Singular Vector Structure and Evolution of a Recurving Tropical Cyclone

HYUN MEE KIM AND BYOUNG-JOO JUNG

Atmospheric Predictability and Data Assimilation Laboratory, Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea

(Manuscript received 8 May 2008, in final form 22 July 2008)

ABSTRACT

In this study, the structure and evolution of total energy singular vectors (SVs) of Typhoon Usagi (2007) are evaluated using the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) and its tangent linear and adjoint models with a Lanczos algorithm. Horizontal structures of the initial SVs following the tropical cyclone (TC) evolution suggest that, relatively far from the region of TC recurvature, SVs near the TC center have larger magnitudes than those in the midlatitude trough. The SVs in the midlatitude trough region become dominant as the TC passes by the region of recurvature. Increasing magnitude of the SVs over the midlatitude trough regions is associated with the extratropical transition of the TC. While the SV sensitivities near the TC center are mostly associated with warming in the midtroposphere and inflow toward the TC along the edge of the subtropical high, the SV sensitivities in the midlatitude are located under the upper trough with upshear-tilted structures and associated with strong baroclinicity and frontogenesis in the lower troposphere. Given the results in this study, sensitive regions for adaptive observations of TCs may be different following the TC development stage. Far from the TC recurvature, sensitive regions near TC center may be important. Closer to the TC recurvature, effects of the midlatitude trough become dominant and the vertical structures of the SVs in the midlatitude are basically similar to those of extratropical cyclones.

1. Introduction

Recently, adaptive observation strategies have begun to apply for tropical cyclone (TC) evolution for the purpose of adaptive observations of TCs (e.g., Peng and Reynolds 2005, 2006; Kim and Jung 2006, 2009; Majumdar et al. 2006; Wu et al. 2007, 2009). The observational regions detected by adaptive (or targeted) observation strategies are called sensitive regions because the observations in those regions may have a large influence on enhancing weather forecasts. In general, adaptive observation strategies may be categorized as uncertainty-based, dynamics-based, and joint uncertainty-dynamics adaptive observation strategies (Kim et al. 2004).

Uncertainty-based adaptive observation strategies (e.g., Lorenz and Emanuel 1998; Hansen and Smith 2000; Morss et al. 2001) use estimates of analysis and forecast errors to identify regions for adaptive observations. Recent uncertainty-based adaptive observation strategies tend to use dynamics of the flow as well as uncertainty information to identify sensitive regions for adaptive observations. In this sense, these kinds of uncertainty-based adaptive observation strategies [e.g., ensemble transform Kalman filter (ETKF; Bishop et al. 2001)] can be termed joint uncertainty-dynamics adaptive observation strategies (e.g., Bishop and Toth 1999; Bishop et al. 2001; Hamill and Snyder 2002; Majumdar et al. 2001, 2002, 2006). Dynamics-based adaptive observation strategies that use the dynamics of the flow to identify sensitive regions are adjoint sensitivity and singular vectors (SVs). The adjoint sensitivity is the gradient of some forecast measure with respect to the model control variables (e.g., Errico 1997) or to the observations (Baker and Daley 2000), and has been used to detect sensitive regions for adaptive observations (e.g., Bergot 1999; Bergot et al. 1999; Pu and Kalnay 1999; Kim and Jung 2006; Wu et al. 2007, 2009). Singular vectors are the fastest growing perturbations during a specified time period (i.e., the optimization interval) for a given norm and basic state (Kim and Morgan 2002), and have been used to detect regions of large sensitivity to small perturbations for the purpose of making adaptive observations (e.g., Palmer et al. 1998; Buizza and Montani 1999; Gelaro et al. 1999; Montani et al. 1999; Peng and Reynolds 2005, 2006; Kim and Jung 2009).
Total energy (TE) SVs (TESVs) and ETKF, the representative strategies for dynamics-based and uncertainty-based adaptive observation strategies, have been used for many midlatitude observing programs. The sensitive regions in the midlatitude observing programs, indicated by the two most extensively used strategies (i.e., TESVs and ETKF), mostly reside in mid-to-lower tropospheric steering levels near the upper trough (Buizza and Palmer 1995; Hoskins et al. 2000; Reynolds et al. 2001), and both strategies correspond relatively well on large scales rather than small scales.

The sensitive regions determined by TESVs and ETKF for TCs vary depending on the verification criterion (i.e., scales) similar to midlatitude cyclones, and the strength of TCs (Majumdar et al. 2006). In Majumdar et al. (2006), the sensitive regions denoted by both TESVs and ETKF were similar for most (around half) of the cases for large (local) target regions. While both strategies indicate sensitive regions near the storm center for major TCs, TESVs and ETKF showed different sensitive regions for weaker TCs for around 70% of the cases. Moreover, for recurving TCs that are influenced more by the environmental flow than the straight-moving TCs (Peng and Reynolds 2006), TESVs usually indicate a midlatitude trough upstream of the TC motion as sensitive (Peng and Reynolds 2006), but the ETKF identifies regions of large ensemble variance that are usually located over the ocean (i.e., subtropical ridge) as sensitive (Majumdar et al. 2006). Meanwhile, Reynolds et al. (2007) demonstrated that SVs with various types of analysis error variance norm decrease discrepancies between target areas computed using SVs and ETKF. By using uncertainty and dynamics information, analysis error variance SVs produce relatively similar sensitive regions with respect to ETKF.

