Targeted observations in DOTSTAR

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Abstract

DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region) is an international research program conducted by meteorologists in Taiwan partnered with scientists at the Hurricane Research Division (HRD) and the National Centers for Environmental Prediction (NCEP) of the National Oceanic and Atmospheric Administration (NOAA).

In addition to various sensitivity products already adopted in DOTSTAR, a new way to identify the sensitive area for the targeted observation of tropical cyclones based on the MM5 adjoint model has been proposed. By appropriately defining the response functions to represent the steering flow at the verifying time, a simple vector, Adjoint-Derived Sensitivity Steering Vector (ADSSV) has been designed to clearly demonstrate the sensitivity locations at the observing time. Typhoons Meari and Mindulle of 2004 have been selected to demonstrate the use of ADSSV. In general, unique sensitive areas 36 h after the observing time are obtained.

The impact of the vortex initialization and the linear and dry assumptions on the ADSSV has also been studied. In order to use the ADSSV in the field program (such as DOTSTAR), the procedure of the model calculation has been designed to meet the realtime need. It is shown that the realtime use of ADSSV is feasible, and the results are fairly consistent with our previous findings.

The ADSSV is implemented and examined in the field project, DOTSTAR starting in 2005, as well as in the surveillance mission of Atlantic hurricanes conducted by HRD. Further analysis of the results of ADSSV and the comparison of different targeted techniques are still ongoing.

Introduction

Since 2003, a field program has been conducted under the name of Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) (Wu et al. 2005). For DOTSTAR, targeted observations constitute one of the most crucial missions. The basis for formulating the observation strategy is to identify the sensitive areas, which would have critical impact on the numerical forecast results and sometimes even the forecast accuracy. Up to the present, three sensitivity products have been used to determine the observation strategy for DOTSTAR. These products are derived from three distinct techniques. First, the Deep-Layer Mean (DLM) winds variance. It is one of the deep-layer steering flows based on the NCEP (National Centers for Environmental Predictions) EFS (Global Ensemble Forecasting System) (Aberson et al. 2003), where areas with the largest forecast deep-layer-mean wind bred vectors represent the sensitive region at the observing time. Second, the Ensemble-Transform Kalman-filter (ETKF, Majumdar 2002). This technique is able to predict the reduction in forecast error variance for feasible deployment of targeted observations based, in this case, on the 40-member NCEP EFS. Third, the Singular Vector (SV) technique (e.g., Palmer et al. 1998). It maximizes the growth of a total energy or kinetic energy norm using, in this case, the forward and adjoint tangent models of the Navy Operational Global Atmospheric Prediction System (NOGAPS, Rosmond 1997; Gelaro et al. 2002).

As mentioned above, the ETKF and SV products are derived from the (total) energy or kinetic energy norm. For the DLM wind variance, high sensitivity has a tendency to appear around the storm region as there is generally higher ensemble variability associated with small displacement of the strong cyclonic wind near the core area. Therefore, none of the above techniques for targeted observations is directly related to the motion (steering flow) of the tropical cyclone.

Theoretical work on the determination of a targeted observation strategy for improving the tropical cyclone track prediction has been lacking in literatures (Rohaly et al. 1998 is a notable exception.). Along with the progress in DOTSTAR, we propose a new method for targeted observations based on the adjoint sensitivity (Zou et al. 1997; Kleist and Morgan 2005) to verify the sensitive areas with respect to the typhoon steering flow. A response function is designed to represent the steering flow at the verifying time, and to assess the adjoint sensitivity with respect to such response functions. A simple parameter is also proposed to interpret the sensitivity with clear physical meanings. The ADSSV will be validated for the binary interaction. The detailed results of this work are also shown in Wu et al. (2007).

Methodology and experiment design

Adjoint models are powerful tools for many studies that require an estimate of sensitivity of model output with respect to input (Errico 1997). Our study utilizes a component of the MM5 (the fifth generation mesoscale model, Pennsylvania State University/National Center for Atmospheric Research) Adjoint Modeling System (Zou et al. 1997), which was used by Kleist and Morgan (2005) to investigate a snowstorm with a poor forecast. This system includes the nonlinear MM5, its tangent linear model, and corresponding dry-physics adjoint model. The domain for the nonlinear and adjoint models is a 60-km, 85×115 (latitude by longitude) horizontal grid, with 20 sigma levels in the vertical. The initial and boundary conditions are from the NCEP GFS (Global Forecasting System) global analysis (1°×1°) interpolated to the MM5 grids.

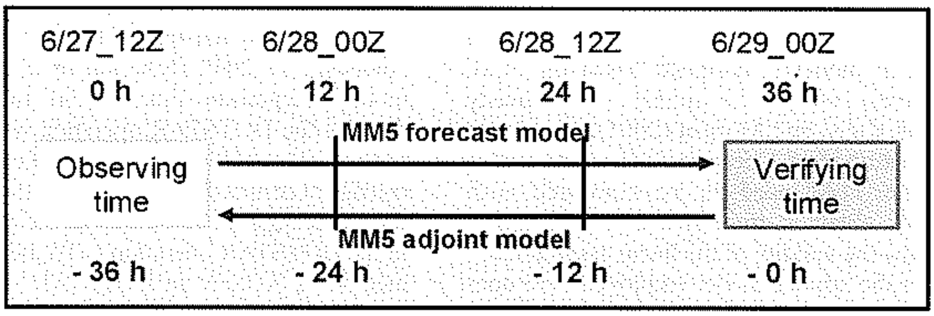

Figure 1. The design of forward and backward model integrations. The 'negative' sign before the time indicates the 'backward' integration (using the negative time step) associated with the adjoint model.

