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Beta Gyres in Global Analysis Fields

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ABSTRACT

A three-component decomposition is applied to global analysis data to show the existence of a beta gyre, which causes Tropical Cyclone (TC) to drift from a large-scale environmental steering current. Analyses from the Global Data Assimilation and Prediction System (GDAPS) of the Korea Meteorological Administration (KMA), the Global Forecast System (GFS) of NCEP, and the Navy Operational Global Atmospheric Prediction System (NOGAPS) are used in this study.

The structure of the beta gyre obtained in our analyses is in good agreement with the theoretical structure, with a cyclonic circulation to the southwest of the TC center, an anticyclonic circulation to the northeast, and a ventilation flow directed northwestward near the center. The circulation of the beta gyre is strongest at the 850-hPa level where the cyclonically swirling primary circulation is strongest, and decreases with height, in a pyramid shape similar to the primary circulation. The individual structure of the beta gyre is case- and model-dependent. At a certain analysis time, one model may clearly reveal a well-defined beta gyre, but the other models may not. Within one model, the beta gyre may be well defined at some analysis times, but not at other times. The structure of the beta gyre in the analysis field is determined by the nature of the vortex initialization scheme and the model behavior during the 6-h forecast in the operational data assimilation cycle.

Key words: tropical cyclone, beta gyre, GDAPS, GFS, NOGAPS, TCM-90 final analyses

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1. Introduction

Tropical cyclone (TC) motion can be divided into an advection by a large-scale environmental steering flow and a departure from that steering. Many early observational and numerical studies have found that TC motion deviates from the environmental steering current (George and Gray, 1976; Chan and Gray, 1982; Carr and Elsberry, 1992). However, no unique or universal methods exist to define the environmental flow because of the difficulty in separating the TC circulation from the background flow, so that the magnitude and direction of this motion deviation depend on the definition of the environmental flow. For a definition of the environmental steering flow as the vertically integrated (850–300 hPa) radial-band average steering at various radii from the center (George and Gray, 1976; Chan and Gray, 1982), the TC generally moves to the left of and faster than this radial-band averaged steering. It has also been found that the TC motion has systematic deviations from the steering current irrespective of the data set or definition of the steering current (Elsberry, 1995).

Chan and Williams (1986) demonstrated with a barotropic, non-divergent model that the hurricane-like vortex can move northwestward (all references to directions are for the Northern Hemisphere) even without the background flow. They showed that the westward and northward positive vorticity advection by the asymmetric flow generated by the Rossby dispersion resulted in a northwestward translation of the vortex. Fiorino and Elsberry (1989) described the TC motion in a quiescent environment in terms of the so-called beta gyre, in that an azimuthal wavenumber

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one asymmetric circulation exists with an anticyclonic gyre to the northeast of the center, a cyclonic gyre to the southwest and a nearly uniform, broad-scale ventilation flow between the gyres. The vortex translation speed and direction are almost equal to the average of this ventilation flow over the area of significant cyclonic circulation in the vortex.

The U.S. Office of Naval Research Tropical Cyclone Motion research team proposed a three-component decomposition of the total wind field, i.e., an axially symmetric component, the environmental flow, and an asymmetric circulation (Elsberry, 1990). The axially symmetric component of the vortex has the highest winds near the center, which decrease as the radius increases. The environmental flow may include a horizontal shear or even a relative vorticity gradient. The asymmetric circulation includes wavenumber one gyres. The meridional shear (or vorticity gradient) of a westerly jet (or an easterly jet) poleward of the tropical cyclone decreases (increases) the "effective beta", and thus may weaken (amplify) the magnitude of the linear beta effect, which then will be modified by the nonlinear effect associated with the vortex circulation. Whereas it is uncomplicated to extract the beta gyre from the predicted fields of an idealized non-divergent barotropic model (Fiorino and Elsberry, 1989), extracting the beta gyre in real atmospheric data is by no means an easy task; again, because no unique method exists for defining the large-scale environmental steering flow.

One practical way of accomplishing the three-component decomposition will be presented in this study, and thereby, the existence of the beta gyre will be shown not only in the case of idealized models, but also in the real datasets. In this investigation, the Global Data Assimilation and Prediction System (GDAPS), the Global Forecast System (GFS), the Navy Operational Global Atmospheric Prediction System (NOGAPS) analysis fields, and the TCM-90 (Tropical Cyclone Motion) final analyses (Rogers et al., 1992) are employed. An asymmetric circulation pattern that is analogous to the beta gyres is found in many of these analysis fields, However, the asymmetric circulation differs from one model to another, which may be attributed to the TC initialization schemes in each model. Although the beta gyre is basically two-dimensional in nature, we have investigated the vertical structure of the beta gyres revealed in several global analysis fields by examining the flow pattern at each level. Furthermore, modifications of the tropical cyclone structure due to asymmetric convection may also lead to some distortion of the beta gyre structure, which eventually may affect the track prediction (Ritchie and Frank, 2007; Fovell and Su, 2007).

Descriptions of the data and the cases included in this study are given in section 2. The TC motion in terms of large-scale environmental steering is investigated with the radial-band average method in section 3. In section 4, a methodology for the three-component decomposition is presented, and it will be shown that the beta gyre does exist even in real atmospheric data. Discussion of different aspects in the asymmetric component, which mainly consists of the beta gyre in these various global analysis fields, will be given in terms of the different TC initialization schemes in each model. Finally, section 5 presents a brief summary and conclusions.

2. Description of data and cases

2.1 *Data*

As indicated above, three global analysis fields (GDAPS, GFS, and NOGAPS), and the TCM-90 final analysis data are used in this study. The GDAPS model is a global spectral model with triangular truncation at 213 waves with 30 vertical levels (T213L30). The GFS model and the NOGAPS model are of T382L64 and T382L30, respectively.

The TCM-90 field experiment (Elsberry, 1990) was conducted in the western North Pacific during August and September 1990. The final summary of all data was collected as a byproduct of the quality control steps in the objective analysis fields at the US National Meteorological Center (NMC). The domain of the TCM-90 final analyses is from 7.5°S to 48.0°N and from 80.0°E to 173.5°E. The horizontal resolution of the TCM-90 final analyses is 0.5°, and vertical resolution is 20 levels.