Recurving TCs in the western Pacific have much influence on the short-term weather forecasts in East Asia and the medium-range weather forecasts of the North America through extratropical transition. The influence of the midlatitude trough on the recurvature of TC has been demonstrated mostly by horizontal collocation of TESVs and the midlatitude trough from statistics from many TC cases (e.g., Peng and Reynolds 2006). Wu et al. (2009) showed that the sensitivities in the midlatitude are indeed associated with and located in the upper trough by using adjoint-derived sensitivity steering vector (ADSSV) and potential vorticity (PV) analysis for Typhoon Shanshan (2006). However, the relationship between sensitivities in the midlatitude upper-level trough found for TCs (Peng and Reynolds 2006; Wu et al. 2009) and sensitivities in mid-to-lower tropospheric steering levels under the midlatitude upper-level trough for extratropical cyclones (Buizza and Palmer 1995; Hoskins et al. 2000; Reynolds et al. 2001; Kim and Morgan 2002) is not clear, especially for recurving TCs experiencing extratropical transition. Moreover, the vertical structures of the sensitivities near the TC center and over midlatitude trough region may be different, and have not been compared.

Kim and Jung (2009) demonstrated that the moist physics and corresponding moist TE norm may result in SV sensitivities concentrated near the TC center and, in the above physics and norm configurations, the large sensitivities remote from the TC center caused by environmental effects may not be detected well enough. At the same time, Kim and Jung (2009) demonstrated that the remote large-scale influence (e.g., midlatitude trough or subtropical ridge) on a recurving TC may be still detected by the TESVs using moist linear physics (i.e., large-scale precipitation) and weighted moist or dry TE norm. The purpose of this study is to evaluate the SV sensitivities near the TC center and midlatitude, and to interpret the dynamical interactions between a recurving TC and the midlatitude system for Typhoon Usagi (2007) by the TESVs with specific physics and norm configurations (i.e., large-scale precipitation as moist linear physics and dry TE norm) used in Kim and Jung (2009). Section 2 describes the experimental framework. The results are presented in section 3. Section 4 contains a summary and discussion.

2. Experimental framework

a. Model and physical processes

This study uses the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5), together with the MM5 adjoint modeling system (Zou et al. 1997) and a Lanczos algorithm, to calculate SVs. The model domain for this study is 50 \( \times \) 50 horizontal grids (centered at 33\(^\circ\)N, 133\(^\circ\)E), with a 100-km horizontal resolution and 14 evenly spaced sigma levels in the vertical, from the surface to 50 hPa. The model’s initial and lateral boundary condition is the National Centers for Environmental Prediction (NCEP) final analysis (FNL; 1\(^\circ\) \( \times \) 1\(^\circ\) global grid). Physical parameterizations used for the nonlinear basic state integrations include the Grell convective scheme, a bulk aerodynamic formulation of the planetary boundary layer, a simple radiation cooling scheme, horizontal and vertical diffusion, dry convective adjustment, and explicit treatment of cloud water, rain, snow, and ice. The same physical parameterizations are used in the tangent linear model (TLM) and adjoint model integrations, although the moist physics scheme used in TLM and adjoint model integrations is large-scale precipitation instead of the Grell convective scheme and explicit treatment of cloud water, rain,
snow, and ice used in basic state integrations. These configurations of physics parameterizations are appropriate to show large-scale sensitivities due to environmental effects as well as small-scale sensitivities close to the TC center, as indicated in Kim and Jung (2009).

For Typhoon Usagi, every twelfth hour from 0000 UTC 1 August to 1200 UTC 2 August 2007 is defined as an initial time, and 36 h after each initial time as the corresponding final time (i.e., verification time). The four experiments are denoted as EXP1, EXP2, EXP3, and EXP4, and the initial and final times of each experiment are specifically shown in Table 1. These experiments are performed to investigate the effects of dynamical features near storm center and midlatitude during recurvature and the extratropical transition of Typhoon Usagi. In addition to the four experiments shown in Table 1, EXP1 with modified dry TE norm without vertical wind perturbation component term in (3) below (named as EXP1_nw) is performed to investigate the SV structures without significant contribution of the vertical wind perturbation component to the dry TE norm.

