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The Effect of Three-Dimensional Variational Data Assimilation of QuikSCAT Data on the Numerical Simulation of Typhoon Track and Intensity

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ABSTRACT

In this paper, the three-dimensional variational data assimilation scheme (3DVAR) in the mesoscale model version 5 (MM5) of the US Pennsylvania State University/National Center for Atmospheric Research is used to study the effect of assimilating the sea-wind data from QuikSCAT on the prediction of typhoon track and intensity. The case of Typhoon Dujuan (2003) is first tested and the results show appreciable improvements. Twelve other cases in 2003 are then evaluated. The assimilation of the QuikSCAT data produces significant impacts on the structure of Dujuan in terms of the horizontal and vertical winds, sea-level pressure and temperature at the initial time. With the assimilation, the 24-h (48-h) track prediction of 11 (10) out of the 12 typhoons is improved. The 24-h (48-h) prediction of typhoon intensity is also improved in 10 (9) of the 12 cases. These experiments therefore demonstrate that assimilation of the QuikSCAT sea-wind data can increase the accuracy of typhoon track and intensity predictions through modification of the initial fields associated with the typhoon.

Key words: QuikSCAT, MM5 3DVAR, numerical simulation, Typhoon Dujuan

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1. Introduction

Data assimilation has recently been recognized as a useful way to provide better "consistent" initial conditions for numerical weather prediction (NWP) in the meteorological community. One of the most attractive and effective methods is variational data assimilation, which is based on the estimation theory that constructs a theoretical basis for variational analyses in the minimization of the bias of analyzed data (Gelb et al., 1974). Two types of variational data assimilations have been used: three dimensional (3DVAR) and four dimensional (4DVAR). Although a full set of data in an assimilation time window has beneficial impacts resulting from strong constraints imposed upon the model integrated state with both physics and dynamics involved, 4DVAR is very time-consuming due to the adjoint nature of model integration in iteratively searching for the optimal solution. On the other hand, 3DVAR, the degraded system of 4DVAR, utilizes observations as well as analyses near the current time (i.e., the "initial time"). Because both model integration and adjoint model integration are not needed in 3DVAR, the filtering processes are greatly simplified with relatively cheaper adjoint operators for ingestion of various observations (Courtier et al., 1998). With the availability of more and more unconventional data (including measurements from satellite, radar and other remote sensors), ingestion of these data into NWP models should show improvements in the numerical forecasts. In practice, whenever these data become available, they should be assimilated during their ingestion time window provided that their error covariance matrices are known.

Much research in satellite data assimilation has been carried out. For example, substantial improvements in numerical forecasts have been attributed to the use of 3DVAR analysis and direct assimilation of TIROS Operational Vertical Sounder (TOVS) and Advanced TOVS (ATOVS) radiances (English et al., 2000; McNally et al., 2000). Recent improvements

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in the European Center for Medium-Range Weather Forecasts (ECMWF) short-range forecasts are in part linked to the progress in the data assimilation system, including assimilation of raw microwave radiances from the TOVS and ATOVS satellite-borne instruments, and retrievals of humidity and surface wind speed from the Special Sensor Microwave/Imager (SSM/I) (Mahfouf and Rabier, 2000; Simmons and Hollingsworth, 2002). Recent observing system experiments have also demonstrated a beneficial impact in using TOVS radiances with 4DVAR particularly in the Southern Hemisphere (Bouttier and Kelly, 2001). Retrievals of SSM/I and other satellite data also contribute to the improvement of the medium-range forecasts. The Japan Meteorological Agency (JMA) also obtained improvements in the performance of their global spectral model after the introduction of 3DVAR with assimilation of TOVS/ATOVS radiances (Kazumori et al., 2003). The improvement in the analysis of the tropical atmosphere further contributed to the reduction of track forecast errors of tropical cyclones (TCs).

Because TCs originate over the ocean where few conventional soundings or surface data are available, it is difficult to define the large-scale flow patterns and the inner structure of TCs. These inaccurate analyses could produce large errors in prediction. The use of satellite observations is likely the best way to reduce the data-sparsity problem. Indeed, cloud images from geostationary satellites have been used in TC forecasts since the early 1970s. Until now, the main application of satellite information in TC forecasting is positioning the cyclone and estimating its intensity. The current Global/Regional Assimilation and Prediction System of the China Meteorological Administration contains a 3DVAR system that focuses on satellite data assimilation (Xue, 2002). In order to have a direct assimilation of the ATOVS radiances, the fast Radiative Transfer model for ATOVS version 6 (RTTOV6), an advanced software package including the fast radiance transfer model and its adjoint developed by ECMWF, is adopted. An experimental system consisting of 3DVAR and a mesoscale model has also been set up and real case tests have been undertaken.

Global coverage of scatterometer data has been routinely available to forecasters and researchers since 1991 from the European Remote Sensing Satellite 1 (ERS-1) and European Remote Sensing Satellite 2 (ERS-2). However, the coverage of TCs is generally not enough because each swath of the satellite is only about 500 km in width. This situation changed following the launch of the Quik Scatterometer (QuikSCAT) satellite in 1999, with its sea-wind instrument offering near-continuous daily coverage of over 90% of the tropical oceans with a wide swath of 1800 km (Liu and Chan, 2002). This enhanced coverage has presented an opportunity for the various TC forecast centers and other operational weather agencies to adapt these data into near-real-time use. The scatterometer provides both surface wind speed and direction which significantly increases the TC forecaster's knowledge of TC formation and TC surface wind structure. Current research shows that QuikSCAT wind speeds are rather accurate, especially for the early detection of TCs using seawind-derived vorticity (Sharp et al., 2002; Pasch et al., 2003).