2.2 *Cases*

The best tracks of the TC cases analyzed in this study are shown in Fig. 1. Typhoon 0514 (NABI) [the numbering of the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center is followed here] was moving northwestward at 1200 UTC 1 September 2005. This is a typical case in which the northwestward environmental steering happens to be aligned with the beta-induced steering, and these two steerings cannot be discerned. Another two cases in which TCs moved northeastward [SONCA (0503) at 1200 UTC 25 April 2005 and SHANSHAN (0613) at 0000 UTC 16 September 2005] are selected as contrasting examples, in which the beta gyre contribution is perpendicular to the steering flow. The TCM-90 final analysis data set, which is believed to be the highest-quality observational data, is also employed. Super Typhoon FLO from the TCM-90 database, which was

Table 1. Description of tropical cyclones, dates, positions, and structure characteristics analyzed in this study.

Case (Analysis time)	Position	P_c (hPa)	V_{max} (kt)	30 kt wind radium (n mi) longest	shortest
SONCA (0503) (1200 UTC 25 April 2005)	17.5°N, 132.3°E	940	85	220	150
NABI (0514) (1200 UTC 1 September 2005)	18.3°N, 139.8°E	930	95	325	325
SHANSHAN (0613) (0000 UTC 16 September 2006)	27.1°N, 125.9°E	930	100	220	220
FLO (9019) (1200 UTC 16 September 1990)	23.7°N, 129.9°E	905	105	300	300
FLO (9019) (1200 UTC 18 September 1990)	29.4°N, 131.0°E	920	100	425	425

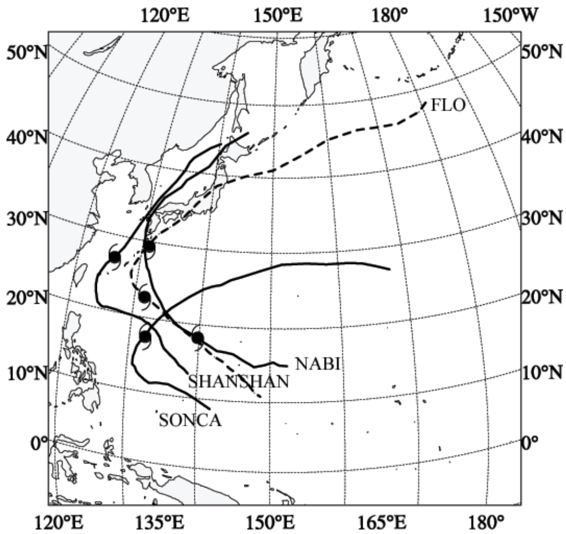

Fig. 1. Best tracks of the TCs used in the analyses. The typhoon symbol in each track means the cases that the analysis is carried out (see Table 1 for the meaning of the TC designations).

a case in which the storm first moved northwestward and later moved northeastward, will also be examined.

Table 1 gives detailed information on the TCs, such as center position, central pressure, maximum wind speed, and 30-kt wind radius, which are based on the best tracks of the RSMC Tokyo-Typhoon Center.

3. Beta gyres in real data

3.1 *Three-component decomposition in the global analysis fields*

Elsberry et al. (1993) applied this three-component decomposition concept to the 50-km horizontal resolution analyses from the TCM-90 field experiment. These researchers defined a large-scale environmental wind field by applying a low-pass filter such that only wave components longer than global wavenumber 15 were retained to represent the steering component. However, these researchers found that the TCM-90 data set was not adequate to confirm the relationship between the gyre orientation and the propagation vector.

In this study, the large-scale environmental field is obtained by a low-pass filter that is similar to the way that Elsberry et al. (1993) applied a filter to the TCM-90 field. Lanczos filtering (Claude, 1979) and the filtering scheme applied in the GFDL hurricane initialization (Kurihara et al., 1993) are adopted. The principal advantage in Lanczos filtering is the use of a "sigma factor" to significantly reduce the amplitude of the Gibbs oscillation. The Lanczos filtering in this analysis separates the total field into a large-scale environmental field and a TC field near the wavelength of 12°N, and is shown in Fig. 2. That is, components with less than around 12°N in wavelength are completely filtered; consequently, no sharp scale cutoff exists in the resulting environment field. The procedure of separating the basic field and the disturbance field in the GFDL hurricane initialization Kurihara et al. (1993) is referred as to GFDL filtering in this study. Kurihara et al. show that disturbances with wavelengths shorter than 9°N are completely filtered out, which means that the disturbance field obtained by the Lanczos filter will include slightly longer wavelength components. In addition, the Lanczos response is larger than that of the GFDL filter for all wavelengths, which means that the Lanczos filter is expected to be more efficient than the GFDL filter in our analysis. That is, the asymmetric circulation, including the beta gyre, can be manifest

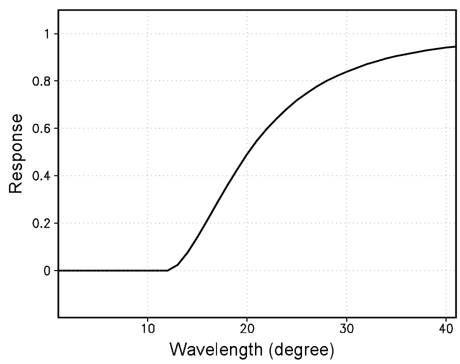

Fig. 2. Response of the Lanczos filter used to separate a total field into the large-scale environmental field and the TC field.