**b. Singular vector formulation**

Singular vectors are calculated by maximizing the Rayleigh quotient $\lambda^2$ (the amplification factor),

$$\lambda^2 = \frac{\langle P\mathbf{x}'(t), C\mathbf{x}'(t) \rangle}{\langle \mathbf{x}'(0), C\mathbf{x}'(0) \rangle},$$

at the time $t = t_{opt}$, where the inner product is denoted by $\langle , \rangle$, $C$ is the matrix operator appropriate to the specific norm, and $P$ is a local projection operator that makes the state vector to be zero outside a given domain (Buizza 1994), which is the verification region in this study. By defining the local projection operator, the amplitude of the state vector with norm $C$ at $t = t_{opt}$ is maximized over a specific region. By assuming linear propagation of the perturbation from the initial time to the final time, the maximum of the Rayleigh quotient is realized when $\mathbf{x}'(0)$ is the leading SV of the TLM $M$ of the nonlinear model for the $C$ norm, that is, $\mathbf{x}'(0)$ satisfies

$$M^T P^T C P M \mathbf{x}'(0) = \lambda^2 C \mathbf{x}'(0).$$

A Lanczos type algorithm (e.g., Ehrendorfer and Errico 1995) is used to solve for $\mathbf{x}'(0)$ in (2). Dry TE norm is chosen for the $C$ norm because SV structures with properly weighted moist TE norm are very similar to those of dry TE norm (Kim and Jung 2009). The dry TE is defined according to Zou et al. (1997) as

$$E_d = \iiint_{x,y} \frac{1}{2} u'^2 + v'^2 + w'^2 + \left( \frac{g}{N^2} \right) \theta'^2 + \left( \frac{1}{\rho c_s^2} \right) p'^2 \, dy \, dx \, ds,$$

where $E_d$ is dry TE in a nonhydrostatic model; $u'$, $v'$, and $w'$ are the zonal, meridional, and vertical wind perturbations, respectively; $\theta'$ is the potential temperature perturbation; $p'$ is the pressure perturbation; $N$, $\theta$, $\rho$, and $c_s$ are the Brunt–Väisälä frequency, potential temperature, density, and speed of sound at reference level, respectively; and $x$, $y$, and $s$ denote the zonal, meridional, and vertical coordinates, respectively.

1 In this study, the optimization time $t_{opt}$ is the final time.

---

### Table 1. Initial and final times for each experiment.

<table>
<thead>
<tr>
<th>Expt name</th>
<th>Initial time</th>
<th>Final time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP1</td>
<td>0000 UTC 1 Aug 2007</td>
<td>1200 UTC 2 Aug 2007</td>
</tr>
<tr>
<td>EXP2</td>
<td>1200 UTC 1 Aug 2007</td>
<td>0000 UTC 3 Aug 2007</td>
</tr>
<tr>
<td>EXP3</td>
<td>0000 UTC 2 Aug 2007</td>
<td>1200 UTC 3 Aug 2007</td>
</tr>
<tr>
<td>EXP4</td>
<td>1200 UTC 2 Aug 2007</td>
<td>0000 UTC 4 Aug 2007</td>
</tr>
</tbody>
</table>

---

### 3. Results

**a. Case overview**

Figure 1a shows the best track and predicted tracks of four experiments (EXP1, EXP2, EXP3, and EXP4) for Typhoon Usagi. Typhoon Usagi moved westward after its formation on 29 July, then moved northwestward after 0000 UTC 30 July. Usagi approached Kyushu Island at 0000 UTC 2 August, and recurved northeastward along the edge of the subtropical high after 1200 UTC 2 August. Four numerical simulations of 36 h in length (Table 1) were performed to investigate the SV structures and
dynamical features associated with the recurvature and extratropical transition of the TC. Even though some of the predicted tracks are shifted slightly to the west relative to the observed track, the predicted tracks generally simulate the observed track well. The mean sea level pressure (MSLP) of the observed typhoon intensified after 0000 UTC 29 July and reached its minimum central pressure (maximum wind speed) of 945 hPa (45 m s$^{-1}$) between 0000 UTC 1 and 0000 UTC 2 August (Fig. 1b). After that time the central pressure of Usagi increased as the northeastward recurvature and extratropical transition began.

Figure 2 shows the upper-level (i.e., 200–400-hPa layer averaged) PV of the NCEP FNL analysis from 0000 UTC 1 to 0000 UTC 4 August 2007. At 0000 UTC 1 August, a large PV reservoir is located over northeast of the Korean peninsula, and isolated large PVs are located over the TC center and northwest of the Usagi (Fig. 2a). The subtropical ridge is located northeast of Usagi. At 1200 UTC 1 August, the isolated large PV northwest of Usagi is elongated as Usagi approached to the high latitude (Fig. 2b). From 0000 to 1200 UTC 2 August, as Usagi moved northward the distance between the large PV reservoir and the TC decreased, and the isolated PV near the TC center is located southwest of the TC (Figs. 2c,d). From 0000 UTC 3 to 0000 UTC 4 August, the TC moved further north undergoing extratropical transition (Figs. 2e,f). The large PV north of the TC remains, but the isolated PV southwest of the TC
Fig. 2. The 200–400-hPa-layer-averaged PV (shaded contours; intervals of 1 PVU) and MSLP (lines; intervals of 4 hPa) at (a) 0000 UTC 1 Aug, (b) 1200 UTC 1 Aug, (c) 0000 UTC 2 Aug, (d) 1200 UTC 2 Aug, (e) 0000 UTC 3 Aug, and (f) 0000 UTC 4 Aug 2007.
has diminished in size and intensity because of a significant weakening of the TC itself (Fig. 1b). At this stage, the subtropical ridge is located southeast of the TC.