At present, research on satellite scatterometer data variational assimilation generally focuses on the ERS-2 and NSCAT (NASA scatterometer) satellite data. For example, Leidner et al. (2003) analyzed the effect of NSCAT wind data on TC forecasts and found major positive impacts of 4DVAR of NSCAT data on TC forecasts of both intensity and position. Recently, advanced meteorological forecast centers such as JMA and the National Centers for Environmental Prediction (NCEP) have also begun assimilating the QuikSCAT data and have found some improvements over the Tropics at the near surface. However, in China, the study of QuikSCAT data variational assimilation and that of its application in TC prediction are still under development, one of which is the focus of the present study.

Some information on the QuikSCAT data and the assimilation procedure are given in section 2. A brief description of the model and some results are given in section 3. Results of a case study of the effect of 3DVAR of QuikSCAT data on the simulation of the initial field structure change as well as track and intensity prediction of Typhoon Dujuan in 2003 are first presented in section 3.2. A set of simulation experiments are then carried out for 12 typhoon cases in 2003 in section 3.3. The objective is to determine qualitatively the effect of the 3DVAR of QuikSCAT data on the numerical simulation of the initial field structure as well as track and intensity predictions of the TCs. Section 4 then gives a summary of the results and a concluding discussion.

2. QuikSCAT data and assimilation procedure

2.1 *QuikSCAT data*

The QuikSCAT Operational Standard Data Products (Level 2.0), which have been processed and distributed by the NASA Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO.DAAC), contain two outputs of wind data. One is the standard wind data, which have been produced using a maximum likelihood estimator (Long and Mendel, 1991) and median filter ambiguity removal algorithm (Shaffer et al., 1991) with the Numerical Weather Product initialization. The other is enhanced wind data processed using the Direction Interval Retrieval with Threshold Nudging (DIRTH) algorithm (JPL, 2001). The standard L2B wind data are used for the present study.

The L2B data have been retrieved with the QuikSCAT-1 geophysical model function, which was developed based on results of post-launch calibration/validation activities. The spatial resolution of the data is 25 km, and the reference height of the wind vectors is 10 m above the sea surface. The multidimensional histogram rain flagging (Huddleston and Stiles, 2000) is applied to indicate the presence of rain. In the present analysis, all data flagged for low and high wind speeds, and all other flagged data, such as the rain flag, are discarded. Data observed in 2003 are used.

The L2B wind vectors observed by the QuikSCAT satellite mission were validated by comparison with wind and wave data from ocean buoys. The buoy wind speeds were converted to equivalent neutral winds at a height of 10 m above the sea surface (Ebuchi et al., 2002). They found that the wind speeds and directions observed by QuikSCAT agree well with the buoy data. The root-mean-squared differences of the wind speed and direction for the standard wind data products are 1.01 m s^{-1} and 23°, respectively. Therefore, we can reliably use QuikSCAT data near the tropical cyclone in this study of QuikSCAT data variational assimilation.

2.2 *The variational assimilation procedure*

The 3DVAR scheme in the MM5 provides a minimization of an objective function (i.e., the cost function) defined as

$$J = \frac{1}{2}\{(\boldsymbol{x}-\boldsymbol{x}_{\rm b})^{\rm T}\boldsymbol{B}^{-1}(\boldsymbol{x}-\boldsymbol{x}_{\rm b}) + [\boldsymbol{y}_{\rm obs} - \boldsymbol{H}(\boldsymbol{x})]^{\rm T}\boldsymbol{O}^{-1}[\boldsymbol{y}_{\rm obs}-\boldsymbol{H}(\boldsymbol{x})]\}\ , \tag{1}$$

where $\boldsymbol{x}$ is the analysis variable vector (n-dimensional), $\boldsymbol{x}_{\rm b}$ the background variable vector (n-dimensional), $\boldsymbol{y}_{\rm obs}$ the observation vector (m-dimensional), $\boldsymbol{B}$ the background error covariance matrix ($n\times n$), $\boldsymbol{O}$ the observation error covariance matrix ($m\times m$), and $\boldsymbol{H}$ the nonlinear operator to transform the analysis variable vector to the observation vector.

At the extreme, the derivative of J would vanish, i.e.,

$$0 = \nabla J = \boldsymbol{B}^{-1}(\boldsymbol{x}-\boldsymbol{x}_{\rm b}) - \boldsymbol{H}'^{\rm T}\boldsymbol{O}^{-1}(\boldsymbol{y}_{\rm obs}-\boldsymbol{H}'\boldsymbol{x})\ , \tag{2}$$

and thus, $\boldsymbol{x}_{\rm a}$, the estimate of x, can be obtained as

$$\boldsymbol{x}_{\rm a} = \boldsymbol{x}_{\rm b} + [\boldsymbol{B}^{-1}+\boldsymbol{H}'^{\rm T}\boldsymbol{O}^{-1}\boldsymbol{H}']^{-1} \times \boldsymbol{H}'^{\rm T}\boldsymbol{O}^{-1}(\boldsymbol{y}_{\rm obs}-\boldsymbol{H}\boldsymbol{x}_{\rm b})\ , \tag{3}$$

where $\boldsymbol{H}' = \partial\boldsymbol{H}/\partial\boldsymbol{x}$ is the tangent linear approximation of the nonlinear operator $\boldsymbol{H}$. Because the transformation operation may be highly nonlinear, an incremental formulation based on the above linearity is often used to obtain the solution. Preconditioning of the incremental formulation is also performed in order to avoid the inversion of the matrix $\boldsymbol{B}$ that in practice is rarely adopted. A more complete technical description of the MM5 (the Mesoscale model version 5) 3DVAR algorithm is contained in Barker et al. (2003).

