Inter-comparison of Targeted Observation Guidance for Tropical Cyclones in the North western Pacific

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Abstract

This study compares six different guidance products for targeted observations over the Northwest Pacific for 84 cases of two-day forecasts in 2006, and highlights the unique dynamical features affecting the tropical cyclone (TC) tracks in this basin. The six products include 3 types of guidance based on total-energy singular vectors (TESVs), the ensemble transform Kalman filter (ETKF), the deep-layer mean (DLM) wind variance, and the adjoint-derived sensitivity steering vector (ADSSV). The similarities among the six products are evaluated using objective statistical techniques to show the diversity of the sensitivity regions in large, synoptic-scale domains, and smaller domains local to the TC.

It is shown that the three TESVs are relatively similar to one another in both the large and the small domains while the comparisons of the DLM wind variance to other methods show rather low similarities. The ETKF and the ADSSV usually show high similarity because their optimal sensitivity usually lies close to the TC. The ADSSV, relative to the ETKF, reveals more similar sensitivity patterns to those associated with TESVs.

Three special cases are also selected to highlight the similarities and differences between the six guidance products and to interpret the dynamical systems affecting the TC motion in the western North Pacific. The adjoint methods are found to be more capable of capturing the signal of the dynamic system that may affect the TC movement or evolution than the ensemble methods.

Key words：Targeted observation, singular vector, ETKF, ADSSV, deep-layer mean wind variance

1. Introduction

The Tropical cyclone (TC) is one of the most threatening natural phenomena that cause great human and economic losses. The lack of observations over the ocean regions where TCs spend most of their lifetime seriously degrades the accuracy of forecasts (Wu 2006). Therefore, it is worthwhile to assimilate the special data obtained from both aircraft and satellites in areas that may have the maximum influence on numerical model predictions of TCs. To achieve this, several mathematical targeted observing strategies have been developed (Majumdar et al. 2006; Wu et al. 2007a). The primary consideration in devising such strategies is to identify the sensitive areas in which the assimilation of targeted observations is expected to have greatest influence in improving the numerical model forecast, by minimizing the analysis error.

The synoptic surveillance missions to improve TC track forecasts have been conducted by NOAA in the Atlantic basin since 1997 (Aberson 2002, 2003). In the north-west Pacific basin, since 2003, Dropwindsonde Observation for Typhoon Surveillance near the Taiwan Region (DOTSTAR) has been conducted under the support of the National Science Council (NSC) in Taiwan (Wu et al. 2005). In the Atlantic Ocean basin, the TC track forecasts have been improved by 15-20% within the five-day forecast period for those missions designed by the targeted strategies (Aberson 2008). In the western Pacific Ocean basin, an average of 20% improvement for the 12-72h track forecasts over the NCEP-GFS, NOGAPS, Japan Meteorological Agency - Global Spectral Model (JMA-GSM), their ensembles, and the WRF model has been demonstrated (Wu et al. 2007b; Chou and Wu 2008).

In Majumdar et al. (2006), five targeted observing guidance products based on 3 different techniques for 2-day forecasts of 78 tropical cyclone cases during the

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2004 Atlantic hurricane season were compared. The results showed that the large-scale characteristics of the ECMWF and NOGAPS TESV guidance products are relatively similar on synoptic scales target region, but are less similar in the local environment of the TC. For major hurricanes, all techniques usually indicate sensitive regions close to the storms. For weaker tropical cyclones, the TESVs only have 30% (20%) similar regions to that from the ETKF (DLM wind variance). The ETKF based on the ECMWF ensemble is more similar to that based on the NCEP ensemble and the DLM wind variance for major hurricanes than for weaker tropical cyclones.