b. Characteristics of SV evolution

The vertically integrated energy-weighted SV$^2$ is used to represent the sensitivity of the Typhoon Usagi. The energy-weighted SV is calculated to combine all the SVs for different model variables with different units into a single SV field with units of energy (J kg$^{-1}$). The leading SVs are used to represent SV structures for the Typhoon Usagi because the structures of the leading SVs are qualitatively similar to the composite structures of the first to third SVs (not shown). The vertically integrated energy-weighted SV and 500-hPa geopotential height at the initial and final times for each experiment are shown in Fig. 3. In EXP1, the initial SV has large sensitivities 300 km southeast and 500 km northwest of the TC center, with minor sensitivities over the edge of

---

2 All the SVs from Fig. 3 to Fig. 16, except Fig. 5, are for the leading SV. In addition, an SV without specification refers to the SV at the initial time and the evolved SVs in all the figures are calculated using TLM.
the subtropical high east of the TC center and over midlatitude trough near northeast China (Fig. 3a). The SV sensitivities 300 km southwest of the TC center are also noticed in Peng and Reynolds (2006) from SV composites of many TC cases, and associated with the inflow to the storm. In EXP2, the major sensitivities, located near the TC center in EXP1, are now located in the midlatitude trough region over northeast China (Fig. 3c). This implies that close to the TC recurvature, the dry TE at the verification time in Fig. 3d is sensitive to the midlatitude trough far northwest of the storm at the initial time in Fig. 3c. The initial SV for EXP3 (EXP4) is located mainly northwest (north) of the TC center over North Korea and East/Japan Sea (Figs. 3e,g). The evolved SVs for EXP1, EXP2, and EXP3 are located in the verification region with confined structures and maximum magnitudes over the TC center (Figs. 3b,d,f). Rather ambiguous structures of the evolved SV with two maxima in EXP4 indicate that the TC already has experienced extratropical transition (Fig. 3h). The initial SVs at different times following the TC recurvature indicate that, relatively far from the region of TC recurvature, the sensitivities near the TC center have larger magnitudes than those associated with midlatitude trough. The sensitivities in the midlatitude trough region become dominant as the TC moves close to the region of northeastward recurvature and undergoes extratropical transition.
Figure 4 shows the vertical profiles of the energy-weighted SV for each experiment. As the initial time proceeds for each experiment, the maximum of the energy-weighted SV moves from the upper to the lower troposphere (Figs. 4a,d,g,j). Similarly, the maximum of the evolved SV at the verification time moves from the mid-to-lower troposphere to the lower boundary in the verification region (Figs. 4b,e,h,k). The maximum of the evolved SV for the whole model domain shows slight upward propagation of TE due to large potential energy (PE) at the upper boundaries (Figs. 4c,f,i,l). Unlike vertical SV profiles for extratropical cyclogenesis, kinetic energy (KE) is dominant except at the upper boundary, and upward propagation of energy due to group velocity propagation, PV unshielding, or wave activity conservation (e.g., Buizza and Palmer 1995; Badger and Hoskins 2001; Morgan 2001; Kim and Morgan 2002) is not distinct for the TC.
The amplification factors of SVs for each experiment are shown in Fig. 5. The leading three SVs explain 42.8%, 40.4%, 46.6%, and 41.1% of the total 20 singular values for EXP1, EXP2, EXP3, and EXP4, respectively. The second SVs in EXP3 and EXP4 have similar amplification factors to the leading SVs (Figs. 5c,d), and the vertically integrated energy-weighted horizontal structures of these second SVs are similar to the leading SVs for EXP3 and EXP4 (not shown).

c. Sensitivities near storm center

1) Initial SV structures

The sensitivities near the TC center are observed to dominate at 0000 UTC 1 August 2007, before the TC recurvature in Fig. 3a. In this sense, EXP1 is investigated to examine SV structures and associated dynamical features near the storm center that may affect TC recurvature. In Fig. 6, vertical structures of various fields through the center of the TC (i.e., along line AA' in Fig. 3a) are shown to interpret sensitivities near the TC center. The vertical structure of PV superposed on the meridional wind and potential temperature is shown in Fig. 6a. The PV column that is larger than 1 PVU is located in the TC center through the troposphere, while larger PV regions are located west, east, and directly over the TC center in the upper boundary. Cyclonic circulations are noticed around the PV column in the TC center and around large PV regions in the upper boundary. Figure 6b shows vertical energy-weighted SV structures superposed with PV larger than 1 PVU through the TC center. Major sensitivities, showing vertically confined structures, are located over the TC center in the midtroposphere, with an upshear-tilted structure. Minor sensitivities west and east of the TC center are located below the large upper PV regions, with slightly upshear-tilted structures. The large PV regions west and east of the TC center in the upper boundary are associated with the isolated PVs to the west of the TC center in Fig. 2a, and over the subtropical high to the east of the TC center, respectively. The 100–200-hPa-layer-averaged PV field shows that large isolated PVs are located not only west but also east of the TC (not shown). The two large local SV maxima below the upper-level trough may be associated with the SV growth by the Rossby wave propagation from weak PV gradient regions to strong PV gradient regions, mentioned in Palmer et al. (1998), Morgan (2001) for extratropical cyclones, and Peng and Reynolds (2006) for TCs. Vorticities of SVs near the TC center show somewhat similar structures to meridional velocities in Fig. 6a (Fig. 6c). Opposite signs of SV vortices alternate around the TC center, and, near the TC center, large positive (negative) SV vorticities are located from the

