Using TIGGE Data to Diagnose Initial Perturbations and Their Growth for Tropical Cyclone Ensemble Forecasts

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ABSTRACT

Ensemble initial perturbations around Typhoon Sinlaku (2008) produced by ECMWF, NCEP, and the Japan Meteorological Agency (JMA) ensembles are compared using The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) data, and the dynamical mechanisms of perturbation growth associated with the tropical cyclone (TC) motion are investigated for the ECMWF and NCEP ensembles. In the comparison, it is found that the vertical and horizontal distributions of initial perturbations as well as the amplitude are quite different among the three NWP centers before, during, and after the recurvature of Sinlaku. In addition, it turns out that those variations cause a difference in the TC motion not only at the initial time but also during the subsequent forecast period. The ECMWF ensemble exhibits relatively large perturbation growth, which results from 1) the baroclinic energy conversion in a vortex, 2) the baroclinic energy conversion associated with the midlatitude waves, and 3) the barotropic energy conversion in a vortex. Those features are less distinctive in the NCEP ensemble. A statistical verification shows that the ensemble spread of TC track predictions in NCEP (ECMWF) is larger than ECMWF (NCEP) for 1- (3-) day forecasts on average. It can be inferred that while the ECMWF ensemble starts from a relatively small amplitude of initial perturbations, the growth of the perturbations helps to amplify the ensemble spread of tracks. On the other hand, a relatively large amplitude of initial perturbations seems to play a role in producing the ensemble spread of tracks in the NCEP ensemble.

1. Introduction

The skill of tropical cyclone (TC) track prediction has improved significantly over the last few decades, due in large part to improvement in numerical weather prediction (NWP) models, data assimilation schemes, and enhanced observations as obtained through satellites and aircraft. However, significant errors can still exist and are often subject to initial condition errors. For example, errors in 3-day predictions vary between less than 50 km and more than 1000 km. For this reason, ensemble techniques are expected to provide useful information on the uncertainty of track predictions, via the ensemble spread, which may differ from one TC to another and from one initial time to another. Goerss (2000) and Elsberry and Carr (2000) demonstrated the benefit of the ensemble spread as a measure of confidence in ensemble TC predictions; a small spread of tracks is often an indication of a small error of an ensemble mean track prediction. Puri et al. (2001) illustrated reasonable forecast performance in the spread of TC tracks and intensities, using the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS; Molteni et al. 1996; Leutbecher and Palmer 2008) and targeted diabatic (moist) singular vectors (SVs) as a generator of initial perturbations (Mureau et al. 1993; Buizza 1994; Buizza and Palmer 1995; Palmer et al. 1998; Barkmeijer et al. 2001). Majumdar and Finocchio (2010) demonstrated that the ECMWF ensemble exhibited the ability to predict track probabilities for Atlantic basin tropical cyclones in 2008. Yamaguchi et al. (2009) constructed a new EPS, the Typhoon EPS, at the Japan Meteorological Agency (JMA), following the philosophy of ECMWF’s moist SV-based EPS. They showed that the ensemble spread can be an effective predictor of confidence information. When the ensemble spread was predicted to be small, the track error was found to be small. When the predicted ensemble spread was large, there was a possibility that the track error was large.

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Many operational NWP centers such as ECMWF, the National Centers for Environmental Prediction (NCEP), and JMA operate their own EPS. An ensemble prediction system consists of a number of numerical integrations that are initialized with different initial conditions in order to represent the uncertainty in the analysis. The method to create initial perturbations, or to estimate the uncertainty in the analysis, is different among the NWP centers. ECMWF adopts the SV method to capture the dynamically most unstable perturbations and computes the moist SVs for TCs to represent the analysis error in and around TCs. NCEP uses an ensemble transform (ET) technique (Wei et al. 2008), which is expected to produce initial perturbations of size consistent with those of operational analysis error variance, similar to bred vectors (BVs; Toth and Kalnay 1993, 1997). JMA operates two kinds of EPS; one is for the medium-range forecasts (WMO 2008) and the other is the Typhoon EPS. Both use SVs, but specifications such as the target regions, the optimization time intervals, and a norm are different between them. While the validity of ensemble TC track predictions has been verified in various EPSs, those predictions sometimes contradict each other. Figure 1 shows an example in which one EPS predicts relatively small ensemble spread while the other possesses large ensemble spread and vice versa. We hypothesize that these differences are attributed to the different methods of creating initial perturbations, resulting in different growth of the perturbations. In addition, initial amplitudes of the perturbations may affect the size of the ensemble spread, especially in the early forecast stage. A systematic intercomparison of global model ensembles for TCs has hitherto been difficult because of the limited access to such operational data. However, the recently established The Observing System Research and Predictability Experiment (THORPEX) Interactive

Fig. 1. Ensemble track forecasts (gray lines) by the (left) ECMWF and (right) NCEP ensembles for (top) Typhoon Sinlaku initialized at 1200 UTC 10 Sep 2008 and (bottom) Typhoon Dolphin initialized at 0000 UTC 13 Dec 2008. The black line is the best track. The black triangles are the forecast positions at 120 h.
Grand Global Ensemble (TIGGE) database makes it possible to conduct an intercomparison study and verify such hypotheses as proposed above.

In this study, ensemble initial perturbations in and around Typhoon Sinlaku (2008), one of the typhoons heavily sampled during the THORPEX Pacific Asian Regional Campaign (T-PARC) and Tropical Cyclone Structure 2008 (TCS-08) field campaigns, are compared using ECMWF, NCEP, and JMA ensembles, which are available on the TIGGE database. First, the vertical and horizontal distributions of perturbation wind, temperature, and specific humidity as well as their amplitudes are compared. Following this, the dynamical mechanisms of the perturbation growth are investigated by comparing the ECMWF and NCEP ensembles to understand how the perturbations change the steering flow and symmetric and asymmetric circulations of Sinlaku. Finally, a statistical verification is conducted to identify whether a relationship exists between the ECMWF and NCEP ensemble spread of tracks during the 2007 and 2008 seasons and to establish how the initial perturbations and their growth affect the ensemble spread of tracks in each EPS.