In the MM5 3DVAR, all observation errors are assumed to be uncorrelated in space and time so that the associated covariance matrix $\boldsymbol{O}$ is diagonal. The diagonal elements of the matrix $\boldsymbol{O}$ are prescribed as those used in the NCEP operational Spectral Statistical Interpolation (SSI) 3DVAR (Parrish and Derber, 1992). The background error covariance matrix $\boldsymbol{B}$ is prescribed as the monthly mean forecast error variances derived from the NMC method. The effect of spatial error correlations existing in $\boldsymbol{B}$ on the analysis vector can then be produced by a recursive filter (Lorenc, 1992) with a correlation length of 10 model grid points. The background vector is given by the previous forecast fields or first guesses from global model assimilation at the initial time.

Observations available over the global telecommunications system (GTS) originate from a wide variety of sources. Errors may be introduced at all stages including measurement, reporting practices, transmission, and decoding. It is essential that careful quality control (QC) be performed to avoid the assimilation of erroneous observations.

An observation preprocessor has been developed to perform QC on the observations. A number of checks are performed including removal of observations outside the domain, excluding location/time duplicates and incomplete observations (e.g., no location), and ensuring vertical consistency of upper-air profiles. Numerous QC checks are redone in 3DVAR itself and an "error_max" check is performed to reject observations whose innovation vector ($\boldsymbol{O}-\boldsymbol{B}$) is greater than 5 times the assumed observation error standard deviation. Meanwhile, QuikSCAT winds at an observation point are removed from the analysis if the QuikSCAT wind speed is greater than 30 m s^{-1} or the QuikSCAT data is contaminated by rain.

In order to asses the influence of the model simulation with the QuikSCAT data on the prediction of typhoon track and intensity, a set of 48-h forecast experiments are designed by comparing the simulation with the QuikSCAT data assimilation to that without for some typhoon cases in 2003. When the QuikSCAT data are assimilated into the model, the data are first added into the reference height of 10 m above the sea surface in the model and then interpolated onto the

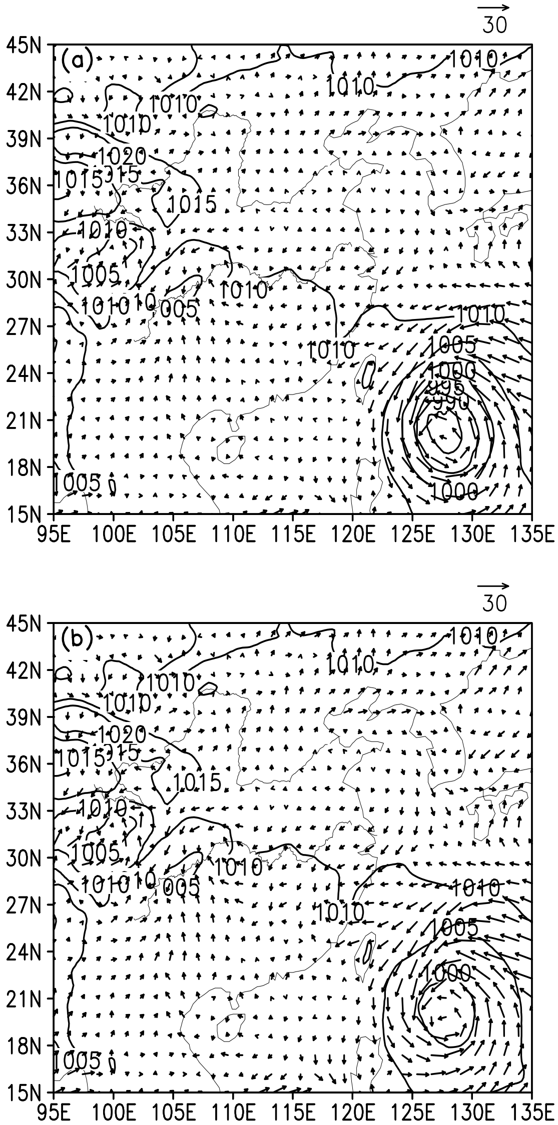

Fig. 1. 10-m wind field (m s^{-1}) and sea-level pressure at 1200 UTC on 31 August 2003 for Typhoon Dujuan (a) with data assimilation and (b) without data assimilation. Contour interval: 5 hPa.

lowest level of the model.

3. Brief description of the model and results

3.1 *Model*

This study utilizes version 3.6 MM5. The domain mesh has 175×175 points horizontally with a 45-km grid spacing and the domain center is at 30°N, 125°E. The model physics include the Grell convective scheme for cumulus parameterization and the Blackadar scheme for Planetary Boundary Layer (PBL) parameterization (Grell et al., 1991; Zhang and Anthes, 1982). The model has 29 vertical layers with the model top at 100 hPa.

The background field is the US NCEP Aviation (AVN) global analysis field data with a 1° × 1° horizontal resolution. The wind direction and speed errors of the QuikSCAT data are from JPL. Details of the error information may be found in the QuikSCAT Science Data Product User's Manual (JPL, 2001).

A month-long series of 12-h and 24-h forecasts for August 2003 have been conducted with the MM5 model. The climatological background error convariances matrix $\boldsymbol{B}$ (see section 2.2) for meteorological elements, such as wind, temperature, moisture and pre-

