 493 km for experiment 2. The larger distance error of experiment 2 comes mainly from the large positive speed bias and the large left direction bias. One may then wonder what is the advantage of

TABLE 1. Typhoon names and watches for experiments 1–4.

Typhoon name	Time (UTC)	Typhoon name	Time (UTC)
Marian	1200 16 May 1990	Ed	0000 15 September 1990
Ofelia	1200 20 June 1990	Flo	0000 14 September 1990
Ofelia	0000 21 June 1990	Flo	1200 14 September 1990
Ofelia	1200 21 June 1990	Flo	0000 15 September 1990
Ofelia	0000 22 June 1990	Flo	1200 15 September 1990
Ofelia	1200 22 June 1990	Flo	0000 16 September 1990
Ofelia	0000 23 June 1990	Gene	1200 25 September 1990
Yancy	0000 15 August 1990	Gene	0000 26 September 1990
Yancy	1200 15 August 1990	Gene	1200 26 September 1990
Yancy	0000 16 August 1990	Gene	0000 27 September 1990
Dot	0000 6 September 1990	Hattie	0000 4 October 1990
Dot	1200 6 September 1990	Hattie	1200 4 October 1990
Dot	0000 7 September 1990	Hattie	0000 5 October 1990
Ed	1200 13 September 1990	Page	1200 27 November 1990
Ed	0000 14 September 1990	Page	0000 28 November 1990
Ed	1200 14 September 1990	Page	1200 28 November 1990

including this process. A more detailed examination of individual cases reveals that experiment 2 produces improved forecasts in some cases and degraded forecasts in others. For example, this process improved the operational forecast for Typhoon Yancy when Yancy made two sudden changes of direction. As shown in Fig. 2a, the persistence included in experiment 2 for the watch of 1200 UTC 15 August pushed the initial track more westward and had the best forecast among all experiments. For the 1200 UTC 17 August watch (Fig. 2b), the sudden westward motion at the initial time was not captured by any experiment, but experiment 2 produces the best speed forecast. (The 48-h distance errors for experiments 1–4 are 282, 46, 252, and 163 km, respectively, for the watch of 1200 UTC 15 August, and 552, 94, 627, and 352 km, respectively for the watch of 1200 UTC 17 August.) Another example is shown in Fig. 3 for Typhoon Dot. For the watch of 0000 UTC 6 September, the direction error in the control run is greatly improved by the preprocessing procedure in experiment 2 (Fig. 3a). However, for the following watch (Fig. 3b), experiment 2 gave the worst forecast with large direction and speed error. (The distance errors at 48 h for the four experiments for the 0000 UTC 6 September watch shown in Fig. 3a are 322, 74, 504, and 157 km, respectively. The errors for the 1200 UTC watch shown in Fig. 3b are 386, 782, 162, and 503 km.) The performance of experiment 2 indeed varies greatly from case to case.

TABLE 2. Forecast errors from experiments 1–4 on cases in Table 1.

Exp.	Forecast time (h)	Distance error (km)	Direction error (deg.)	Speed error (km h^{-1})
1	12	143	−7	−6
	24	241	−6	−2
	36	346	−9	−1
	48	474	−10	−1
2	12	146	−17	3
	24	268	−19	3
	36	393	−20	3
	48	493	−10	2
3	12	173	3	−12
	24	231	3	−7
	36	305	−1	−6
	48	412	3	−5
4	12	102	−9	−4
	24	160	−9	−2
	36	243	−11	−1
	48	351	−12	−1

Experiment 3 improves the forecasts for most cases more consistently by reducing the direction errors but has on the average a slow speed bias, especially for the 12-h forecast. The averaged 48-h distance error in experiment 3 is 412 km. For the case shown in Fig. 3b, experiment 3 produces the best forecast. Another example is shown in Fig. 4 for Typhoon Hattie at 0000 UTC 4 October. At that time, there was a midlatitude trough passing to the north of the typhoon that apparently induced Hattie to recurve. The forecast tracks in experiments 1 and 2 show a due west movement. Experiment 3 shows a much improved direction prediction but the speed is too slow to be caught by the trough to recurve into the westerlies at the right time. In experiment 4 the forecast is greatly improved by having both processes.

Including both preprocessing procedures in experiment 4 gives consistently better performance than the other three experiments. The predictions are better than the control forecasts (experiment 1) for 26 cases out of the total 32 cases tested. The mean 24-h distance error is reduced from 241 km in experiment 1 to 160 km in experiment 4, a 34% improvement. The 48-h distance error is reduced from 474 to 351 km, a 26% improvement (Table 2). Typhoon Hattie shown in Fig. 4 is among those where experiment 4 provides the best forecast. In the Hattie case, the distance error for the

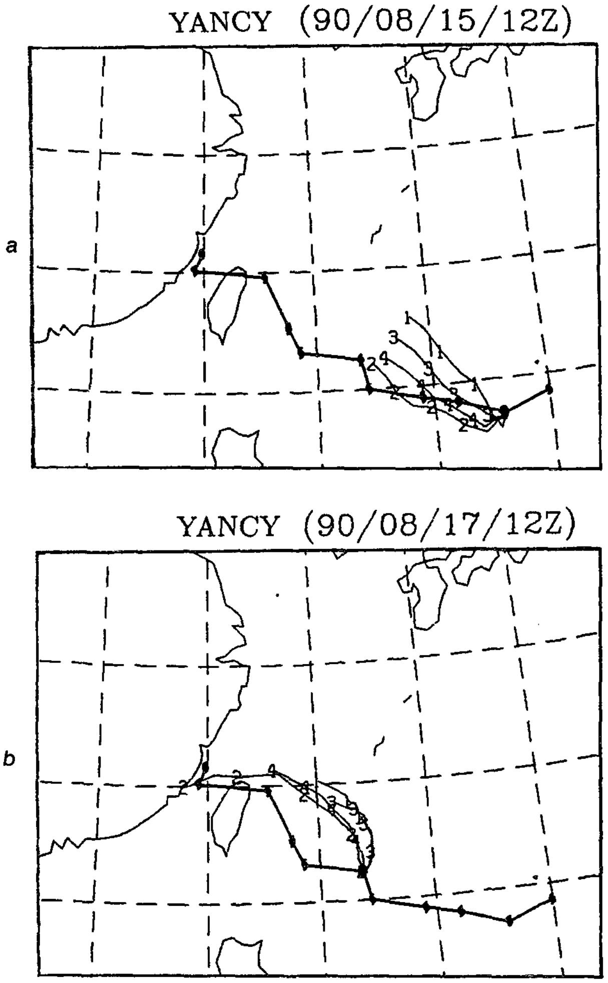


FIG. 2. Best track (heavy line) and 48-h forecast tracks from experiments 1–4 for Typhoon Yancy in 1990: (a) 1200 UTC 15 August; (b) 1200 UTC 17 August.

48-h forecast is reduced from 591 km in the control run to 69 km in experiment 4. Another example is shown in Fig. 5 for Typhoon Flo where the distance error is reduced from 562 to 96 km. It is interesting to note that the improvement in experiment 4 is due to the preprocess in experiment 2 for some cases (i.e., Figs. 3a and 5) and due to the preprocess in experiment 3 for some other cases (i.e., Fig. 4). Sometimes, the track position from experiment 4 falls in between those of experiments 2 and 3 (Figs. 2a and 3b). Overall, the slow speed bias in experiment 3 is offset by the fast speed bias in experiment 2. In addition, the leftward bias in experiment 2 seems to be compensated by the rightward bias in experiment 3.