The paper is organized as follows. Section 2a is an overview of Sinlaku and section 2b provides the specifications of ECMWF, NCEP, and JMA EPS, mainly focusing on the method to generate the initial perturbations. Section 3a presents the vertical and horizontal distributions of the initial perturbations around Sinlaku, and section 3b shows how the steering flow and symmetric and asymmetric winds are modified by the perturbations. Sections 4a–c illustrate the dynamical mechanisms of the perturbation growth by the ECMWF ensemble from a perspective of the baroclinic energy conversion in a vortex, the baroclinic energy conversion associated with the midlatitude waves, and the barotropic energy conversion in a vortex. Section 4d shows statistical verification results regarding the relationship between the ECMWF and NCEP ensemble spread of tracks during the 2007 and 2008 seasons. Section 5 discusses the growth of SV in a vortex and section 6 presents the conclusions.

2. Typhoon Sinlaku and Ensemble Prediction System at ECMWF, NCEP, and JMA

a. Synopsis of Typhoon Sinlaku

According to the Regional Specialized Meteorological Center (RSMC) Tokyo–Typhoon Center (RSMC Tokyo–Typhoon Center 2008), Sinlaku formed as a tropical depression (TD) over the northwestern Pacific Ocean east of Luzon Island, Philippines, at 0000 UTC 8 September 2008. Moving toward the north-northwest, it was upgraded to tropical storm (TS) intensity over the same waters at 1800 UTC that day. Keeping its north-northwestward track, Sinlaku was upgraded to typhoon (TY) intensity and reached its peak intensity with maximum sustained winds of 100 kt and a central pressure of 935 hPa over the sea northeast of Luzon Island at 1200 UTC 10 September. Weakening its intensity and turning to the northwest, Sinlaku was downgraded to severe tropical storm (STS) intensity around northern Taiwan at 0600 UTC 14 September. After recurvature, it was upgraded again to TY intensity off the southern coast of Shikoku Island, Japan, at 0000 UTC 19 September. Keeping its east-northeastward track, Sinlaku transformed into an extratropical cyclone east of Japan at 0000 UTC 21 September. The best-track minimum sea level pressure and sustained maximum wind through Sinlaku’s life cycle analyzed by RSMC Tokyo–Typhoon Center are shown in Fig. 2.

The synoptic environments around Sinlaku at 0000 UTC 10, 15, and 18 September 2008, which are based on the analysis field of the nonperturbed member of the ECMWF ensemble, are presented in Fig. 3. On 10 September (hereafter referred to as the before-recurvature stage of Sinlaku), Sinlaku was located west of the Pacific high. As will be seen (in Fig. 8), Sinlaku slowly moved northward by the steering flow associated with the Pacific high. On 15 September (hereafter referred to as the during-recurvature stage of Sinlaku), Sinlaku was located in a confluent area induced by the westerly jet and the southerly flow at the west edge of the Pacific High. On 18 September (hereafter referred to as the after-recurvature stage of Sinlaku), Sinlaku was located by both features; it was located north of the Pacific high and south of the westerly jet, being advected by the confluent westerlies.

b. Specifications of the Ensemble Prediction Systems

This section gives a brief overview of the techniques used to create initial perturbations at ECMWF, NCEP,
and JMA, mainly referring to Leutbecher and Palmer (2008) for ECMWF EPS, Wei et al. (2008) for NCEP EPS, and WMO (2008) for JMA EPS. The techniques are philosophically similar in a sense that the initial perturbations are generated to represent initial uncertainty, but different in terms of the framework and the design of the EPS such as perturbed areas and a norm that constrains the structures of the perturbations. Table 1 summarizes those differences as well as other specifications including the model resolution and the ensemble size.

1) ECMWF SINGULAR VECTOR METHOD

ECMWF creates initial perturbations based on the SV method. The SVs with large singular values represent fast-growing perturbations over a prescribed time interval (optimization time interval) under the assumption that the perturbations grow linearly (Lorenz 1965). The fast-growing perturbations are considered to be responsible for large forecast uncertainty at the optimization time, thus they lead to sufficient dispersion in the most uncertain directions. The SVs are computed with an optimization of a total energy norm:

$$\frac{1}{2} \int_{P_0}^{P_1} \int_S \left( u'^2 + v'^2 + \frac{c_p}{T_r} T'^2 + w' \frac{L_c}{c_p T_r} q'^2 \right) dp dS + \frac{1}{2} \int_S \frac{R_d T}{P_r} (\ln P')^2 dS,$$  

(1)

where $u'$, $v'$, $T'$, $q'$, and $P'$ are perturbations of zonal velocity, meridional velocity, temperature, specific humidity, and surface pressure, respectively. Here $c_p$ is the specific heat of dry air at constant pressure, $L_c$ is the latent heat of condensation, and $R_d$ is the gas constant for dry air. Here $T_r = 300$ K is a reference temperature, $P_r = 800$ hPa is a reference pressure, and $\int_S$ and $\int_{P_0}^{P_1}$ denote the horizontal and vertical integrations, respectively, using a pressure coordinate. The $w_q$ is a constant that determines the relative weight of the specific humidity perturbation. ECMWF adopts $w_q = 0$, so the initial perturbations do not include a specific humidity component.

Dry SVs are targeted for each hemisphere with an optimization time interval of 48 h. The vertical integration of the total energy is limited up to about 100 hPa at a final norm. Note that 48-h linearly evolved dry SVs (Barkmeijer et al. 1999; Puri et al. 2001) are also used to construct initial perturbations in order to represent slowly growing perturbations related to large-scale flows (there is no constraint on the vertical levels for the evolved SVs). In addition, moist SVs are computed, targeted for TCs with an optimization time interval of 48 h. The vertical integration of the total energy is limited up to about 500 hPa at a final norm. Different from SVs in the extratropics, the evolved moist SVs are not considered in creating initial perturbations.