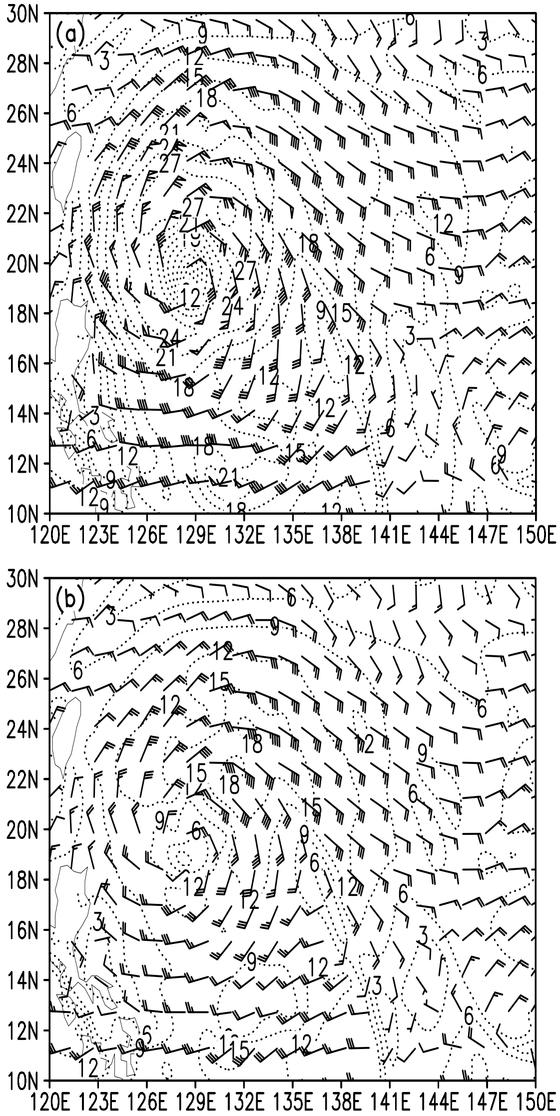

Fig. 2. Model-simulated 10-m wind vectors and isotach (dashed lines) at 1200 UTC on 31 August 2003 for Typhoon Dujuan (a) with data assimilation and (b) without data assimilation. Each flag indicates 20 m s^{-1}, contour interval: 3 m s^{-1}.

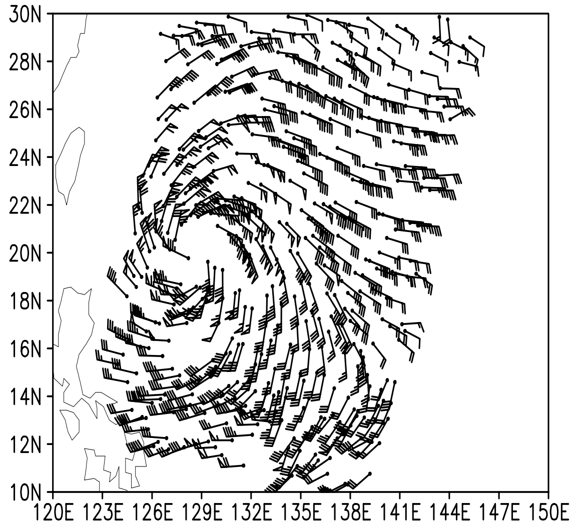

Fig. 3. Observed QuikSCAT 10-m wind vectors from 1030 UTC to 1330 UTC on 31 August 2003 for Typhoon Dujuan. Each flag indicates 20 m s^{-1}.

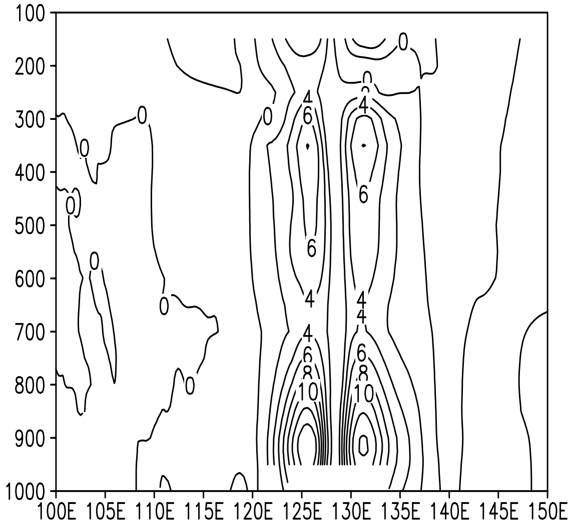

Fig. 4. Increase in horizontal wind speed at the initial time along 20.2 °N with data assimilation. Contour interval: 2 m s^{-1}.

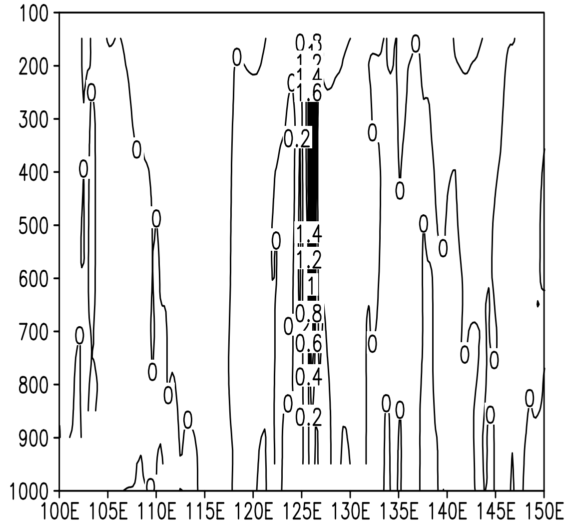

Fig. 5. As in Fig. 4, except for vertical wind speed. Contour interval: 0.2 m s^{-1}.

ssure, is estimated via the National Meteorological Center (NMC) method of averaged forecast difference statistics of the monthly model forecasts for August 2003.

3.2 *Case study*

Typhoon Dujuan in 2003 is first chosen as a case study because it went across the Taiwan Strait and made landfall in South China. The QuikSCAT L2B sea-wind data from 1030 UTC to 1200 UTC on 31 August in 2003 form the observation field data for the 3DVAR. Data assimilation time starts from 1200 UTC on 31 August and the forecasts run for 48 h ending at 1200 UTC on 2 September.