Of all the operational runs in 1990, forecast position errors for Typhoon Marian are the highest. None of the experiments designed here show any improvement at all for Marian (Fig. 6). The poor performance of Marian from the control run was due to insufficient domain coverage on the west side of Marian, leading to a poor forecast of the synoptic flow (Peng et al. 1993). When the large-scale pattern is not properly forecast by the model, adjustments of the initial condition are not likely to improve the track forecast. The case with the largest distance error in experiment 4, comparing with the control run, is for Typhoon Ofelia at 1200 UTC 20 June (Fig. 7) where the 48-h forecast distance error increases from 285 to 502 km. In this case, the forecast direction is neither improved or deteriorated by these two preprocessing procedures. However, the forecast speed is faster in experiment 4, leading to a larger distance error. This is true for all six cases in which the forecast distance errors of experiment 4 are larger than the control experiment.

A Student's t-test is carried out for the 32 cases in experiments 1 and 4. The test shows that the mean error in experiment 4 is significantly better than that in experiment 1 on a 90% confidence level. The positive impact on track forecast in experiment 4 has led to the

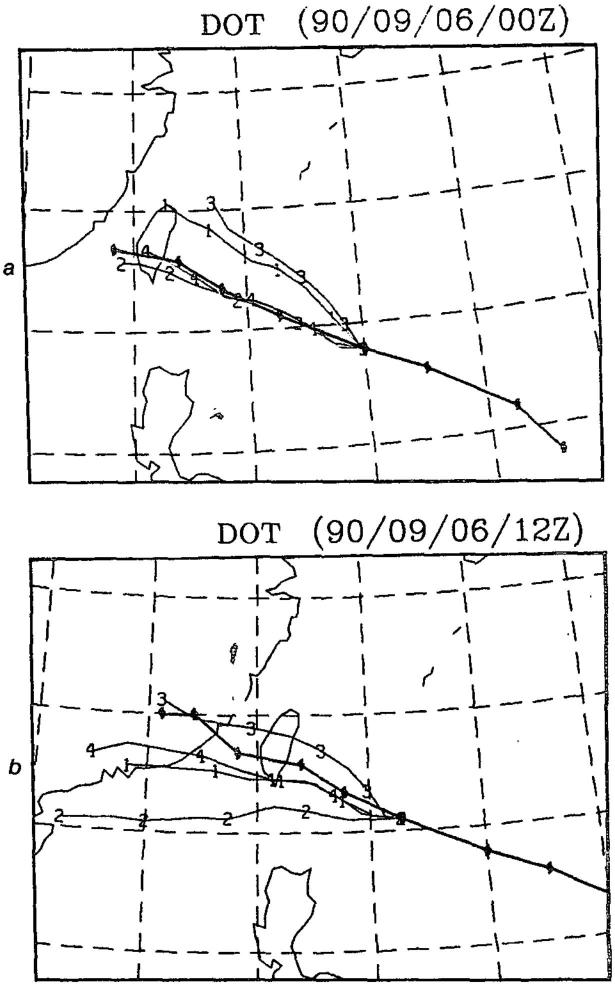


FIG. 3. Same as in Fig. 2 except for Typhoon Dot: (a) 0000 UTC 6 September; (b) 1200 UTC 6 September.

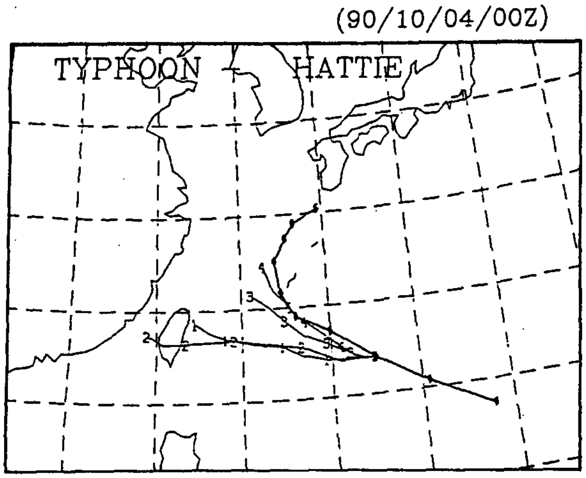


FIG. 4. Same as in Fig. 2 except for the watch of 0000 UTC 4 October for Typhoon Hattie.

implementation of these two preprocessing procedures in the operational TFS prior to typhoon season of 1991. A few typhoons in the early season of 1991 have also been tested with these four experiments and the results are consistent with the 1990 cases.

In experiment 3 (persistence preprocessing only), a slow bias causes the 12-h forecast to have the worst distance error among all experiments. This is in contrast to DeMaria's (1987) barotropic model in which the procedure of implementing persistence results in the largest improvement in the 12-h forecast. This discrepancy is due to the lack of corresponding adjustment of the mass field when the past motion vector is added. Even though the nonlinear normal mode initialization may have made the correct adjustment in producing balanced fields, the balancing is achieved at the expense of a reduced steering flow. As noted previously, each process can improve the direction forecast alone. But the best error reduction is found in experiment 4, where the past motion vector is applied twice before the desired effect is achieved. In the future, we will investigate the effectiveness of including both the motion vector and a balanced mass fields. It is anticipated that when a balanced mass field is bogussed, the magnitude of the asymmetry can be reduced.

Observational studies indicate that while the vertical-averaged steering flow agrees best with the typhoon movement, the steering flow at each level is different (Chan and Gray 1982). Therefore, placing a constant steering flow in the vertical underestimates the actual environmental flow in some levels and overestimates it in other levels. This suggests that the replacing of the environmental flow by the previous storm motion should be implemented with a vertical weighting function. There may also be a relationship between the intensity of the storm and the depth of the steering layer as suggested by Velden and Leslie (1991) using a barotropic model. With 300 tropical cyclones in the Australian region, they found that for weaker systems (>975 hPa) the best results were obtained using 850–500-hPa layer-mean wind as the steering flow, while for very intense storms (<955 hPa) the best was the 850–300 hPa layer mean. These results might be considered in the design of the vertical weighting function.