Note that ECMWF adopts stochastic physics technique (Buizza et al. 1999). As studied by Puri et al. (2001), however, the stochastic perturbations have little influence on ensemble track predictions.

To generate initial perturbations from the initial dry and moist SVs and evolved dry SVs, a Gaussian sampling technique is used, and a total of 50 perturbations are created (a linear combination of 25 orthogonal perturbations are added to and subtracted from the

4 To avoid duplication, the singular vectors targeted on a tropical cyclone are computed in the subspace orthogonal to the space spanned by the leading 50 extratropical singular vectors (Leutbecher 2007).
analysis field). The amplitude of the perturbations is determined in an empirical way so that the ensemble predictions have an appropriate ensemble spread.

2) NCEP ENSEMBLE TRANSFORM TECHNIQUE

The ET technique is the successor of the breeding method at NCEP (Toth and Kalnay 1993, 1997) and was first proposed by Bishop and Toth (1999) for targeting observation studies. The ET method produces initial perturbations along directions that are constrained by the global distribution of analysis error variance. The initial perturbations are computed in a matrix $\mathbf{Z}'$, which is obtained through

$$
\mathbf{Z}' = \mathbf{Z}' \mathbf{T},
$$

where $\mathbf{T}$ is an ensemble transformation matrix, and $\mathbf{Z}'$ is a matrix whose columns compose the differences of state vectors between an ensemble mean and a perturbed forecast. The transformation matrix $\mathbf{T}$ is designed so that the initial perturbations reflect the analysis error variances of the data assimilation scheme at NCEP. Unlike SVs where the linear growth of the perturbations over an
optimization time interval of 48 h is assumed, the ET method does not explicitly solve for perturbation growth.

NCEP ensemble does not adopt the plus–minus symmetric addition of initial perturbations used at ECMWF. For the amplitude of the perturbations, the NCEP ensemble considers a regionally varying rescaling to ensure that the amplitude varies in accordance with the uncertainties in the analysis. Finally, the amplitude is empirically adjusted so that the system can get sufficient ensemble spread in the predictions.

3) JMA SINGULAR VECTOR METHOD

JMA also uses the SV method. The main differences from that of ECMWF are the targeted areas and the norm. Moist SVs are targeted for the whole tropics (20°S–30°N), not each TC, while dry SVs are targeted for the Northern Hemisphere only (30°–90°N). The total energy norm includes the specific humidity term, and \( w_q = 0.04 \) is used for both dry and moist SVs. In the initial norm, the vertical integration of the total energy is limited up to about 5 (700) hPa for wind and temperature (specific humidity) perturbations.

Initial perturbations are created by linearly combining initial dry and moist SVs, 48-h linearly evolved dry SVs and 24-h linearly evolved moist SVs so that the spatial distribution of perturbations becomes large (like ECMWF, there is no constraint on the vertical levels for the evolved SVs). Like the ECMWF and NCEP ensembles, the amplitudes of the perturbations are determined in a statistical way in order to obtain the sufficient ensemble spread in the predictions.

3. Comparison of initial perturbations

a. Vertical and horizontal distributions of the initial perturbations

The vertical and horizontal distributions of the initial perturbation kinetic energy, the first and second terms in Eq. (1), are displayed in Fig. 4 for the ECMWF, NCEP, and JMA ensembles before, during, and after recurvature.\(^5\) The horizontal resolution and vertical levels of the TIGGE data are 0.5° × 0.5° and 1000, 925, 850, 700, 500, 300, 250, and 200 hPa, respectively. Prior to computing the perturbation kinetic energy averaged over all the ensemble members, each ensemble member is shifted to a storm-relative Cartesian coordinate system, with the central position determined by the location of the minimum streamfunction of the nonperturbed member at 850 hPa. For the vertical distribution, the perturbation kinetic energy at each level is averaged over all ensemble members over a 2000 km × 2000 km domain centered on Sinlaku. The horizontal distributions are computed by averaging the energy over all ensemble members and over all vertical levels. The corresponding vertical and horizontal distributions of initial

\(^5\) Note that the verification for the JMA ensemble is based on initial time 1200 UTC because the JMA ensemble is initiated only at 1200 UTC, so the corresponding before-, during-, and after-recurvature stages represent 1200 UTC of 10, 15, and 18 September 2008, respectively.

\(^6\) The user can specify the horizontal resolution on the TIGGE Web site.
FIG. 4. Vertical and horizontal distributions of kinetic energy component of initial perturbations around Typhoon Sinlaku (top) before, (middle) during, and (bottom) after recurvature by the ECMWF, NCEP, and JMA ensembles. (left) The vertical distributions (ECMWF thick lines, NCEP thin lines, and JMA dashed lines). (all others, left to right) The horizontal distributions of ECMWF, NCEP, and JMA, respectively. The domain for the horizontal distributions is 2000 km × 2000 km centered on Sinlaku. Note that the scales in horizontal distributions are different among the NWP centers.
perturbation available potential energy, the third term in Eq. (1), are shown in Fig. 5. Similarly, the vertical and horizontal distributions of perturbation specific humidity energy, the fourth term in Eq. (1), are presented in Fig. 6 ($w_q = 1$ in this study). This part of the comparison is only for NCEP and JMA because ECMWF does not include initial perturbations of specific humidity.

ECMWF perturbs only wind and temperature. In the before-recurvature stage, the ECMWF wind perturbation has a peak at 700 hPa on average and is largest in the near environment of Sinlaku (see Fig. 4). Looking at each ensemble member (not shown), the maximum amplitude is found to be 4.4 m s$^{-1}$, appearing about 700 km away from the typhoon center while the amplitude within 100 km from the typhoon center is only 1.6 m s$^{-1}$ at most. As the typhoon moves northward, the amplitude of wind perturbation above 500 hPa becomes larger, corresponding to the change in the area of highest amplitude from the typhoon surroundings to the synoptic features north of the typhoon (see Fig. 3). This would imply the upward energy transfer and the conversion of the available potential energy into the kinetic energy by the evolved dry SVs (see Fig. 4; Hoskins et al. 2000; Montani and Thorpe 2002). As with the wind perturbation, the temperature perturbation also has a peak in the midtroposphere (e.g., the maximum amplitude in the before-recurvature stage is 2.6 K at 500 hPa and about 500 km away from the typhoon center, implying that the perturbation has little change in the warm core structure in the inner region). The area of the highest temperature perturbation shifts from the typhoon surroundings to the synoptic features as the typhoon moves northward. However, in contrast to the wind perturbation, the altitude with the maximum amplitude of the temperature perturbation is confined to around 500 hPa throughout the life of the typhoon. The vertical profiles of the wind and temperature perturbations are quite similar to those of perturbations seen in the Typhoon EPS at JMA, which also uses moist SVs targeted for TCs (Yamaguchi et al. 2009).

