Total Energy Singular Vector Guidance Developed at JMA for T-PARC

Takuya Komori
Numerical Prediction Division, Japan Meteorological Agency

Ryota Sakai
River Office, Osaka Prefectural Government

Hitoshi Yonehara
Numerical Prediction Division, Japan Meteorological Agency

Takashi Kadowaki
Numerical Prediction Division, Japan Meteorological Agency

Kiyotomi Sato
Numerical Prediction Division, Japan Meteorological Agency

Takemasa Miyoshi
University of Maryland

Munehiko Yamaguchi
Numerical Prediction Division, Japan Meteorological Agency
(Present affiliation: Rosenstiel School of Marine and Atmospheric Science, University of Miami)

Abstract

A sensitivity analysis system was developed at the Japan Meteorological Agency (JMA), using a singular vector (SV) method with a moist total energy (TE) metric at both the initial and final times, to provide daily realtime guidance for the targeted observations in the THORPEX Pacific Asian Regional Campaign (T-PARC) period from August through early October of 2008. For effective decision making regarding the targeted observations for tropical cyclones (TCs), a lead time of at least two days was needed for each observation. The product with a one-day lead time was also required to refine judgment for the execution and location of the special observations. Accordingly, two types of sensitivity analysis were performed using two forecast fields (T+24h and T+48h) of the operational

Global Spectral Model (GSM) at a resolution of TL959L60[1]. For the daily sensitivity analysis three common fixed target areas were specified among the guidance providers to enable inter-comparison of the sensitivity guidance in each of their calculations. JMA also conducted further sensitivity analysis using an adaptive target area in the vicinity of the TC location, because such an area is preferable when targeting a TC. Some target observations demonstrated significant impacts for operational TC track forecasts. On the other hand, a number of common and different features were found among SV guidance providers in realtime intercomparison during the T-PARC period. Some extra experiments for the case of the recurving TC revealed that differences in moist processes in the tangent linear and adjoint (hereafter TL/AD) model can explain the distinct features to a certain extent. The results highlighted a number of features of SV sensitivities.

1. Introduction

From August through early October of 2008, as part of THe Observing-system Research and Predictability Experiment (THORPEX) framework, JMA conducted the THORPEX Pacific Asian Regional Campaign (T-PARC) project (Komori et al. 2009, Yamashita et al. 2009) in collaboration with other nations and projects (Wu et al. 2007, Elsberry and Harr 2008, Reynolds et al. 2009b, and Kim et al. 2010). T-PARC was a multi-national and multi-institution field campaign designed to enhance understanding of the mechanism behind TCs and improve forecast skill for them, in particular as a demonstration of the Global Interactive Forecast System (GIFS) - a major THORPEX objective. While the T-PARC project encompassed many objectives, JMA's major focus was on TC track forecasting, especially in the recurvature stage. This is because recurving TCs have large forecast uncertainty, and better forecasting skills are of great importance to people living in Pacific basin countries, including Japan, from the perspective of natural disaster reduction and mitigation.

With the aim of supporting the field campaign and the GIFS, monitoring was performed in regard to information on daily forecast uncertainty and the ensemble spread of TC track forecasts, provided by the operational Typhoon Ensemble Prediction System (TEPS) (Yamaguchi and Komori 2009, Yamaguchi et al. 2009) and the one-Week Ensemble Prediction System (WEPS) (Sakai et al. 2008). JMA also provided TC tracks derived from the operational GSM, TEPS (4 times a day, 11 members) and WEPS (once a day, 51 members) to science committees in real-time. The format used was Cyclone XML (CXML; more detailed information is available at: http://www.bom.gov.au/bmrc /projects/THORPEX/TC/index.html). Currently, CXML files are exchanged through the archive centers of the THORPEX Interactive Grand Global Ensemble (TIGGE) project.

During the project, the special observations were conducted, including dropsonde deployment by a manned Falcon aircraft, enhanced radiosonde observations by research vessels and fixed observation stations, and MTSAT rapid-scan operations (Bessho et al. 2010). Figure 1 illustrates the locations of the supplemental observations (except MTSAT rapid-scan) for all TCs during the T-PARC period. These were referred to as targeted observations because they were performed in

[1] We use T as an abbreviation for triangular truncation with a Gaussian grid, TL for triangular truncation with a linear Gaussian grid, and L for vertical layers. TL959L60 therefore denotes spectral triangular truncation at a wave number of 959 with a linear Gaussian grid and 60 vertical layers.

consideration of sensitive areas where additional atmospheric observations were assimilated to improve the analysis field and thereby reduce forecast uncertainty (Aberson 2003, Langland 2005). Most of the data were distributed in real time through the Global Telecommunication System (GTS) to enable their use in operational numerical weather prediction (NWP) systems worldwide. The efficacy of the targeted observations is discussed in an accompanying paper (Yamashita and Ohta 2010).