3. Impact of vortex intensity on track forecast

In the earlier version of the TFS, three vortices with different intensities were spun up for bogussing for operational predictions (Peng et al. 1993). During forecast integration, artificial heating was applied to maintain the radial temperature gradient of the vortex at no less than 50% of its initial value. In this way, even though the intensities of the initial bogus vortices in the TFS are related to the observed intensities, the central pressure is rarely lower than 970-hPa during forecast integration. For most cases since the inception of the TFS, the forecast tracks are not very sensitive to the forecast intensities of the vortices in the model. We have noticed, however, that there are cases where forecast tracks are better when the intensity of the vortex is closer to the estimated intensity of the typhoon. Two sets of experiments are demonstrated here to demonstrate the impact of vortex intensity on track forecast. One case involves multiple typhoons and the other case, a single typhoon.

a. A case with multiple typhoons

The operational procedure of TFS prior to the 1992 season used identical bogus vortices for all typhoons that existed simultaneously within the model domain. The choice of bogus vortex was based on the size and intensity of the strongest typhoon within the domain. Although forecasts for multiple typhoon cases based

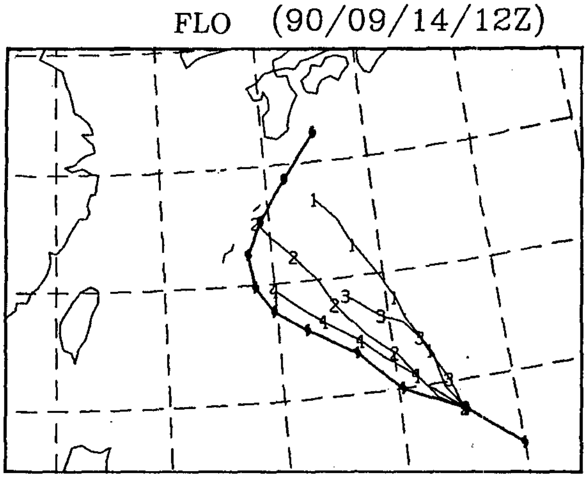


FIG. 5. Same as in Fig. 2 except for the watch of 1200 UTC 14 September for Typhoon Flo, one of the best forecasts made by experiment 4.

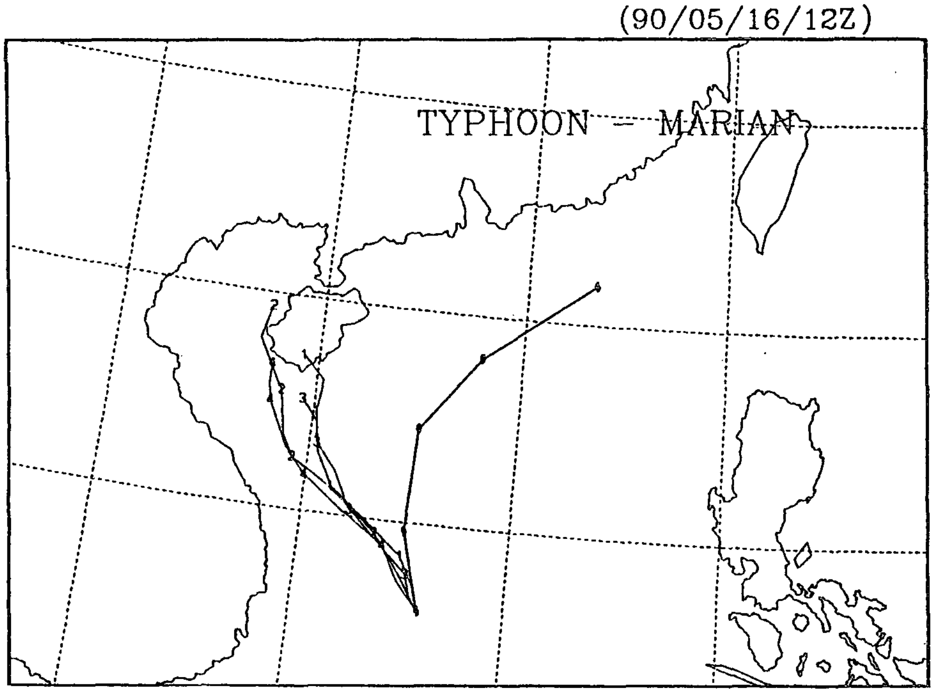


FIG. 6. Results from experiments 1–4 for the watch of 1200 UTC 16 May for Typhoon Marian, a bad forecast made by experiment 4.

on this procedure were often no worse than the single storm cases, the interactions between the storms might not be simulated properly when the typhoons have very different intensities, especially in environments with weak mean flows. The effect of using different spunup vortices for coexisting typhoons according to their respective intensities is tested.

Our test case involves Typhoon Nat of 1991, which at an early stage coexisted with Tropical Storm Luke and, at a later stage, with Typhoon Mireille. The best tracks determined at the CWB for these three typhoons are plotted in Fig. 8. Between 16 September and 2 October 1991, Nat made several drastic loop motions and appeared to threaten Taiwan in three separate periods. Nat was a weak tropical storm during most of its two-week life span, except during 21 to 23 September when it reached typhoon intensity. Between 15 and 17 September, both Nat and Luke moved westward under the influence of a subtropical ridge. At 12 UTC 17 September, Luke made a sudden and sharp 90° turn to the north, while Nat, which was located 1500 km to the southwest of Luke, made a near 180° turn toward the east. These turns appeared to be the result of the Fujiwhara effect (Fujiwhara 1921). Luke continued to move northward and eventually dissipated. By 20 September, as the subtropical high started to strengthen, a more intense typhoon Mireille moved toward Nat. At 1200 UTC 21 September, Nat made another sharp, near 180° turn westward. Afterward, the weaker Nat seemed to be under the influence of Mireille. Mireille started as a midget typhoon and later intensified to a super typhoon. It tracked the periphery of the subtropical ridge and recurved northeast before reaching 125°E. Mireille turned out to be the worst storm that struck Japan in three decades.

In the operational runs, both Mireille and Nat were bogussed with an identical spunup vortex, with a minimum sea level pressure near 985 hPa, which is the

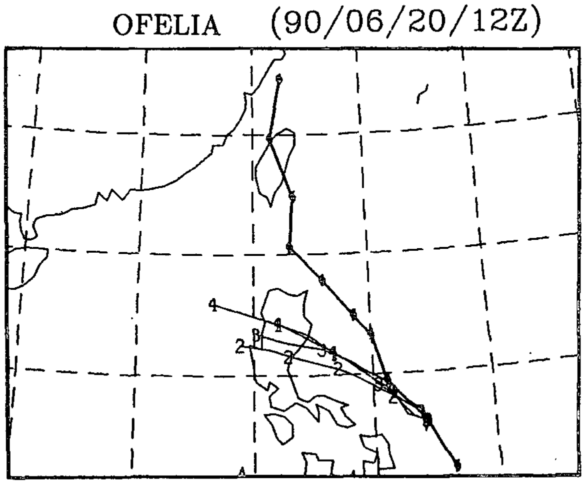


FIG. 7. Results from experiments 1–4 for the watch of 1200 UTC 20 June for Typhoon Ofelia, the worst forecast made by experiment 4.