NCEP perturbs all components: wind, temperature, and specific humidity. The amplitude of the wind perturbation is larger than ECMWF, especially in the upper troposphere. For example, it is 9.2 times as large as ECMWF at 200 hPa in the before-recurvature stage; the amplitude averaged over the 2000 km $\times$ 2000 km domain about the typhoon center is 3.4 m s$^{-1}$. This trend is common in the other stages. In the before-recurvature stage, there are large amplitudes in the temperature and specific humidity perturbations within about 300 km from the typhoon center. Looking at each ensemble member (not shown), the maximum amplitude of the temperature perturbation is found to be 2.1 K at 250 hPa while that of the specific humidity perturbation is 1.8 g kg$^{-1}$ at 700 hPa. Considering that the temperature anomaly due to the warm core structure in the nonperturbed field (not shown) is about 4.0 K at 250 hPa, the temperature perturbation enhances the warm core by about 50% with respect to the nonperturbed member. The specific humidity perturbation increases the moisture by 16% at 700 hPa with respect to the nonperturbed field.

JMA also perturbs all components: wind, temperature, and specific humidity. JMA’s perturbations are characterized by the large amplitude of the specific humidity perturbation. For example, the amplitude averaged over the 2000 km $\times$ 2000 km domain about the typhoon center is 1.25 g kg$^{-1}$, 3.7 times as large as NCEP at 925 hPa in the before-recurvature stage. However, the perturbation area is not in the typhoon surroundings but mainly to the south of the typhoon. This is because JMA’s moist SVs are not targeted for each TC, but for the entire tropics. That is why the amplitude of the specific humidity perturbation south of the typhoon becomes smaller as the typhoon moves north. On the other hand, the amplitude of the wind perturbation is small. For example, the amplitude averaged over 2000 km $\times$ 2000 km domain about the typhoon center is 0.24 m s$^{-1}$; a quarter of ECMWF at 700 hPa in the before-recurvature stage. This trend is common in the other stages.

As seen in Figs. 4–6, the horizontal and vertical structures of the initial perturbations as well as their amplitudes are found to be quite different among the NWP centers. It would be then inferred that those differences cause the different modification of the TC motion at the initial times and subsequent forecast times. In section 3b, the evolution of the initial perturbations associated with Sinlaku’s motion and how these perturbations modify the flow field of Sinlaku and its environment are examined.

b. Modifications of the steering flow and symmetric and asymmetric circulations by perturbations

In principle, the total wind in the region of a TC can be decomposed into an environmental steering flow, a symmetric vortex, and an asymmetric circulation (Carr and Elsberry 1992). The TC motion can be governed by 1) the steering flow associated with TC-background synoptic flow and 2) the asymmetric circulation, which includes an azimuthal wavenumber 1 circulation like the beta gyres (George and Gray 1976; Chan and Gray 1982; Fiorino and Elsberry 1989). This section describes how the initial wind perturbation modifies the symmetric vortex of Sinlaku, the steering vector and the advection vector associated with the asymmetric circulation (hereafter referred to as asymmetric propagation vector), using the ECMWF and NCEP ensembles. In addition, the time
FIG. 5. As in Fig. 4, but for perturbation available potential energy.
evolution of the steering and asymmetric propagation vector is compared between the two ensembles.

There is no unique method to define the steering flow because of the difficulty in dividing the background flow from a TC circulation itself. Here, the Lanczos filtering developed and studied by Kim et al. (2009) is used to separate the total wind into the background and residual flow and the residual from which the symmetric and asymmetric circulations are calculated. The Lanczos filtering filters out components with less than about 12° latitude–longitude in wavelength from the total wind field. Different from Kurihara et al. (1993), no sharp cutoff wavelength exists in the resulting background and residual flow in the Lanczos filtering. For the calculation of the steering and asymmetric propagation vector, the 500-hPa wind field of each ensemble member is used. First, the total wind is separated into the background and residual flow by the Lanczos filtering. Second, a TC center is defined as a minimum streamfunction position using the residual flow. Third, the symmetric circulation centered on the TC center is computed from the residual flow. Fourth, the asymmetric circulation is obtained by extracting the symmetric circulation from the residual flow. Finally, the steering (asymmetric propagation) vector is calculated by averaging the background (asymmetric) flow over 300 km from the TC center. We confirmed that in each ensemble member, the combination of the steering and asymmetric propagation vector accurately

Fig. 6. As in Fig. 4, but for perturbation specific humidity energy and for the NCEP and JMA ensembles. Note that the scales in horizontal distributions for JMA are different among the initial times.
represented Sinlaku’s motion, which was estimated by using 6-hourly forecast position data (not shown).

Figure 7 shows the radial profile of the symmetric tangential wind at 850 hPa in the before-recurvature stage of Sinlaku by ECMWF (left) and NCEP (right). The following four features can be seen in Fig. 7:

1) The size of the typhoon (radial profile of the symmetric tangential wind) is similar among the ensemble members in each EPS.
2) The range of the maximum tangential wind is less than 1 m s\(^{-1}\).
3) The radius of the maximum tangential wind does not change significantly.
4) The differences of the above three quantities between ECMWF and NCEP are much larger than the differences caused by the initial perturbations in each ensemble.

