Adaptive Observation Guidance Applied to Typhoon Rusa: Implications for THORPEX-PARC 2008

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Abstract

In this study, total energy (TE) singular vectors (SVs) based on the fifth generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) and its tangent linear and adjoint models with a Lanczos algorithm are applied to Typhoon Rusa. The structures of SVs are evaluated to understand the sensitivity of forecasts with respect to the initial conditions, and thence to suggest the sensitive regions in terms of adaptive observations. In addition, the implications of applying this adaptive observation strategy for the THORPEX-Pacific Asian Regional Campaign (T-PARC) are discussed. Sensitive regions identified by TESVs are located horizontally in inflow regions along the edge of the subtropical high and the mid-latitude trough. Sensitive regions are located vertically in the mid-troposphere with several secondary peaks throughout the troposphere. In contrast to the upward energy propagation mechanism of SV development in extratropical cyclones, this does not occur for Typhoon Rusa. Vertically-confined, upshear-tilted SV structures under the mid-latitude trough are noticed for the temperature component of SV. The results of this study are quite consistent with recent studies on targeted observation strategies of tropical cyclones, and demonstrate that the TESVs can capture the signal of the environmental features affecting the evolution of Typhoon Rusa. The TESV guidance shown in this study will be calculated and provided for real-time field experiments during the T-PARC.

Key words: Adaptive observations, adaptive observation guidance, sensitive regions, THORPEX, T-PARC, singular vectors, tropical cyclone

1. Introduction

Two kinds of uncertainties may be involved in numerical weather prediction (NWP). One stems from an imperfect model, insufficient knowledge or imperfect parameterization of the physical processes involved, and imperfect numerical solution of the governing partial differential equations. The other is initial condition (i.e., analysis) uncertainty, which is caused by imperfect realization of the current state of the atmosphere. The initial condition is produced by a data assimilation system that combines observations and prior information (typically a previous numerical forecast) while taking into account the uncertainties associated with each. Both types of uncertainties may degrade NWP forecasts by amplifying during the forward model integration. Although the initial condition uncertainties may evolve as a major part of forecast error for short-term weather forecasts, such uncertainties may be reduced by enhancing the type and number of observations. In the past, meteorological observational sites usually were near human residences to monitor weather conditions for living or industrial purposes. More recently, more weather observations have become available in previously data-void areas.

Adaptive (or targeted) observation guidance (or strategies) recently have been developed to reveal regions where more observations would improve weather forecasts. That is, the goal of adaptive (or targeted) observations is to decrease the forecast error by placing observations in regions where additional

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observations are expected to improve a forecast of interest. These regions may be considered "sensitive" in the sense that changes to the initial conditions in these regions are expected to have a larger effect on a particular measure of forecast skill than changes in other regions (Kim et al., 2004).

Adaptive observation strategies may be roughly categorized as uncertainty-based and dynamics-based strategies. Uncertainty-based adaptive observation strategies use estimates of analysis and forecast errors (e.g., Bishop and Toth, 1999; Bishop et al., 2001; Hamill and Snyder, 2002; Aberson and Etherton, 2006; Majumdar et al., 2006). The Ensemble Transform Kalman Filter (ETKF) is the typical uncertainty-based adaptive observation strategy. Dynamics-based adaptive observation strategies use the dynamics of the flow (Bergot, 1999; Bergot et al., 1999; Pu and Kalnay, 1999; Buizza and Montani, 1999; Gelaro et al., 1999; Langland et al., 1999; Montani et al., 1999; Peng and Reynolds, 2005, 2006; Majumdar, 2006; Kim and Jung, 2006; Wu et al., 2007). Adjoint sensitivity and singular vectors (SVs) are typical of the dynamics-based adaptive observation strategy. 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). Given an initial norm, a final norm, a basic state, and a forecast model, SVs are those perturbations that amplify the most rapidly over a specified time period. Because SVs grow rapidly, they have been used for adaptive observations by identifying regions with large sensitivity to small perturbations (e.g., Palmer et al., 1998).