In support of these observations, many institutions provided information on sensitive areas as guidance using a wide variety of methods as following:

1) Singular Vector (SV) method from JMA (Komori et al. 2009), ECMWF, the NRL global model (Reynolds et al. 2009b) and Yonsei University (Kim et al. 2010)
2) Ensemble Transform Kalman Filter (ETKF) method from UKMO and the University of Miami/National Centers for Environmental Prediction (NCEP)
3) Adjoint-Derived Sensitivity Steering Vector (ADSSV) method from National Taiwan University (Wu et al. 2007)
4) Ensemble-based sensitivity method from the University of Washington
5) Adjoint sensitivity method from the NRL Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Reynolds et al. 2009b).

These products were compared on the website in real time, and were discussed at daily planning meetings on the web.

The purpose of this paper is to describe the product features of the JMA sensitivity analysis system implemented for the T-PARC project using an SV method with a moist total energy (TE) norm. Section 2 describes the specifications, Section 3 outlines the performance and product features, and Section 4 provides a summary.

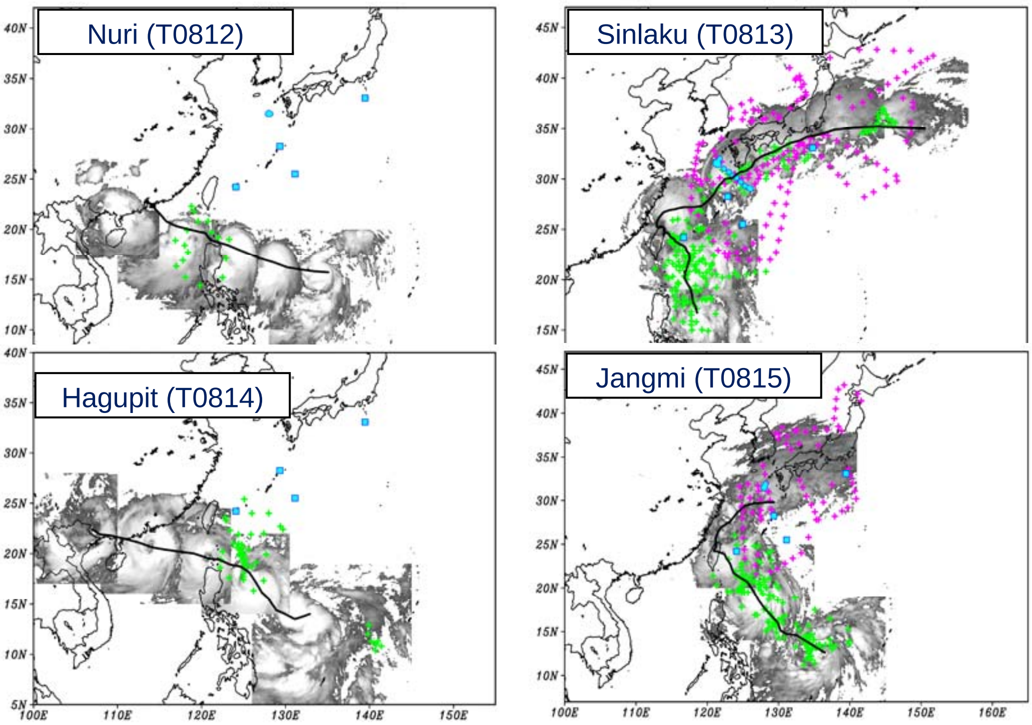

Figure 1　Schematic maps of the supplemental observational points.　The best tracks of the RSMC Tokyo - Typhoon Center for each typhoon are shown by the black lines.　Extra observation points for upper-soundings by JMA research vessels and ground observatories (blue points), dropsondes released by the Falcon aircraft (pink) and those released by other planes (green) are overlaid on the sensitive area.