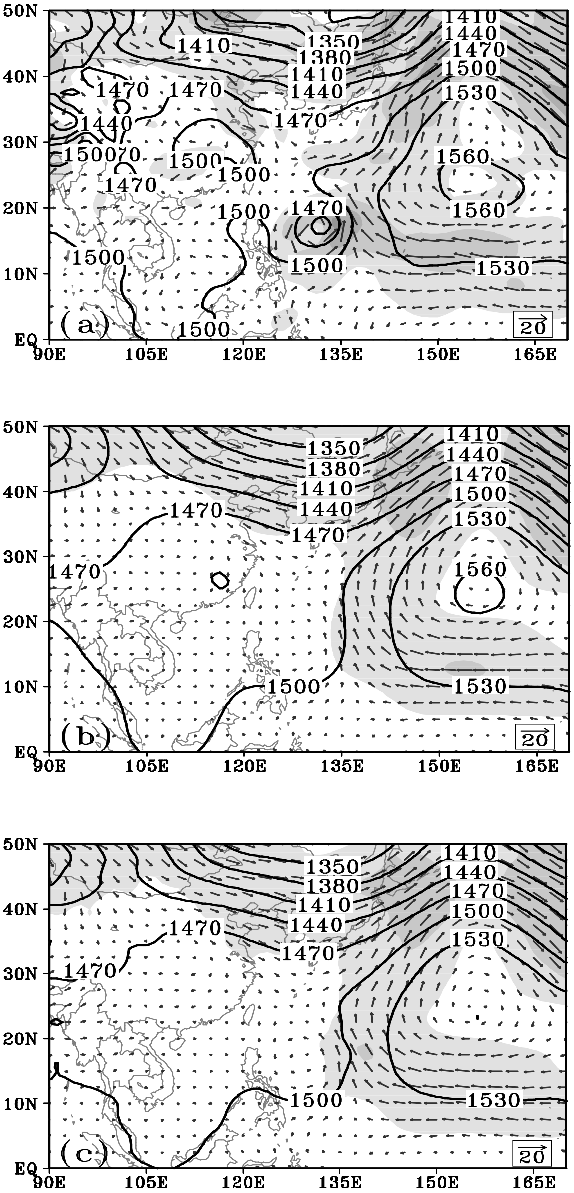

Fig. 3. GDAPS 850 hPa wind (m s^{-1}) and height (m, contour interval of 30 m) fields at 1200 UTC 25 April 2005: (a) total field before filtering, and environmental field after filtering (b) by the Lanczos method or (c) by the GFDL method.

better for the range of wavelengths larger than 9°N. A similar attempt to search for the beta gyre is found in Chan and Cheung (1998), wherein the GFDL filtering is applied to the TCM-90 final analysis data.

The GDAPS height and the wind fields at 850 hPa at 1200 UTC 25 April 2005 are illustrated before filtering (Fig. 3a) and after filtering by the Lanczos method (Fig. 3b) and the GFDL method (Fig. 3c). The circulation of SONCA (0503) is on the cyclonic shear side of a concentrated current between the monsoon trough and the subtropical ridge at that time. Notice that the large-scale field obtained by applying the Lanczos filter (Fig. 3b) has smoother features than that obtained by the GFDL method (Fig. 3c).

The 850-hPa wind and height components of the total field near the center of SONCA at 1200 UTC 25 April 2005 is shown in Fig. 4a. The environmental field that consists of wavelengths longer than 12°N (Fig. 4c) can be obtained by applying the filter to the total field, and the TC component (Fig. 4b) is obtained by removing the environmental field from the total field. The subtropical high pressure east of SONCA is well represented in Fig. 4c. The TC field (Fig. 4b) can also be divided into the axially symmetric component (Fig. 4d) and the asymmetric component (Fig. 4e). Features in the asymmetric field that resemble the beta gyre include a clockwise circulation to the northeast and a counter-clockwise circulation to the southwest of the center of SONCA, as well as a nearly uniform northwestward flow between these circulations. The GFDL filtered fields (not shown) have slightly different features from those of the Lanczos filter (Fig. 4), but basically have a similar structure. Thus, all results and the corresponding discussions in the remainder of this article will be based on the Lanczos filtering.

3.2 *Some aspects of the asymmetric components in the global analysis fields*

The asymmetric components in the three-component decomposition were searched for beta gyres as in Fig. 4e in the GDAPS, GFS, and NOGAPS models. In the following sections, only a few special noteworthy cases will be discussed. These cases are denoted with typhoon symbols in Fig. 1.

3.2.1 *Case 1—SONCA (0513)*

The same procedure of searching for pairs of circulations in the asymmetric circulation, as in Fig. 4e, has been applied to the NOGAPS and GFS analyses at the analysis time of 1200 UTC 25 April 2005 (Fig. 5). The asymmetric wind and geopotential fields in the GFS have a clear beta gyre around the center of SONCA, even though the magnitude is not as large as that in the GDAPS fields. However, the asymmetric field in the NOGAPS analysis has no evidence of a beta gyre (Fig. 5b). The NOGAPS pattern in Fig. 5b is basically a wavenumber two circulation, i.e., with cyclonic circulations to the east and west of the TC center, and anticyclonic circulations to the north and south of the center. Another different aspect between Fig. 5a and Fig. 5b is in the axisymmetric geopotential circulation denoted by the dotted circles. It is apparent that SONCA at this time is more intense in the NOGAPS analysis than in the GFS analysis.