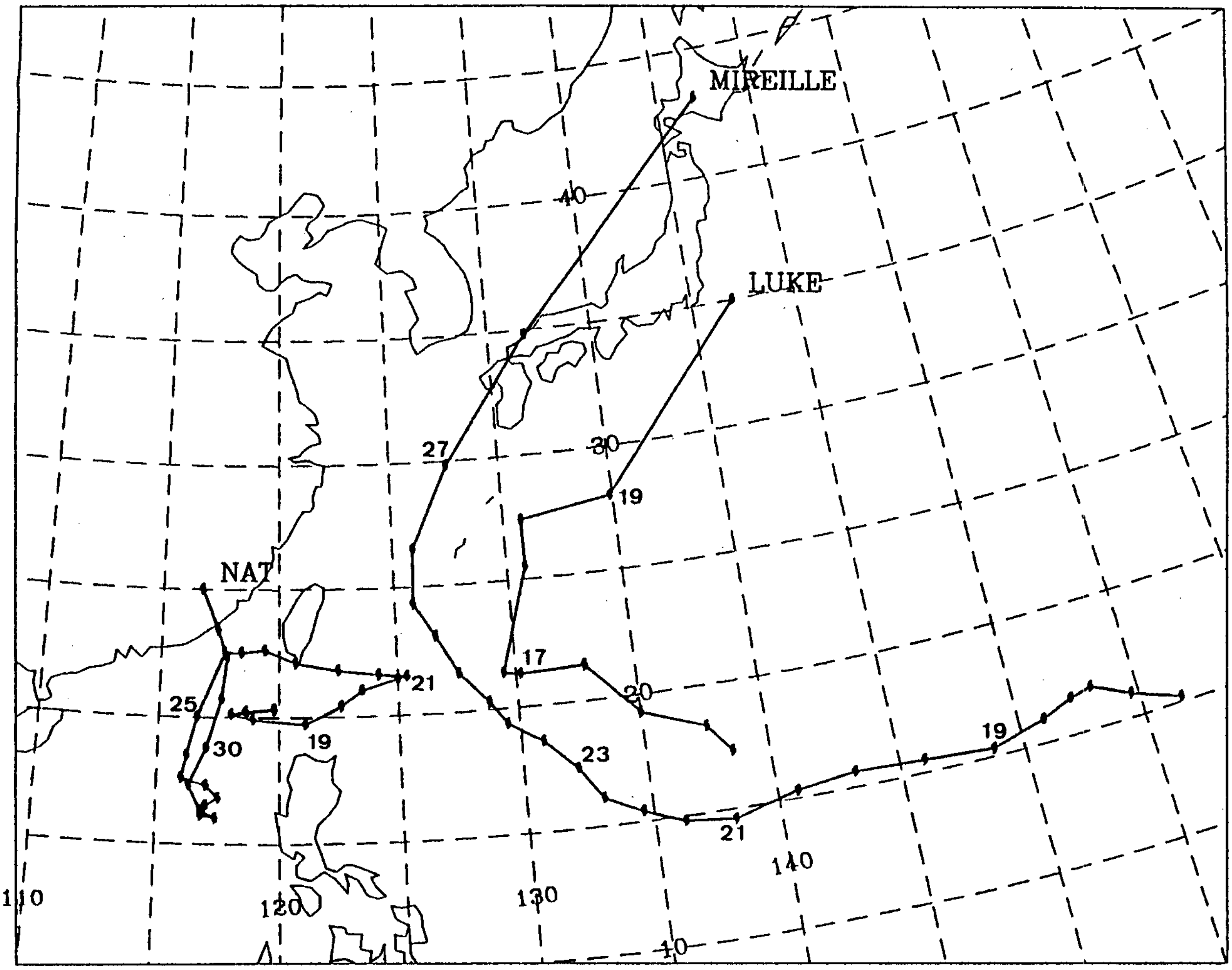


FIG. 8. Best tracks for Typhoon Luke, Nat, and Mireille of 1991, labeled every 12 h. The time period is from 0000 UTC 15 September to 1200 UTC 19 September for Luke, from 0000 UTC 17 September to 0000 UTC 2 October for Nat, and from 1200 UTC 16 September to 0000 UTC 28 September for Mireille.

strong vortex in Table 1 of Peng et al. (1993). For the watch of 0000 UTC 25 September, Mireille recurved to the northeast while Nat moved to south for the first 24 h and then turned southeast (Fig. 9). The mutual interaction between them is clearly shown in their relative distance diagram (Fig. 10). The operational forecast track for Mireille (Fig. 9) has the same direction as the best track although there was an initial kink toward the southwest and the forecast speed was too slow. The operational forecast track for Nat, also shown in Fig. 9, is toward west northwest, more than 90° away from the best track. The steering flow in which Nat was embedded was weak; therefore, the interaction between these two typhoons might have been the dominant factor that affected the motion of Nat.

Noticing that the bogus vortex in the operational forecast was too strong for Nat and too weak for Mireille, we conduct an experiment using different spunup vortices. A new vortex other than those listed in Table 1 of Peng et al. (1993) is spun up with higher sea surface temperature (303°). This new spunup vortex, which has a minimum sea level pressure of 972 hPa, is used for Mireille. The weak and small vortex listed in Table 1 of Peng et al. (1993), which has a minimum pressure of 990 hPa, is used for Nat. In this experimental run, considerable improvement in the track forecasts are produced for both typhoons (Fig. 9). The southward movement of Typhoon Nat is now correctly captured by the TFS and the speed forecast of Mireille is also improved. The 48-h forecast error is reduced from 788 to 166 km for Nat and from 608 to 410 km for Mireille. There are a few more cases in which Nat was poorly forecasted in the operational runs. Unfortunately, those data were lost and are not available for further studies.

Using different bogus vortices for multiple typhoons was implemented in the operational version of the TFS before the season of 1992. The number of spunup vortices for bogussing has also been increased from three