3.2.1 *Wind and pressure fields*

The sea-level pressure and 10-m wind field at 1200 UTC on 31 August 2003 for Typhoon Dujuan without data assimilation shows a cyclonic circulation with a maximum wind speed of 20 m s^{-1} and the center position at 19.1°N, 127.8°E (Fig. 1b) with a 133-km distance error compared with the best-track position (20.2°N, 128.3°E). With data assimilation, the sea-level pressure gradient is relatively larger (Fig. 1a) and the maximum wind speed is 30 m s^{-1} with the center located at (20.3°N, 127.7°E), giving a 64-km error. Meanwhile, comparing the 10-m wind field of the model data with the observed QuikSCAT data, it is clear that the wind field distribution after the 3DVAR is quite close to the observed QuikSCAT data (Figs. 2 and 3). However, the simulation without the data assimilation is not so good in either the wind speed or wind direction.

Data assimilation also increases the horizontal wind speeds of the TC at the initial time (Fig. 4). It is apparent that the vertical cross section of the TC from east to west along 20.2°N has a symmetric configuration of horizontal wind speeds around the TC center. The maximum of the horizontal wind speed increase occurs in the lower troposphere and its secondary center is located in the upper troposphere. The vertical wind speeds are also increased at the center of the TC with a maximum vertical wind speed increase of 1.6 m s^{-1} with data assimilation (Fig. 5).

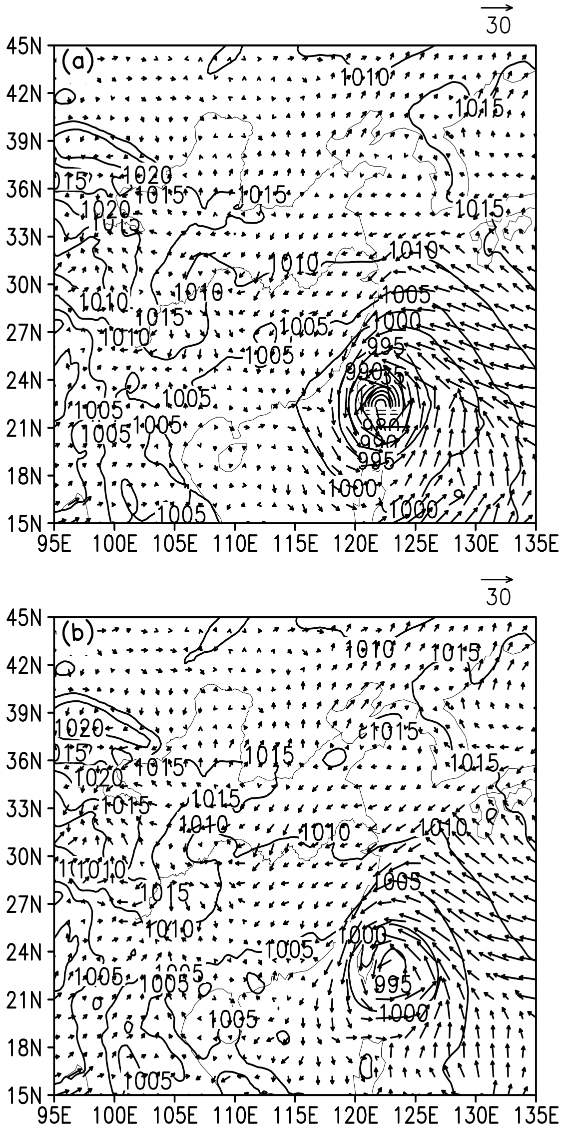

Fig. 6. As in Fig. 1, except for 24-h prediction valid at 1200 UTC on 1 September 2003.

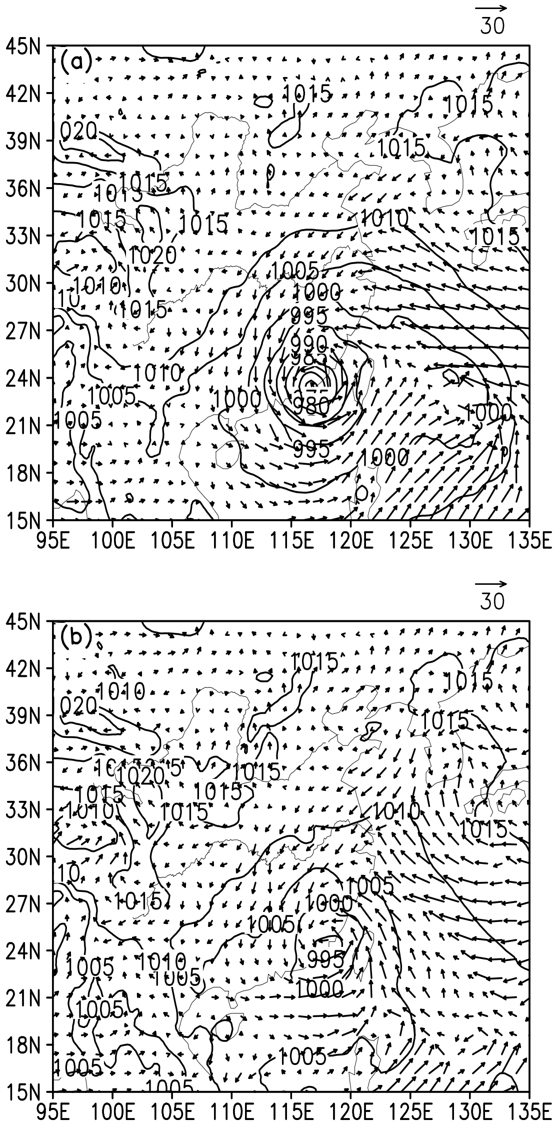

Fig. 7. As in Fig. 1, except for 48-h prediction valid at 1200 UTC on 2 September 2003.

The data assimilation also has a positive impact on the 24-h simulation of the sea-level pressure (Fig. 6). The 24-h simulated sea-level pressure near the TC center without data assimilation is much higher than that with data assimilation, the latter being 955.9 hPa, which agrees very well with the best-track intensity. A similar result is obtained for the 48-h simulation. Without data assimilation, the minimum sea-level pressure is 993.6 hPa versus 968 hPa with data assimilation (Fig. 7), which again is very close to the best-track intensity of 960 hPa.