2. Specifications

Using the moist SV method with a moist TE norm (Barkmeijer et al. 2001), JMA provided daily sensitivity guidance for the targeted observations conducted during the T-PARC period.　The SV method can emphasize dynamical perturbation with a rapid growth rate from small initial-condition uncertainties during an optimization time interval (OTI), and has been implemented as a perturbation generator to calculate initial perturbation growth using the TL/AD model at a resolution of T63L40 for the global domain in JMA's operational TEPS and WEPS.　The configulation of the moist TE norm at the initial and final times, evaluating the growth rate of perturbations, is the same as TEPS except for the initial field and target areas.　The equation for the norm is as follows:

$$
\begin{aligned}
(x, \mathbf{E}x) \;=\; & \frac{1}{2}\int_0^1 \int_S (\nabla\Delta^{-1}\zeta_x \cdot \nabla\Delta^{-1}\zeta_x + \nabla\Delta^{-1}D_x \cdot \nabla\Delta^{-1}D_x \\
& \quad + g(\Gamma_d - \Gamma)^{-1}\frac{T_x T_x}{T_r} \\
& \quad + w_q \frac{L_c^2}{c_p T_r} q_x q_x) dS \left(\frac{\partial p}{\partial \eta}\right) d\eta \\
& + \frac{1}{2}\int_S \frac{R_d T_r}{P_r} P_x P_x dS
\end{aligned}
\qquad (1)
$$

where ζ_x, D_x, T_x, q_x and P_x are the vorticity, divergence, temperature, specific humidity and surface pressure components of vector x, respectively, and **E** represents a norm operator. Note that the temperature lapse rate Γ is taken into consideration as an available potential energy term (Lorenz, 1955). c_p is the specific heat of dry air at a constant pressure, L_C is the latent heat of condensation, and R_d is the gas constant for dry air. T_r = 300 K is a reference temperature, Pr = 800 hPa is a reference pressure, and w_q is a constant ($w_q = 1$ for the moist TE norm and $w_q = 0$ for the dry TE norm). A representative value of $2/3\Gamma_d$ is used for Γ. In Eq. (1), the vertical integration of the kinetic energy term and the available potential energy term is calculated beneath the 26th model level (around 100 hPa), and the specific humidity term is limited to the 15th model level (around 500 hPa).

To enable planning for the special targeted observations, information on the sensitivity area at the time of observation was needed at least two days in advance. The product with a one-day lead time was also required to refine judgment for the execution and location of the special observations. Accordingly, two types of sensitivity guidance were computed using two forecast fields (T + 24 h and T + 48 h), made by high-wavenumber truncation for the operational GSM, at a resolution of TL959L60. For the daily sensitivity analysis, three common fixed target areas (referred to as GUAM, TAIWAN and JAPAN) were specified among the guidance providers to enable inter-comparison of the sensitivity guidance in each of their calculations. These areas were utilized to support not only recurving TCs, but also TCs in the generation and extratropical transition (ET) stages. JMA also conducted further sensitivity analysis using an adaptive target area (referred to as MVTY) in the vicinity of the TC location because such an area is preferable when targeting a TC (Figure 2). When a TC was analyzed by the Regional Specialized Meteorological Center (RSMC) Tokyo - Typhoon Center, the MVTY target area was automatically defined according to the TC position forecasted by the operational GSM.

The OTIs of SVs for the GUAM, TAIWAN and JAPAN regions were also common, with the value chosen as 48 hours. Reynolds and Rosmond (2003) showed the legitimacy of OTIs from 24 hours to 72 hours for synoptic scale dynamics under the assumption of linearity, especially in the case of dry SVs. As for moist processes in JMA's TL/AD model, both large-scale cloud and deep convection schemes were implemented. As discussed in previous studies (e.g. Coutinho et al. 2004, Hoskins and Coutinho 2005), the higher growth rates of moist SVs make it preferable to use a shorter time, for which the perturbation linearity assumption is more likely to be valid. Accordingly, an OTI of 24 hours was adopted for SVs in the MVTY target area. The area size of MVTY was determined based on the statistical TC position error forecasted by the operational GSM (T + 24 h and T + 48 h). The specifications of JMA's sensitivity analysis for T-PARC are shown in Table 1.