Using the same database as Majumdar et al. (2006), Reynolds et al. (2007) identified and interpreted systematic structural differences between these techniques. Their results showed that when the sensitive areas are close to the storm, the TESV presents a maximum in an annulus around the storm, but the ETKF shows a maximum at the storm location itself. When the sensitive areas are remote from the storm, the TESV maxima generally occur northwest of the storm, whereas the ETKF maxima are more scattered relative to the storm location and often occur over the Northern North Atlantic.

As a follow-up study, this study compares six different targeted guidance products based on 84 cases of two-day forecasts of the Northwest Pacific TCs in 2006, and highlights the unique dynamical features that affect the TC tracks in this basin. The six types of guidance are three TESVs from different global models, the ETKF based on the multi-model ensemble members, the DLM wind variance, and the ADSSV. In contrast to the Atlantic region, the Northwest Pacific region has more dynamical systems affecting the TC motion (Wu 2006), such as the mid-latitude trough, the subtropical jet, the southwesterly monsoon and binary interactions. Further analysis is thus conducted to identify the similarities and differences between all these different targeted methods and to interpret their dynamic meanings.

2. Targeted observing techniques

Based on different models and techniques, the six targeted observing products are summarized in Table 1. The three TESV products, called 'ECSV', 'NGPSV' and 'JMASV' respectively in this study, utilize the first three SVs from three global models, ECMWF, NOGAPS and JMA/Ensemble Prediction System (EPS). The 'ETKF' method uses multi-model ensemble members. For the TESV and ETKF methods, the model initial time t_i is 48 h prior to the observing (analysis) time t_a. The error propagation from t_a to the verifying time t_v is considered. The period of t_a-t_i is selected for planning synoptic surveillance missions, since the decision for aircraft deployment is required at least 36 h prior to t_a in order to meet the air traffic control requirement. For the ADSSV method, the initial condition of the MM5 is based on the 48-h forecast of the NCEP/GFS. The trajectory of t_a to t_v is then obtained from the MM5 forward integration. The DLM wind variance, also called 'NCVAR' in this study, is calculated based on the 10 NECP/GEFS ensemble members before May 31st, and after May 31st with 14 ensemble members. This is a method in which only the period between t_i and t_a is considered. The resolution of the trajectory and output of the six methods are also shown in Table 1.

3. Quantitative Comparison

From the 2006 season, 84 cases in which the Joint Typhoon Warning Center (JTWC) issued forecasts at 0000 UTC that existed at 48 (t_a) and 96 (t_v) hours were selected for this study. These cases include studies of 19 TCs (Fig. 1). Multiple cases from the same storm are separated by 24 h on successive days. To be consistent with the work in Majumdar et al. (2006), the verification area is chosen to be centered at the 96-h (t_v) TC position forecasted by the JTWC. Figure 2 is a representative example to indicate the patterns of the six sets of guidance for a selected case [i.e., case # 10 (WP04, Typhoon Ewiniar)]. In this section, the statistical technique introduced in Majumdar et al. (2006) are used to show the quantitative diversity of the six methods. The statistics here are also compared with the results of Majumdar et al. (2006) for the Atlantic TCs.

For each of the 84 cases, there are 15 pairs of maps for the 6 targeted methods to be compared. In this test, the grid point locations corresponding to the number of X highest values are first stored for each map and then the number C of the common grid points between each of the 15 pairs are found in each case. A Modified Equitable Threat Score (METS, Majumdar et al. 2002),

$$\mathrm{METS} = \frac{C - E(C)}{2X - C - E(C)} \qquad (1)$$

is used to show the commonality between any two maps. In (1), E(C) is the expected number of common grid points, which is estimated between all 84 cases. More details of E(C) are introduced in Appendix B of Majumdar et al. (2002). The values of METS for each pair of maps are calculated for each case. When the METS is equal to 1, the value of C is the same as that of X. That means the two maps contain identical targets. A METS greater than (less than) 0 indicates that a larger (smaller) number of common grid points occur than by chance. In the following discussion, the percentage of cases out of 84 in which METS > 0 (Majumdar et al. 2006) is adopted to show the similarity of the targeted methods.