Similar features are seen in the during- and after-recurvature stages and in 500-hPa wind field (not shown). Figure 8 shows the modification and time evolution of the steering and asymmetric propagation vector by the ECMWF (left) and NCEP (right) perturbations for the before-recurvature stage of Sinlaku. The following four features can be seen in Fig. 8:

1) The ECMWF ensemble shows the growth of the steering and asymmetric propagation vector while the NCEP ensemble does not.
2) The spread of the asymmetric propagation vector in ECMWF is larger than in NCEP.
3) Although the spread of the steering vector in ECMWF is smaller than that in NCEP at FT + 0 h, they become almost the same at FT + 48 h.
4) The growth of the steering and asymmetric propagation vector in ECMWF is larger in the early forecast period. The average perturbation wind magnitude of the steering (asymmetric propagation) vector is 0.37 (0.28), 1.04 (0.79), 1.06 (0.69), 0.94 (0.75), and 0.98 (0.86) m s\(^{-1}\) at 0, 12, 24, 36, and 48 h, respectively.

Similar features are seen in the during- and after-recurvature stages. Additionally, to examine the robustness of the Lanczos filtering, sensitivity tests were conducted by changing the cutoff wavelength in the Lanczos filtering and the radius to calculate the steering and asymmetric propagation vector. Cutoff wavelengths of 10° and 14° in the Lanczos filtering and a radius of 500 km to calculate the steering and asymmetric propagation vector were used. We found that those qualitative features mentioned above are not sensitive to the choice of the cutoff wavelength and the radius.

The differences of the initial modification and growth of the steering and asymmetric propagation vector led to the differences in the spread of ensemble TC track predictions between the two ensembles. However, it remains to be seen what dynamical mechanisms cause the growth of the steering and asymmetric propagation vector in ECMWF EPS. In sections 4a–c, we investigate the dynamical mechanisms that lead to the growth of perturbation kinetic energy in ECMWF EPS.

4. Dynamical mechanisms of the growth of the steering and asymmetric propagation vector

In this section, we first investigate the growth of the steering and asymmetric propagation vector in ECMWF EPS from a perspective of 1) the baroclinic energy conversion in a vortex, 2) the baroclinic energy conversion associated with the midlatitude waves, and 3) the barotropic energy conversion in a vortex.

a. Baroclinic energy conversion in a vortex

The dynamics of baroclinic energy conversion in the midlatitude waves can be applied to a TC-like vortex in
FIG. 8. Steering (circles) and asymmetric propagation (triangles) vector by the (left) ECMWF and (right) NCEP ensembles at (top) FT + 0 h, (middle) FT + 12 h, and (bottom) FT + 48 h for Typhoon Sinlaku before recurvature. The black (gray) is for the nonperturbed member (ensemble members). FT stands for forecast time.
a cylindrical coordinate system. The upper-left panel in Fig. 9 shows the schematic to illustrate the baroclinic energy conversion in a vortex. In the case of the mid-latitude dynamics, the crisscross mark and the circle centered at the mark represent the North Pole and a certain latitude, respectively, while in the case of a vortex they represent a TC center and a circulation at a certain radius, respectively. The only difference between the midlatitude and a vortex is the background temperature gradient; the north is colder than the south in the midlatitude while the TC center is warmer than the outer region (see Fig. 10a). Thus, in the vortex case, a temperature perturbation (wave perturbation) needs to be 90° ahead of a streamfunction perturbation so that the perturbation can obtain available potential energy from mean available potential energy.

The baroclinic energy conversion between azimuthal mean available potential energy $\overline{A}$ and eddy available potential energy $\overline{\overline{A}}$ in a cylindrical coordinate is written as (e.g., Kwon and Frank 2008)

$$\frac{\partial \overline{\overline{A}}}{\partial t} = -\left(\frac{h}{s}\right)^2 u' \overline{\theta_A'} \frac{\partial \overline{\overline{A}}}{\partial r} - \left(\frac{h}{s}\right)^2 \omega \overline{\theta_A'} \frac{\partial \overline{\overline{A}}}{\partial p}, \tag{3}$$

where $u'$ is the eddy radial velocity (negative for inflow); $\overline{\theta_A'}$ and $\overline{\overline{A}}$ are the eddy and azimuthal mean potential temperature, respectively; and $\omega$ is the eddy vertical velocity (negative for upward flow). Here $r$ and $p$ denote radius and pressure, respectively, and the overbar refers to an azimuthal average. Also, $h = (R/p)(R/p_R)^{\kappa}$, where $R$ is the gas constant, $p_R$ is a reference pressure, and $\kappa$ is $R/c_p$, and $s^2 = -h(\partial \overline{\theta_A}/\partial p)$, which represents the vertical stability of the atmosphere. In addition to this, the eddy available potential energy needs to be converted into the eddy kinetic energy ($K'$) in order for the perturbation to obtain kinetic energy through the baroclinic process. This conversion is given by

$$\frac{\partial K'}{\partial t} = -h(\omega \overline{\theta_A'}). \tag{4}$$

We focus on the first term in Eq. (3), the radial eddy heat flux, to demonstrate how ECMWF perturbations cause the growth of the steering and asymmetric propagation vector through the baroclinic energy conversion in a vortex. Suppose that streamfunction and temperature perturbations as described in the top- and middle-left panels in Fig. 9 exist in a cylindrical coordinate. The corresponding radial heat flux is then given in the lower-left panel in Fig. 9 (instead of potential temperature, temperature is used for simplicity). Considering that the radial gradient of background temperature is negative ($\partial \overline{\theta_A}/\partial r < 0$), it turns out that the time change of the eddy available potential energy is positive ($\partial \overline{\overline{A}}/\partial t > 0$). The figures on the right are equivalent to the figures on the left in Fig. 9; streamfunction (shade) and temperature (contour) perturbations at 500 hPa by ECMWF ensemble member 21 for the before-recurvature stage (top), corresponding azimuthal structures at 500 km from the center of Sinlaku (middle), and the radial heat flux (bottom). It is found that the azimuthal mean available potential energy will be converted into the eddy available potential energy from southwest to northeast of Sinlaku, with its peak at around south and east of Sinlaku.