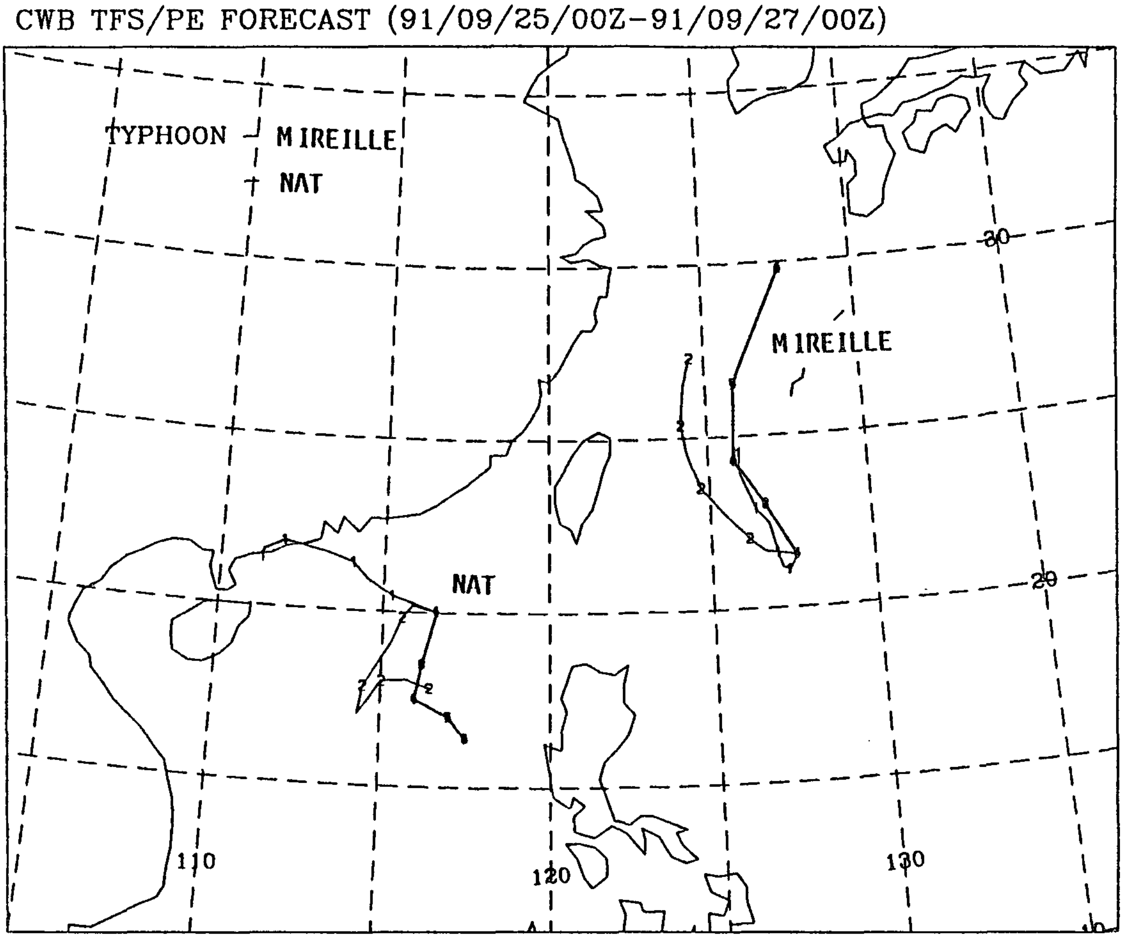


FIG. 9. Best tracks (heavy lines with typhoon symbols) for Typhoon Mireille and Typhoon Nat for the watch of 0000 UTC 25 Sep. 1991. Thin lines labeled "1" are the forecast tracks by the operational run where identical vortices were used for both typhoons. Thin lines labeled "2" are the forecast tracks using different vortices for Mireille and Nat.

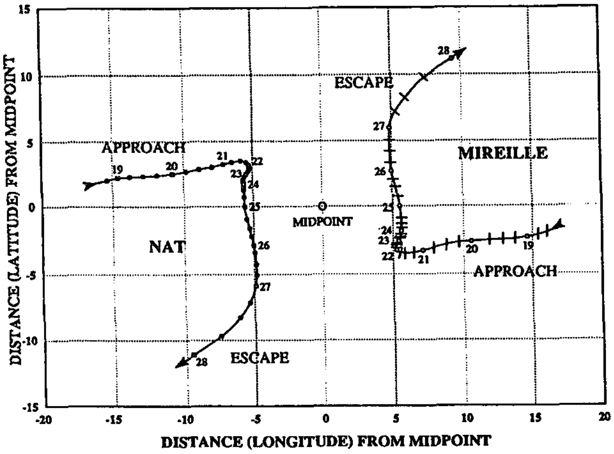


FIG. 10. A plot of 6-hourly positions relative to the common midpoint shows the binary interaction between Typhoons Mireille and Nat (22W) (adopted from Fig. 3-21-2 of the 1991 Annual Tropical Cyclone Report, JTWC, Guam).

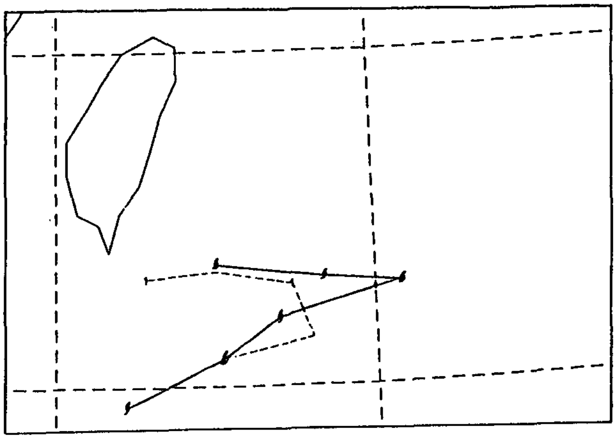


FIG. 11. Best track (solid line) and 48-h forecast for Typhoon Nat by the TFS (dashed line) of 12 UTC 19 September 1991.

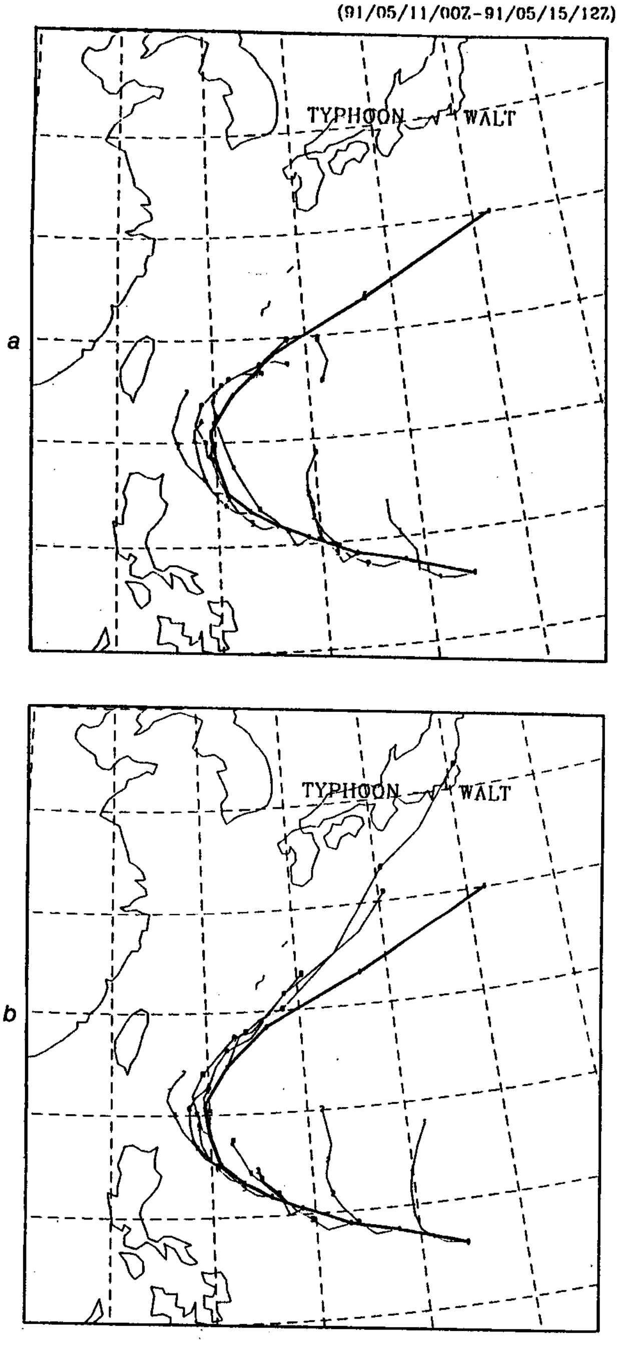


FIG. 12. Best track and forecast tracks for Typhoon Walt of 1991: (a) forecast made by operational TFS where the artificial heating is at the 50% level, (b) forecast made by TFS with the artificial heating raised to 100% level.