Sensitive regions for adaptive observations change depending on weather events, forecast regions of interest, and adaptive observation strategies. Until recently, most of the studies that have used adaptive observation strategies to identify sensitive regions for adaptive observations have focused on extratropical cyclogenesis over the northeast Pacific (e.g., North Pacific Experiment (NORPEX); Winter Storm Reconnaissance Program) or Atlantic (i.e., Fronts and Atlantic Storm Track Experiments (FASTEX); Atlantic THORPEX). Recently, adaptive observation strategies have been applied for tropical cyclone (TC) evolution. Aberson (2003) conducted sensitivity analysis study on tropical cyclones in the Atlantic. Majumdar et al. (2006) and Reynolds et al. (2007) have compared various adaptive observation strategies for Atlantic hurricanes.

To prepare for the THORPEX-Pacific Regional Campaign (T-PARC), which is planned for the western North Pacific in 2008 to improve typhoon forecasts, some studies have addressed sensitive regions for Pacific typhoons using adaptive observation guidance. Peng and Reynolds (2006) used SVs to study the dynamics of TC evolution in both the Atlantic and the Pacific during the 2003 summer season. Kim and Jung (2006) investigated sensitive regions for Typhoon Rusa using adjoint-based forecast sensitivities. Wu et al. (2007) utilized an adjoint-derived sensitivity steering vector (ADSSV) technique to detect sensitive regions for adaptive observations of several typhoons.

Typhoon events that affect Korea are closely related to the scientific issues of typhoon track targeting and recurvature considered in T-PARC. Therefore, to prepare for T-PARC, dynamics-based adaptive observation strategies (i.e., adjoint-based forecast sensitivities and SVs) using the fifth-generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) and its tangent linear and adjoint models have been applied to several typhoons. The focus of this study is Typhoon Rusa, which caused significant societal and economic damage in Korea.

In this study, adaptive observation guidance using SVs is applied to Typhoon Rusa to understand forecast sensitivity with respect to the initial conditions, and thence to suggest the sensitive regions in terms of adaptive observations. Section 2 describes the mathematical formulations used to calculate total energy (TE) norm SVs (TESVs). Case study descrip-

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1) The Observing system Research and Predictability Experiment (THORPEX) is a WMO/WWRP program from 2003 to 2012 to accelerate improvements in the accuracy of 1 to 14-day high impact weather forecasts for the benefit of the society and economy (WMO, 2004).
tion and configurations of the model and SV calculations are presented in section 3, and the SV sensitivities for Typhoon Rusa and linearity evaluation are presented in section 4. In section 5, implications for T-PARC are presented. Section 6 contains a summary and discussion.

2. Total energy norm SVs

The calculation of SVs essentially involves selecting the projection coefficients subject to the constraints that the initial disturbance has unit amplitude in a specified norm and evolves to have maximum amplitude in a specified norm after some finite optimization time, \( t = \tau_{\text{opt}} \). In this study, the initial and final norms are the dry TE defined by Zou et al. (1997) as

\[
E_d = \int \int \int_{\alpha,\beta,\gamma} \left[ \frac{1}{2} \left( u'^2 + v'^2 + w'^2 + \left( \frac{g}{N^2} \right) \theta'^2 \right) \left( \frac{1}{\rho c_s} \right)^2 p'^2 \right] dydxds,
\]

where \( E_d \) is the dry TE in a non-hydrostatic model, \( u', v', w' \) are the zonal, meridional, vertical wind perturbations, \( \theta' \) is the potential temperature perturbation, \( p' \) is the pressure perturbation, \( \bar{N}, \bar{\theta}, \bar{\rho}, c_s \) are Brunt-Väisälä frequency, potential temperature, density, speed of sound at the reference level, and \( x, y, \sigma \) denote zonal, meridional, and vertical coordinates, respectively.

The constrained optimization problem seeks to maximize the Rayleigh quotient, \( \lambda^2 \) (the amplification factor),

\[
\lambda^2 = \left( PMx(0), CPMx(0) \right) \left( x(0), Cx(0) \right),
\]

at the time \( t = \tau_{\text{opt}} \), where the inner product is denoted by \( \left< \cdot, \cdot \right> \), \( P \) is a local projection operator that makes the state vector be zero outside a given domain\(^2\) (Buizza, 1994b), \( M \) is the tangent linear model (TLM) of the nonlinear model, and \( C \) is the dry TE norm. In (2), the state vector at the initial time is assumed to evolve linearly. By defining the local projection operator, the amplitude of the state vector with norm \( C \) at the optimization time is maximized over a specific region. The maximum of this ratio is realized when \( x(0) \) is the leading SV of the TLM \( M \) for the \( C \) norm, that is, \( x(0) \) satisfies

\[
M^T P^T C P M x(0) = \lambda^2 C x(0).
\]

The generalized eigenvalue problem in (3) can be reduced to an ordinary eigenvalue problem by multiplying both sides of (3) by the inverse of the square root of \( C \). Then a Lanczos type algorithm (e.g., Ehrendorfer and Errico, 1995; Kim, 2003; Kim et al., 2004) is used to solve for \( x(0) \) in (3).