Figure 11 shows the 6-hourly time evolution of the wind perturbation (left), the azimuthal structures of streamfunction and temperature perturbations at 500 km from the center of Sinlaku (middle), and the radial heat flux (right). Note that the wind field of the nonperturbed member and ensemble member 21 is shifted to a storm-relative coordinate at each verification time. It is found that where the wind perturbation grows well corresponds to the region where the radial heat flux is positive, especially south and east of Sinlaku. As seen in the flow over the center of the storm, the growth of the wind perturbation leads to the change in the advection flow of Sinlaku. As a result of the significant modification of both the steering and asymmetric propagation vectors, the track of ensemble member 21 becomes one of the most different tracks from that of the nonperturbed member (not shown).

Unfortunately, the second term in Eq. (3) cannot be examined here because vertical velocity fields are not available on TIGGE. Nevertheless, it has been shown that the growth of the wind perturbation occurs at the location where the radial heat flux is positive. Thus, it can be inferred that the positive (negative) temperature perturbation leads to an ascending (descending) motion so that the time change of the eddy kinetic energy can become positive [$-h(\omega \overline{\theta_A'}) > 0$]. In addition, we need to verify the relative amplitude of the second term to the first term in Eq. (3). We will examine these energetics in the future using a simplified model.

Figure 12 shows the 6-hourly time evolution of the vertical structure of streamfunction and temperature perturbations. The wind perturbation grows mostly at the 500-hPa level where the amplitude of the temperature

7 Note that potential temperature is divided into a basic state, which only depends on height, azimuthal mean, and derivative from the mean: $\overline{\theta(r,\lambda,p,t)} = \overline{\theta}(p) + \overline{\overline{\theta}}(r,p,t) + \theta(r,\lambda,p,t)$.

8 Ensemble member 22 also provides a largely different track from the nonperturbed run because ECMWF EPS adopts plus-minus perturbations (see section 2b for more details).
perturbation, which is the energy source for the wind perturbation, is maximum. For the vertical structure, it is found that the streamfunction perturbation is tilted toward the downstream. Note that the increasing azimuthal angle is in a cyclonic direction, with 0, π/2, π, and 3π/2 corresponding to east, north, west, and south, respectively. This characteristic is identical to the westward tilting of the midlatitude baroclinic energy conversion given that the temperature perturbation is ahead of the streamfunction perturbation in the case of the baroclinic energy conversion in a vortex.

Perturbation structures as seen in this paragraph are not unique to ensemble member 21, but are common features for many ensemble members. However, they become less distinctive at the during- and after-recurvature stage of Sinlaku when the TC is more influenced by the midlatitude waves.

b. Baroclinic energy conversion associated with the midlatitude waves

As previously studied by Buizza (1994), Palmer et al. (1998), and Buizza and Montani (1999), SVs capture the
baroclinic energy conversion in the midlatitude waves. Figure 13 shows an example where a streamfunction perturbation at 500 hPa by ECMWF ensemble member 50 for the after-recurvature stage is associated with the midlatitude waves at the initial time, and then leads to the change in the advection flow of Sinlaku, mainly modifying the steering flow. Figure 14 is another example where both features, the baroclinic energy conversion in a vortex and the midlatitude, appear simultaneously in one ensemble member. This is a case of ECMWF ensemble member 35 for the during-recurvature stage. There are positive and negative streamfunction perturbations south to east of Sinlaku and a positive temperature perturbation right in the middle of them. This is a characteristic of the baroclinic energy conversion in a vortex as seen in section 4a. On the other hand, there also exist perturbations north of Sinlaku, which capture the baroclinic energy conversion of the midlatitude waves. In fact, the perturbations along with 100° to 140°E at 33°N are tilted toward the west, which is a feature of baroclinic energy conversion in midlatitude waves. Consequently, both the steering and asymmetric propagation vectors are modified during the period of the perturbation growth.

c. Barotropic energy conversion in a vortex

The total eddy kinetic energy can also grow through the radial eddy momentum flux. This is described as

$$\frac{\partial K}{\partial t} = -\bar{\nu}' \frac{\partial \bar{u}}{\partial r} - \bar{u}' \frac{\partial \bar{v}}{\partial r} + \bar{u} \frac{\partial (\frac{\partial v}{\partial r} - \frac{\partial \bar{u}}{\partial r})}{\partial r},$$

where $\bar{u}'$ and $\bar{v}'$ are the eddy and azimuthal mean tangential velocity, respectively. Figure 15 shows the impact of ensemble perturbations on the modification of the growth of the local eddy kinetic energy. That is the difference of the time change of eddy kinetic energy ($\partial K'/\partial t$) between a nonperturbed member and an ensemble member (ensemble member 21 for the ECMWF ensemble and ensemble member 11 for the NCEP ensemble before recurvature). It is found that the rate of the change of the eddy kinetic energy of the NCEP ensemble is smaller than that of the ECMWF ensemble in the region of the TC center, say 300 km from the center. These features are common in other ensemble members. This would result in the different growth of the asymmetric propagation vector between the ECMWF and NCEP ensembles.

The baroclinic features as described in sections 4a,b are less distinctive in NCEP EPS compared to ECMWF EPS. In addition, the barotropic energy conversion is

Fig. 10. Temperature gradient (a),(b) every 0.2 $\times$ 10$^{-5}$ K m$^{-1}$ and (c) every 0.02 $\times$ 10$^{-5}$ K m$^{-1}$ (negative: gray, positive: black, zero contour omitted) at 500 hPa by the nonperturbed member of the ECMWF ensemble for the before-recurvature stage of Sinlaku. Here (a) is based on the total temperature field, and (b) and (c) are calculated from the high- and low-frequency component of the total temperature field. The contours are described in a domain of 1500 km from the storm center.
less likely to occur in NCEP EPS than ECMWF EPS as illustrated in Fig. 15. As Fig. 4 shows, the amplitude of the wind perturbation is larger in NCEP in and around Sinlaku. However, the perturbations are not efficient in modifying the growth of the eddy kinetic energy. Rather, as Fig. 8 shows, perturbations associated with the motion of Sinlaku seem to be saturated at the initial time in the NCEP ensemble.