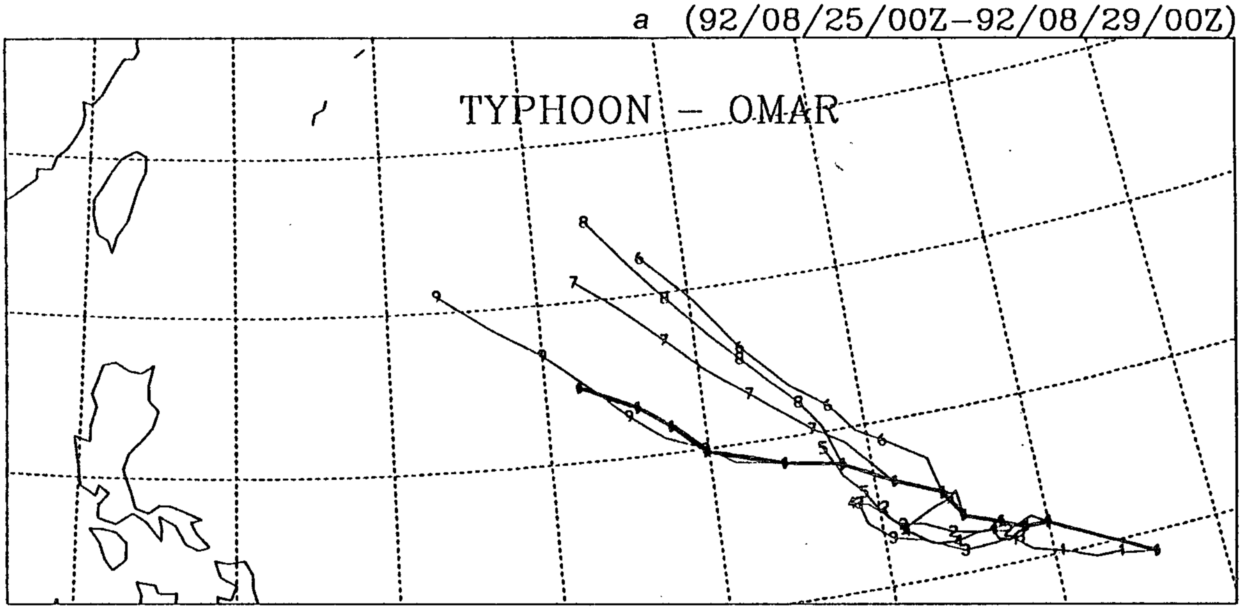
(Table 1 of Peng et al. 1993) to four, including the one used for Mireille in the experimental run. This new vortex is chosen when the estimated typhoon intensity reaches below 975 hPa.

Despite the fact that the typhoons were bogussed improperly in some watches, the operational forecasts from TFS provided useful guidance for the erratic Nat. In one of the sudden turnings, Typhoon Nat changes its direction almost 180° between 1200 UTC 20 September and 0000 UTC 21 September. The operational forecast of the TFS for the watch at 1200 UTC 19 September is very successful in capturing the turning by forecasting a northward motion in the first 12 h, then changing to a westward motion 12 h later (Fig. 11), even though the start of the westward motion was forecast 12 h too early. The predicted erratic behavior of Nat was sufficient for duty forecasters in CWB to stay alert. As discussed in Peng et al. (1993), TFS provided valuable guidance during periods of irregular typhoon motions, such as Typhoon Sarah in 1990. A discussion on the performance of several operational global and regional models for Nat is given in Chan (1995). For 1200 UTC 19 September, the Typhoon Track Model of Japan Meteorological Agency, the OTCM, and the global model of the U.K. Meteorological Office forecast an eastward movement, whereas the U.S. Naval Operational Global Atmospheric Prediction System and the European Center global model forecast a westward turning at 1200 UTC 21 September.

b. Single typhoon case

The first operational forecast by the TFS in 1991 was for Typhoon Walt. Walt first moved west-northwestward under the influence of the subtropical ridge building westward (Fig. 12). After recurving on 15 May, Walt started to interact with the upper-level westerlies and accelerated toward the east-northeast. After 16 May, Walt merged with a passing frontal system and acquired extratropical characteristics. The forecast by the operational TFS tracked the recurvature fairly well (Fig. 12a). The forecast speed of the storm after recurving, however, was too slow. In addition, in the last two watches of operational run at 0000 UTC and 1200 UTC 15 May, the forecast track diverted away from the best track substantially. During this period, the estimated minimum pressure of Walt reached 935 hPa, whereas the minimum pressure of the vortex in the TFS was between 977 and 990 hPa. In the experimental runs, the artificial heating was increased by a factor of 2 of the operational run for all watches. As a result, the forecast intensity was increased to 952 hPa for earlier watches at lower latitude and to 985 hPa for later watches at latitudes higher than 25°N. The forecast track positions improved substantially as shown in Fig. 12b. Conversely, increasing the artificial heating in the first two forecasts shown in Fig. 12a at 0000 UTC and 1200 UTC 11 May did not improve the northward direction bias; however, it corrected the slow speed bias, resulting in larger distance errors than the operational runs.

Starting from January 1992, the artificial heating applied to the bogus vortex in the operational TFS is increased to 100% of the initial vortex when the estimated real typhoon intensity reaches 950 hPa or lower.