Typhoon Mindulle in 2004, one of the observed by DOTSTAR, is chosen as a test case to examine the proposed new method for targeted observations based on the adjoint sensitivity. Note that Mindulle is the sole one out of the ten DOTSTAR cases in 2004 where dropsonde data assimilated into the NCEP GFS model did not improve the track forecasts (figures not shown). The study is based on a 36-h MM5 simulation initialized at 1200 UTC 27 June 2004. The 'forward' and 'backward' integrations were executed by the MM5 forecast model and the adjoint model, respectively, as indicated in Fig. 1. The 'negative' sign before the time indicates the 'backward' integration (using the negative time step) associated with the adjoint model.

The work is aimed to identify the sensitive areas at the observing time (1200 UTC 27 June), which will affect the steering flow of Mindulle at the verifying time (0000 UTC 29 June). Therefore, we define the response function(s) as the deep-layer mean wind within the verifying area. A square of 600 km by 600 km, centered around the MM5-simulated storm location at the verifying time, is used to calculate the background steering flow (Chan and Gray 1982). Two responses functions are then defined: R_1, the 850-300-hPa deep-layer area average (Wu et al. 2003) of zonal component (u), and R_2, the average of meridional component (v) of the wind vector, i.e.

$$R_1 \equiv \frac{\int_{850hPa}^{300hPa}\int_A u \; dxdydp}{\int_{850hPa}^{300hPa}\int_A dxdydp}, \quad \text{and}$$

$$R_2 \equiv \frac{\int_{850hPa}^{300hPa}\int_A v \; dxdydp}{\int_{850hPa}^{300hPa}\int_A dxdydp}. \tag{1}$$

In other words, by averaging out the axisymmetric component of the strong cyclonic flow around the storm center, the vector of (R_1, R_2) represents the background steering flow across the storm center at the verifying time. It should be noted that as a wind vector, (R_1, R_2) is totally different from the kinetic energy norm stated above.

In order to interpret the sensitivity with clear physical meanings, we design a unique new parameter, Adjoint-Derived Sensitivity Steering Vector (ADSSV), to identify the sensitive areas at the observing time to the steering flow at the verifying time. The ADSSV with respect to the vorticity field (ς) can be shown as

$$ADSSV \equiv \left(\frac{\partial R_1}{\partial \varsigma}, \frac{\partial R_2}{\partial \varsigma}\right), \tag{2}$$

where, at a given point, the magnitude of ADSSV indicates the extent of the sensitivity, and the direction of the ADSSV represents the change in the response of the steering flow with respect to a vorticity perturbation placed at that point. For example, if at a given forecast time at one particular grid point the ADSSV vector points to the east, an increase in the vorticity at the very point at the observing time would be associated with an increase in the eastward steering of the storm at the verifying time.

Summary and prospects

In addition to various sensitivity products we have adopted in DOTSTAR, a new sensitivity measurement has been proposed based on the adjoint model. In short, by appropriately defining the response functions to represent the mean steering flow at the verifying time, we can derive its sensitivity to the flow field at the observing time to help formulate the observation strategy. In particular, a simple vector, the ADSSV with respect to the vorticity field, is proposed to clearly demonstrate the sensitivity to the storm motion. We believe that ADSSV can be applied to scientific research in many aspects and can be tested in the field project to help improve the typhoon track prediction.

Subsequent work is being carried out to consolidate this study, and will be presented in other papers.

(1) Linearity test and impact of the dry-physics adjoint model

The adjoint model is designed based on TLM, which is a linear assumptive model. As already demonstrated in Kleist and Morgan (2005), in order to validate this assumption, perturbations that evolve linearly via the TLM need to be compared with difference fields obtained from two nonlinear model forecasts to show the validity of the linear assumption.

Note that the adjoint model employed here does not include the moist physics. Although it is definitely critical to the development of the tropical cyclone system, we believe that the tropical cyclone movement is mainly controlled by the large-scale flow field, which is less likely to depend on the moist physics. Further test on this can be conducted using the moist version of the adjoint model.

(2) Impact study

The above validation study of the binary interaction between Fengshen and Fongwong indicates that the ADSSV can well represent the signal of the one-way binary interaction process. Besides the binary interaction, the ADSSV can also be used to show how the critical weather system affects the typhoon motion, such as the impact from the approaching trough. To validate the sensitivity derived from the adjoint modeling system in more details, we also plan to design other experiments, such as to perturb the wind (vorticity) fields in the initial time (such as those in the area with large magnitude of ADSSV), and investigate the response to the simulated typhoon track.

(3) Application of the ADSSV method to other adjoint modeling systems

Besides the MM5 adjoint modeling system, there are other adjoint models, such as NOGAPS. How the ADSSV method will appear in different modeling systems is an interesting issue worthy of further study.

(4) Operation in the field programs

While the above task continues, we are in the process of implementing the currently designed method (using ADSSV) for real-time use in DOTSTAR, as well as for Atlantic hurricanes (in collaboration with Sim Aberson), in 2005 (Etherton et al. 2006). A longer model integration time would then be called for because the DOTSTAR operation would require a lead time of at least 48 h. The preliminary test is showing consistent results when we run the model for up to 84 h, thus indicating the feasibility of the current system used in the DOTSTAR operation. We believe that using the method of ADSSV in DOTSTAR will shed new light on the targeted observations for tropical cyclones. Meanwhile, work is also ongoing to compare the several different techniques used for the targeted observations of tropical cyclones.

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