3.2.2 *Temperature fields*

The QuikSCAT data assimilation also affects the temperature structure of Typhoon Dujuan at the initial time (Fig. 8). Without data assimilation, the initial vertical temperature profile near the typhoon center is quite uniform. The warm core of the temperature anomaly is located at 300 hPa with a maximum anomaly of 2.0°C (Fig. 8b). However, with data assimilation, the initial vertical temperature profile near the typhoon center is much more structured (Fig. 8a). The warm core, located at 128.0°E, is at 200–300 hPa with a maximum anomaly of 6.0°C. It is obvious that the intensity of the warm core with data assimilation is higher. Another warm core can be found near the surface around the typhoon center. This may be a result of full dynamical adjustment not being achieved. Therefore, the warm core has not been completely adjusted to the height of 200–300 hPa yet.

Such an adjustment obviously takes place after integration has started, as can be seen from the evolu-

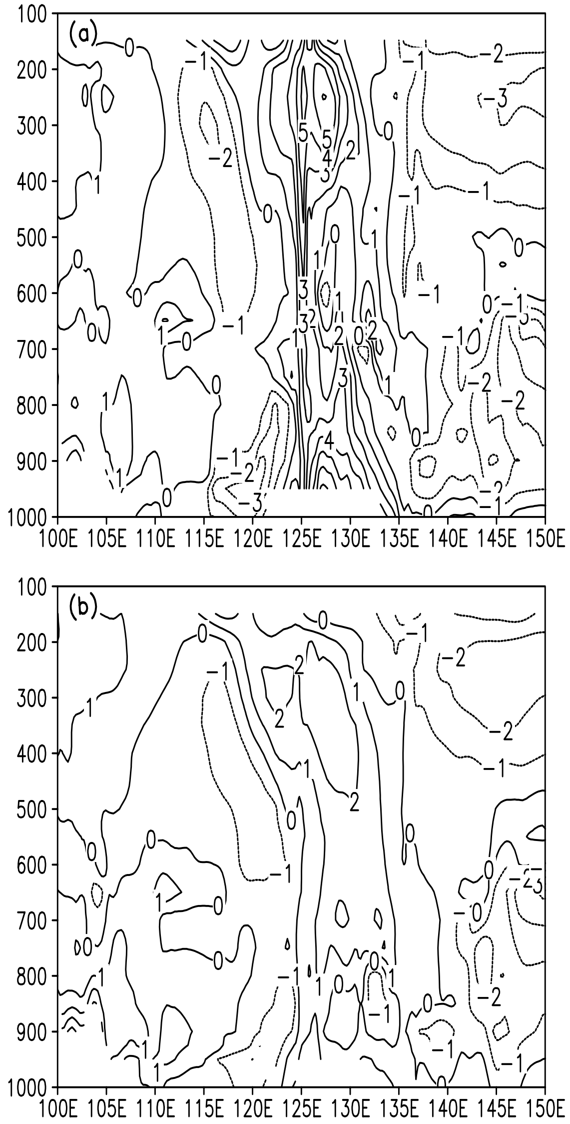

Fig. 8. Temperature anomaly at initial time along 20.2°N (a) with data assimilation and (b) without data assimilation. Contour interval: 1°.

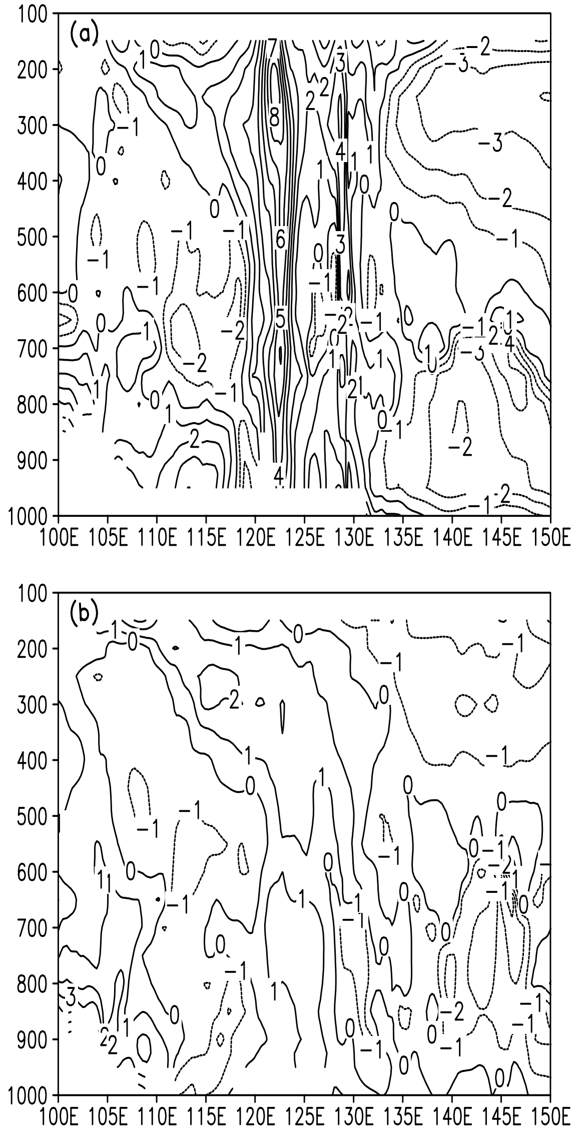

Fig. 9. As in Fig. 8, except for 24-h prediction valid at 1200 UTC on 1 September 2003 and along 21.6°N.

tion of the warm core structure in the 24-h and 48-h forecasts (Figs. 9 and 10). The warm core is reasonably maintained in the experiment with data assimilation compared with that without data assimilation.

The reason why the QuikSCAT surface wind data can improve the overall wind and temperature fields well into the upper troposphere is that 3DVAR uses the background error covariance to propagate the information around, including from the lower to upper levels. When QuikSCAT surface winds are assimilated, they should impact the lower level first, and then the upper level. The influence should be relatively larger at the lower than at the upper levels. The results depend on the length scales and variance scales of the background error covariance. Furthermore, it would be better to use the background error statistics based on one's own model domain (region) and forecasts.

3.2.3 *Track and intensity prediction*

The track prediction of Typhoon Dujuan with data assimilation is better than that without data assimilation, especially for the first 24 h (Fig. 11). The intensity prediction with data assimilation is even better (Fig. 12). The trend of typhoon intensity is very consistent with the observed, particularly for the 24–48 h forecast period. The reason why the use of the QuikSCAT surface wind can improve the track forecast is that the assimilation of the QuikSCAT data produces positive impacts on the structure of TCs in terms of the horizontal and vertical winds, sea-level

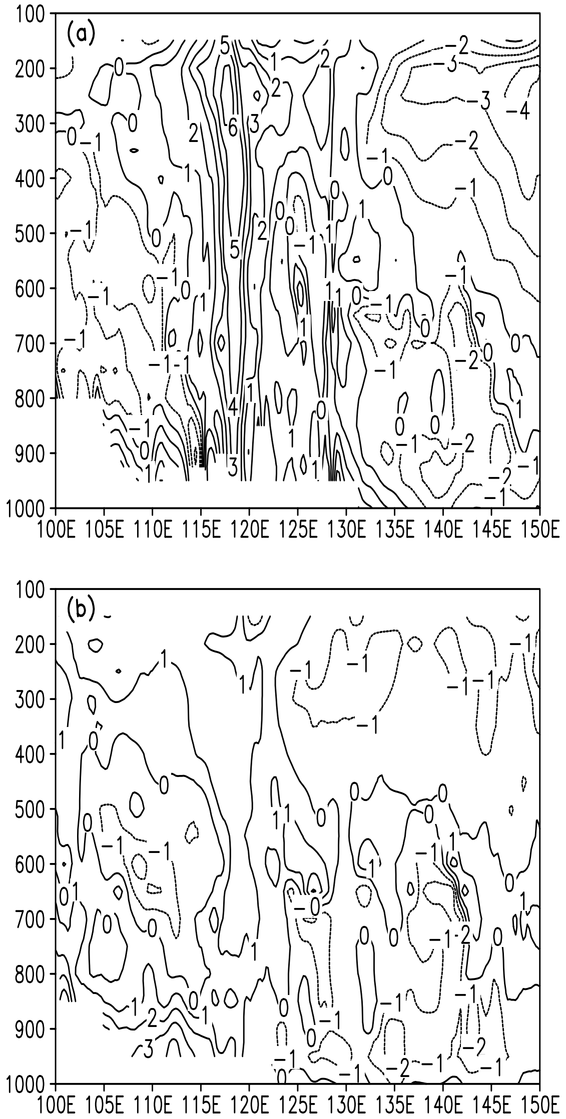

Fig. 10. As in Fig. 8, except for 48-h prediction valid at 1200 UTC on 2 September 2003 and along 22.6°N.

pressure and temperature at the initial time. Moreover, the increase in horizontal wind vectors at 500 hPa at the initial time with data assimilation shows that it can influence the steering flow direction to change towards the southwest (Fig. 13), which agrees well with the best track (see Fig. 11).

3.3 *Expanded sample*

The case study of Typhoon Dujuan (2003) shows that assimilation of QuikSCAT data has some impact on its three-dimensional wind structure, sea-level pressure and temperature at the initial time, as well as improved track and intensity predictions. The question is whether these results can be generalized. To address this question, 12 other typhoon cases in 2003 are chosen. All 12 typhoon cases had their cyclonic circulations almost completely covered by the QuikSCAT swath. The same experiments are performed in each case.

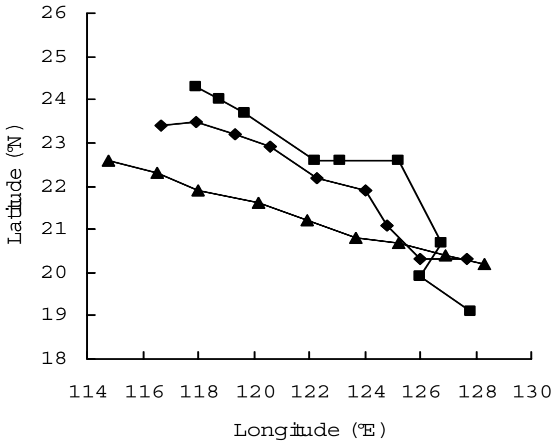

Fig. 11. Track forecasts of Typhoon Dujuan (0–48 h). (Output for each 6 h, the initial position of the real-time typhoon is located at 20.2°N, 128.3°E, ◆: with data assimilation, ■: without data assimilation and ▲: best-track)

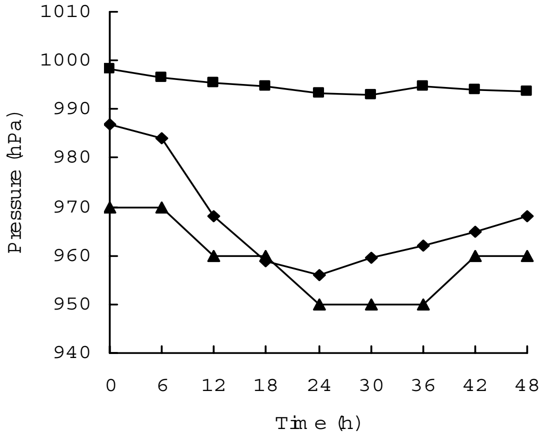

Fig. 12. As in Fig. 9 except for the intensity forecasts.

