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Comments on “Interaction of Typhoon Shanshan (2006) with the Midlatitude Trough from both Adjoint-Derived Sensitivity Steering Vector and Potential Vorticity Perspectives”

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1. Introduction

Wu et al. (2009; hereafter W09) use the adjoint-derived sensitivity steering vector (ADSSV; Wu et al. 2007) to investigate the influence of several synoptic features on the steering of Typhoon Shanshan (2006). Response functions are defined describing the zonal and meridional steering of a tropical cyclone (TC), and sensitivities of these steering functions with respect to vorticity perturbations at model initialization are used to define the most sensitive areas of the model’s initial conditions to the steering of the cyclone 36 hours into the forecast. The potential vorticity (PV) of synoptic features in regions of high sensitivity is inverted to recover a balanced flow to verify the importance of these features on the steering of Shanshan, and this analysis is compared to the spatial distribution of adjoint sensitivities for TC steering. The ADSSV has been implemented in the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) field campaign (Wu et al. 2005). There are several outstanding problems with this methodology, as it applies to objectively defining regions for targeted observations, due to the lack of any dynamical interpretation of the adjoint-derived sensitivity gradients, and the lack of tests for the appropriateness of the response functions used to describe TC steering.

2. Methodology

W09 use the adjoint of Version 1 of the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Zou et al. 1997), modified by Kleist and Morgan (2005) to perform a 36-hour forecast of Typhoon Shanshan (2006), that defines the basic-state about which the adjoint model is linearized. The adjoint
sensitivities are integrated using dry dynamics. Two response functions are used to define the 36-hr zonal and meridional steering of the TC respectively:

\[
R_1 = \int_{A}^{0.875} \int_{0.225}^{0.875} u \, dxdy \, d\sigma \\
R_2 = \int_{A}^{0.875} \int_{0.225}^{0.875} v \, dxdy \, d\sigma
\]

(1)  

(2)

Zonal (meridional) steering is defined as the averaged zonal (meridional) flow in a volume bounded by an area \( A \) defined as a 600 km x 600 km box centered on the TC, and bounded between sigma levels that correspond approximately to the 850 hPa and 250 hPa pressure levels. In this way, the response functions are defined to represent the environmental zonal and meridional flow (Chan and Gray 1982) as a tropospheric average wind in the vicinity of the cyclone. The gradients of these response functions are used by the adjoint model to compute sensitivity of zonal and meridional steering with respect to vorticity. These sensitivities are combined into a vector:

\[
ADSSV = \left( \frac{\partial R_1}{\partial \zeta}, \frac{\partial R_2}{\partial \zeta} \right)
\]

(3)

that describes the vector-change in the steering of the TC at 36 hours into the forecast given a vorticity perturbation to the initial conditions.

3. Interpretation

The main criticism of this methodology is in the definitions of \( R_1 \) and \( R_2 \). These response functions, which have been shown to accurately represent the steering of TCs by the environmental steering flow, depend partially on the assumption that the TC is at the center of
the region in which the averaging of the wind field is being performed, as well as the size of that region. The horizontal averaging removes the symmetric circulation about the TC vortex, and the remaining flow is characterized as the “environmental steering flow” which advects the TC.

However, the sensitivity gradients $\frac{\partial R_1}{\partial \zeta}$ and $\frac{\partial R_2}{\partial \zeta}$ describe only how the averaged zonal or meridional wind within the response function domain will change as a result of perturbations to the vorticity in the initial conditions. The methodology used by W09 does not take into account that sensitivities to $R_1$ and $R_2$ may result from small perturbations to the final-time location of the TC, which would not constitute an actual change to the steering of the TC at model verification time. One can imagine that a northward (westward) perturbation to the final-time location of the TC would contribute positively to $R_1$ ($R_2$) by allowing the TC’s own symmetric circulation to contribute positively to the flow inside of the response function domain (Fig. 1).

While W09 claim to provide a dynamical interpretation of these sensitivities through a PV diagnosis of the relevant synoptic features steering Shanshan, no results of tests to substantiate these interpretations are provided. For example, while W09 were able to show that strong sensitivities were coincident with a midlatitude trough, and that the balanced flow associated with the PV of the trough was relevant to the steering of Typhoon Shanshan, no test was performed to determine how perturbations to the initial condition vorticity within the trough would impact the steering of Shanshan. The coincidence of sensitivities with a synoptic feature is insufficient to show the importance of that feature (Langland et al., 1996).

Tests performed using the Navy Operational Global Atmospheric Prediction System (NOGAPS) global spectral model and its adjoint (Hogan et al. 1993, Rosmond et al. 2002) have uncovered a complex dynamical interpretation of steering sensitivities, which is influenced in part by the fact that small perturbations of the final-time location of the TC can have a large
impact on the response functions $R_1$ and $R_2$. A 36-hour simulation of Typhoon Meari (2004) is performed with the NOGAPS model at T159 resolution. The model is initialized with $1^\circ \times 1^\circ$ analyses from Fleet Numerical Meteorology and Oceanography Center at 0000 UTC 24 September 2004. The response function is defined as the average zonal wind in a $15^\circ \times 15^\circ$ box centered on the TC. The vertical extent of the response function box is bounded between the 0.992 sigma and 0.295 sigma surfaces, approximately corresponding to the 990 hPa and 300 hPa pressure surfaces. The adjoint model is integrated backward 36 hours to calculate sensitivities of $R_1$ with respect to vorticity at model initialization.

The model initial conditions are then perturbed at 500 hPa by scaling the adjoint-derived forecast sensitivity $\frac{\partial R_1}{\partial \zeta}$ (Fig. 2a) so as to make an acceptably scaled perturbation vorticity field, such that perturbations to initial vorticity are no greater than $2.5 \times 10^{-5} \text{s}^{-1}$ (Fig. 2b). The forward model is then run 36 hours again to produce a “perturbed” simulation, compared to the control (unperturbed) simulation used to define the basic-state of the adjoint model. The difference between these two non-linear runs (perturbed – control) can easily be calculated to evaluate the growth and behavior of perturbations in the model. At model verification, perturbation heights and perturbation zonal wind at 500 hPa in the region where the response function is defined clearly show that the perturbations added to the initial conditions resulted in a northward transport of the cyclone (Fig. 3a). As described above, such a perturbation to the location of the TC within the response function box would allow the TC’s own symmetric circulation to contribute positively to $R_1$, the average zonal wind in a box centered at the cyclone’s location in the unperturbed forecast. One can clearly see that the vast majority of perturbation zonal flow is due to a tripole of negative and positive perturbation zonal flow caused by the northward translation of the TC (Fig. 3b).
Any contribution to the averaged perturbation zonal flow in the response function box by this feature has nothing to do with the zonal steering of the TC at this time. The contribution of this feature to the averaged perturbation zonal flow is partially a function of the size of the response function box. A box that is too small to encapsulate the entire tripole will be strongly affected by a small translation of the TC. A larger box can be employed to reduce this effect by allowing negative and positive portions of the tripole to cancel out in the averaging, but it isn’t clear that the effect can be completely removed in this way. Since the goal of this methodology is to calculate sensitivities to the environmental flow in the vicinity of the TC, the response function box must be limited in size to remain meaningful, creating a difficult trade-off. In addition, if the TC in the nonlinear forecast with perturbed initial conditions is of a different intensity than in the control run, or if asymmetries in the TC develop in the perturbed run that are not present in the control run, there will be less symmetry between the negative and positive portions of the tripole, making this problem more pronounced.

The faulty assumption that the ADSSV directly relates to sensitivities to TC steering is carried into the PV diagnosis of synoptic features relevant to the steering of Shanshan in W09. While care is taken to show that sensitivities to TC steering are co-located with a midlatitude trough, and that the PV associated with the trough plays an important role in the steering of Shanshan, it is assumed that perturbations to the initial conditions in the location of the trough will affect the steering of Shanshan in the way described by the ADSSV. It has just been shown that this is not necessarily the case, as perturbations to the final-time location of the TC can have a large influence on $R_1$ and $R_2$ which has no bearing on the steering of the TC.

4. Test for Validity of Results
A simple test was performed to determine the validity of the adjoint-derived sensitivities and the assumption of linearity for this case. One can calculate the change in the response function \((R_1)\) when the model initial conditions have been perturbed by calculating the difference in \(R_1\) between the perturbed and control nonlinear runs.

\[
\Delta R_1 = R_1|_{\text{perturbed}} - R_1|_{\text{control}} \tag{4}
\]

Assuming that perturbations added to the initial conditions will evolve linearly, this value can be estimated by evaluating the inner product of the sensitivity of \(R_1\) with respect to model initial conditions \((\frac{\partial R_1}{\partial x_0})\) with the perturbation to model input \((x_0')\):

\[
\Delta R_1 \approx \delta R_1 = \left\langle \frac{\partial R_1}{\partial x_0}, x_0' \right\rangle \tag{5}
\]

Provided that these two calculations are very similar, one can assume that the perturbations added to the model initial conditions evolved linearly through time, and the adjoint sensitivities correctly describe the sensitivity of the response function to those perturbations. For this case, \(\Delta R_1 = 2.34 \text{ ms}^{-1}\), and the estimate of \(\Delta R_1\), calculated using adjoint sensitivities and initial condition perturbations, yielded \(\delta R_1 = 1.94 \text{ ms}^{-1}\), indicating that the linearized dynamics of the adjoint model could account for 82.8% of the total change in the response function. An analysis of the evolution of perturbations in the forecast model shows that a considerable fraction of perturbation zonal flow in the response function box is directly related to a small northward translation of the TC by 36 hours, and not to any actual change in the steering of the TC at that time.

5. Conclusions
An adjoint model is a powerful tool for objectively defining targeting regions for adaptive observations. The ability to calculate regions of dynamical sensitivity of specific aspects of a model forecast to the model initial conditions can provide valuable a priori information regarding the potential impact of improved initial conditions on the steering of a modeled TC. Such information is invaluable for defining optimal regions to take targeted observations when improvement of a specific aspect of the model forecast (as measured by the response function) is the primary goal.

It has been shown that the response functions used by W09 to describe the zonal and meridional steering of a TC must contend with both steering effects and non-steering effects related to small perturbations of the development and final-time location of the TC. Perturbing the model based on these sensitivities leads to effects that will change the response function in ways that have nothing to do with changes to the steering of the TC. The influence of non-steering effects on the sensitivity gradients is dependent on the size of the response function box, as well as perturbations to the intensity, asymmetry, and final-time location of the TC due to perturbations added to the model initial conditions. Furthermore, the lack of dynamical interpretation and testing of these sensitivity gradients has allowed these problems to escape notice. It is likely that similar problems exist for a variety of response functions used to describe various aspects of model forecasts, and in the future these response functions will have to be tested in a similar manner for their validity.

A solution to this problem will take the form of redefining the response functions used to describe the zonal and meridional steering of the TC such that the effect of small perturbations of the final-time location of the TC within the response function box is removed. Vigorous testing
of these response functions must then be performed to demonstrate that initial perturbations in sensitive regions evolve into perturbations that are directly related to the steering of the TC.

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References


Figure 1. Conceptual diagram illustrating the effect of small perturbations to the final-time location of a TC on response functions $R_1$ and $R_2$. (a) A northward translation of the TC allows the symmetric circulation of the TC vortex to positively contribute to $R_1$. (b) A westward translation of the TC allows the symmetric circulation of the TC vortex to positively contribute to $R_2$.
Figure 2. (a) Sensitivity of $R_1$ with respect to vorticity (every $3 \times 10^5$ m, dashed contours negative) and (b) perturbation vorticity (every $5 \times 10^{-6}$ s$^{-1}$, dashed contours negative) and perturbation winds (ms$^{-1}$) at 500 hPa at model initialization for simulation of Typhoon Meari (2004).
Figure 3. Perturbation winds at 500 hPa with (a) perturbation heights (every 15 m, dashed contours negative) and (b) perturbation zonal flow (every 4 ms\(^{-1}\), dashed contours negative) at model verification for 36 hour simulations of Typhoon Meari (2004) initialized at 0000 UTC 24 September 2004. Perturbation values are calculated as the difference between a control run and a run with perturbed initial conditions.
Figure Captions

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