The reason for having the beta gyre in some analy-

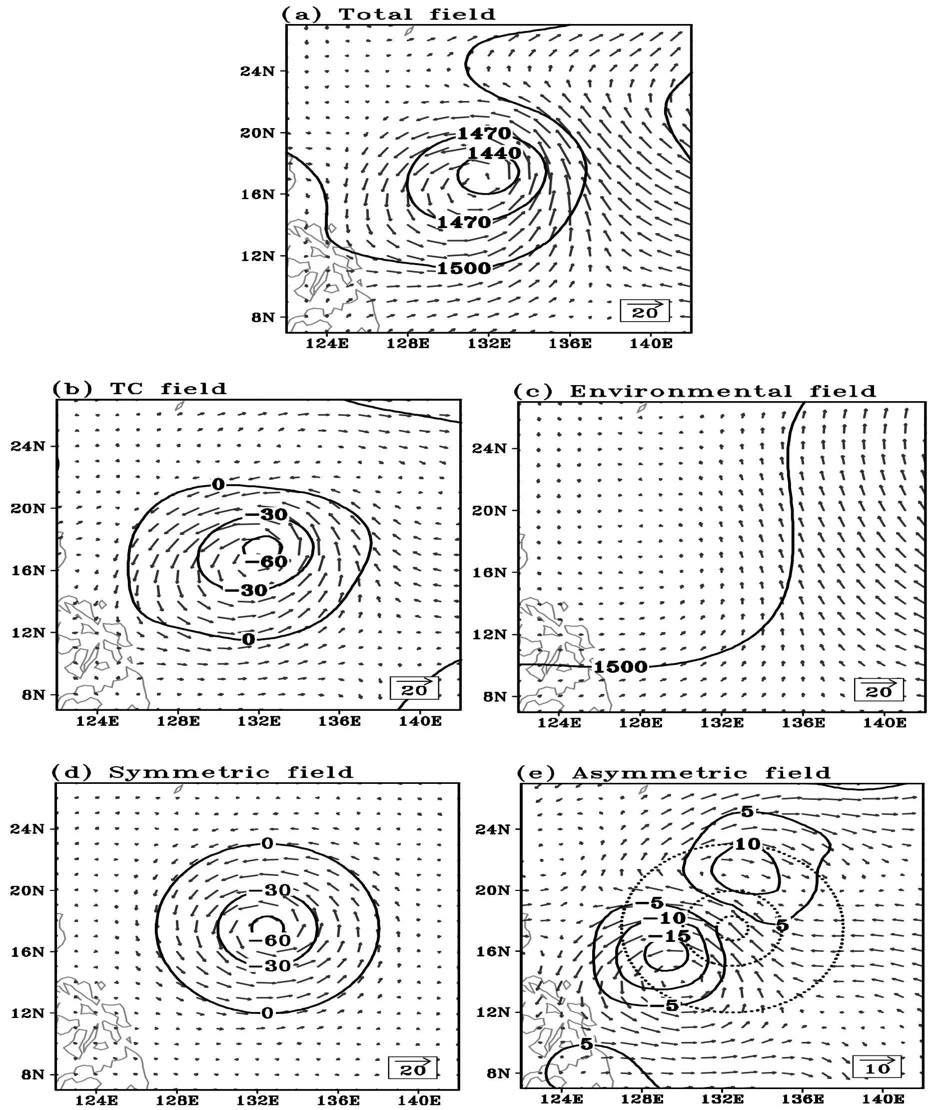

Fig. 4. GDAPS 850 hPa wind and height fields as in Fig. 3, except for SONCA at 1200 UTC 25 April 2005: (a) total, (b) TC, (c) environmental, (d) axisymmetric, and (e) asymmetric field. The sum of (d) and (e) is equal to (b). The dotted circles represent the symmetric height fields and hereafter.

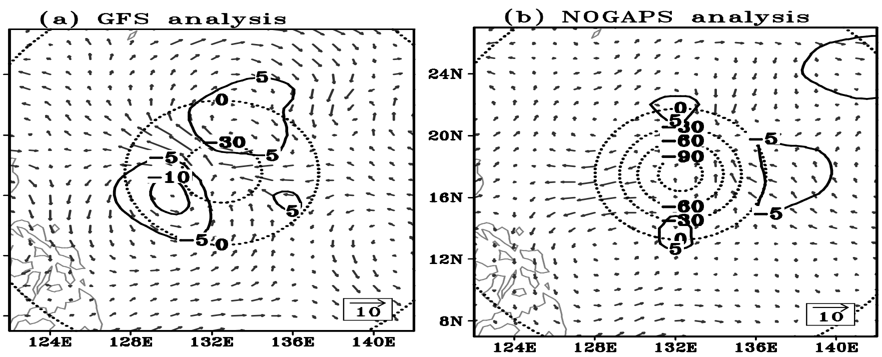

Fig. 5. 850 hPa asymmetric wind (m s^{-1}) and height (m) fields as in Fig. 4c near the center of SONCA (a) in the GFS and (b) in the NOGAPS analyses at the same analysis time as in Fig. 4.

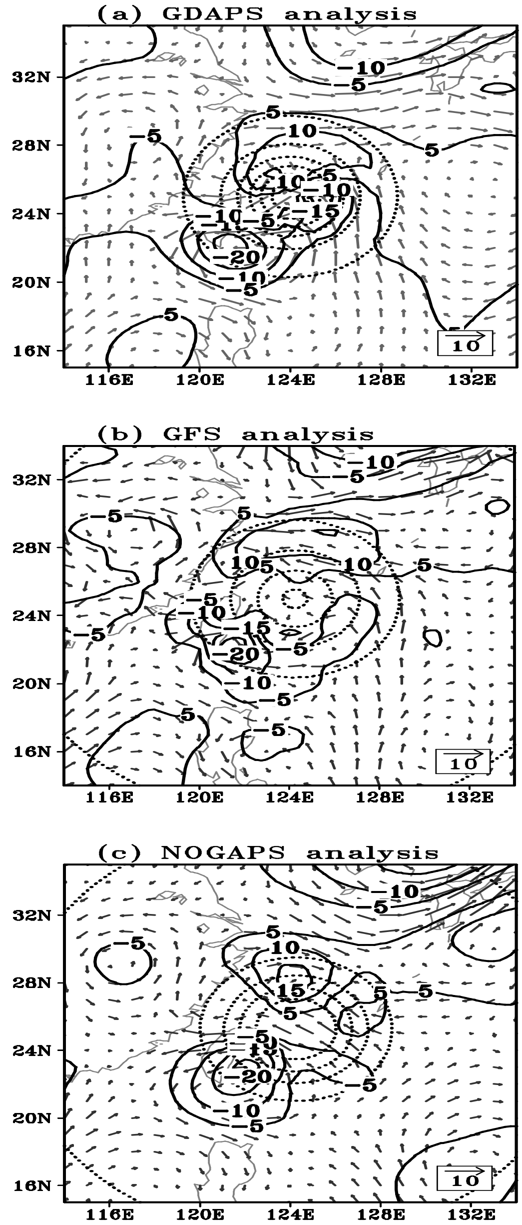

Fig. 6. 850 hPa asymmetric wind and height fields as in Fig. 5 near SHANSHAN in the (a) GDAPS, (b) GFS, and (c) NOGAPS analyses at 0000 UTC 16 September 2006.

ses and not in other analyses will be discussed in section 3.3, where it is conjectured that this difference may be related to the TC initialization scheme.

3.2.2 *Case 2—SHANSHAN* (*0613*)

SHANSHAN moved northeastward and then recurved to move northeastward (Fig. 1). At 0000 UTC 16 September 2006, SHANSHAN retained a well-defined TC structure, and the maximum wind estimate by the RSMC Tokyo at this time was 100 kt with a central pressure of 930 hPa. This case is analyzed with northeastward motion in expectation of observing features of the beta gyre such as counter-rotating circulations and the ventilation flow aligned northwestward, while the main steering by the environment is toward the northeast.

Whereas the asymmetric circulations in the GDAPS analysis (Fig. 6a) and the GFS analysis (Fig. 6b) do not show the beta gyre, the NOGAPS analysis (Fig. 6c) has a beta gyre, although the signal is not as clear as in the previous GDAPS example (Fig. 4e) and in the GFS example (Fig. 5a). At this time, SHANSHAN was moving toward the midlatitude trough and beginning to interact with the baroclinic environment. The cyclonic circulation in the northern region of the domain in Fig. 6 appears to be a part of the midlatitude trough, although most of the large-scale circulation of the midlatitude trough is filtered out by the Lanczos filtering. More complex features other than a simple wavenumber one pattern are present in every panel in Fig. 6. The overall pattern in the geopotential field and the wind field shown in the GDAPS analysis (Fig. 6a) does include a cyclonic gyre to the southwest and an anticyclonic gyre to the northeast side of the center, but the direction of the ventilation flow is mostly eastward, which is not consistent with a beta gyre. The asymmetric component in the GFS analysis (Fig. 6b) is even less similar to a beta-gyre-like circulation. The overall pattern of the cyclonic gyre to the southwest and the anticyclonic circulation to the northeast of the center is present, but no ventilation flow is evident. Small but strong mesoscale circulations are apparent. One explanation for these circulations may be the convection near the center, although it is not clear whether such mesoscale convection in the analysis is real or artificial. Another plausible explanation is that the observations' distribution may have affected the operational data assimilation cycle to produce the non-beta-like asymmetric circulations. This data assimilation, including the TC initialization scheme within each model, will be discussed in detail in the next section.

3.3 *First-guess field in data assimilation cycle and TC initialization*

It is hypothesized that each global analysis field has different shapes for beta gyres because each global forecast model has a different TC initialization procedure. In the GDAPS tropical cyclone initialization, an axially symmetric vortex is constructed with the TC information, such as central pressure, maximum wind, and 30 (50) kt wind radii, then and placed at the position of the TC. The asymmetric component extracted from the previous six-hour forecast is then added to become the first-guess field in the operational data assimilation cycle. Observations are then blended with this first-guess field via a three-dimensional variational (3DVAR) analysis to produce the final analysis data (Lim et al., 2002). Therefore, it is natural that GDAPS should possess beta gyres generated by the previous six-hour model forecast. Since strong convection around the TC center may occur during the six-hour forecast, the inclusion of the asymmetric component may thus result in mesoscale circulation features, as in Fig. 6a.

A similar pattern may be present in the GFS initial analysis because a vortex re-location technique is utilized. That is, the symmetrical and asymmetrical vortex components from the previous six-hour prediction are simply re-located to the new official warning position at the corresponding time (Rhome, 2007). Therefore, the asymmetric component of the GFS field may contain similar characteristics to those of GDAPS if convective mesoscale circulations have occurred during the six-hour model forecast of the TC that is relocated. As indicated previously, it is possible that an indicated strong mesoscale circulation may be real or merely a spurious feature, although the latter case is more likely.

If the above hypothesis is correct, an inspection of the asymmetric circulation in the global model initial analysis to detect the existence of a well-defined beta gyre may be a useful indicator of the quality of the TC initialization. If necessary, an additional step of removing the spurious mesoscale circulation by an azimuthal Fourier decomposition (e.g., Zhong et al., 2007) may improve the TC initialization.

The NOGAPS TC initialization is patterned after that of the United Kingdom Meteorological Office (Fiorino et al., 1993). Thirteen synthetic tropical cyclone observations that represent a symmetric vortex are added to a spectral triangular T20 (i.e., all wavelengths shorter than wavenumber 20 are not included) representation of environmental flow at each level. An adjustment vector is applied uniformly at each of the 13 points at all levels between 850 hPa and 400 hPa to account for any departure of the environmental flow from the past 12 hours TC motion vector. The synthetic observations do not have an asymmetric component to represent beta gyres. However, the adjustment vector difference between the synthetic observations and the NOGAPS background might well introduce a ventilation-type component that would exist between the beta gyres. The final analysis will be a compromise between the synthetic observations and the background field.

A first-guess field of decent quality will normally guarantee a good analysis field. Three other examples of the asymmetric components analyzed with the use of the first-guess field of GDAPS at each analysis time in Fig. 1 are shown in Fig. 7. The SONCA and the NABI cases (Figs. 7a, 7b) have beta-gyre-like circulations to a reasonable degree in the first-guess fields, which mostly are six-hour integrations. In the SHANSHAN case (Fig. 7c), a beta-gyre-like circulation is present in the outer region, but a shorter wave circulation appears to be dominant close to the center. This small-scale circulation may be related to spurious convective activity or some unknown baroclinic effects within the model during the six-hour integration. Con-

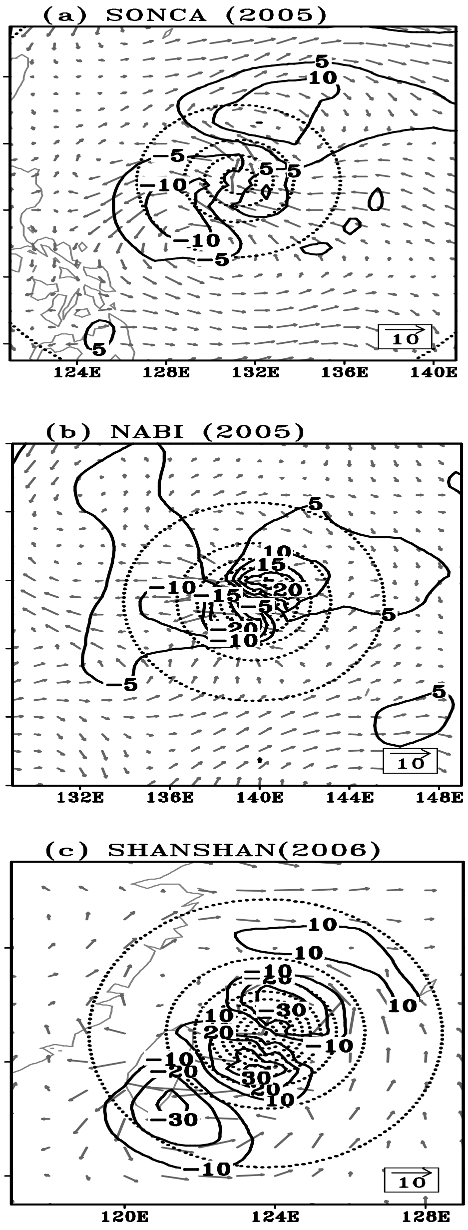

Fig. 7. 850 hPa asymmetric wind and height fields as in Fig. 5, except based on the GDAPS first-guess fields for (a) SONCA, (b) NABI, and (c) SHANSHAN.