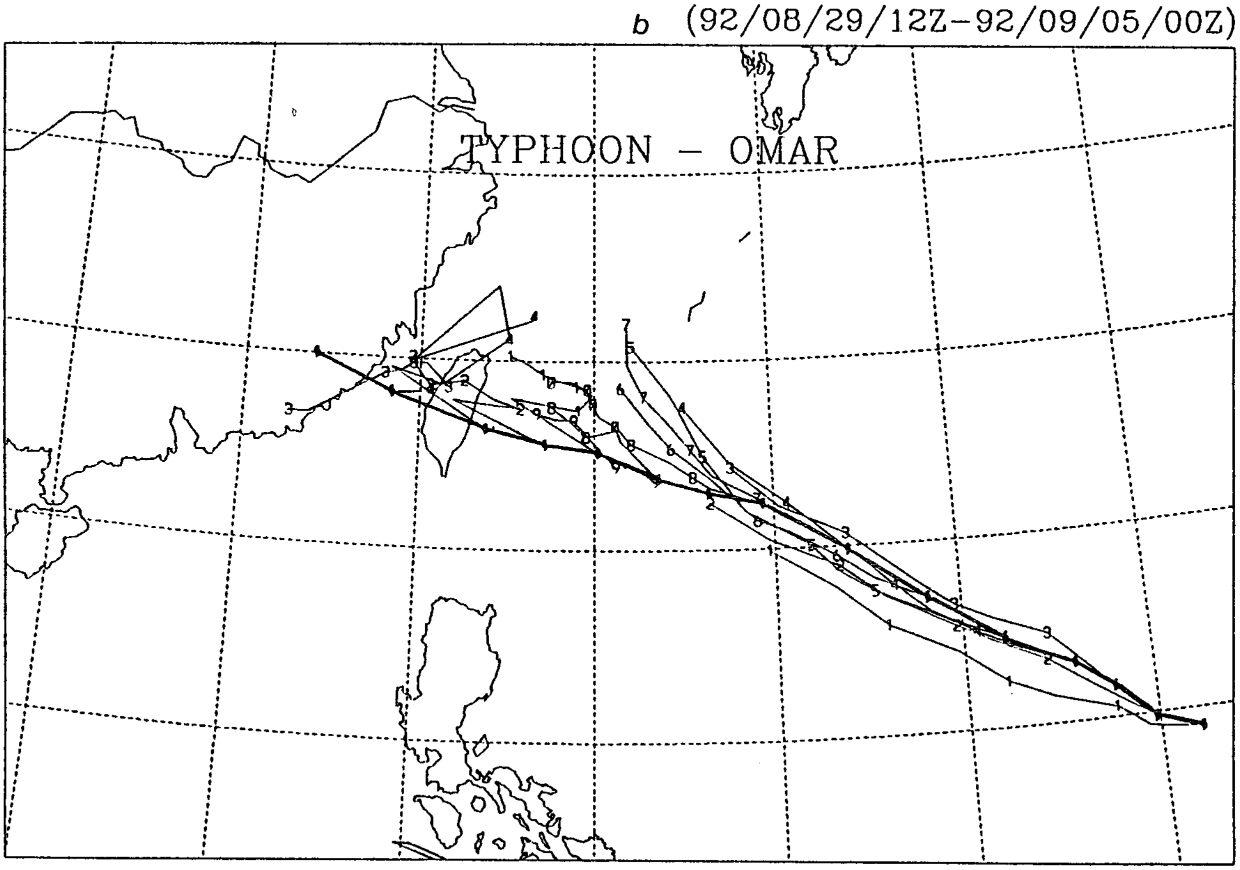


FIG. 13. Best track and operational forecasts from TFS for Typhoon Omar of 1992: (a) from 0000 UTC August 25 (line labeled "1") to 0000 UTC August 29, (b) from 1200 UTC 29 August (line labeled "1") to 0000 UTC 5 September.

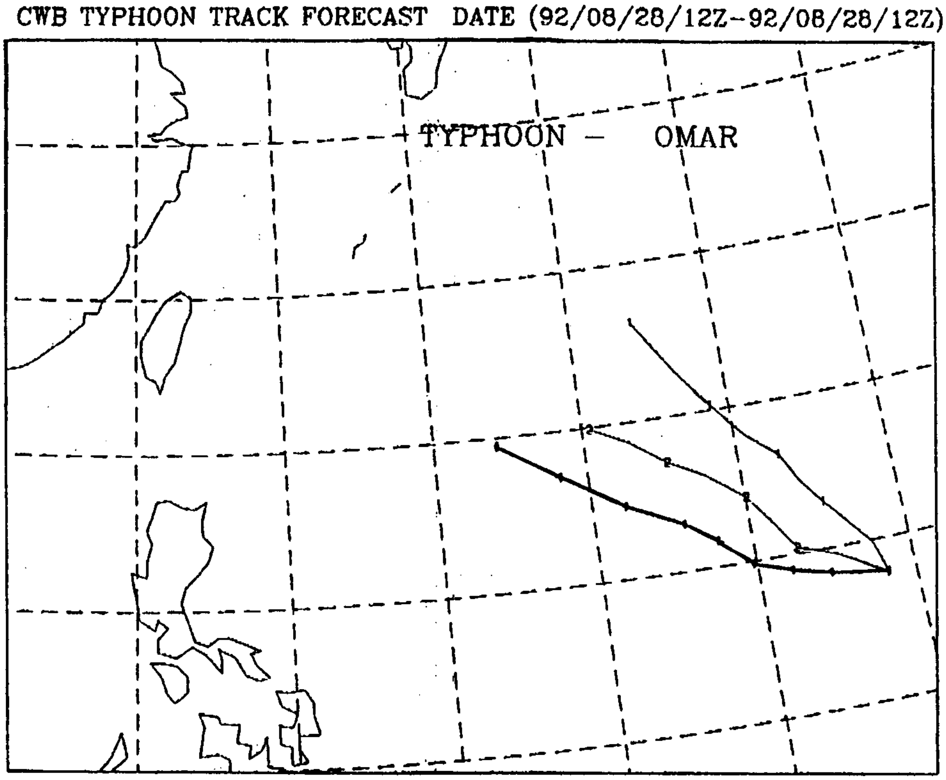


FIG. 14. Rerun of the watch of 1200 UTC 28 August for Typhoon Omar (line labeled "8" in Fig. 13a) by TFS where the bogus vortex uses the stronger spunup vortex (line labeled "2"). The forecast track from the operational run where the weaker spunup vortex was used is the line labeled "1."

4. Performance of TFS in 1991 and 1992

a. Forecast errors

The average track error for 18 typhoons forecasted by the TFS in 1991 is 187 km (121 cases) for 24-h forecasts and 316 km (105 cases) for 48-h forecasts. The average track error for 14 typhoons in 1992 is 203 km (123 cases) for 24-h forecasts, and 373 km (98 cases) for 48-h forecasts. The forecasts in 1992 were more challenging for both objective aids and subjective forecasts because many of the typhoons were weak with ill-organized structure. One of the interesting cases in 1992 was Typhoon Omar, an intense typhoon that hit Guam, and affected Taiwan and Hong Kong. The best track and operational forecast by TFS for Omar is given in Fig. 13. The overall performance of TFS is fairly good except for the three consecutive watches starting at 1200 UTC 27 August (tracks labeled by 6, 7, and 8 in Fig. 13a). Postoperational examination of the official estimation of the intensity suggested that the storm intensity was underestimated for all three watches, resulting in a choice of the medium strength bogus vortex in the TFS. Comparison of the operationally determined intensities for these three watches with those determined by the Joint Typhoon Warning Center (JTWC) confirmed that the CWB estimated wind speeds were about 10 m s^{-1} too low. For subsequent watches, the estimated intensity of Omar was corrected and made stronger, allowing the automated procedure in the TFS to bogus a stronger vortex, resulting in better forecasts (track labeled by 9 in Fig. 13a and those in Fig. 13b). When these three watches were rerun with the stronger vortex, the forecast track is greatly improved. One case for 1200 UTC 28 August is shown in Fig. 14 where the intensity was 976 hPa in the operational run and 962 hPa in the experimental run. This further supports our assertion in section 4 that the closer the intensity of the bogus vortex is to the real typhoon, the better the forecast.

b. Comparisons of TFS, CLIPER, and OTCM

The relative error of TFS with respect to the empirical CLIPER method is defined as R, following DeMaria (1987):

$$R = \frac{(E_c - E_t)}{(E_t + E_c)} 100\%, \qquad (4)$$

where E_t is the forecast distance error of the TFS and E_c is that of the CLIPER. A negative value of R indicates the TFS is less skillful compared with the CLIPER and a positive value of R indicates the TFS is better than the CLIPER. With a homogeneous sample, $R = -9\%$ for 1989 and $R = -10\%$ for 1990. That is, the performance of the TFS was inferior to the CLIPER for these two years.

Comparison between TFS and CLIPER for homogeneous samples in 1991 and 1992 shows that the TFS performed better than the CLIPER in 1991 with an averaged $R = 5\%$ (Table 3). In 1992, the CLIPER outperformed the TFS again with $R = -10\%$. As mentioned above, many typhoons in 1992 have weak intensities and ill-defined structures. Numerical forecast models, such as the TFS, usually performed poor for weak typhoons.