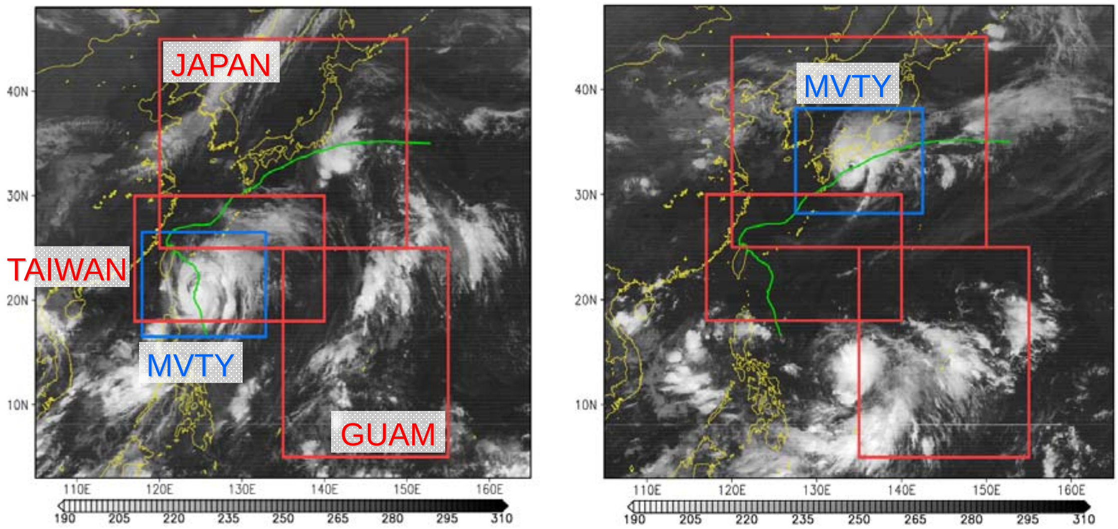

Figure 2 Schematic maps showing the four target areas (defined in Table 1) overlaid on MTSAT IR images from 00 UTC on 11 September (left) and 19 September (right) 2008. The best track of typhoon Sinlaku is shown by the green lines.

Table 1 Specifications of JMA's sensitivity analysis system for T-PARC

Forecast domain	Global			
Initial time	00 UTC			
Initial field with lead time	24 hour/48 hour forecast field by operational GSM at a resolution of TL959L60			
Method	Singular vector			
Inner model resolution	Spectral triangular truncation at a wave number of 63 (T63), 40 levels (from surface to 0.4 hPa)			
Norm	Moist total energy			
Target area	GUAM (05 – 25N, 135 – 155E)	TAIWAN (18 – 30N, 117 – 140E)	JAPAN (25 – 45N, 120 – 150E)	*MVTY
Optimization time interval	48 hours			24 hours
Physical process	**Full physics			

*The MVTY target area is automatically defined in the vicinity of each TC position forecasted by the operational GSM. The area is specified as 10 deg. x 10 deg. for the 24-hour forecast field and 15 deg. x 10 deg. for the 48-hour forecast field, based on the statistical TC position error of the operational GSM.

**Full physics: Initialization, horizontal diffusion, surface turbulent diffusion, vertical turbulent diffusion, gravity wave drag, long wave radiation, large-scale cloud and deep convection

3. Performance

3.1 Case studies of sensitivity guidance

Among the four TCs in Figure 1, Typhoon Sinlaku (the 13th named TC in the western North Pacific of 2008) had an especially great impact on Japan with its recurvature, reintensification and extratropical transition. In the early recurvature stage, the analysis field had a high level of uncertainty associated with the large spread for the track forecast in the operational TEPS and WEPS. Accordingly, collaborative targeted observations were planned with other institutions at daily meetings. Figure 3 (a) shows an MTSAT IR image and the observational locations from around 00 UTC on 11 September 2008. The locations were comprehensively decided based on the sensitivity guidance produced by a number of institutions. Additionally, Figure 3 shows JMA's sensitivity guidance for the MVTY target region, a vertically integrated total energy (TE) representation of the leading SV normalized by the maximum value of TE in the global domain with a two-day lead time (b) and a one-day lead time (c). These results indicate useful cases because the sensitivity guidance calculated from the analysis field (Figure 3 (d)) indicates analogous characteristics in comparison with those computed from forecast fields (Figures 3 (b) and (c)). The value of the similarity index (Buizza 1994) between the leading SVs computed from the two-day forecast field and that of the analysis field is 0.85, indicating good usability for guidance provided in advance (Komori et al. 2009).

Figure 4 (a) shows large precipitable water along with strong winds and convergence to the east of Sinlaku. The 500-hPa field of the final SV for the MVTY target area (Figure 4 (b)) has large heat release and vorticity to the northeast of Sinlaku. Such vorticity may have caused a change in the typhoon's location. The extra experiments in Section 3.2 also outline the important role of deep convection in this mechanism. The nonlinear evolved perturbation (Figure 4 (c)) from the initial SV shows a structure similar to that of the linearly evolved final SV, indicating the legitimacy of the linearity assumption in calculating the SV.

Figure 5 represents sensitivity guidance computed for three fixed target areas with different locations and sizes (TAIWAN, GUAM and JAPAN) at the same time, and shows the dependency of the SV structure on the target areas. The superimposed analysis stream lines in Figure 5 (a) indicate that the sensitivity locations emphasized by the leading SV are influenced by the mid-latitude upstream trough, a subtropical high-pressure system and the TC's surrounding flows. These figures also illustrate that the MVTY adaptive target area with a 24 h OTI (Figure 3 (b)) seems to be preferable to the fixed target areas with a 48 h OTI (Figures 5 (a), (b) and (c)) to detect sensitive areas efficiently in the vicinity of the TC. These results are due to the longer (48h) OTI and the higher-latitude target areas, which make it easier to capture the influence of the mid-latitude trough. The results are consistent with those of Komori and Kadowaki (2010).