The growth of eddy kinetic energy through baroclinic energy conversion in the midlatitude waves is most likely due to the evolving global ECMWF SV perturbations. We speculate that the growth via baroclinic...
and barotropic energy conversion near the vortex may be captured in the trailing global SVs and the leading diabatic SVs computed in the TC region.

d. Evolution of ensemble spread of tracks in 2007 and 2008 seasons

To compare quantitatively how the initial perturbations and their growth affect the ensemble spread of tracks in ECMWF and NCEP EPS, a statistical relationship between their respective spreads of ensemble track predictions is examined for the 2007 and 2008 seasons. Figure 16 shows the verification results for 1- (top) and 3-day (bottom) forecasts of the 2007 (left) and 2008 (right) seasons. The verification only includes TCs whose intensity is tropical storm or stronger. First, the correlation of the spread between the ECMWF and NCEP ensembles is found to be weak. The correlation coefficient of 1-day forecasts is 0.26 and 0.27 for 2007 and 2008, respectively, while that of 3-day forecasts is 0.56 and 0.21, respectively. The low correlation

FIG. 12. (from top to bottom) 6-hourly time evolution (FT + 0 h to FT + 18 h) of the vertical structure of (left) streamfunction (every 250 000 m² s⁻¹, negative: gray, positive: black, zero contour omitted) and (right) temperature (every 0.5 K, negative: gray, positive: black, zero contour omitted) perturbations by ECMWF ensemble member 21 for the before-recurvature stage of Typhoon Sinlaku. The perturbations are at 500 km from the storm center.
may arise because of the different methods of creating initial perturbations in the respective ensembles, as well as their respective differences in initial amplitudes and the growth of ensemble perturbations as previously presented. Second, NCEP’s spread for 1-day forecasts is larger than ECMWF on average. This can be attributed to the fact that the spread in the initial steering wind is larger in the NCEP ensemble. Third, the spread of ECMWF usually becomes larger than NCEP for 3-day forecasts. This likely arises because of the differences of the energy growth between ECMWF and NCEP. While ECMWF starts from relatively small amplitudes of initial perturbations, the growth of the perturbations help to amplify the ensemble spread of tracks. On the other hand, the relatively large amplitudes

Fig. 13. (left) Initial streamfunction perturbation (shading, divided by 100 000) at 500 hPa by ECMWF ensemble member 50 for the after-recurvature stage of Typhoon Sinlaku and the initial streamfunction field at 500 hPa by the nonperturbed member (contours, every 5 000 000 m$^2$ s$^{-1}$). (right) Evolution of the wind perturbations (m s$^{-1}$) at FT + 12 h. Wind perturbations are described in a domain of 3000 km × 3000 km centered at the storm center.

Fig. 14. (left) Initial streamfunction (shading, divided by 100 000) and temperature (contours, every 0.5 K, negative: dashed lines, positive: solid lines, zero contour omitted) perturbations at 500 hPa by ECMWF ensemble member 35 for the during-recurrence stage of Typhoon Sinlaku. (right) Vertical structure of the initial streamfunction (shading, divided by 100 000) and temperature (contours, every 0.5 K, negative: dashed lines, positive: solid lines, zero contour omitted) perturbations along 100°–140°E at 33°N [see black solid line in (left)].
of initial perturbations seem to play a role in producing the ensemble spread of tracks in NCEP.

5. Discussion

a. Singular vector growth in TCs

The growth of SVs in a TC, or a TC-like vortex, have been studied in many contexts. Nolan and Farrell (1999) illustrated the nonmodal growth of SVs through the Orr mechanism (Orr 1907) using a barotropic model. The SVs are initially tilted against the shear of the background tangential winds and obtain eddy kinetic energy through the wave–mean flow interaction described in Eq. (5). The growth continues until the against-shear property vanishes. Peng and Reynolds (2006) showed that initial SVs of the U.S. Navy Operational Global Atmosphere Prediction System (NOGAPS) appear about 500 km from storm centers where the radial potential vorticity gradient changes sign (necessary condition for the barotropic instability of normal modes). It is found that such a condition can be created by the influence of surrounding synoptic features. Peng et al. (2009) demonstrated that exponentially growing perturbations (not SVs) exist in the outer region of a TC-like vortex, which satisfies the necessary condition of the barotropic instability of normal modes. The upshear tilt of the asymmetric vorticity causes energy transfer continuously from the symmetric mean flow to the asymmetric disturbances. In addition to above mechanisms, we illustrated the baroclinic energy conversion in a vortex as a mechanism of the SV growth in a vicinity of a TC (see Fig. 9). Streamfunction and temperature perturbations are embedded in a cylindrical coordinate system centered on a TC with the temperature perturbation 90° ahead of the streamfunction perturbation. Consequently, the perturbation kinetic energy can grow with time through the conversion of the azimuthal mean available potential energy into the eddy available potential energy and then the subsequent conversion of the eddy available potential energy into the eddy kinetic energy.

In the case of the Orr mechanism, the SV maxima are located where the radial gradient of the background tangential wind takes the most negative value. In the case of barotropic energy conversion of normal modes, they are located where the radial potential vorticity gradient changes sign (more far away from a storm center compared to the Orr mechanism). In the case of baroclinic energy conversion, they would be located where the radial potential temperature gradient takes the most negative value. We note that it is also of importance to identify where the fastest-growing perturbations appear in TCs because SVs are also used as sensitivity analysis guidance for adaptive observations.