To provide a thorough comparison of all the guidance products, following Majumdar et al. (2006), we conduct the comparison based on two domains of different sizes. One is the larger domain (80 - 180°E, -10 - 65°N), the other is the smaller domain (3000 by 3000 km centered at each model storm center). The larger domains tend to highlight the large-scale sensitivity environment (away from the storm), which could be related to targeting of extra satellite observations (such as rapid-scan winds). On the other hand, the smaller domains focus more on the local sensitivity features around the storm region, which is likely more relevant for synoptic surveillance (such as in DOTSTAR).

a. Fixed large domain (80-180°E, -10-65°N)

A domain containing the western North Pacific basin and Eastern Asia continental region including the Indian Ocean is chosen for the comparison based on METS. In total there are 3149 grid points in this 80-180°E, -10-65°N area with 1.5° × 1.5° resolution. Figure 2 shows the targeted guidance for case # 10, Typhoon Ewiniar at t_a = 0000 UTC 2 July, 2006. The 63 leading grid points, which is 2% (this threshold value can be modified, as discussed later) of the total number of grid points, correspond to the sensitive regions (X=63). The value of E(C) is 2.48 under the 2% threshold mentioned above.

Table 3 shows the percentages among the 84 cases of those with METS > 0 for X = 63. ECSV and NGPSV are highly similar (METS > 0) in 90% of the 84 cases . The three TESVs are quite similar to one another, consistent with the results in Majumdar et al. (2006) that the targeted methodology usually gives similar guidance irrespective of the model. The percentage of METS > 0 for the comparison of ETKF and the three TESVs are around 50-60%. However, the percentage increases to around 89% when ETKF is compared with ADSSV. For ADSSV, the similarity reaches 70% when it is compared to NGPSV and around 50% when compared to the other two TESVs. The similarities between NCVAR and other methods, except the 43% for ETKF, are generally lower than 10%, indicating that NCVAR persistently shows rather different sensitivity locations as compared to other targeted methods. On the other hand, NCVAR and ETKF usually show sensitivities around the mid-latitude jet and extra-tropical cyclones which are far from the TCs. Thus, the similarity is higher for this pair than that between NCVAR and other methods.

The similarity of the targeted methods under different TC intensities (table not shown) shows that there is no general difference between the three intensity categories among the 15 pairs. This finding is somewhat different from the study of the Atlantic TCs (Majumdar et al. 2006), which pointed out that there is more agreement between each comparison pairs for major hurricanes than for TCs of weaker intensities.

b. Small domain (3000 by 3000 km) centered at each model storm center

The common targeted locations are also examined in relatively smaller domains in which synoptic surveillance would typically be conducted. A 21 by 21 grid of 150-km resolution is created for every case in a storm-relative coordinate centered at each model storm center. The values obtained from the methods are interpolated linearly onto the grids. Figure 3 shows the targeted guidance in the small domain for case # 10 with X = 31 leading grid points, which is 7% of total 441 grid points. The E(C) is 5.30 for this 7% threshold.

Table 6 shows the percentage of cases with METS >0 for X=31 among the 84 cases in the small domain. As expected, the three TESV methods are very similar to one another. The percentages of ETKF as compared to the three TESV methods are around 45%. The similarity between NGPSV and ADSSV is 39%, the same as that between JMASV and ADSSV. The similarity is only 30% in the comparison between ECSV and ADSSV. Because some of the NCVAR leading grid points are shown to be closer to the storm for the small-domain comparison (i.e., the synoptic surveillance scale), larger similarities for NCVAR versus the TESV methods and ADSSV are found for the small domain than for the large domain. The similarity between NCVAR and ETKF reaches 69% which is the highest percentage among all 15 pairs in the small-domain comparison. The reason of this result is that the maximum sensitivities are usually around the TCs in both methods on the synoptic surveillance scale.

4. Discussions of some representative special cases

In contrast to the Atlantic region, the western North Pacific region contains more dynamical systems affecting the TC motion, such as the mid-latitude trough, the subtropical jet, the southwesterly monsoon and binary interactions. In this study, we select three special cases to highlight not only the similarities and differences between different targeted methods but also to interpret the dynamic meanings. The first case is affected by the subtropical high (Fig. 4). In this case, the three TESVs and ADSSV show that major sensitivities are located to the east of the TC center by about 500 km. The locations with the highest sensitivity collocate well with the border between the TC and the subtropical high. As shown in Wu et al. (2007a), such sensitivity patterns indicate the steering effect of the subtropical high on storm movement. The second case is affected by the mid-latitude trough (Fig. 5). In this case, all six methods consistently pick up the sensitivity signals associated with the mid-latitude trough while the four adjoint methods (TESVs and ADSSV) produce high sensitivities at the center and the upstream region of the trough and the ensemble methods show sensitivity in the downstream region of the trough. The strong impact of the mid-latitude trough to the movement and evolution of TC is well captured 48 h before the verification time. The third case is associated with the subtropical jet in the late typhoon season of 2006 (Fig.6). The sensitivities of TESVs appear in a belt zone along the 20-30°N, well collocated with the subtropical jet. The ADSSV shows a relatively short belt pattern of sensitivity at the southern edge of the jet. The ETKF also shows a belt pattern located at 30-45°N but is more likely related to a mid-latitude cyclone at lower levels.

5. Summary and future prospects

To highlight the unique features that affect the tropical cyclones over the western North Pacific, in this study, three TESVs from different global models, the ETKF based on multi-model ensemble members, the NCEP/GEPS DLM wind variance, and the MM5 ADSSV are compared against each other based on 84 cases of Northwest Pacific TCs in 2006.

The similarities among the six guidance products are evaluated by objective statistical technique as introduced in Majumdar et al. (2006) to show the diversity of the sensitivity regions in these products. The results show that the three TESVs are quite similar to one another in both the large and the small domains, especially regarding the comparison between ECSV and NGPSV. This is consistent with the findings in Majumdar et al. (2006) that the targeted methodology usually gives similar guidance irrespective of the model. Except for the comparison between NCVAR and ETKF, both of the statistical results show rather low similarities when NCVAR is compared to other targeted methods, especially on the synoptic scale. That is because the maximum sensitivity of NCVAR is usually located near the mid-latitude jet or extra-tropical storm whose high wind leads to the large DLM wind variance which is also captured by ETKF but is sometimes irrelevant to TC evolution. On the other hand, when focusing on the surveillance scale, the maximum sensitivity of NCVAR around the TC results in higher similarity when compared to the three TESVs and ADSSV in the small domain. In both the large and the small domains, ETKF and ADSSV show high similarity because their sensitivity results are usually close to the TC and in the TC itself. Meanwhile, higher similarities are found between ADSSV and the three TESVs methods as compared to those between ETKF and the TESVs especially in the large domain. This is primarily because ETKF tends to have high sensitivity uniformly around the storm center while both ADSSV and TESVs can capture similar sensitivity patterns in particular areas around and outside of the storm center.

From the analysis of three cases, it is noted that the ajdoint-based methods are more likely to capture the signals associated with the dynamic systems that may affect TC movement/evolution than the ensemble methods. Furthermore, an ensemble method including dynamic information and data assimilation information (i.e., ETKF) can provide more valuable information than a method that only considers the ensemble variance (i.e. NCVAR).

Further research includes the interpretation of the dynamics of these targeting methods on a case-by-case basis (e.g., Wu et al. 2008). It is believed that results from this work would not only provide better insights into techniques, but also offer useful information to assist in future targeted observations, especially for the DOTSTAR, TH08 (Typhoon Hunting 2008) and TCS-08 (Tropical Cyclone Structure - 2008) associated with the T-PARC (THORPEX - Pacific Asian Regional Campaign) program in 2008, as well as the targeting of other data from satellites, radars, unmanned aircrafts, and balloons.

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TABLE 1. Summary of six targeted methods.

Method	ECSV	NGPSV	JMASV	ETKF	ADSSV	NCVAR
Model	ECMWF	NOGAPS	JMA/EPS	ECMWF NCEP/GEFS CMC	MM5	NCEP/GEFS
No. ensemble/SVs	3SVs	3SVs	3SVs	ECMWF: 51 NCEP/GEFS: 60 CMC: 34 Total 154 members	-	14 ensembles (10 ensembles for first 8 cases)
Resolution of trajectory	T63L40	T239L30	T319L40	ECMWF: T399L62 NCEP/GEFS: T126L28 CMC: 1.2°	60 km	T126L28
Resolution of output	T63L40	T79L30	T63L40	2°	60 km	1°
ti –ta	48 h	48 h	48 h	66-48 h	-	48 h
ta -tv	48 h	48 h	48 h	48 h	48 h	-

TABLE 2. Percentage of the 84 cases in which METS > 0 for X = 63 in the large domain.

Methods	NGPSV	JMASV	ETKF	ADSSV	NCVAR
ECSV	90.48	84.52	55.95	53.57	4.76
NGPSV		79.76	58.33	70.24	3.57
JMASV			53.57	51.19	5.95
ETKF				89.29	42.86
ADSSV					7.14

TABLE 3. Same as in Table 2, but for X = 31 in the small domain.

Methods	NGPSV	JMASV	ETKF	ADSSV	NCVAR
ECSV	66.67	61.90	44.05	30.95	29.76
NGPSV		60.71	44.05	39.29	26.19
JMASV			46.43	39.29	25.00
ETKF				51.19	69.05
ADSSV					21.43

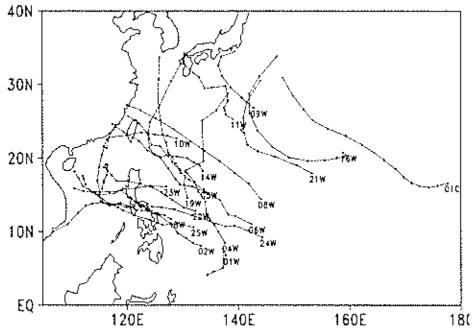

Figure 1. The JTWC best tracks of the 19 TCs. Each symbol is plotted at 12-h intervals. Except for '01C' (Typhoon Ioke) from the Central Pacific, all other TCs are numbered in Northwest Pacific orders. For example, '02W' is Typhoon Chanchu whose annual cyclone number is 02 in the Western North Pacific basin in 2006.

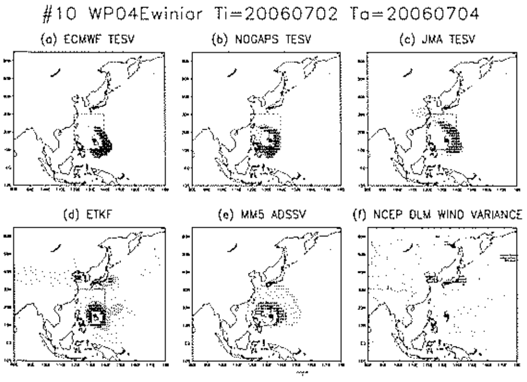

Figure 2. The large-domain common targeted location comparison of (a) ECSV, (b) NGPSV, (c) JMASV, (d) ETKF, (e) ADSSV and (f) NCVAR for case #10, Typhoon Ewiniar, at ta=0000 UTC 2 July 2006 and tv=0000 UTC 4 July 2006. Except for (f), the verifying areas of the other 5 methods are indicated by the red squares. The JTWC best track and each model forecast of case #10 valid at ta are denoted by the solid and empty typhoon symbols, respectively. The brown dots represent X=63 grid points with highest value.

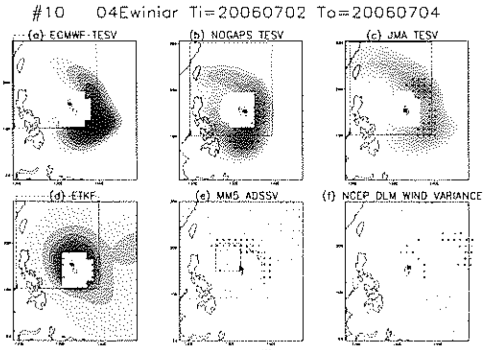

Figure 3. Same as Fig. 2, but for the small-domain common targeted location comparison and the brown dots represent X=31 grid points with highest value.

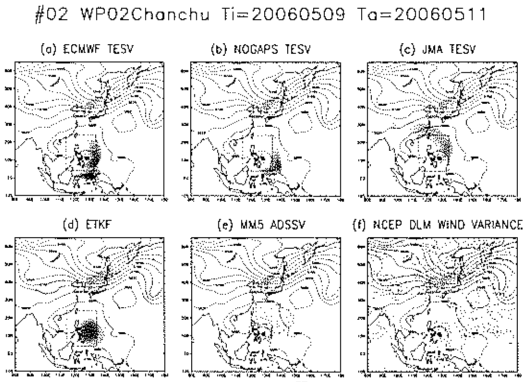

Figure 4. The sensitivities of (a) ECSV, (b) NGPSV, (c) JMASV, (d) ETKF, (e) ADSSV and (f) NCVAR superposed with the geopotential height field (contour interval of 60 gpm) from NCEP FNL at 500 hPa of case # 2, with 0000UTC 11 May as the observing time (ta). Except for (f), the verifying areas of the other 5 methods are shown as the red squares in (a)-(e). The JTWC best track at ta are denoted by the solid typhoon symbols.

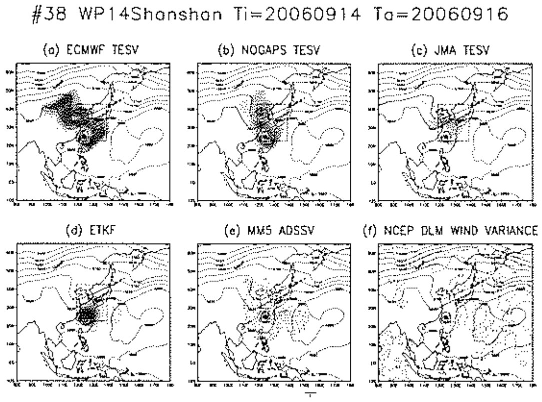

Figure 5. Same as Fig. 4, but for case #33 with 0000UTC 14 September as the observing time.

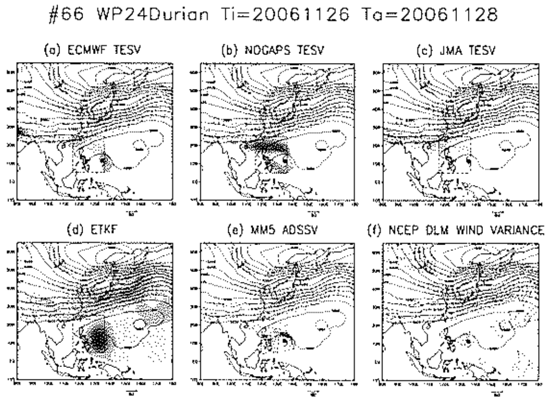

Figure 12. Same as Fig. 10, but for the sensitivities superposed with the geopotential height field (contour interval of 60 gpm) and wind field (vector; the scale is indicated by the arrow to the lower right) at 500 hPa of case #66 with 0000UTC 26 November as the observing time.