**Fig. 5.** Amplification factors for the individual SVs with 36 h optimization time for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4.
TC center to the east (to the west), with maximum positive sensitivities over the maximum of the energy-weighted SV denoted in Fig. 6b. Vertical cross sections through the center of large magnitudes of SVs northwest and southeast of the TC center in Fig. 3a show physically similar vertical structures with Fig. 6 (not shown).

To gain more physical insights, each component of SV is shown in Fig. 7. The large zonal wind component of SV is located under the isolated upper-level PV to the west of the TC center, showing upshear-tilted structures (Fig. 7a). The sign of the SV and the upper-level zonal basic state is the same, which implies that the interaction of the zonal basic state wind and zonal wind perturbation of the same sign may be beneficial to enlarge the dry TE of the evolved SV in the verification time. Positive zonal component of SVs throughout most of the domain has the opposite sign of the basic state, which implies that the different signs for the basic state and perturbation around the TC center may be necessary to keep the TC structure vertical so that the energy of the evolved SV in the verification time becomes the maximum. At the same time, the positive sign of the zonal wind component of the SV perturbation induces inflow toward the TC along the subtropical ridge, which possibly leads to growth of dry TE in the verification region at the final time. The sign of the meridional basic state is the same as that of the meridional wind component of the SV in the midtroposphere to the east of the TC center. This implies that the increase of the meridional basic state wind by the meridional wind perturbation increases the inflow to the TC, and also is associated with the increase of the energy of the evolved SV. In the midtroposphere of the eastern wall of TC center, the large negative vertical wind component of the SV is located and corresponds well with the large energy-weighted SV in Fig. 6b, which implies that the
Fig. 7. Vertical cross sections along the line AA' indicated in Fig. 3a of PV (thick lines; intervals of 1 PVU), superposed on (a) the zonal wind basic state (thin lines; intervals of 3 m s$^{-1}$) and SV (colored contours; intervals of 1 m s$^{-1}$), (b) the meridional wind basic state (thin lines; intervals of 5 m s$^{-1}$) and SV (colored contours; intervals of 2 m s$^{-1}$), (c) the vertical wind basic state (thin lines; intervals of 2 cm$^{-1}$) and SV (colored contours; intervals of 2 m s$^{-1}$), and (d) the potential temperature basic state (thin lines; intervals of 5 K) and SV (colored contours; intervals of 0.4 K), for EXP1. The left and right ends of the x axes of each figure correspond to A and A', respectively, in Fig. 3a.

large energy-weighted SV in the midlevel in Fig. 6b is mostly associated with the vertical wind component of SV (Fig. 7c). The region of large negative vertical wind component of SV in Fig. 7c corresponds well with the region of large positive temperature perturbation in Fig. 7d. The downward (upward) motion induced by the negative (positive) vertical component of SV causes warming (cooling) in the corresponding region, and the warming in the TC center is likely to lead to the increase of the energy of the evolved SV at the final time.

Vertical cross sections of various basic and SV fields through the TC center at the initial time indicate that energy-weighted SV sensitivities in the midtroposphere are mostly associated with the vertical wind and temperature component of SVs, showing small upshear-tilted structures near TC center and below upper trough. Horizontal wind components of SVs indicate that the inflow toward the TC along the southeast part of TC and edge of the subtropical high is an important mechanism for the growth of the energy of the evolved SVs.

2) EVOLVED SV STRUCTURES

Figure 8 shows the vertical cross section of various fields through the center of the evolved SV (i.e., along line EE') in Fig. 3b. Large PVs are located in the mid-to-upper levels in the TC center, with other PV maxima to west and east of the TC center in the upper boundaries (Fig. 8a). As shown in Fig. 6a for the initial time, the meridional winds are cyclonic circulations around the TC center with maximum winds near lower boundary, and around the high PVs in the upper boundary. The energy-weighted SVs show large sensitivities over the TC.
center with a maximum in the lower boundary (Fig. 8b). The vorticity component of the evolved SV is positive (negative) in the lower (lower and upper) eastern (western) side of TC center (Fig. 8c). Figure 9 shows the evolved structures of each component of the initial SVs shown in Fig. 7, superposed on each basic state. The strong positive signs of the zonal wind component of the SV throughout the domain and of the meridional wind component of the SV to the east of the TC center indicate strong inflow to the east of the TC (Figs. 9a,b).