The performance of TFS is comparable to the OTCM in 1989 and 1990 (Peng et al. 1993). The average distance error from the OTCM in 1991 is 215 km (761 cases) for the 24-h forecast, and 359 km (618 cases) for the 48-h forecast (1991 Annual Tropical Cyclone report, JTWC, Guam). Comparison between TFS and OTCM in 1991 and 1992 based on homogeneous samples is given in Table 4. In 1991, there are 71 homogeneous cases, the average 48-h forecast error is 291 km for the OTCM and 308 km for the TFS. Both models did better in 1991. For 1992, there are 85 homogeneous cases and the average 48-h forecast is 398 km for the OTCM and 370 km for the TFS. A Student's t-test for the forecast errors from the TFS and OTCM show no significant difference between them. The performances of these two models are quite consistent with previous years (Peng et al. 1993).

TABLE 3. Homogeneous comparison of TFS and CLIPER forecast errors (km) at 48 h for 1991–1992. The relative errors are measurement of TFS skill relative to CLIPER.

Typhoon	No. of cases	CLIPER	TFS	Relative error (%)
Walt	8	438	373	11
Caitlin	5	271	310	−10
Ellie	6	388	348	2
Fred	1	562	147	59
Gladys	5	260	282	−4
Ivy	4	502	360	18
Mireille	9	203	326	−19
Nat	9	354	331	1
Ruth	9	301	207	17
Seth	11	403	302	17
1991	67	346	309	5
Janis	5	364	258	17
Kent	15	304	231	14
Lois	3	329	617	−30
Mark	1	243	519	−36
Omar	19	263	431	−24
Polly	1	225	473	−36
Ted	4	392	430	−5
Yvette	5	266	473	−28
Angela	3	221	518	−40
Brian	4	370	202	29
Colleen	8	376	517	−16
Gay	7	351	268	13
1992	75	311	377	−10
Average	142	329	343	−8

TABLE 4. Homogeneous comparison of TFS and OTCM forecast errors (km) at 48 h for 1991–1992.

Typhoon	No. of cases	OTCM	TFS
Walt	6	211	322
Yunya	2	210	227
Zeke	3	157	389
Amy	2	194	238
Brendan	3	122	331
Caitlin	8	197	328
Ellie	6	273	348
Fred	4	392	229
Gladys	7	495	252
Kinna	2	538	319
Mireille	9	244	274
Nat	12	439	414
Ruth	7	138	198
1991	71	291	308
Bobbie	8	427	519
Janis	5	321	258
Kent	13	520	231
Lois	1	308	542
Mark	1	93	519
Omar	14	360	434
Polly	3	609	293
Ryan	7	331	275
Ted	4	396	430
Yvette	8	438	419
Angela	3	329	518
Brian	3	499	151
Colleen	8	534	517
Gay	7	216	268
1992	85	398	370
Average	156	344	339

5. Summary and future plans

Two preprocessing procedures to improve the initial condition of a numerical typhoon forecast model have been tested with the operational Typhoon track Forecast System (TFS) at the CWB in Taiwan. The first procedure is to replace the environmental flow around the storm by the past storm movement. The second procedure is to add a prototype wavenumber-1 asymmetry to the bogus vortex. Incorporating both processes has shown positive impact on the track forecasts.

It has also been demonstrated for the TFS that, the closer the vortex intensity is to the estimated typhoon's intensity, the better the track forecasts. This is especially important when there are possible interactions between the typhoon and other midlatitude or tropical systems.

The TFS forecast tracks exhibit an initial track bias in the 6-h forecast, indicating a possible imbalance between the bogus vortex and the environment. Efforts are undertaken to find the cause and possible improvement. In Kurihara et al. (1993), the imbalance is removed by carrying out the spinup procedure in an axisymmetric version of the model during which the radial profile is nudged toward some observation and empirical knowledge. The asymmetry is then generated by a barotropic model using this spunup vortex. We have conducted tests to spinup the bogus vortex in concurrent environmental fields for every watch but without the nudging process as in Kurihara et al. (1993). We found that this procedure did not improve the 6-h bias. In the future, the asymmetry generated by diabatic processes during the spinup will be removed to improve the initial track bias.

Several tasks are planned in the continued effort to improve the TFS forecast. First, in the use of previous storm movement to replace the environmental flow, a vertical speed variation that depends on the storm intensity will be tested. Second, more categories of the spunup vortex will be constructed, so that a closer match between the bogus and the observed vortex intensities can be made. Third, an artificial heating that is determined by satellite IR and microwave retrieval will be tested. Finally, efforts are underway to develop a new dynamic model with a higher horizontal and vertical resolution.

Acknowledgments. The authors thank three anonymous reviewers for their valuable comments and suggestions that lead to improvement of the manuscript.

REFERENCES

Bender, M. A., R. J. Ross, R. E. Tuleya, and Y. Kurihara, 1993: Improvements in tropical cyclone track and intensity forecasts using the GFDL initialization system. *Mon. Wea. Rev.*, **121,** 2046–2061.

Carr, L. E., and R. L. Elsberry, 1992: Analytical tropical cyclone asymmetric circulation for barotropic model initial conditions. *Mon. Wea. Rev.*, **120,** 644–652.

Chan, J. C., 1995: Performance of global and regional NWP models in their prediction of Typhoon Nat (1991). *Wea. Forecasting.*, **10,** 400–410.

——, and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, **110,** 1354–1374.

——, and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, **44,** 1257–1265.

DeMaria, M., 1987: Tropical cyclone track prediction with a barotropic spectral model. *Mon. Wea. Rev.*, **115,** 2346–2357.

Fiorino, M., and R. Elsberry, 1989: Some aspects of vortex structure related to tropical cyclone motion. *J. Atmos. Sci.*, **46,** 975–990.

Fujiwhara, S., 1921: The natural tendency towards symmetry of motion and its application as a principle in meteorology. *Quart. J. Roy. Meteor. Soc.*, **47,** 287–293.

Kurihara, Y., M. A. Bender, and R. J. Ross, 1993: An initialization scheme of hurricane models by vortex specification. *Mon. Wea. Rev.*, **121,** 2030–2045.

Liou, C.-S., T. Terng, W. S. Kao, T. Rosmond, C. Chen, J. H. Chen, and C. Y. Tsay, 1989: Global forecast at Central Weather Bureau. *Pap. Meteor. Res.*, **12,** 205–228.

Mathur, M. B., 1991: The National Meteorological Center's Quasi-Lagrangian Model for hurricane prediction. *Mon. Wea. Rev.*, **119,** 1419–1447.

Peng, M. S., and R. T. Williams, 1990: Dynamics of vortex asymmetries and their influence on vortex motion on a β-plane. *J. Atmos. Sci.*, **47,** 1987–2003.

——, B. F. Jeng, and C.-P. Chang, 1993: Forecast of typhoon tracks in the vicinity of Taiwan during 1989–1990 using a dynamical model. *Wea. Forecasting,* **8,** 309–325.

Ross, R., and Y. Kurihara, 1992: A simplified scheme to simulate asymmetries due to the beta effect in barotropic vortices. *J. Atmos. Sci.*, **49,** 1620–1628.

Velden, C. S., and L. M. Leslie, 1991: The relationship between tropical cyclone intensity and the depth of the environmental steering layer in the Australian region. *Wea. Forecasting,* **6,** 244–253.