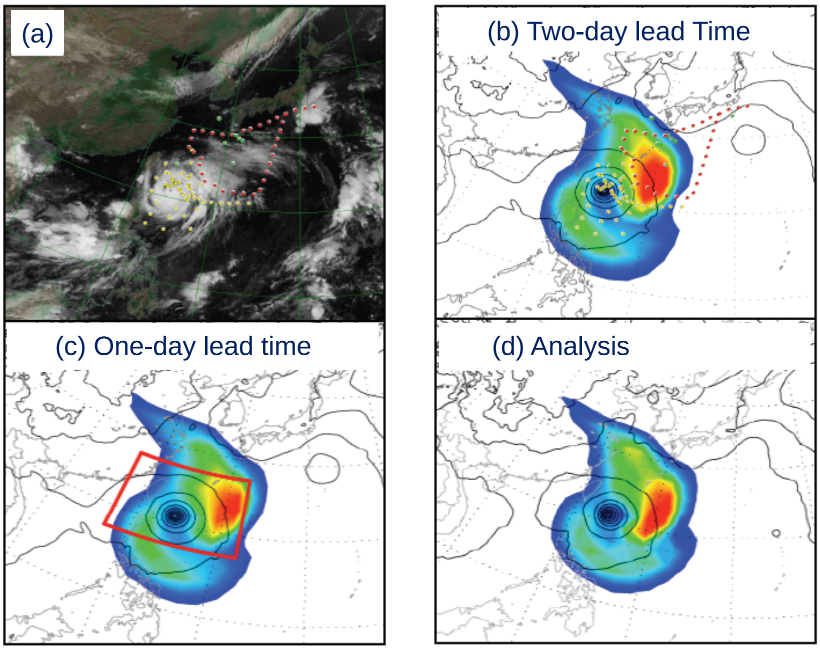

Figure 3 The leading SVs for the MVTY target area computed from (b) the two-day forecast, (c) the one-day forecast and (d) the analysis field at 00 UTC on 11 September 2008. The observation points of upper-soundings by JMA research vessels and ground observatories (green points), dropsondes released by the Falcon aircraft (red) and those released by other planes (yellow) are plotted (a) on the MTSAT image and (b) on the sensitive area.

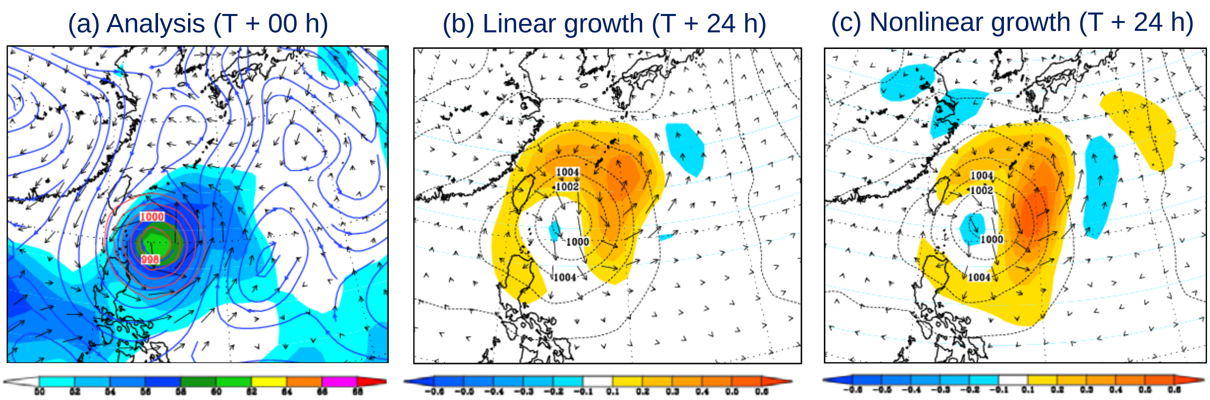

Figure 4 The sea level pressure (contour) and wind fields (vector) at 500 hPa for (a) the analysis field at a resolution of T63L40, (b) the final SV (linear growth of the initial SV) for the MVTY target area and (c) the nonlinear perturbation evolved 24 hours from the initial SV (shown in Figure 3 (d)). The shaded areas represent (a) total precipitable water vapor in each column, and (b)/(c) temperature perturbation. The 500-hPa stream lines (blue) are superimposed on the analysis field.