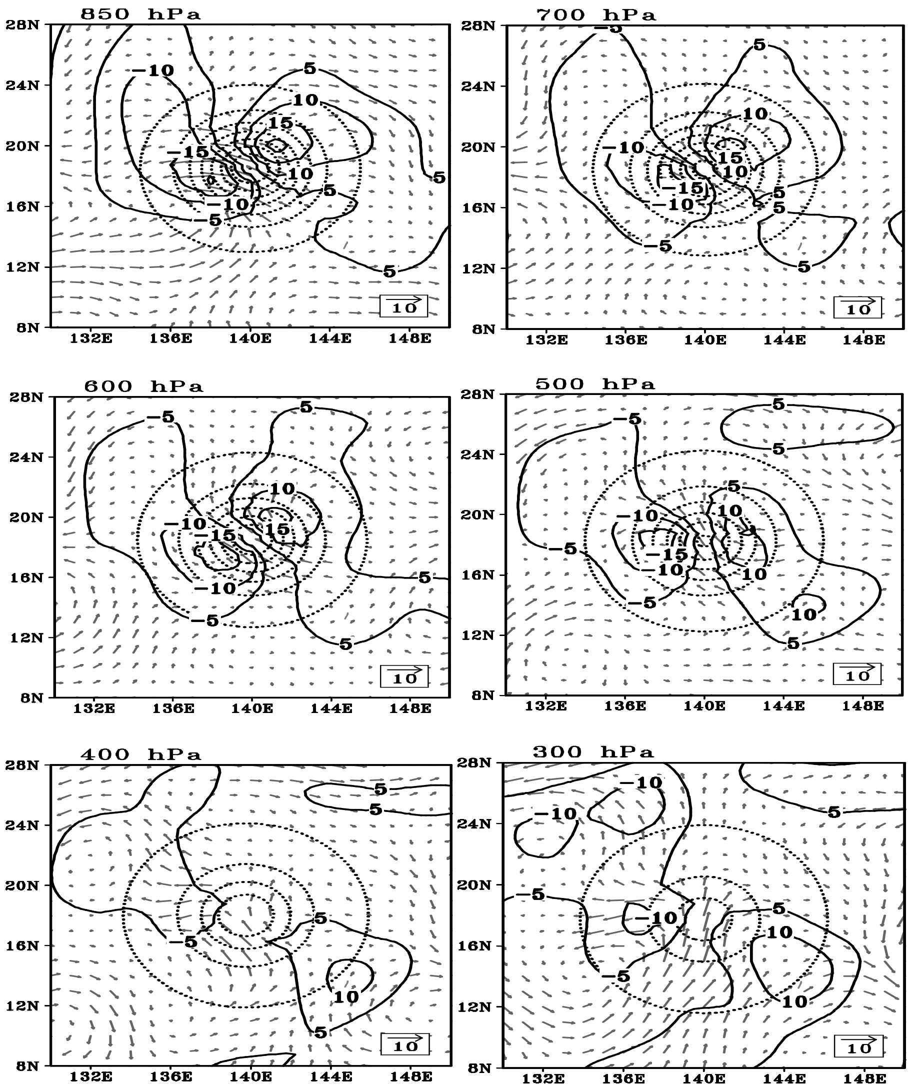

Fig. 8. Asymmetric wind and height fields as in Fig. 5, except from 850 hPa to 300 hPa (see labels at top-left) near NABI at 1200 UTC 1 September 2005 from the GDAPS analysis.

sequently, the absence of a well-defined beta gyre in the initial analysis field (Fig. 6a) may be attributed to the GDAPS analysis from this bad first-guess field (Fig. 7c).

3.4 *Vertical structure of beta gyre*

The height-dependence of the TC structure affects the vertical structure of the beta gyre. Near the center of a mature TC, the primary TC circulation of cyclonically swirling wind extends from the surface to the tropopause. At high levels, an anticyclone is found aloft. That is, the vertical structure of the TC is like a pyramid-shaped cyclonic circulation piercing upward into an anticyclone aloft, which is basically of an equivalent barotropic nature. If the structure of the primary circulation has a pyramid shape, the beta gyre should have a similar shape. In this section, the vertical variations of the beta gyre are investigated.

Asymmetric wind and height fields at different levels in the GDAPS analysis for NABI (0514) at 1200 UTC 1 September 2005 are shown in Fig. 8. The beta gyre indeed has an equivalent barotropic structure as in the primary circulations, in the sense that its magnitude is largest at the lower level and decreases with height. Although a well-defined beta gyre is present mostly in the lower to middle troposphere, no beta gyre is evident above the 400 hPa level. The structure of the beta gyre and the magnitude of the corresponding ventilation flow primarily depend upon the magnitude of the outer wind and the TC size (Fiorino and Elsberry, 1989; Smith and Ulrich, 1990). Therefore, the structure of the asymmetric circulation and its vertical variations should be case-dependent. The other cases in Fig. 1 have also been examined (Kim, 2008), and the vertical structures are indeed case-dependent, i.e., the strongest and best-defined beta-gyre-like circulations are found at the lower levels and diminish aloft (Kim, 2008).

3.5 *Beta gyre in the TCM-90 final analyses*

The TCM-90 final analyses are based on a high-quality observational data set obtained from a field experiment conducted in the western North Pacific during August and September 1990. In addition to the U.S. Office of Naval Research TCM-90 experiment, the coordinated observations were gathered by the ESCAP (Economic and Social Commission for Asia and the Pacific)/WMO (World Meteorological Organization) Typhoon Committee, and the Taiwan Area Typhoon Experiment. During the IOPs (Intensive Observation Periods), six-hour rawinsonde coverage from conventional surface stations, four additional over-ocean rawinsondes from ships, many asynoptic observations such as radar wind profilers, drifting buoys, and three flights into Typhoon FLO were added, with an aim of producing quality data (Elsberry et al., 1990; Harr et al., 1991). The TCM-90 final analysis data were produced with the use of the NCEP Eta model FDDA (Four-Dimensional Data Assimilation) in which the six-hour model forecast and all conventional special TCM-90 observations are blended.