Of the 12 cases, 11 (10) cases with data assimilation have an improved 24-h (48-h) track prediction (Fig. 14). Notice that in some cases, the improvements are very significant. The average forecast error for the 24-h forecast with data assimilation is 118 km vs. 236 km without data assimilation, and 226 km vs. 452 km for the 48-h forecast. For intensity, 10 (9) cases with data assimilation have improved predictions at 24 (48) h (Fig. 15). Moreover, the average intensity error is 11 hPa with data assimilation vs. 21 hPa without data assimilation for the 24-h prediction, and 11 hPa vs. 18 hPa for the 48-h forecast.

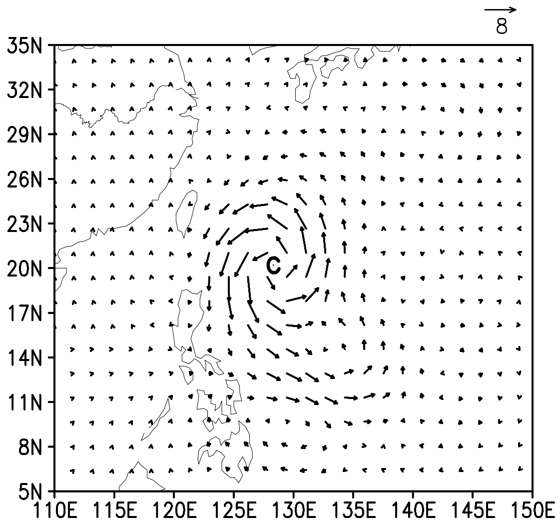

Fig. 13. Increase in horizontal wind vectors at 500 hPa at the initial time with data assimilation. C notes the real-time central position of typhoon Dujuan.

4. Summary and discussion

4.1 *Summary*

The present study examines the effect of assimilating the sea-wind data from QuikSCAT on the prediction of typhoon track and intensity with the three-dimensional variational data assimilation scheme (3DVAR) in the mesoscale model version 5 (MM5) of the US Pennsylvania State University/National Center for Atmospheric Research.

The case of Dujuan is first tested and the results show appreciable improvements. The most encouraging result is that the assimilation of the QuikSCAT data not only produces significant impacts on the structure of Dujuan in terms of the horizontal and vertical winds, sea-level pressure and temperature at the initial time, but it also results in obvious improvements in the track and intensity forecasts.

Twelve other cases in 2003 are then further evaluated in order to determine whether these results can

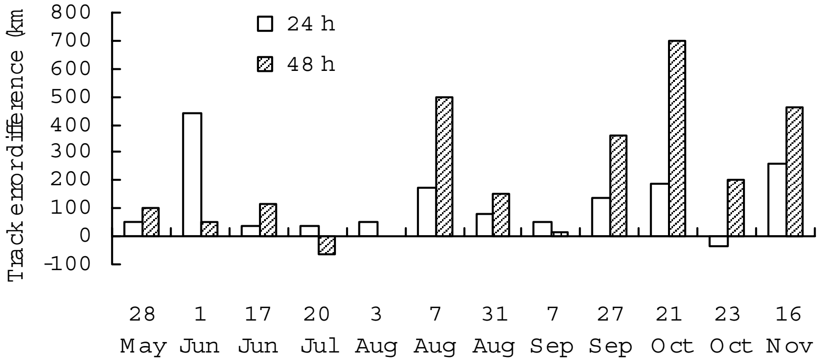

Fig. 14. 24- and 48-h difference (i.e., without assimilation minus with assimilation) in track forecast errors between that without and that with assimilation for each of the 12 cases. A position value indicates a smaller error with data assimilation.

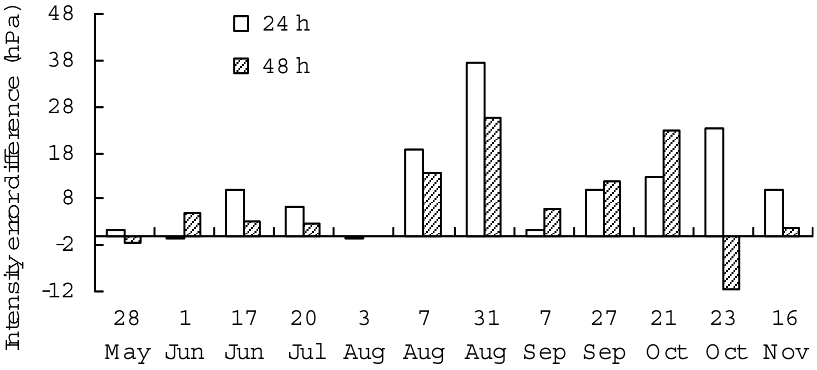

Fig. 15. As in Fig. 14 except for intensity forecast errors.

be generalized or not. These 12 cases, with almost complete coverage by the QuikSCAT swath, show that the improvements in the TC track and intensity forecasts are significant. The 24-h (48-h) track predictions of 11 (10) out of the 12 typhoons are improved with assimilation. The 24-h (48-h) predictions of typhoon intensity are also improved in 10 (9) of the 12 cases with data assimilation.

In summary, the results have shown that assimilating QuikSCAT data provides significant improvements not only in TC structure, but also TC track and intensity forecasts if the TC circulation is almost completely covered by the QuikSCAT swath.

4.2 *Discussion*

Because of the lack of data over tropical regions, one of the major difficulties in TC numerical prediction is TC initialization. Initial vortices provided by the large-scale analysis from operational centers are often ill-defined, too weak, and sometimes misplaced. This may be one of the main reasons for the sometimes large position and intensity errors for TC forecasts. Therefore, it is necessary to find an initialization procedure to produce a more realistic initial vortex. