Targeted Observation of Tropical Cyclones

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ABSTRACT

The advance in targeted observations of tropical cyclone movement is reviewed in this article. The targeted observations from DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region) in understanding and improving the tropical cyclone track predictability is highlighted, along with the progress of the field program of THORPEX-PARC in the summer of 2008. The impact of the dropwindsonde data from DOTSTAR has been demonstrated. A specific targeted method (Adjoint-Derived Sensitivity Steering Vector) for tropical cyclone motion has been proposed. Intercomparison of all targeted observation guidance products for western North Pacific typhoons have also been conducted.

1. Introduction

Over the past 30 years, persistent and steady progress on the track forecasts of TCs have been well demonstrated through the improvement of the numerical models, the data assimilation system, and the new data available to the forecast system (Wu 2006). In addition to the large amount of satellite data, the special dropwindsondes data deployed from the surveillance aircraft have also provided significant added values in improving the track forecasts.

In order to optimize the limited aircraft resources, targeted observations in the critical areas which have the maximum influence on numerical weather forecasts of TCs are of great importance. Therefore, targeted observing strategies for aircraft missions must be further developed. And it is the prerequisite for the device of observing strategy to identify the sensitive areas that have the greatest influence in improving the numerical forecast, or minimizing the track forecast error.

To make use of the available data or the potentially new data, it is important to evaluate the potential impact and to test the sensitivity of the simulation and prediction of TCs to different parameters. This understanding can be of great use in designing a cost-effective strategy for targeted observations of TCs (Morss et al. 2001; Majumdar et al. 2002a, b; Aberson 2003; Wu et al. 2005).

In this section, three issues related to the author’s works are addressed: first, the impact of the DOTSTAR data; second, results from a set of Observation System Simulation Experiments (OSSEs); and third, an innovative development of the new targeted observation strategy, Adjoint-Derived Sensitivity Steering Vector (ADSSV).
2. Impact of dropwindsonde data on TC track forecasts in DOTSTAR

Since 2003, the research program of “Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region” (DOTSTAR, Wu et al. 2005, 2007b) has continuously conducted dropwindsonde observations of typhoons in the western North Pacific (Fig. 1). Three operational global and two regional models were used to evaluate the impact of the dropwindsonde on TC track forecasting (Wu et al. 2007b). Based on the results of 10 missions conducted in 2004 (Wu et al. 2007b), the use of the dropwindsonde data from DOTSTAR has improved the 72-h ensemble forecast of three global models, i.e., the Global Forecasting System (GFS) of National Centers for Environmental Predictions (NCEP), the Navy Operational Global Atmospheric Prediction System (NOGAPS) of the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the Japanese Meteorological Agency (JMA) Global Spectral Model (GSM), by 22% (Fig. 2).

Wu et al. (2007b) showed that the average improvement of the dropwindsonde data made by DOTSTAR to the 72-h typhoon track prediction in the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane models is an insignificant 3%. It is very likely that the signal of the dropwindsonde data is swamped by the bogusing procedure used during the initialization of the GFDL hurricane model. Chou and Wu (2008) showed a better way of appropriately combining the dropwindsonde data with the bogused vortex in the mesoscale model in order to further boost the effectiveness of dropwindsonde data with the implanted storm vortex.

Figure 1. Best tracks of the 31 typhoons with 38 DOTSTAR observation missions from 2004 to 2008. The squares indicate the storm locations when the DOTSTAR missions were taken. The numbers on the squares represent the sequence of the missions. (From Wu et al. 2007b)
Figure 2. This represents 6-72-h mean track error reduction (in km) after the assimilation of the dropwindsonde data into each ten models. The storm name is abbreviated by its first four alphabets, while Min1, Min2 and Min3 stands for the first, second, and third cases in Mindulle. (From Wu et al. 2007b)

3. OSSE study (Wu et al. 2006)

As the conventional observations usually have far less degrees of freedom than the models, the four-dimensional variational data assimilation (4DVAR) has become one of the most advanced approaches in combining the observations with the model in such a way that the initial conditions are consistent with the model dynamics and physics (Guo et al. 2000). Based on 4DVAR, a bogus data assimilation method had been developed by Zou and Xiao (2000) to improve the initial conditions for TC simulation.

A set of Observation Systems Simulation Experiments (OSSEs) have been performed to identify the critical parameters and the improved procedures for the initialization and prediction of TCs. A control experiment is carried out to create the imaginary “nature” data for Typhoon Zane (1996), using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5). Then the initial data from the control experiment is degraded to produce the new initial condition and simulation, which mimics typical global analysis that resolves the Zane circulation. By assimilating some variables from the initial data of the control experiment into the degraded initial condition based on 4DVAR, the insight into the key parameters for improving the initial condition and prediction of TCs is attained (Wu et al. 2006).

It is shown that the wind field is critical for maintaining a correct initial vortex structure of TCs. The model's memory of the pressure field is relatively short. Therefore, when only the surface pressure field is assimilated, due to the imbalance between the pressure and wind fields, the pressure field adjusts to the wind field and the minimal central sea-level pressure of the storm rises quickly.

It is well demonstrated that taking the movement of the TC vortex into consideration during the data assimilation window can improve the track prediction, particularly in the early integration period. When the vortex movement tendency is taken into account during the bogus data assimilation period, it can partially correct the steering effect in the early prediction and the simulation period (Fig. 3). This concept provides a new and possible approach to the improvement of TC track prediction.
Figure 3. The 72-h JTWC best track (indicated with typhoon symbol) and the simulated storm tracks from experiments NO-DA, DA-FIX and DA-MOVE for Typhoon Zeb (1998), shown for 12-h intervals from 0000 UTC 13 Oct. to 0000 UTC 16 Oct. 1998. NO-DA: a standard MM5 simulation with an initial bogused vortex following Wu et al. (2002) without data assimilation. DA-FIX: experiment assimilated the above bogused vortex (fixed in location) based on a 30-min window 4DVAR data assimilation. DA-MOVE: experiment in which the vortex is assimilated with the same initial data except it moved in 3-h window assimilation. (From Wu et al. 2006)

4. Targeted observations for TCs

(1) Adjoint-Derived Sensitivity Steering Vector (ADSSV) (Wu et al. 2007a, 2009a)

By appropriately defining the response functions to represent the steering flow at the verifying time, a simple innovative vector, Adjoint-Derived Sensitivity Steering Vector (ADSSV), has been designed (Wu et al. 200a) to clearly demonstrate the sensitive locations and the critical direction of the typhoon steering flow at the observing time.

Because the goal is to identify the sensitive areas at the observing time that will affect the steering flow of the typhoon at the verifying time, the response function is defined as the deep-layer-mean wind within the verifying area. A 600 km by 600 km square area centered on the MM5-simulated storm location is used to calculate the background steering flow as defined by Chan and Gray (1982), and two response functions are defined: $R_1$, the 850-300 hPa deep-layer area average (Wu et al. 2003) of the zonal component ($u$), along with $R_2$, the average of the meridional component ($v$) of the wind vector, i.e.,

$$ R_1 \equiv \frac{\int_{850\text{hPa}}^{300\text{hPa}} \int_{A} u \, dx \, dy \, dp}{\int_{850\text{hPa}}^{300\text{hPa}} \int_{A} dx \, dy \, dp} \quad \text{and} \quad R_2 \equiv \frac{\int_{850\text{hPa}}^{300\text{hPa}} \int_{A} v \, dx \, dy \, dp}{\int_{850\text{hPa}}^{300\text{hPa}} \int_{A} dx \, dy \, dp}. \quad (1) $$
By averaging, the axisymmetric component of the strong cyclonic flow around the storm center is removed, and thus the vector of \((R_1, R_2)\) represents the background steering flow across the storm center at the verifying time. To interpret the physical meaning of the sensitivity, a unique new parameter, ADSSV, is designed to relate the sensitive areas at the observing time to the steering flow at the verifying time. The ADSSV with respect to the vorticity field \((\zeta)\) is

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

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

The ADSSV, based on the MM5 forecast (Fig. 4), extends about 300-600 km from the north to the east of Typhoon Meari (2004). The directions of the ADSSVs indicate greater sensitivity in affecting the meridional component of the steering flow.

In Wu et al. (2009a), the ADSSV is calculated from the nonlinear forecast model
of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Meso scale Model (MM5) and its adjoint to interpret the dynamical processes in the interaction between Typhoon Shanshan (2006) and the midlatitude trough. The ADSSV results imply that high-sensitivity regions affecting the motion of Typhoon Shanshan are located at the edge of the subtropical high and the 500-hPa midlatitude trough over northern central China. These ADSSV signals (Fig. 5) are in very good agreement with the quantitative evaluation based on the potential vorticity (PV) diagnosis. The vertical structure of the ADSSV is also shown for more physical insights into the typhoon–trough interaction. The maximum ADSSV occurs at 800–500 hPa to the southeast of Shanshan (associated with the subtropical high), while distinct ADSSV signals are located upstream of the storm center at about 500–300 hPa (associated with the mid- to upper-tropospheric midlatitude trough). Overall, it is demonstrated that the ADSSV features can well capture the signal of the large-scale trough feature affecting the motion of Shanshan, which can also be well validated from the PV analysis.

![ADSSV(VOR), Geop. Height(shaded) at 500hPa](image)

Figure 5. ADSSV with respect to the vorticity field at 500 hPa at the observing time, superposed with the geopotential height (magnitude scaled by the color bar to the right; m) at 500 hPa for (a) EXP1, (b) EXP2, and (c) EXP3. The magnitude of the ADSSV is normalized by the maximum value in the domain (the value smaller than 0.25 is omitted). The best track from CWB analysis and 48-h model-predicted track are indicated with the black typhoon symbols and the red circles for every 12 h, respectively. The dashed square box represents the verifying area at the verifying time. (From Wu et al. 2009a).

(2) Recent techniques for targeted observations of TCs
To optimize the aircraft surveillance observations using dropwindsondes, targeted observing strategies have been developed and examined. The primary consideration in devising such strategies is to identify the sensitive areas in which the assimilation of targeted observations is expected to have the greatest influence in improving the numerical forecast, or minimizing the forecast error. Since 2003, four objective methods have been tested for operational surveillance missions in the environment of Atlantic hurricanes conducted by the National Oceanic and Atmospheric Administration (NOAA) (Aberson 2003) and DOTSTAR (Wu et al. 2005). These products are derived from four distinct techniques: the ensemble Deep-Layer Mean (DLM) wind variance (Aberson 2003), the ensemble-transform Kalman-filter (ETKF, Majumdar et al. 2002), the total-energy singular vector (TESV) technique (Peng and Reynolds 2006), and the Adjoint-Derived Sensitivity Steering Vector (ADSSV) (Wu et al. 2007a). The above techniques have been applied in a limited capacity to identify locations for aircraft-borne dropwindsondes to be collected in the environment of the TCs. For the surveillance missions in Atlantic hurricanes conducted by NOAA Hurricane Research Division (HRD; Aberson 2003) and the DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region; Wu et al. 2005), other than the ADSSV method shown above, three other sensitivity techniques have also been used to determine the observation strategies:

(i) Deep-Layer Mean wind variance

Based on the deep-layer mean (DLM; 850-200-hPa averaged) steering flows from the NCEP Global Ensemble Forecasting System (EFS; Aberson 2003), areas with the largest (DLM) wind ensemble spread represent the sensitive regions at the observing time. The DLM wind ensemble spread is chosen because TCs are generally steered by the environmental DLM flow, and the dropwindsondes from the NOAA Gulfstream IV sample this flow.

(ii) Ensemble Transform Kalman Filter (ETKF)

This ensemble transform Kalman filter (ETKF) (Bishop et al. 2001) technique predicts the reduction in forecast error variance for a variety of feasible flight plans for deployment of targeted observations based on the 40-member NCEP EFS (Majumdar et al. 2006). That is, the ETKF uses the differences among ensemble members to estimate regions for observational missions. The ETKF takes the approach of DLM wind variance further. While DLM wind variance indicates areas of forecast uncertainty at the observation time, it does not correlate initial condition uncertainty with the errors in the forecasts. The ETKF explicitly correlates errors at the observation time with errors of the forecasts and identifies ensemble variance that impacts the forecasts in the verifying area at the verifying time.

(iii) Singular Vector (SV) technique

The SV technique maximizes the growth of total energy or kinetic energy norm (e.g., Palmer et al. 1998; Peng and Reynolds 2006) using the adjoint and forward-tangent models of NOGAPS (Rosmond 1997; Gelaro et al. 2002), along with the ensemble prediction system (EPS) of JMA and the Singular Vector products from European Center for Medium Range Forecast (ECMWF). Peng and Reynolds (2006) have demonstrated the capability of the SV technique in identifying the sensitive regions suitable for targeted observations of TCs.
The above techniques have been applied in a limited capacity to identify locations for aircraft-borne dropwinsondes to be collected in the environment of the TCs. To gain more physical insights into these targeted techniques, studies to compare and evaluate the techniques have been conducted by Majumdar et al. (2006), Etherton et al. (2006), and Reynolds et al. (2007).

(3) Intercomparison of the targeted techniques (Wu et al. 2009b)

Wu et al. (2009) compares six different guidance products for targeted observations over the northwest Pacific Ocean for 84 cases of 2-day forecasts in 2006 and highlights the unique dynamical features affecting the tropical cyclone (TC) tracks in this basin. The six products include three types of guidance based on totalenergy singular vectors (TESVs) from different global models, the ensemble transform Kalman filter (ETKF) based on a multimodel ensemble, the deep-layer mean (DLM) wind variance, and the adjointderived sensitivity steering vector (ADSSV). The similarities among the six products are evaluated using two objective statistical techniques to show the diversity of the sensitivity regions in large, synoptic-scale domains and in smaller domains local to the TC. It is shown (Fig. 6) that the three TESVs are relatively similar to one another in both the large and the small domains while the comparisons of theDLM wind variance with 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 among the six guidance products and to interpret the dynamical systems affecting the TC motion in the northwestern Pacific. Among the three storms studied, Typhoon Chanchu was associated with the subtropical high, Typhoon Shanshan was associated with the midlatitude trough, and Typhoon Durian was associated with the subtropical jet. 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 are the ensemble methods.
Summary

DOTSTAR, a TC surveillance program using dropwindsondes has been successfully launched since 2003. To capture the sensitive areas which may influence TC track, a newly-designed vector, ADSSV, has been proposed (Wu et al. 2007a). Aside from being used to conduct research on the impact of targeted observations, the DOTSTAR’s tropospheric soundings around the TC environment may also prove to be a unique dataset for the validation and calibration of remotely sensed data for TCs in the Northwest Pacific region.

Five models (4 operational and 1 research models) were used to evaluate the impact of dropwindsonde data on TC track forecasts during 2004. All models, except the GFDL hurricane model, show positive impacts from the dropwindsonde data on TC track forecasts. In the first 72 h, the mean track error reductions in the three operational global models, NCEP GFS, NOGAPS and JMA GSM, are 14, 14, and 19%, respectively, and the mean track error reduction of the ensemble of the three global models is 22%.

Along with the development of ADSSV in DOTSTAR, an important issue on the targeted observations based on various techniques have been studied (Wu et al. 2009). The THORPEX-PARC (T-PARC) program had been successfully carried out in the summer of 2008, where DOTSTAR participated the international T-PARC initiative under World Meteorological Organization (collaborating with the Japanese program, Typhoon Hunting 2008, TH08, as well as Tropical Cyclone Structure 2008, TCS-08). Joint flights among DOTSTAR, Falcon (DLR), P3 (NRL) and C130 (USAF) for Typhoons Nuri, Sinlaku, Hagupit, and Jangmi have been successfully conducted during T-PARC in the summer of 2008. The unprecedented data obtained would provide a great opportunity for the advance of the research on TC genesis, structure change, targeted observation, recurvature, and extratropical transition.

References


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