Vertical cross sections of various basic fields and SV fields through the TC center at the final time indicate that large dry TE of the evolved SV is located in the lower atmosphere, and physically attributed to the inflow toward the TC along the southeast part of TC and edge of the subtropical high, and warming in broad regions of the midtroposphere.

d. Sensitivities in midlatitude

1) EVOLUTION OF VERTICAL SV STRUCTURES

To understand the dynamical features associated with SV sensitivities over the midlatitude trough in Fig. 3, evolution of the vertical structures of the initial SV for EXP1, EXP2, EXP3, and EXP4 are examined (Fig. 10). The SVs are located in the lower-to-midtroposphere under the upper trough, with upshear-tilted structures for all the experiments. The PV intrusion by upper tropopause folding is distinct in EXP1 and EXP2 (Figs. 10a,b). Structures of SVs in Fig. 10 show typical SV and adjoint sensitivity structures (i.e., baroclinic perturbation structures) for extratropical cyclone development (e.g., Reynolds et al. 2001; Kleist and Morgan 2005). Using wave dynamics and PV unshielding in complex and simple models, SV growth and the propagation
mechanism from mid-to-lower troposphere to the upper troposphere has been examined extensively to interpret extratropical cyclone development (e.g., Buizza and Palmer 1995; Badger and Hoskins 2001; Morgan 2001; Kim and Morgan 2002). Unlike the initial SV structures, which correspond well with SV structures of extratropical cyclones (Fig. 10), much of the energy associated with evolved SVs is still located in the mid-to-lower troposphere (Figs. 4 and 11), and most of the major evolved SV structures are collocated with the TC at the final time (Fig. 11). Compared to the other experiments, upward propagation of energy from lower troposphere to the mid-to-upper troposphere is relatively distinct in EXP2 (Figs. 4e and 11b), which is associated with upper-trough development and tropopause folding at the initial time in Fig. 10b. In EXP4, the SVs are tilted downshear and are not collocated with the TC at the final time (Fig. 11d), which implies that the TC undergoes extratropical transition.

Overall, the increasing magnitude of the sensitivities over midlatitude trough regions in Figs. 3 and 10 is associated with the recurvature and extratropical transition of the TC. Initial SV structures of the TC in the midlatitude are similar to those of extratropical cyclones, with maximum magnitudes in the lower-to-midtroposphere for all the experiments. However, the sensitivities in the midlatitude have smaller magnitudes than those near the TC center for EXP1, and as a result the associated energy of the initial SV is concentrated in the mid-to-upper troposphere in Fig. 4a. For other experiments, maxima of the energy-weighted initial SVs are located in the lower troposphere (Figs. 4d,g,j), which implies that the sensitivities...

Fig. 9. Vertical cross sections along the line EE’ indicated in Fig. 3b of PV (thick lines; intervals of 1 PVU), superposed on (a) the zonal wind basic state (thin lines; intervals of 3 m s⁻¹) and SV (colored contours; intervals of 20 m s⁻¹), (b) the meridional wind basic state (thin lines; intervals of 6 m s⁻¹) and SV (colored contours; intervals of 20 m s⁻¹), (c) the vertical wind basic state (thin lines; intervals of 8 cm⁻¹) and SV (colored contours; intervals of 0.2 m s⁻¹), and (d) the potential temperature basic state (thin lines; intervals of 5 K) and SV (colored contours; intervals of 4 K), for EXP1. The left and right ends of the x axes of each figure correspond to E and E’, respectively, in Fig. 3b.
in the midlatitude are dominant for this stage of the TC development. Discrepancies in the vertical energy structures of the evolved SVs of the TC and extratropical cyclones may be due to the combination of wave energy propagation to the upper troposphere by initially upshear-tilted midlatitudinal sensitivities in the lower to midtroposphere and direct advection of the TC energy to the evolved SVs in the verification region. Because of the combination of two kinds of energy, the vertical energy structures are rather homogeneous (Figs. 4b,e), but energy is more concentrated in the lower troposphere after the TC undergoes extratropical transition (Figs. 4h,k).

2) MIDLATITUDE SV STRUCTURES OF EXP1

Similar to section 3c, the midlatitude SV of EXP1 is examined in detail to investigate the SV structures and dynamical features influencing TC recurvature. Midlatitude SVs for other experiments showed similar vertical structures to those of EXP1, as shown in Fig. 10. The vertically integrated energy-weighted SV for EXP1 in Fig. 3a is decomposed into three levels, each representing one part of the atmosphere (Fig. 12). The energy-weighted SVs in the lower part (from 700 hPa to the surface), middle part (380–650 hPa), and upper part (100–300 hPa) of the atmosphere are shown in Figs. 12a,b,c, respectively. As shown in Fig. 10, large sensitivities in the midlatitude are located in the lower part (Fig. 12a), not in the upper part where the upper trough is located. In the midlevel, major sensitivities are located around 300 km north of TC center, with minor sensitivities 300 km south of the TC center and with a slight trace of sensitivities over the midlatitude (Fig. 12b). Major sensitivities 300 km northwest of the TC center are associated with the isolated high PV in the upper level in Fig. 2 (Fig. 12c). Large sensitivities southeast of the TC center in Fig. 3a are caused by the accumulation of rather minor sensitivities throughout all the levels. As noticed in Peng and Reynolds (2006), radial winds superposed on the SVs at each part of the atmosphere show that large SV sensitivities are mostly associated

Fig. 10. Vertical cross sections of energy-weighted SVs (10^{-3} J kg^{-1}, shaded contours with variable intervals) superposed on PV (thick lines; intervals of 1 PVU) and potential temperature (thin lines; intervals of 3 K) at 0 h for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. Capital letters I, I’, B, B’, C, C’, and D, D’ below the x axis of each figure correspond to those in Figs. 3a,c,e,g.
with the inflow region. Peng and Reynolds (2006) also showed that the initial SV maximum is located where the PV gradient changes sign and the final SV maximum is located where the PV gradient is a maximum. Figure 13 shows isentropic PVs across the sensitive regions of the initial and evolved SVs. Figure 13a shows that the initial SV maximum of Usagi is indeed collocated with the regions of PV gradient changes sign, and the final SV

**FIG. 12.** Vertically integrated energy-weighted SVs ($10^{-3}$ J kg$^{-1}$; shaded contours with variable intervals) for the (a) lower part (from 700 hPa to the surface), (b) middle part (380–650 hPa), and (c) upper part (100–300 hPa) of the atmosphere, superposed on radial winds at (a) 850, (b) 500, and (c) 300 hPa. The line II in (a) is the same as that in Fig. 3a.

**FIG. 11.** Vertical cross sections of energy-weighted SVs ($10^{-3}$ J kg$^{-1}$; shaded contours, with an interval of $20 \times 10^{-3}$ J kg$^{-1}$) superposed on PV (solid lines; intervals of 1 PVU) and potential temperature (thin lines; intervals of 3 K) at 36 h for (a) EXP1, (b) EXP2, (c) EXP3, and (d) EXP4. Capital letters E, E’, F, F’, G, G’, and H, H’ below the x axis of each figure correspond to those in Figs. 3b,d,f,h.
maximum is also collocated with the regions of maximum PV gradient (Fig. 13b).

To understand the dynamical mechanisms associated with large sensitivities in the lower level in the midlatitude, lower level temperature superposed on streamline at 850 hPa (Fig. 14a), and frontogenesis (Fig. 14b) and vertical wind (Fig. 14c) at 950 hPa superposed on MSLP, are shown. At the initial time of EXP1, a large low-level baroclinic zone and a front were located over northeast China (Figs. 14a,b). Vertical winds near the front show upward (downward) motion south (north) of the front (Fig. 14c). The vertical cross sections through the front in Fig. 14b (along line II) are shown in Fig. 15. Large PV intrusions by tropopause folding (Fig. 15a) and the frontogenesis function near the surface (Fig. 15b) are shown. Large upshear-tilted, vertical wind components of SV structures are located under the upper trough (Fig. 15c), and the maximum sensitivities correspond well with the lower boundary frontogenesis function (cf. Figs. 15b,c). Large SV sensitivities are mostly attributed to the vertical wind component of SV (cf. Figs. 10a,15c).

3) EFFECTS OF VERTICAL WIND ON MIDLATITUDE SV STRUCTURES OF EXP1

As denoted in Fig. 15c, the contribution of the vertical wind component to the dry TE in Eq. (3) is dominant.
Because the formulation of (3) is based on variables calculated in MM5, the TE norm used for SV calculation in other global models does not include an explicit formulation of the vertical wind component. In that sense, the lower to midlevel sensitivities in Figs. 10 and 15c may be associated with the specific norm formulation used for this study. To verify whether the lower-to-midlevel sensitivity is related with the dynamic
signal or norm formulation, a dry TE norm without the vertical wind component is used to calculate SVs for EXP1 (i.e., EXP1_nw). The vertically integrated energy-weighted SV without the vertical wind perturbation component in the dry TE norm formulation is shown in Fig. 16a. Relative to Fig. 3a, major sensitivities northwest and southeast of the TC center become weak. Minor sensitivities over the midlatitude trough show shrunken size and magnitude (Fig. 16a). The lower level (700 hPa to surface) SV shows a small magnitude of sensitivities over the midlatitude trough region (Fig. 16b). The vertical cross section shows similar upshear-tilted sensitivity structures with a bit higher maximum sensitivity regions (Fig. 16c). These results suggest that the large lower-to-midlevel sensitivities over the midlatitude trough region may not be attributed to the specific formulation of the dry TE norm. Instead, the vertical wind component in the dry TE norm formulation makes the maximum sensitivities closer to the lower boundary and increases their magnitudes.

e. Linearity evaluation

To verify the linearity assumption on which SV calculation is based, the ratio of 36 h linearly and non-linearly evolved perturbation magnitudes (e.g., Zou et al. 1997) is compared in Table 2. Similar to Errico and
Raeder (1999). SVs are used as finite perturbations for linearity evaluation because the linearity of the finite perturbations has more practical interests. The typical analysis error magnitudes of 4 m s\(^{-1}\) for \(u'\) and \(v'\), and 2 K for \(T'\) are used for maximum amplitudes of the initial perturbations for nonlinear evolution, as in Errico and Raeder (1999). Overall, the linearly and nonlinearly evolved SVs have better agreement for EXP1, EXP2, and EXP3 than EXP4 (Table 2). In spite of magnitude differences of the linearly and nonlinearly evolved SVs in Table 2, the major structures of the linearly and nonlinearly evolved SVs in the verification region are quite similar except slight phase differences (not shown). The linearity of the Typhoon Usagi is more extensively examined in the companion paper of Kim and Jung (2009).

### Table 2. The ratio of linearly evolved leading SVs to nonlinearly evolved leading SVs in the whole domain.

<table>
<thead>
<tr>
<th>Measure</th>
<th>(u)</th>
<th>(v)</th>
<th>(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXP1</td>
<td>1.29</td>
<td>1.18</td>
<td>1.06</td>
</tr>
<tr>
<td>EXP2</td>
<td>1.36</td>
<td>1.12</td>
<td>1.25</td>
</tr>
<tr>
<td>EXP3</td>
<td>0.95</td>
<td>0.57</td>
<td>0.90</td>
</tr>
<tr>
<td>EXP4</td>
<td>0.67</td>
<td>0.59</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Vertical cross sections of various basic and SV fields through the TC center at the final time indicate that large dry TE of the evolved SV is located in the lower atmosphere, and physically attributed to the inflow toward the TC along the edge of the subtropical ridge in the southeast part of the TC as in Peng and Reynolds (2006) and warming in broad area of the midtroposphere.

Vertical cross sections of various basic and SV fields at the initial time through large sensitivities in the midlatitude trough region indicate that energy-weighted SV sensitivities in the midlatitude are located in the lower-to-midtroposphere under the upper trough during the TC evolution. These large sensitivities in the lower troposphere are associated with strong baroclinicity and accompanying frontogenesis in the lower troposphere. Unlike the initial SV structures, which correspond well with SV structures of extratropical cyclones (e.g., Buizza and Palmer 1995; Badger and Hoskins 2001; Morgan 2001; Kim and Morgan 2002), much of the energy associated with evolved SVs is still located in the mid-to-lower troposphere, which is different from the SV energy maximum in the upper troposphere at the final time for extratropical cyclones. Differences in the vertical energy structures of the evolved SVs of the TC and extratropical cyclones may be due to the combination of the wave energy propagation to upper troposphere by initially upshear-tilted lower to midtropospheric sensitivities in the midlatitude and direct advection of the TC energy to the evolved SVs in the verification region. Because of the combination of two kinds of energy, the vertical energy structures show rather homogeneous structures relatively far from the TC recurvature, but energy is more concentrated in the lower troposphere after the TC undergoes extratropical transition. The low-level sensitivities derived from TESVs for Usagi may appear to be inconsistent with the upper-level sensitivities derived from ADSSV in Wu et al. (2009). Wu et al. (2009) demonstrated that the steering flow of the TC is influenced by the midlatitude upper-level trough. Given the rapid evolution of low-level SVs to perturbations that have significant amplitude at the tropopause level (e.g., Fehlmann and Davies 1997; Gelaro et al. 1999, 2000), the SV and ADSSV results do not necessarily contradict each other.

Given the results in this study, sensitive regions for adaptive observations of TCs may be different following the TC development stage, similar to Reynolds et al. (2007). Far from the TC recurvature, sensitive regions near TC center may be important. On the other hand, close to the TC recurvature, effects of midlatitude trough become dominant and the vertical structures of the sensitivities in the midlatitude are similar to (different from) those of extratropical cyclones at the initial (final) time.

4. Summary and discussion

In this study, the structure and evolution of SV sensitivities near the storm center and midlatitude are evaluated for Typhoon Usagi, and the dynamical features associated with recurvature and extratropical transition of Typhoon Usagi are investigated using TESVs.

Horizontal structures of the initial SVs at different times following the TC recurvature show that, relatively far from the region of TC recurvature, the sensitivities near the TC center have larger magnitudes than those associated with the midlatitude trough. The sensitivities in the midlatitude trough region become dominant as the TC moves close to the region of recurvature, and undergoes extratropical transition. Vertical cross sections of various basic state and SV fields through the TC center at the initial time indicate that energy-weighted SV sensitivities in the midtroposphere are mostly associated with the vertical wind and temperature component of SVs, showing small upshear-tilted structures near the TC center below the upper trough. At the same time, vertical structures of the horizontal wind component of SVs indicate that the inflow toward the TC along the southeast part of TC and the edge of the subtropical high is important to the growth of the energy of the evolved SVs, as indicated in Peng and Reynolds (2006).
Acknowledgments. The authors thank two anonymous reviewers for their valuable comments. This study was supported by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-2102. This research was partially supported by the Brain Korea 21 (BK21) program.

REFERENCES