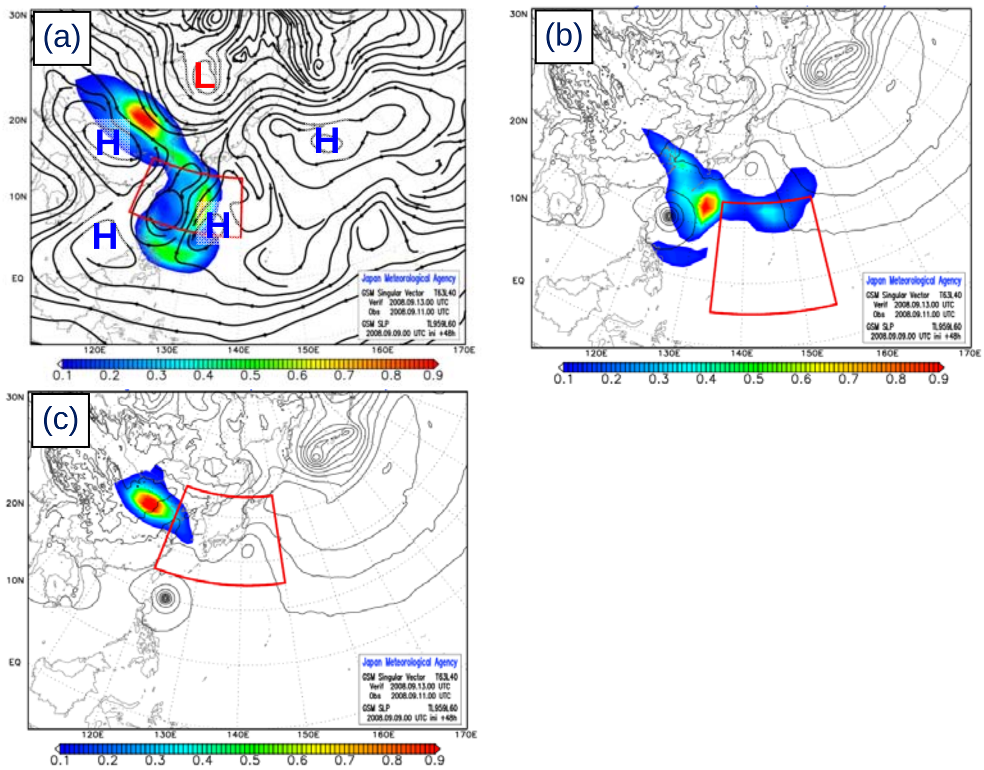

Figure 5　As per Figure 3 (b), but for the fixed target areas of (a) TAIWAN, (b) GUAM and (c) JAPAN. The stream lines at 500 hPa (a) and the surface pressure of the analysis field (b)/(c) are superimposed.

3.2 Impact of moist processes in the TL/AD model

Section 3.1 demonstrated the dependence of SVs in terms of 1) the location and size of the target area, 2) the OTI used to specify the growth period, and 3) the performance of the inputted analysis or forecast field. It is also well known that SVs depend on the selection of other specifications: 4) the metric and associated norm at the initial and final times, 5) the physical and dynamical processes in the TL/AD model, and 6) the resolution of the TL/AD model. Many researchers have focused on SV inter-comparison (Majumdar et al. 2006, Reynolds et al. 2007, and Wu et al. 2009) and on recurving TCs with a local target area (Peng and Reynolds 2006, Kim and Jung 2009, Chen et al. 2009 and Reynolds et al. 2009a), discussing SV features and the important role of upstream mid-latitude troughs, subtropical ridges and the flows surrounding TCs with several configurations.

In the T-PARC project, real-time inter-comparison of sensitivity analysis was performed on the website, offering comprehensive information on sensitive areas as guidance for effective decision-making related to target observations in the vicinity of a TC. However, sensitivity guidance providers using the SV method (such as JMA, ECMWF, NRL and Yonsei University) had different configurations, especially the norm, the moist processes and the resolution of the TL/AD model, causing the features of the guidance to vary in some cases. The SV dependence for the recurving Sinlaku with the resolution of the TL/AD model was investigated by Komori and Kadowaki (2010).

The present study therefore includes some extra experiments for the case of the recurving Sinlaku to investigate the impact of the norm and moist processes in the TL/AD model.

Figure 6 shows the results of these extra experiments, indicating the sensitivity guidance computed from the two-day forecast field valid at 00 UTC on 11 September 2008. In the T-PARC project, a moist SV with a moist TE norm was applied (Figures 6 (a) and (b)), which is the same configuration as the operational TEPS. In the "dry" norm, the water vapor component was set to zero. Figures 6 (c) and (d) illustrate that without a water vapor effect in the norm, the sensitive area, influenced by the confluence to the east of Sinlaku and the upstream mid-latitude trough, becomes relatively weak compared with the south side of Sinlaku. These trends are outstanding in the dry SV, having no convection and large-scale cloud scheme, with a dry TE norm (Figures 6 (e) and (f)). Hence, further experiments were performed to divide the effects of convection and the large-scale cloud scheme in the TL/AD model (Figure 7). The results show that the convection scheme in the model played a more important role than the large-scale cloud scheme in the feature of vertically integrated TE in the T-PARC project, supporting the mechanism by which the moisture convergence and associated convection caused heat release in the eastern confluence location of Sinlaku (Figure 4). Furthermore, analysis of the TIGGE ensemble data set indicates a large spread in the strength of the subtropical high pressure system (not shown), which also supports the high sensitivity in the confluence area between Sinlaku and the subtropical high pressure system.

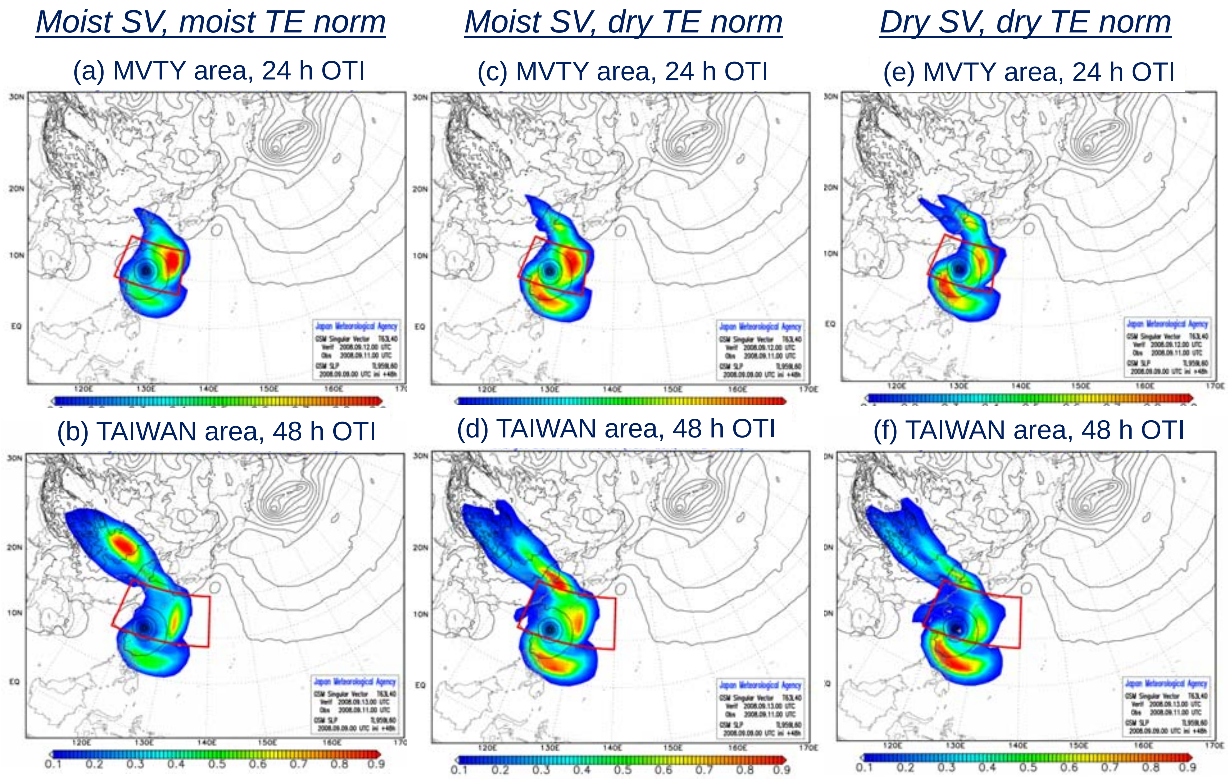

Figure 6 The vertically integrated TE of the leading SV computed from the two day forecast field, valid at 00 UTC on 11 September 2008 with different configurations of moist processes in the TL/AD model and norm: (a), (b): moist SV with a moist TE norm; (c), (d): moist SV with a dry TE norm; (e), (f): dry SV with a dry TE norm. The target area and OTI were specified as: (a), (c), (e): MVTY area with a 24-hour OTI; and (b), (d), (f): TAIWAN area with a 48-hour OTI.

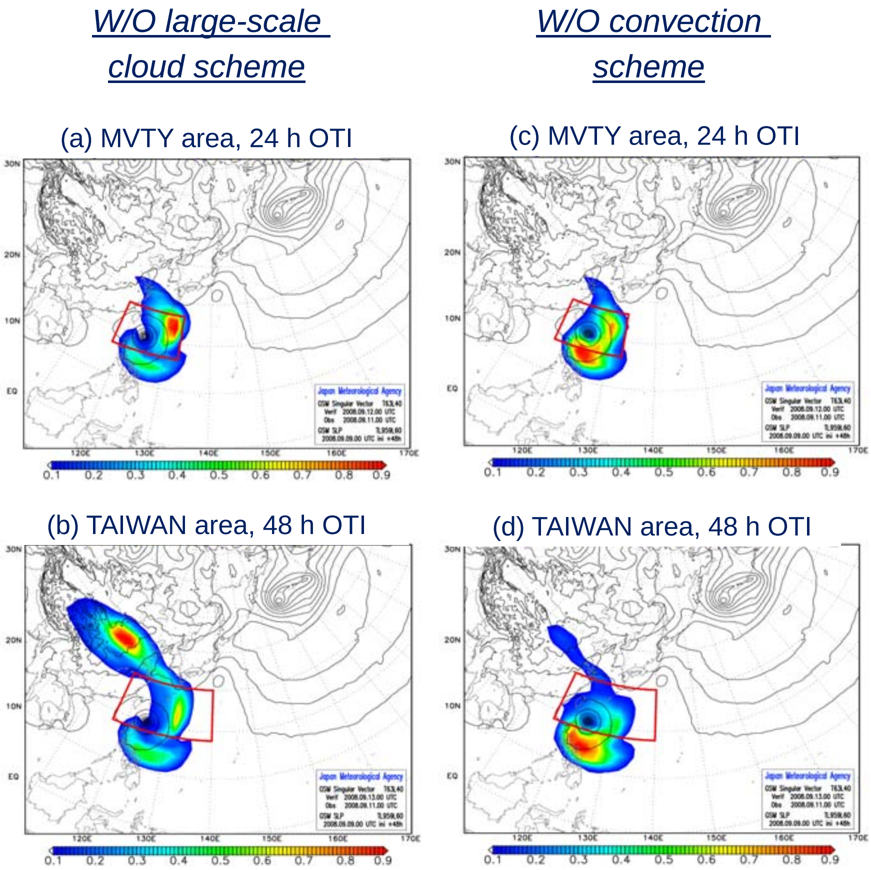

Figure 7 As per Figures 6 (a) and (b) but for situations (a)/(b) without a large scale cloud scheme, and (c)/(d) without a deep convection scheme in the TL/AD model.

4. Summary

The sensitivity analysis system for the T-PARC project was developed by JMA using the SV method to provide guidance for special observations, thereby contributing to improvement of the analysis/forecast field by data assimilation. In addition to three fixed target areas with a 48-hour OTI, which were common among the SV providers, JMA conducted further sensitivity analysis for an adaptive target area with a 24-hour OTI in the vicinity of a TC. The location of the adaptive target area was automatically decided by the operational GSM. We applied a moist SV with a moist TE norm, and both a deep convection and a large-scale cloud scheme were implemented in the TL/AD model. This system worked well, and the related daily products were compared on the website during the T-PARC period.

The case study of daily sensitivity guidance for typhoon Sinlaku highlighted a number of features. In the recurvature stage, due to the longer OTI and the higher latitude target areas, SVs with fixed target areas tended to capture the remote influence of the mid-latitude trough compared to the SV for the adaptive target area. The adaptive target area with a 24-hour OTI therefore seems preferable for the detection of sensitive areas in the TC's vicinity. The nonlinear evolved perturbation from the initial SV shows a structure similar to that of the linearly evolved final SV, indicating the legitimacy of the linearity assumption in calculating the SV. The results also suggest that moisture convergence and deep convection caused heat release and associated vorticity to the east of Sinlaku at the confluence between the typhoon itself and the subtropical high-pressure system.

On the other hand, some extra experiments were conducted using JMA's sensitivity analysis system to investigate the influence of different configurations among SV providers in the T-PARC project. Without a water vapor effect in the norm, the sensitive areas in the eastern confluence location and the upstream mid-latitude trough become relatively weak. These trends stood out in the dry SV, having no convection and a large-scale cloud scheme, with a dry TE norm. Further experiments revealed that the convection scheme in the TL/AD model played an important role in forming the characteristics of the SV, which followed the mechanism of moisture convergence and associated convection in the eastern confluence location.

Future experiments should focus on building a comprehensive understanding of JMA's SV characteristics through statistical investigation, which will contribute to the development of a new JMA operational global analysis system as well as TEPS and WEPS.

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