3. Case study and model description

a. Case study

In addition to a record-breaking daily rainfall amount of 870.5 mm on the east coast of the Korean peninsula on 31 August 2002, Typhoon Rusa caused

\[
\text{Fig. 1. The RSMC Tokyo-Typhoon Center best track (+ symbols) and the 24-h MM5 forecast track (-●-) of Typhoon Rusa. Each symbol is plotted at 6 hour intervals.}
\]

\(^2\) In this study, the regions of non-zero projection operator are referred to as the verification region.
Fig. 2. 200-500 hPa layer-average PV (shading interval of 1 PVU) and mean sea-level pressure (MSLP) (contour interval of 4 hPa) of analyses at (a) 1200 UTC 30, (b) 0000 UTC 31, (c) 1200 UTC 31 August 2002, and of forecasts at (d) 1200 UTC 30, (e) 0000 UTC 31, and (f) 1200 UTC 31 August 2002. The box in (f) denotes the geographic region for maximizing the dry TE at 24 h, which is referred to as the verification region.
many casualties and extensive property damage in Korea. After its formation on 23 August 2002, Typhoon Rusa moved northwestward and recurved northeastward along the edge of the subtropical high after 1200 UTC 30 August (Fig. 1a). Rusa approached the southern part of the Korean peninsula at 0600 UTC 31 August. The MM5 model is integrated for 24 hours from 1200 UTC 30 to 1200 UTC 31 August 2002 (Fig. 1). Even though the predicted motion was slightly faster than observed, the predicted path generally simulates the observed track well.

Analyses of 200 – 500 hPa layer-average potential vorticity (PV) from 1200 UTC 30 to 1200 UTC 31 August 2002 are shown in Fig. 2. At 1200 UTC 30 August, a large PV reservoir was north of the Korean peninsula, and isolated regions of large PV were over the center and northwest of Rusa (Fig. 2a). At 0000 UTC 31 August, the isolated large PV region northwest of Rusa merged with the large PV over the TC center as Rusa approached higher latitudes (Fig. 2b). At 1200 UTC 31 August, the large PV near the storm center merged with the PV reservoir north of the Korean peninsula (Fig. 2c). The fifth-generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) forecasts (Figs. 2d, e, and f) have similar overall characteristics as the analysis fields, which implies that the predicted fields generally simulate the analysis fields well.

b. Model and SV configurations

To calculate SVs, this study uses the MM5 adjoint modeling system (Zou et al., 1997) and a Lanczos algorithm. The model is centered at 36° N and 123° E with a 100 km horizontal grid spacing in a 50 x 50 domain and 14 evenly spaced sigma levels in the vertical from the surface to 50 hPa. The model initial and lateral boundary conditions are from the National Centers for Environmental Prediction (NCEP) final analysis (FNL; 1° x 1° global grid). The Optimum Interpolation Sea Surface Temperature (OISST) version 2 (Reynolds et al., 2002) is used for the lower boundary condition over the ocean. 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 radiational 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 TLM and adjoint model integrations, except the effect of moisture is neglected. The initial time of the SV calculation is 1200 UTC 30 August 2002, the same as that of the MM5 model integration, and the optimization time interval is 24 hours.

4. Characteristics of TESVs

a. Growth rates and structures of SVs

The amplification factors of individual SVs are shown in Fig. 3. The relative contributions of the leading five SVs to energy of the total 20 SVs are 51.8%, which implies the leading five SVs explain more than half of the total energy. Horizontal structures of each SV component on 800 hPa are shown in Fig. 4. A large positive (negative) zonal wind component of SV is located around 400 km (1000 km) southeast of the storm center (Fig. 3).

