Diagnosis of Large Prediction Errors on Recurvature of Typhoon Fengshen (2008) in the NCEP-GFS Model

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Abstract

The steering-flow analysis based on potential vorticity (PV) diagnosis is used to examine the reasons why the National Centers for Environmental Prediction Global Forecast System (NCEP-GFS) model showed large track forecast errors with over-recurving movement in Typhoon Fengshen (2008). In particular, two forecasts initialized at 0000 UTC 19 and 20 June 2008 are demonstrated in this study. The deep-layer-mean (DLM) steering flow between 925 and 300 hPa with tropical cyclone components filtered out is directed to the west or northwest in the analysis field, which can account for the continuous westward and northwestward movement in the best track. However, the DLM steering flow is shown more toward the north in the forecast fields. Four distinct PV features associated with the corresponding subtropical high, monsoon trough, continental high, and midlatitude trough are identified to diagnose their balanced steering flows around the storm. The result based on PV analysis indicates that the reduced westward steering flow in the forecast field is mainly attributed to the subtropical high which is over-predicted to extend southwestward, as well as the continental high with underestimated coverage, as characterized by the geopotential height at 500 hPa. The steering flow associated with the monsoon trough plays an essential role while Typhoon Fengshen (2008) experiences northward recurvature in both analysis and forecast fields. Therefore, the associated reduced westward steering flow in the NCEP-GFS model leads to the over-recurvature of Fengshen.

Keywords potential vorticity diagnosis; deep-layer-mean steering flow; subtropical high; monsoon trough

1. Introduction

It is well known that about 75 % of the tropical cyclones (TCs) in the western North Pacific (WNP) form in monsoon environment (McBride 1995). In particular, the monsoon trough or intertropical convergence zone (ITCZ) in the WNP is a favorable environment for TC formation. The equatorial westerlies and trade wind easterlies within the trough provide the necessary low-level relative vorticity and convergence, and low-to-mid-level moisture is abundant in the area as well (Gray 1998). The TC characteristics, such as their structure, intensity, and trajectory, as well as its formation and early development, are substantially affected by the monsoon trough (Chen et al. 2014). For example, the axis of the monsoon trough has meridional variation in its position and southeastward extent.
sion (or retreat) within a season, which modulates the motion of TCs that develop near the trough (Atkinson 1971; Cheung 2004). In addition, the studies of Harr and Elsberry (1995a, b) showed that the synoptic pattern of monsoon trough and subtropical high ridge within the 700-hPa circulation in the WNP primarily determines the TC activity and dominant track types in the basin.

Some later studies further demonstrated the close relationships between synoptic patterns and TC characteristics. Lander (1996) examined the low-level monsoon flow patterns in the WNP for the period between 1978 and 1994 and identified five recurring configurations corresponding to the long-term average, the twin-trough pattern, the active mei-yu pattern, the monsoon gyre, and the reverse-oriented monsoon trough. It was shown that these patterns of the monsoon circulation are associated with certain specific characteristics of TC motion and structure. Under the context of diagnosing large TC track forecast errors, Carr and Elsberry (2000) utilized the synoptic pattern/region conceptual models to identify the predominant error mechanisms. Carr and Elsberry (1995) used a non-divergent barotropic model to simulate sudden track changes due to the interaction between TC circulation and monsoon gyre. It was found that the smaller TC vortex initially moved according to the cyclonic steering flow of the larger monsoon gyre. Later, the two vortices merged to form a single one, and an anticyclone developed to the southeast because of the Rossby wave dispersion. Consequently, a southerly jet was generated in between the monsoon gyre and the newly developed anticyclone, which provided a northward steering to the TC vortex and thus caused a change in direction. After the simulation conducted by Carr and Elsberry (1995), Nieto Ferreira and Schubert (1997) based their experiment on a nonlinear shallow-water model to further demonstrate that a TC vortex has a larger westward component of motion within an environment of zonally symmetric potential vorticity (PV) strip like one in a monsoon trough, compared with that in a quiescent environment (their Fig. 9).

In short summary, besides the role of providing a favorable environment for TC formation and development, the variability of the synoptic pattern of the monsoon trough and circulation in the WNP on synoptic, intra-seasonal, seasonal, and inter-annual timescales is an essential factor for modulating the characteristic track types of TCs within the corresponding time periods (Elsberry 2004). We focus on the synoptic scale features including the monsoon trough.

Wu and Emanuel (1993, 1995a, b) first applied the concept of PV analysis to the study of TC motion. Owing to its conservation property, principle of superposition, and ease of inversion to wind field, there are a series of subsequent studies that applied PV analysis to quantitative diagnosis of TC-motion-related issues (e.g., Shapiro 1996, 1999; Wu et al. 2003, 2004, 2012; Yang et al. 2008). An advantage of the PV analysis is its capability to extract the TC motion associated with the synoptic scale features. In particular, large track forecast errors with a northward (or northeasterward) bias are persistently existent in the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model for Typhoon Fengshen (2008) which is located in lower latitudes (see Fig. 1). Since numerical model outputs are used as the major guidance for official TC track forecasts nowadays, it is valuable to understand this type of systematic bias in major operational models. It is also important to better understand why sometimes the modeling systems result in major forecast bust.

This study aims at conducting quantitative PV diagnosis to examine the reasons why the NCEP-GFS has such track errors and to indentify the steering flows associated with distinct synoptic scale features. The
data and PV diagnosis are described in Section 2. The comparison of the synoptic field and steering flows between the analysis and forecast data based on PV analyses is presented in Section 3, and the summary of this study is given in Section 4.

2. Data and methodology

2.1 NCEP analysis and forecast data

The Global Tropospheric Analyses (GTA) from the Final Global Data Assimilation System (GDAS FNL) and the GFS forecast of NCEP for Typhoon Fengshen (2008) are utilized to conduct the PV diagnosis in this study. The NCEP-GFS (Sugi et al. 1998; Han and Pan 2011) is an operational global data assimilation and model system providing forecasts four times per day. In addition, its horizontal resolution was spectral triangle 382 (T382 ~ 35 km) with 64 vertical sigma levels during 2008. The available output fields from the model are 6-hourly in temporal resolution and 1° × 1° (latitude by longitude) in spatial resolution, with 26 vertical levels between 1000 and 10 hPa.

2.2 PV diagnosis

The methodology of the PV analysis applied in this study is similar to that in Wu et al. (2003, 2012) and Yang et al. (2008), as briefly outlined below. The merit of the PV invertibility states that, given a distribution of PV, a prescribed balance condition, and boundary conditions, the balanced mass and wind fields can be recovered. By taking the axisymmetric average relative to the center of the storm as the mean part (q̄) and the rest as the total perturbation field (q′), q′ = q − q̄, the piecewise PV inversion is performed to calculate the balanced flow and mass fields associated with each PV perturbation. Following Wu et al. (2003), the steering flow (V_{SDLM}) based on the PV calculation is defined as the deep-layer-mean (DLM; 925–300 hPa) wind vector averaged over the inner 3° latitude/longitude around the storm center (based on the location of the maximum PV at 850 hPa). The motion vector in the best track or the model TC is calculated based on a 12-h period centered at a particular time (i.e., V_{BT/CMF}) = (X_{t+1} + X_{t−1})/12h). The principles for partitioning PV perturbation fields as in Wu et al. (2012) are adopted here, including the synoptic scale features corresponding with subtropical high (q′_{SH}), monsoon trough (q′_{MT}), continental high (q′_{CH}), and midlatitude trough (q′_{TV}), q′ = q′_{SH} + q′_{MT} + q′_{CH} + q′_{TV}. To facilitate the PV perturbation partitioning, the boundary between the subtropical high and the continental high with negative PV perturbation is generally set along a line extending from 23°N, 120°E to 55°N, 160°E (just south of the Kamchatka Peninsula). The division between the midlatitude trough and the monsoon trough with positive PV perturbation falls between 22°N and 25°N depending on their respective locations, i.e., according to the evolution of the monsoon trough. The PV perturbations partitioned as described above represent the climatology-mean location and size of the synoptic systems, i.e., subtropical high on the Pacific Ocean, continental high on the Eurasia, midlatitude trough within the midlatitude westerly flow, and monsoon trough in the low-latitude easterly flow. Note that, as addressed in Wu et al. (2012), the DLM steering flow based on the PV inversion is not sensitive to the small-scale features located on the edge of each PV perturbation. In addition, the value “AT (along track)” has been designed to quantitatively measure the influence of the steering flow associated with each PV perturbation in the direction parallel to the steering flow associated with the total PV perturbation (q′). That is, AT for a particular PV perturbation (q′; s represents SH, MT, CH, or TR) is defined as

\[
AT(q'_s) \equiv \frac{V_{SDLM}(q'_s) \cdot V_{SDLM}(q'_s)}{|V_{SDLM}(q'_s)|^2},
\]

where \( V_{SDLM}(q'_s) \) and \( V_{SDLM}(q'_s) \) indicate the DLM steering flow associated with \( q'_s \) and \( q'_s \), respectively. AT is a normalized quantity, and by definition, \( AT(q'_s) = AT(q'_s) + AT(q'_{nos}) \), where \( q'_{nos} \) represents the rest of the PV perturbation excluding the portion represented by \( q'_s \) and \( q'_s = q'_s + q'_{nos} \). The merit of diagnosing AT is to quantify the relative contribution of individual components of the steering flow based on piecewise PV inversion, since the cross-track components of the steering flow should be cancelled out between PV perturbations.

3. Results

3.1 Synopsis of Typhoon Fengshen (2008)

Typhoon Fengshen developed from a tropical disturbance located at about 155 n mi (287 km) northwest of Palau. The Japan Meteorological Agency (JMA) declared the disturbance to be a tropical depression on 17 June, and the Joint Typhoon Warning Center (JTWC) released a TC formation alert for the system (07W) later at 1200 UTC 18 June. A second warning at 1800 UTC 18 June from JTWC identified the system as a tropical storm, and JMA also declared that the system reached an intensity of 35 kt (18 m s⁻¹) at 0000 UTC 19 June. The tropical storm intensified quite rapidly to a typhoon (65 kt or 33 m s⁻¹) at 1800 UTC 19 June when it was east of the Philippines and
developed about one day later to its lifetime maximum intensity of 110 kt (56 m s$^{-1}$) at 0000 UTC 21 June with a minimum central surface pressure of 945 hPa (Fig. 1).

During the formation period of Fengshen, the synoptic environment in the WNP consisted of a reverse-oriented monsoon trough characterized by the wind field at 850 hPa (figure not shown). Typhoon Fengshen continued to develop and came into the monsoon-gyre-like environment. The geopotential height at 500 hPa from GTA analyses showed that the continental high covered an area from 130°E to the west of Hainan when Fengshen was located at central Philippines at 0000 UTC 21 June (Fig. 2a). The area of the continental high remained to the north of Fengshen 12 h later (Fig. 2d), and the subtropical high over the Pacific extended westward. At 0000 UTC 22 June, the area of the continental high evidently shrank (Fig. 2g), and Fengshen continued to move north–northwestward (Fig. 1). At later times, the subtropical high strengthened and expanded to the east of Fengshen (figure not shown), pushing the storm to move northwestward until its landfall near Hong Kong.

In Figs. 2a, 2d, and 2g, the strength and the cover-
age of both the continental high and the subtropical high change over time. One can expect from the flow pattern in Figs. 2a, 2d, and 2g the contribution of the subtropical high to a northeastward TC steering current on its western edge and the contribution of the continental high to a westward TC steering current on its southern edge. Another interesting phenomenon is a cyclonic circulation with an approximately 1500-km width on the southwestward flank of Fengshen. This cyclonic circulation corresponds to the monsoon trough (shown later).

3.2 Evaluation of the NCEP-GFS forecast fields

The fact that almost all numerical guidance products from operational centers have exceptionally large track forecast errors (Figures not shown) indicates an important prediction issue in Typhoon Fengshen. This is particularly true for all forecasts initialized before 24 June in which Fengshen unrealistically recurved toward the north. Taking the NCEP-GFS model as an example, the NCEP-GFS forecasts initialized from 0000 UTC 19 June to 0000 UTC 22 June all showed over-recurrence as compared with the best track (Fig. 1). In particular, the storm in the NCEP-GFS forecast initialized at 0000 UTC 20 June moved west-northwestward in the first 12 h, but then turned north-northwestward sharply during the model integration from 18 to 30 h. During this period, the forecast track moved northward and northeastward. Other forecasts initialized at different times showed a significant turn toward the northeast as well, which resulted in very large forecast errors toward the end of all 72-h forecasts.

The synoptic environment at 500 hPa in the forecast field was compared to that in the analysis field (Fig. 2). In the 48-h forecast initialized at 0000 UTC 19 June 2008, it is apparent that the continental high over southern China was predicted to be weaker and smaller (Fig. 2b), as compared to the analysis field (Fig. 2a). Meanwhile, the forecasted storm moved northward with the translation speed of about 3 m s$^{-1}$. The edge of the subtropical high extended further westward to the south of the storm at 60 h (Fig. 2e), and the continental high remained weak. At 72 h, the subtropical high extended to 130°E (Fig. 2h; indicated by the contour of 5860 gpm), and the forecasted storm slowly moved northeastward. In addition, the weak continental high located to the north of Fengshen in the analysis field (Fig. 2g) further weakened and dissipated in the forecast field (Fig. 2h). Similar variations associated with the prediction of the subtropical high and the continental high in the forecast initialized at 0000 UTC 20 June 2008 were also observed (Figs. 2c, f, i). The NCEP-GFS forecast fields, initialized at 0000 UTC 19 and 20 June, respectively, also showed a large range of cyclonic circulation on the southwestward flank of Fengshen. As discussed in the previous section, the monsoon trough provides favorable environmental conditions for the tropical cyclone formation and can affect Fengshen’s movement during its lifetime. The impact of the monsoon trough on the movement of Fengshen is discussed later in this section.

In order to explore the difference of environmental flows between the analysis and forecast fields, the filtering method as in Kurihara et al. (1993, 1995) was adopted to acquire the environmental flow fields. Figure 3 shows the difference of 925–300-hPa DLM environmental winds in the 36-h forecast initialized at 0000 UTC 19 June and the 24-h forecast initialized at 0000 UTC 20 June where the storm movement became distinctively bifurcated from the best track (Fig. 1). Apparently, the DLM environmental flow in the analysis field had more west–northwestward and northwestward components of about 0.75–1 m s$^{-1}$ in the vicinity of storm centers, as compared to that in the forecast field (Fig. 3). This is consistent with the fact that the analyzed storm persistently moved toward the west and northwest.

To further understand the reason why the tracks in the NCEP-GFS forecasts show such distinct bias, the steering flows were calculated by averaging the environmental winds between 925 and 300 hPa within a circle with a radius of 3° centered at the corresponding storm center, details of which are illustrated in Fig. 4. The motion vectors in the best track and the forecasts are defined and mentioned in Section 2.2. Note that the motion vector in the best track instead of that in the GTA analyses is demonstrated since both storm center positions have a good agreement with the error within 0.2° (latitude degrees). At 1200 UTC 20 June, the westward movement of Fengshen was generally consistent with the DLM steering flow in the analysis field (Fig. 4a), and its translation speed was moderately larger than the magnitude of the steering flow. This result appears consistent with the study of Galarneau and Davis (2013; see their Fig. 4), which indicated that some bias exists between the DLM steering flow and the actual storm movement, and the DLM steering flow can roughly explain 80% of the variability of the storm movement. The bias between the DLM steering flow and the actual storm movement probably results from the beta effect, diabatic heating, and asymmetric structure (Chan et al. 2002; Chen et al. 2014; Nasuno
especially in the environment of Typhoon Fengshen (2008) where strong vertical shear is present (Yamada et al. 2016). The motion vector in the 36-h forecast initialized at 0000 UTC 19 June was northward with a speed of about 3.5 m s$^{-1}$ (Fig. 4a), and the steering flow in the forecast field pointed to the northwest.

The comparison of the steering flows between the analysis and forecast fields indicates a more north-eastward component in the forecast field than in the analysis field (Fig. 4a), and both can also be identified in the 24-h forecast initialized at 0000 UTC 20 June (Fig. 4b). Although the steering flow depicted in Fig. 4 is a snapshot at one forecast time, the result of the steering flow in the forecast field pointing more to the north as compared to the analysis field is persistent in the following integration times (figure not shown). The track bias in the NCEP-GFS forecast is primarily attributable to the discrepancy in the DLM steering flows.

3.3 PV diagnosis between the analysis and forecast fields

To further consolidate the understanding of the factors influencing the movement of Fengshen, a quantitative comparison applying PV diagnosis based on the analysis and forecast data has been carried out.
and explored in this subsection.

a. Total PV perturbation fields

The total PV perturbations at 500 hPa and the 925–300-hPa DLM winds in the analysis and the forecast initialized at 0000 UTC 20 June are shown in Fig. 5, as well as the approximate regions of the four inverted PV features \( (q' = q'_{\text{SH}} + q'_{\text{MT}} + q'_{\text{CH}} + q'_{\text{TR}}) \). The outlines of the four inverted PV regions are shown in Fig. 5a. There is no PV signal from Fengshen in the PV perturbation field since the mean PV associated with Fengshen was removed. The distribution of four pieces of particular PV perturbation identified in Fig. 5 is generally consistent with the synoptic scale features shown in Fig. 2. It is noteworthy that, to the southwest side of Fengshen (Fig. 5), a positive PV patch is present, which is associated with the aforementioned major portion of the monsoon trough. As shown in Yang et al. (2008), the monsoon trough could affect the process of the binary interaction. Herein, the role of the monsoon trough in the motion of Fengshen is examined. The positive PV perturbation located to the southwest of Fengshen ranges about 0.3–0.4 PVU during 21–23 June in the analysis (Figs. 5a–c). Meanwhile, the variations of the maximum intensities of the 24-, 48-, and 72-h PV perturbations in the same region in the NCEP-GFS forecast initialized at 0000 UTC 20 June are 0.2, 0.4, and 0.3 PVU (Figs. 5d–f) on 21, 22, and 23 June, respectively. The different value of the maximum positive PV intensity will correspond to the different magnitude of the balanced steering flow associated with the monsoon trough.

b. DLM steering flows

Figure 6 displays the difference in the DLM steering flows associated with each PV perturbation between forecasts initialized at 0000 UTC 19 (Fig. 6a) and 20 (Fig. 6b) June, and the analyses during the 3-day period. It is shown in Fig. 6 that, except for the magnitude, the difference in the storm movements between the forecast and analysis fields (indicated by the row with “TCMV”) approximately agrees well with the difference in the balanced steering flows associated with all PV perturbations combined \( (q') \), indicating that the track deflection can be represented by the balanced steering-flow difference based on the PV inversion. However, note that the magnitude of the balanced steering-flow difference associated with all PV perturbations combined is generally smaller than that of the storm movement difference, which is likely due to the constraint of data resolution and calculation errors of PV inversion as addressed in Wu et al. (2012), and the influence of storm-scale processes and uncertainties in the wind field analyses (e.g., Chan et al. 2002; Chen et al. 2014; Galarneau and Davis 2013; Nasuno et al. 2016; Yamada et al. 2016). In the forecast initialized at 0000 UTC 19 June, it is found that the steering-flow difference associated with the subtropical high mostly points to the east–northeast with a magnitude of about 1–1.5 m s\(^{-1}\) until 0000 UTC 21 June, after which the steering-flow difference turns southeast (Fig. 6a). Meanwhile, the steering-flow difference associated with the continental high in the forecast field is more eastward by approximately 0.5–1.5 m s\(^{-1}\) after 0000 UTC 20 June. In contrast, the steering difference associated with the midlatitude trough is quite limited, with a difference almost less than 0.5 m s\(^{-1}\). The monsoon trough plays an essential role in the northward movement of Fengshen during the turning period.

As for the forecast initialized at 0000 UTC 20 June, it is shown in Fig. 6b that the variation of the steering flow associated with the subtropical high is generally consistent with that associated with the total PV perturbation, except for the time after 1200 UTC 22 June. Moreover, the steering-flow difference induced by the continental high increases to about 2 m s\(^{-1}\) after 1200 UTC 21 June, mostly pointing to the east–southeast. It is worth noting that the tendency in the monsoon trough during the turning period of Fengshen was opposite to that in the continental high with comparable magnitudes in both forecasts. That is, the bias associated with monsoon trough accelerates westward movement, which partly offsets the eastward bias associated with the continental high while accounting for a substantial part of the northward bias.

The above results indicate that PV diagnosis in Fig. 6 indicates that the difference in the steering flows between the forecast and analysis fields is primarily attributed to that associated with the subtropical high, the continental high, and the monsoon trough. As indicated by the synoptic pattern in Fig. 2, the subtropical high in the forecast field is over-predicted to extend southwestward, which produces the reduced westward steering flow (i.e., the anomalous eastward wind barbs before 0000 UTC on 21 June and after 0000 UTC 22 June; in the fourth row of Fig. 6). In addition, the southwestward steering flow associated with the continental high in the forecast becomes weaker as a consequence of its underestimated coverage and strength as compared to the analysis field (i.e., the anomalous eastward wind barbs before 0000 UTC on 21 June and after 0000 UTC 22 June; in the second row of Fig. 6).
Fig. 5. Total potential vorticity perturbation \( q' \); scaled in \( 10^{-2} \) potential vorticity units (PVU), where 1 PVU = \( 10^{-6} \) K m\(^2\) kg\(^{-1}\) s\(^{-1}\); the positive PV perturbation is shaded with contour intervals of 0.1 PVU at 500 hPa and the 925–300-hPa DLM wind (one full wind barb = 5 m s\(^{-1}\)) from NCEP GTA analyses valid at 0000 UTC (a) 21, (b) 22, and (c) 23 Jun 2008. (d)–(f) are the same as (a)–(c), respectively, but are taken from the NCEP-GFS forecast initialized at 0000 UTC 20 Jun 2008. The definitions of the arrow and circle are the same as in Fig. 2. Regions of the four PV perturbations associated with subtropical high (SH), monsoon trough (MT), continental high (CH), and midlatitude trough (TR) are marked. The solid (dashed) line in (a) generally indicates the partition boundary of the positive (negative) PV perturbation between MT and TR (SH and CH).
c. AT analysis

Figure 7 shows the time evolution of AT as defined in Section 2.2 associated with the four PV perturbations or the projections of the steering flows parallel to the entire steering-flow vector defined as the balanced flow associated with the combination of all PV perturbations. It should be noted that the cross-track effect cannot be identified by the design of AT. It is obvious in Fig. 7a that the AT associated with the Pacific subtropical high \( (q'_s) \) is always larger than 0.4 from 0000 UTC 19 to 25 June, except the period between 0600 UTC 22 and 0600 UTC 23 June, which indicates its major contribution to the along-track steering flow of Fengshen. The AT associated with the continental high \( (q'_c) \) shows positive values before and after 0000 UTC 21 and 1200 UTC 22 June, but with negative values during the intervening time, indicating an opposite steering effect to the northward motion of Fengshen.

Fig. 6. Time series of the difference in the storm movement (TCMV) bottom row and the 925–300-hPa DLM steering flows between the NCEP-GFS forecast and the GTA analyses associated with the total PV perturbation \( (q') \), subtropical high (SH), monsoon trough (MT), continental high (CH), and midlatitude trough (TR) for (a) the forecast initialized at 0000 UTC 19 Jun 2008 and (b) the forecast initialized at 0000 UTC 20 Jun 2008. The time sequence is indicated at the bottom of each panel at 6-h intervals. One full wind barb (a flag) represents 1 (5) m s\(^{-1}\). The vertical thin solid (dotted) lines in each panel show the start recurving time of Fengshen in NCEP-GFS forecast (best track/GTA analyses).
Regarding the contribution from the two high-pressure systems, the AT (values with two opposite signs mean the steering effect is canceled out) ranges from 0.40 to 0.72, with an average of 0.60. In other words, the DLM steering flow associated with the two high-pressure systems would account for 60% of the steering flow associated with all PV perturbations combined. The remaining steering-flow contribution is expected to come from other features, as well as the uncertainty (about 10%; Wu and Emanuel 1995a, b) associated with the PV inversion. The AT associated with the monsoon trough \(q_{\text{MT}}\) shows negative values in the beginning. After 1800 UTC 20 June, the AT values turn positive and gradually rise to the maximum value of 0.27 at 0600 UTC 22 June, indicating that the monsoon trough also plays an essential role in contributing to the along-track component of the steering flow after 1800 UTC 20 June. On the contrary, the AT associated with the midlatitude trough \(q_{\text{TR}}\) is always negative, indicating a steering-flow direction against the motion of Fengshen.

In summary, the averages of absolute AT values associated with the subtropical high, monsoon trough, continental high, and midlatitude trough from 0000 UTC 19 to 25 June are about 0.48, 0.13, 0.15, and 0.24, respectively (Fig. 7a), although the latter three are partially or all in the opposite direction of the overall balanced steering flow. On the basis of the definition of AT, these values represent the relative contribution to the overall balanced steering flow. Therefore, it can be concluded that the Pacific subtropical high has primary influence (i.e., 48%) on the steering flow of Fengshen, and the influence of the midlatitude trough is secondary, with about 24% negative contribution. It is worth noting that the overall steering flow that advects the TC is a composite of these. The sign of change in the AT values between the continental high and the monsoon trough during 21–22 June appears to be associated with the abruptly northward turn of Fengshen, namely, the AT associated with the monsoon trough and the continental high switched their roles in the recurving movement of Fengshen in the NCEP GTA (Fig. 7a).

Figures 7b and 7c show the AT values associated with the subtropical high, monsoon trough, continental high, and midlatitude trough for the forecast initialized at 0000 UTC 19 and 20 June, respectively. The role of four PV perturbations in the forecast fields is similar to those from the NCEP GTA analyses, except during the northward-turning period. However, the AT value associated with the continental high (monsoon trough) changes from positive (negative) values to negative...
(positive) and later decreases (increases) gradually. As to the biases in the forecasts, AT associated with the continental high (monsoon trough) decreases (increases) earlier than that in the GTA, leading to the earlier switch of their roles in affecting the movement of Fengshen, i.e., earlier recurvature. Some AT biases associated with the subtropical high between the NCEP-GFS and GTA during the recurving movement of Fengshen are also found. It is shown that the biases of the recurving movement of Fengshen can be attributed to the combined biases of the continental high, subtropical high, and monsoon trough. The large track forecast errors in the case of Fengshen might be attributed to the variation in the strength and size of these synoptic scale features, highlighting the importance of accurately representing these features with an improved forecasting system such as numerical models and model initial conditions employing advanced data assimilation systems.

4. Discussion and summary

Large track forecast errors are identified in the case of Typhoon Fengshen (2008) in the NCEP-GFS model initialized at the forecast times from 0000 UTC 19 to 22 June 2008, with over-recurvature toward the north and northeast as compared to the best track. The PV diagnosis is conducted in this study based on the NCEP analysis and forecast fields (initialized at 0000 UTC 19 and 20 June) to examine the causes of such large biases. On the basis of the principles of partitioning PV fields following Wu et al. (2012), four distinct PV perturbations (i.e., subtropical high, monsoon trough, continental high, and midlatitude trough) are identified to calculate their balanced steering flows around the storm.

The comparison of the geopotential height at 500 hPa between the analysis and forecast fields indicates that the reduced westward steering flow in the forecast field is mainly attributed to the over-predicted subtropical high, extending southwestward with its edge located to the southeast of the storm. In addition, the range and strength of the continental high to the north of the storm are moderately underestimated in the forecast field as compared to the analysis field. After employing the filtering procedure to acquire the environmental flow, more northward or eastward DLM (925–300 hPa) steering flow around the storm in the forecast field is clearly shown, which is indicative of why Fengshen actually moved to the northwest or north as compared to the analysis, and the steering flow associated with the monsoon trough plays an essential role in the bias of earlier northward recurvature of Fengshen. The difference in the DLM steering flows associated with the total PV perturbation between the forecast and analysis fields is generally consistent with the difference in the storm movements. Such result indicates that the balanced steering flow based on PV diagnosis can be used to identify track variations with anomalous eastward direction in the forecast field.

In summary, this study employs the PV diagnosis to demonstrate the key factors for the over-recurvature in NCEP-GFS forecasts in Fengshen, aiming for a better understanding of the major forecast bust in GFS. To improve track forecasts, the importance of well representing major synoptic scale features in the model, particularly the subtropical high, the continental high, and the monsoon trough, is highlighted. It is interesting to note that, on the contrary, the underestimated subtropical high and overestimated continental high cause the southward track forecast bias in Typhoon Sinlaku (2002) (Wu et al. 2004). This study highlights how the analysis can be applied in assessing the causes of model forecast bias. More insights can be developed when such analysis is conducted in other cases with special data from targeted observations in The Observing System Research and Predictability Experiment (THORPEX) and THORPEX-Pacific Asian Regional Campaign (T-PARC; WMO 2006; Elsberry and Harr 2008; Wu et al. 2009, 2012).

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