The radial gradient of the background tangential wind, the location where the radial potential vorticity gradient changes sign, and the radial potential temperature gradient are dependent on the horizontal resolution of models used for the SV computations. Considering that SV calculations at ECMWF and JMA are performed with relatively low-resolution tangent-linear and adjoint models (see Table 1), those features mentioned above and locations of SV maxima will change as the resolution is increased. Another point of interest is the relative efficiency of the SV growth in each mechanism and how the perturbation affects the motion of a vortex. The growth rate (singular values) would be different among each mechanism, also depending on the initial state of a vortex. In addition, it is not clear how different SVs associated with each dynamical mechanism cause the spread of ensemble TC track predictions. We will investigate the energetics of those mechanisms as well as the SV dependency on a model resolution in a future study, using a simplified model.
b. Why do singular vectors targeted for TCs tend to appear away from the storm center and asymmetric about it?

As studied by Peng and Reynolds (2006), Reynolds et al. (2007), Yamaguchi et al. (2009), and Wu et al. (2009), SVs targeted for TCs tend to appear away from the center of TCs, about 500–700 km away from the center. In addition, the SVs are asymmetric about the storm center; SVs are more likely to appear the north to east of TCs rather than the west. These might be related to the fact that the amplitude of the azimuthal mean radial temperature gradient is large around 500 to 700 km away from storm centers and that the amplitude is locally magnified by TC surrounding synoptic features. We applied the Lanczos filtering to the temperature field on which the baroclinic energy conversion happened; namely the temperature field of the non-perturbed member of the ECMWF ensemble for the before-recurvature stage of Sinlaku (see Fig. 10a). We divided the total temperature field into the high- and low-frequency component to find the azimuthal mean temperature gradient (Fig. 10b) and temperature gradient created by the TC surrounding environment (Fig. 10c).

It is found that the amplitude of azimuthal mean temperature gradient takes a relatively large value about 500 km away from the storm center. It is locally amplified by the low-frequency component of the total temperature field, which we believe represents the surrounding synoptic features like the Pacific high and midlatitude waves. The local amplification would more likely occur north to east of TCs rather than the west because, in general in the western North Pacific, the Pacific high locates the eastern side of TCs, and midlatitude waves located on the northern side of TCs. In the future, we will examine those features, the azimuthal mean temperature gradient, and the local amplification for more TC cases from a perspective of their representation in NWP models and observations.

6. Conclusions

Ensemble initial perturbations and their growth were investigated in order to understand the ensemble spread of tracks. Using the recently established TIGGE database, vertical and horizontal distributions of initial perturbations around Typhoon Sinlaku (2008) were first
compared among ECMWF, NCEP, and JMA, before, during, and after recurvature. It was found that the initial amplitude of NCEP wind perturbations was generally larger than that of ECMWF, particularly in the upper troposphere. For example, the 200-hPa NCEP perturbations were nearly 10 times as large as ECMWF in the before-recurvature stage of Sinlaku. Accordingly, the modification of the advection vector by the initial perturbations was larger in the NCEP ensemble than the ECMWF ensemble. ECMWF wind perturbations were of peak amplitude in the midtroposphere in the before-recurvature stage. As Sinlaku moved northward, the amplitude of the upper-tropospheric wind perturbations increased due to upward energy transfer and the conversion of the available potential energy into kinetic energy (Hoskins et al. 2000; Montani and Thorpe 2002), which is associated with the synoptic features north of the typhoon that played a role in its recurvature. Conversely, the peak amplitude of ECMWF temperature perturbations was confined to the mid troposphere. JMA’s perturbations were characterized by the large amplitude of specific humidity, which was nearly 4 times as large as NCEP at 925 hPa in the before-recurvature stage. In contrast, the JMA wind perturbations were small, being only a quarter the size of ECMWF at 700 hPa prior to recurvature.

The subsequent growth of the advection flow of Sinlaku was found to be generally larger in ECMWF than NCEP. The dynamical perturbation growth in the ECMWF ensemble was found to be associated with 1) baroclinic energy conversion in a vortex, 2) baroclinic energy conversion associated with midlatitude waves, and 3) barotropic energy conversion in a vortex. For baroclinic energy conversion in the vortex, the temperature perturbation is 90° ahead of the streamfunction perturbation so that the perturbation can obtain the eddy available potential energy from the mean available potential energy, leading to the modification of the steering and asymmetric propagation vector. As previously studied, the baroclinic energy conversion associated with the midlatitude waves caused the change in the steering flow. In addition, the radial eddy momentum flux near the center of Sinlaku was larger in the ECMWF ensemble than the NCEP ensemble. This barotropic process would result in the difference of the growth of the asymmetric propagation vector between them. A statistical verification demonstrated that NCEP’s spread for 1-day forecasts was larger than ECMWF on average, likely due to the relatively large initial perturbation amplitudes and the accordingly large modification of the steering flow at the initial time. For 3-day forecasts, however, the spread of ECMWF became larger than that of NCEP due to the larger energy growth in ECMWF. In summary, it appears that though the ECMWF initial perturbation amplitudes are small, the growth of the perturbations help to obtain an appropriately large ensemble spread of tracks. Meanwhile, the relatively large amplitudes of initial perturbations seem to play a role in obtaining the ensemble spread of tracks in NCEP. Those results are comparable to those of Magnusson et al. (2008), who compared the skill of two versions of the ECMWF EPS: one based on SVs and the other based on bred vectors (BVs). They found that the initial amplitude of BVs needed to be amplified significantly to secure a sufficient ensemble forecast spread while the growth of SVs, whose amplitude is on the order of analysis error, played an important role in the SV-based EPS.

Future work includes investigating more typhoon cases to obtain statistical significance and extending the verification into other basins such as the Atlantic in which the results may differ. For example, as noted in Majumdar and Finocchio (2010), the ability of the ECMWF ensemble to produce appropriately dispersive probabilistic forecasts of tropical cyclone track was significantly higher in the Atlantic basin than in the Northwestern Pacific basin for the 2008 season. Further studies are also required to determine optimal perturbation methods to produce a consistently reliable spread of tracks. An extension to the studies of Magnusson et al. (2008) and Buizza et al. (2008) who investigated different initial perturbation techniques in the ECMWF EPS would be recommended for tropical cyclones. In parallel, new methods to parameterize model error, for example via stochastic perturbations (McLay et al. 2007) warrant further investigation.

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REFERENCES