3) All the SVs from Fig. 4 to Fig. 7 are for the leading SV. In addition, SV without specification refers to the SV at the initial time.
4a). Regions of large zonal wind components of SVs correspond well with inflow regions toward the storm center, as mentioned by Peng and Reynolds (2006) and Kim and Jung (2008a). The meridional wind component of the SVs (Fig. 4b) has two large positive sensitivity regions around 1000 km east and 700 km west of the storm center. The larger magnitude sensitivity region to the east (i.e., in the right semi circle of the storm center) is also associated with the inflow toward the TC in the western quadrant of the subtropical high (Fig. 4b). Although the temperature component of the SVs also has maxima in the right semi circle of the storm, it is part of an overall elongated structure from northeast China to the East China Sea (Fig. 4c).

Vertical structures of each component of the SV along the solid lines in Fig. 4 are shown in Fig. 5. The vertical structure of the zonal wind component of the SV is shown superposed on the PV in Fig. 5a. The PV column larger than 1 PVU through most of the troposphere is located near the TC center, with another larger PV region northeast of the Korean peninsula that corresponds to the mid-latitude trough in Fig. 2. The zonal wind component of the SV has large positive and negative sensitivities in the lower troposphere south of the TC center, which is associated

Fig. 4. Leading SVs on 800 hPa at the analysis time: (a) zonal wind component of SV (contour interval of 1 m s⁻¹), (b) meridional wind component of SV (contour interval of 1 m s⁻¹), and (c) temperature component of SV (contour interval of 0.5 K). △ indicates the center of Typhoon Rusa.
with the large positive and negative sensitivities southeast of the TC center in Fig. 4a. For the meridional wind component of the SV (Fig. 5b), maximum sensitivities have vertically confined structures that are west and east of the TC center in the mid-troposphere, with the larger magnitudes east of the TC center. The positive sign of the meridional wind component of the SV perturbation is consistent with inflow toward the TC, which likely leads to growth of dry TE in the verification region at the final time. By contrast, the temperature component of the SV (Fig. 4c) has an upshear-tilted structure under the upper trough, which is a typical SV structure for extratropical cyclones (e.g., Kleist and Morgan, 2005).

Horizontal structures of each component of the 24-h evolved SV on 350 hPa are shown in Fig. 6. A large positive (negative) zonal wind SV component is over (500 km north of) the storm center (Fig. 6a). The vertical cross-section along the line DD' through the TC center indicates that the zonal wind SV component has a maximum in the lower part of the TC center (Fig. 7a).
The evolved SV has large positive sensitivities northeast (i.e., right semi circle) of the TC center (Fig. 6b). The vertical cross-section of the meridional wind component of the SV along the line EE' indicates that the largest magnitude of the SV is now in the upper troposphere (Fig. 7b). The SV temperature component has its maximum over the TC center (Fig. 6c). The vertically-integrated, energy-weighted SV is used to represent general features of the sensitivity of Typhoon Rusa. The energy-weighted SV is calculated to combine all the SVs for different model varia-

The PV is vertical at this time and the upper and lower boundary temperature perturbations have increased, similar to extratropical cyclones (Fig. 7c).

**b. Energy-weighted SVs**

The vertically-integrated, energy-weighted SV is used to represent general features of the sensitivity of Typhoon Rusa. The energy-weighted SV is calculated to combine all the SVs for different model varia-
bles with different units into a single SV field with the unit of energy (J kg\(^{-1}\)). The vertically-integrated, energy-weighted 1\(^{st}\), 2\(^{nd}\), 3\(^{rd}\) SV and MSLP at the initial and final times are shown in Fig. 8. For the leading SV, the initial SV has large sensitivities of elongated half-circled structures from northeast China to the East China Sea (Fig. 8a). The sensitive regions are closely associated with the mid-latitude trough and the region between the typhoon and the subtropical ridge to the east. The 2\(^{nd}\) SV has structures very similar to the leading SV except larger mid-latitude sensitivities (Fig. 8c), and the 3\(^{rd}\) SV has major sensitivities north of the Korean peninsula (Fig. 8e). The 1\(^{st}\) and 2\(^{nd}\) evolved SVs after 24 h have large sensitivities over the TC center (Figs. 8b and d), and 600 km north of the TC center for the 3\(^{rd}\) SV (Fig. 8f). These variations in the evolved SVs imply that the TC forecasts may be sensitive to the choice of the initial conditions, and the sensitivities of the forecast to the initial conditions can be indicated by SVs. Adaptive observations in the sensitive regions indicated by SVs may reduce the initial condition uncertainties in

![Diagram](image-url)
Fig. 8. Vertically-integrated, energy-weighted SV (J kg$^{-1}$, shaded, interval varies) and MSLP (solid, contour interval of 4 hPa) at (a), (c), (e) 0h and (b), (d), (f) 24 h for 1$^{st}$, 2$^{nd}$, and 3$^{rd}$ SV, respectively. The boxes in (b), (d), and (f) denote the verification region.
those sensitive regions, and lead the better forecasts. The largest contributions to the vertically-integrated, energy-weighted leading SV in Fig. 8a are from two layers, corresponding to the lower and middle parts of the atmosphere (Fig. 9). The energy-weighted SVs in the lower part (Fig. 9a) are associated with the sensitivity region in Fig. 8e to the north of the typhoon. The energy-weighted SV in the middle part (Fig. 9b) is associated with the mid-latitude trough and the region between the typhoon and the subtropical high to the east (Fig. 9b). In conjunction with Fig. 8, large sensitivities in the mid-latitudes are located in the lower and middle part of the troposphere, which is consistent with the results in Kim and Jung (2008a).

Vertical profiles of the 1st, 2nd, and 3rd energy-weighted SVs are shown in Fig. 10. The maximum of the leading SV for both the total energy and kinetic energy at the initial time (Fig. 10a) is located near the mid-troposphere with several secondary peaks near lower troposphere, mid- to upper- troposphere, and at the upper boundary. By contrast, the leading SV for the potential energy has a smaller contribution and a more uniform structure (also true for the 2nd and 3rd SV). The leading SV at the final time (Fig. 10d) has increased in amplitude by at least an order of magnitude and has maxima at the lower and upper troposphere. Major and minor peaks of the 2nd SV for both the total and kinetic energy at the initial (Fig. 10b) and final (Fig. 10e) times are similar to those of the leading SV at the corresponding times, except for a relatively smaller peak in the upper troposphere at the final time. The maxima of the 3rd SV for the total and kinetic energy at the initial (Fig. 10c) and final (Fig. 10f) times are located in the lower troposphere and the 3rd SV for the potential energy also has a maximum in the lower troposphere.

The composites of the vertical profiles of the 1st to 5th energy-weighted SVs for the total, kinetic, and potential energy (Fig. 11) have similar characteristics to those of the two leading SVs in Fig. 10. While the maximum of the composite SV at the initial time (Fig. 11a) is near the mid-troposphere, with secondary peaks near lower troposphere and the upper boundary, the maximum of the composite SV at the final time (Fig. 11b) is located in the lower troposphere, with a secondary peak at the upper troposphere. In contrast to the vertical SV profiles for extratropical cyclones, the kinetic energy (KE) of the initial SV is dominant except at upper boundary. In addition, upward energy propagation during SV evolution in extratropical cyclones (e.g., Buizza and Palmer, 1995; Badger and Hoskins, 2001; Morgan, 2001; Kim and Morgan,
2002) is not noticed for Rusa, which is similar to the results in Kim and Jung (2008a).

c. Validation of linearity

The linear growth assumption of SVs is verified by examining the ratio (Zou et al., 1997) and similarity index (Buizza, 1994a) of 24-h linearly and nonlinearly evolved perturbation magnitudes and structures, respectively. For nonlinear evolution, the scaled leading SV that has maximum magnitudes of 4 m s$^{-1}$ for $u'$ or $v'$, or 2 K for $T'$ (e.g., Errico and Reader, 1999) is used as a finite perturbation because the linearity of the finite perturbation has more practical interests. The finite perturbation is obtained by multiplying a fixed number to the leading SV so that the maximum magnitude of $T'$ is 2 K and that of $u'$ and $v'$ is below 4 m s$^{-1}$. The ratios for $u'$, $v'$, and $T'$ components are 0.885, 0.993, and 0.784, respectively, and the similarity index is around 50 %, which implies similar magnitudes and structures between linear and nonlinear evolutions. The linearity can be further verified by comparing individual structures of the linearly and nonlinearly evolved SVs in the verification region (Fig. 12). The nonlinearly and linearly evolved zonal wind components of the leading SV at 850 hPa (Figs. 12b and c) are quite similar.

5. Implications for T-PARC

As mentioned in the Introduction, T-PARC will occur in the western North Pacific during 1 August
Fig. 11. Vertical distributions of the energy-weighted SVs (J kg$^{-1}$, TE; solid, kinetic energy; dashed, potential energy; dotted): (a) composite of 1$^{st}$ SV to 5$^{th}$ SV at 0 h and (b) composite of 1$^{st}$ SV to 5$^{th}$ SV at 24 h. The ordinate represents the vertical level ($\tilde{z}$) and the abscissa denotes the energy-weighted SVs (J kg$^{-1}$).

Fig. 12. Zonal wind components of (a) initial leading SV (m s$^{-1}$), (b) linearly evolved leading SV, and (c) nonlinearly evolved leading SV. The boxes in (b) and (c) denote the verification region.
to 6 October 2008 (WMO, 2008). Various organizations have developed real-time strategies to suggest possible target regions for adaptive observations to improve tropical cyclone track forecasts. These include TESV strategy from the Japan Meteorological Administration (JMA) (Yamaguchi et al., 2008), MM5 TESV strategy from Yonsei University (YSU) (Kim and Jung, 2008a, b), Ensemble Transform Kalman Filter (ETKF) by the University of Miami (Majumdar, 2006), analysis of ensemble deep-layer mean (DLM) wind variance by NOAA (Aberson, 2003), TESV strategy by the Naval Research Laboratory (NRL) (Peng and Reynolds, 2006), and TESV strategy by the European Center for Medium-range Weather Forecasts (ECMWF) (Buizza et al., 2007). A few more real-time adaptive observation strategies are planned for the T-PARC period. These sensitivity products for adaptive observations will be collected by JMA, Earth Observing Laboratory (EOL) of National Center for Atmospheric Research (NCAR), and PREVention, Information and Early Warning (PREVIEW) of ECMWF, and used to decide on the target regions for adaptive observations of typhoons.

Adjoint-based sensitivities (i.e., adjoint-based forecast sensitivities and SVs) using MM5 and its tangent linear and adjoint models have been applied to high-impact weather events (e.g., typhoon, heavy rainfall and snowfall events associated with extratropical cyclones, sand and dust storm, etc.) in Korea (e.g., Kim and Jung, 2006; Kim et al., 2008; Kim and Jung, 2008a, b). Adjoint-based sensitivity products as presented in this article may contribute to T-PARC by suggesting sensitive regions for adaptive observations of typhoons. One caution is that the input data for the real-time SV calculation for T-PARC are forecast fields instead of analyses as in this study, due to the preparation time necessary for real-time adaptive observations as explained in Kim et al. (2004) and Majumdar et al. (2006). In addition to applications to field experiments such as T-PARC, these strategies can be used to determine permanent or semi-permanent observational sites to improve forecasts and predictability of high-impact weather events in Korea.

6. Summary and discussion

In this study, SVs are applied to Typhoon Rusa as an adaptive observation strategy to understand the sensitivity of the forecast with respect to the initial conditions, and thence to suggest the sensitive regions in terms of adaptive observations. Because Typhoon Rusa is nearing recurvature during the period of this study, sensitive regions by SVs are located in the mid-latitude trough regions as well as the inflow regions along the subtropical high, which is similar to the results in Peng and Reynolds (2006) and Kim and Jung (2008a).

Both the SVs in this study and the adjoint sensitivities in Kim and Jung (2006) indicate that the inflow regions in the right semi circle of the storm are sensitive regions for Rusa. However, the sensitive regions in the mid-latitude trough predicted by SVs are not indicated by the adjoint sensitivities. This difference may be attributed to the different configurations of physical processes used for SV and adjoint sensitivity calculations (Kim and Jung, 2008b). In the present study, moist basic state and dry linear integrations are used for SV calculations to detect large-scale influences on the evolution of Typhoon Rusa, such as the mid-latitude trough. In contrast, the adjoint sensitivities in Kim and Jung (2006) used moist basic state and linear integrations so that large sensitivities are concentrated near the storm center. Differences in the vertical distributions of the energy-weighted SV in this study and adjoint sensitivities also may be explained by different configurations of physical processes for sensitivity calculations. Moist processes used in adjoint sensitivity calculations make the sensitivity maximum close to the lower boundary (i.e., close to the source of moisture) as indicated in Kim and Jung (2008b).

Some implications of this adaptive observation strategy for T-PARC and other applications have also been discussed. The results of this study are quite consistent with recent studies on targeted observation strategies of tropical cyclones and demonstrate that the TESVs can capture the signal of the environmental features affecting the evolution of Typhoon Rusa. The TESV guidance shown in this study will
be calculated and provided for real-time field experiments during T-PARC.

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