The existence of beta gyres in the TCM-90 data was examined by applying exactly the same analysis technique for almost every analysis time along the track of Typhoon FLO, but no beta gyres were found. This agrees with Elsberry et al. (1993) who also found no beta gyres in the TCM-90 final analyses. On 16 September (Fig. 9a), FLO was moving northwestward, and the large-scale environmental steering flow field (not shown) obtained by eliminating only the axisymmetric component did have northwestward flow near the center of FLO. However, no evidence of a beta gyre is found in the asymmetric wind and height fields (Fig. 9a). At 1200 UTC 18 September (Fig. 9b), FLO was moving northeastward after having recurved 24 hours before, and the environmental steering flow (not shown) was again consistent with a northeastward track. Asymmetric flow has a northwestward ventilation flow northwest of the TC center due to counter-rotating gyres of an anticyclonic circulation to the north and a cyclonic circulation to the southwest of the center. Furthermore, the strong cyclonic circulation on the southeast side makes this pattern difficult to be considered a beta gyre. Chan and Cheung (1998) presented counter-rotating gyres in the azimuthal wavenumber-1 component of the TCM-90 data, but those cannot be considered to be beta gyres, as the ventilation flow should be toward the northwest direction.

It may seem surprising that a well-defined beta gyre is not found in the TCM-90 final analyses, which are based on the best quality data set for western North Pacific tropical cyclones. Based on the cases of operational model analyses in section 3.2, an explanation is that no TC synthetic observations were included, and except for limited periods when dropwindsondes were available from the NASA DC 8, inadequate observations were available to define the vortex structure. Without a well-defined vortex in the initial conditions for the Eta model, the six-hour forecast used in the FDDA cycle does not generate beta gyres in the background field for the next analysis. This situation is in contrast to the GDAPS and GFS initial conditions that do have asymmetries which then lead to beta-like gyres. Without this asymmetric circulation in the background field, the TCM-90 final analysis blending technique that uses a statistical relationship between the six-hour model forecast and the observations (Titley and Elsberry, 2000) cannot generate beta gyres with the available observations.

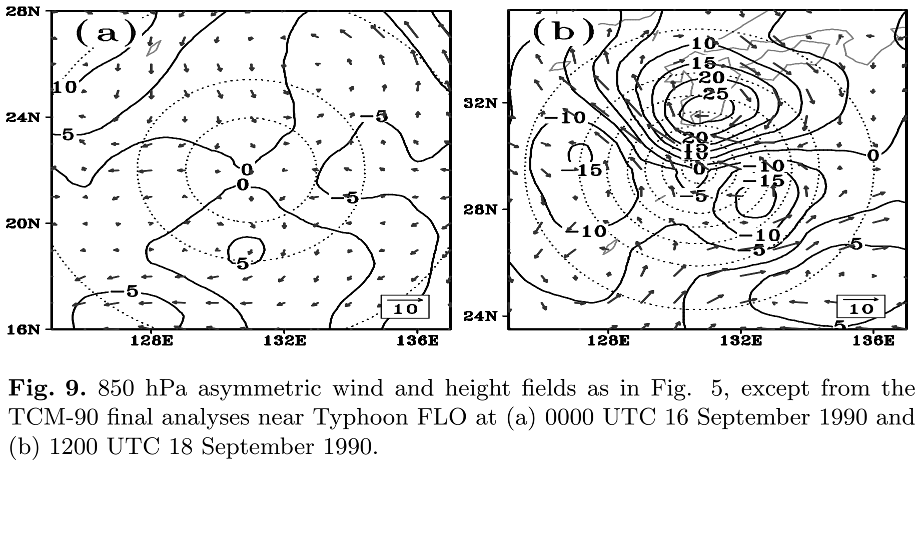

Fig. 9. 850 hPa asymmetric wind and height fields as in Fig. 5, except from the TCM-90 final analyses near Typhoon FLO at (a) 0000 UTC 16 September 1990 and (b) 1200 UTC 18 September 1990.

4. Summary and conclusions

A three-component decomposition suggested by Fiorino and Elsberry (1989) is applied to three global analyses (GDAPS, GFS, and NOGAPS) to examine the existence of beta gyres that causes TCs to drift relative to the large-scale environmental steering current. Extracting the beta gyres from these operational analyses is by no means a simple task compared to the case of an idealized nondivergent barotropic numerical model, because no clear way exists to separate the TC component and the environmental component from the total field. In this study, GFDL filtering (Kurihara et al., 1993) and Lanczos filtering (Claude, 1979) are applied to the global analyses to derive an environmental field from the total field. That is, all wave components shorter than wavelengths of either 12°N (Lanczos) or 9°N (GFDL) are completely filtered out. The direction of the environmental steering is consistent with the TC motion at the analysis time. After removal of the environmental component from the total field, the resulting disturbance field is separated into the axisymmetric component and the asymmetric component. The beta gyre is then examined as the main part of the asymmetric component.

The structure of the beta gyre in the asymmetric component analyses has several elements of structure that agree with the theoretical studies of beta gyres: a cyclonic circulation to the southwest of the TC center, an anticyclonic circulation to the northeast and a ventilation flow near the center that is directed northwestward. The circulation of the beta gyre is strongest at the 850 hPa level where the cyclonically primary circulation is the strongest, and decreases with height, in a pyramid shape similar to the primary circulation (Elsberry, 1995).

The individual structures of the beta gyres are indeed case- and model-dependent. At any analysis time, one model may have a well-defined beta gyre, while other models may not. For one model, the beta gyre may be well defined at some analysis times but not at other times. The structure of the beta gyre and the strength of the ventilation flow should depend upon the outer wind structure of tropical cyclone (Elsberry and Stenger, 2008) at the time of analysis.

An *a priori* assumption is that a beta gyre should be revealed in the three-component decomposition technique for most of the global analyses in which a six-hour forecast is used as a first-guess field in the vortex initialization stage, since the asymmetric circulation generated within the six-hour forecast should contain the beta gyre. However, this is not always true. In the cases without a clear beta gyre, there are usually small-scale circulations around the TC center, which are conjectured to be related to spurious convective activity or some unknown baroclinic effects within the model during the six-hour integration.

Different vortex initialization schemes in each model may also result in different aspects of the beta gyre of each model. In GDAPS, an asymmetric component of the TC is extracted from the previous six-hour forecast and then added to a symmetric vortex to become the first-guess field for the operational data assimilation cycle. The observations that are blended with this first-guess field in the 3DVAR technique for the initial analysis (Lim et al., 2002) may then distort the beta gyres. In the GFS vortex-relocation technique, both the symmetric and the asymmetric vortex components from the previous six-hour prediction are moved to the new official warning position at the corresponding time (Rhome, 2007). Therefore, the asymmetric component of the GFS field should have similar characteristics to those of GDAPS in the sense that a beta gyre should be present, but convective mesoscale circulations may also occur during the six-hour model run. In the NOGAPS TC initialization technique, the 13 synthetic tropical cyclone observations only represent a symmetric vortex that is added to a spectral triangular T20 (i.e., all wavelengths shorter than wavenumber 20 are not included) representation of environmental flow at each level. The synthetic observations, thus, do not have an asymmetric component to represent beta gyres. However, a second step in the NOGAPS initialization is the addition of the difference between the azimuthally-averaged synthetic observations and the NOGAPS background from the past 12-h motion, which might represent the ventilation component of the beta gyre without the anticyclonic and cyclonic circulations. The subsequent blended analysis of the synthetic observations and the background field may then also distort the flow around the TC.

As in Elsberry et al. (1993), the same three-component decomposition applied to the TCM-90 final analyses did not reveal beta gyres even though this data set was based on a comprehensive set of observations. The proposed explanation based on the GDAPS and GFS analyses that did contain beta gyres is that the procedure to generate the TCM-90 final analysis did not have a TC bogus vortex as in those models, nor adequate observations to define the TC vortex structure. Thus, the six-hour integration of the Eta model to provide the background fields for the TCM-90 final analyses did not generate beta gyres.

It is anticipated that a better understanding of the beta gyres, and their proper incorporation in operational model analyses and forecasts, will lead to further improvements in tropical cyclone track forecasts and warnings.

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REFERENCES

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

Chan, J. C.-L., and R. T. Williams, 1986: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. *J. Atmos. Sci.*, **44**, 1257–1265.

Chan, J. C.-L., and K. K. W. Cheung, 1998: Characteristics of the asymmetric circulation associated with tropical cyclone motion. *Meteor. Atmos. Phys.*, **65**, 183–196.

Claude, E. D., 1979: Lanczos filtering in one and two dimensions. *J. Appl. Meteor.*, **18**, 1016–1022.

Elsberry, R. L., 1990: International experiments to study tropical cyclones in the western North Pacific. *Bull. Amer. Meteor. Soc.*, **71**, 1305–1316.

Elsberry, R. L., 1995: Tropical cyclone motion. Chapter 4, *Global Perspectives on Tropical Cyclones.* World Meteorological Organization Tech. Document WMO/TD-No. 695, 289pp.

Elsberry, R. L., and R. A. Stenger, 2008: Advances in understanding of tropical cyclone wind structure change. *Asia-Pacific Journal of Atmospheric Sciences*, **44**, 11–24.

Elsberry, R. L., B. C. Diehl, J. C.-L. Chan, P. A. Harr, G. J. Holland, M. Lander, T. Neta, and D. Thom, 1990: ONR tropical cyclone motion research initiative: Field experiment summary. Naval Postgraduate School Tech. Rep. NPS-MR-91-002, 106pp.

Elsberry, R. L., P. H. Dobos, and D. W. Titley, 1993: Extraction of large-scale environmental flow components from the TCM-90 analyses: Implications for tropical cyclone motion studies. Preprints, *20th Conf. Hurr. Trop. Meteor.*, Amer. Meteor. Soc., Boston, MA 02108, 485–488.

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

Fiorino, M., J. S. Goerss, J. J. Jensen, and E. J. Harrison, 1993; An evaluation of the real-time tropical cyclone forecast skill of the Navy operational global atmospheric prediction system in the western North Pacific. *Wea. Forecasting*, **8**, 3–24.

Fovell, R. G., and H. Su, 2007: Impact of cloud microphysics on hurricane track forecasts. *Geophys. Res. Lett.*, **34**, L24810, doi: 10.1029/2007GL031723.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor.*, **15**, 1252–1264.

Harr, P. A., T. Neta, and R. L. Elsberry, 1991: ONR Tropical Cyclone Motion Research Initiative: Data users guide to observations. Naval Postgraduate School Tech. Rep. NPS-MR-91-002, 124pp. [Available from Naval Postgraduate School, Monterey, CA 93943]

Kim, S.-H., 2008: Dynamics of tropical cyclone motion realized in the global analysis fields. M. S. thesis, Dept. of Atmos. Sci., Kongju National University, 53pp.

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.

Lim, J.-H., K.-M. Chu, D.-K. Rha, and J.-Y. Cho, 2002: Typhoon initializing process of global data assimilation and prediction system and verification of tropical cyclone forecast in 2001. Korea Meteorological Administration Tech. Rep., 2002-5, 71pp. (in Korean)

Rhome, J. R., 2007: Technical summary of the National Hurricane Center track and intensity models, NWS National Hurricane Center. [Available at http://www.nhc.noaa.gov]

Ritchie, E. A., and W. M. Frank, 2007: Interactions between simulated tropical cyclones and an environment with a variable Coriolis parameter. *Mon. Wea. Rev.*, **135**, 1889–1905.

Rogers, E., S. J. Lord, D. G. Deaven, and G. J. DiMego, 1992: Data assimilation and forecasting for the tropical cyclone motion experiment at the National Meteorological Center. General Sciences Corp., Laurel, MD, 22pp. [Available from NCEP Environmental Modeling Center, 5200 Auth Road, Camp Springs, MD 20746]

Smith, R, K., and W. Ulrich, 1990: An analytical theory of tropical cyclone motion using a barotropic model. *J. Atmos. Sci.*, **47**, 1973–1986.

Titley, D. W., and R. L. Elsberry, 2000: Large intensity changes in tropical cyclones: A case study of Supertyphoon Flo during TCM-90. *Mon. Wea. Rev.*, **128**, 3556–3573.

Zhong, Z., X.-T. Wang, and J.-S. Zhang, 2007: The possible mechanism on formation and intensification of the maximum wind core in tropical cyclone. *Journal of the Korean Meteorological Society*, **43**, 185–194.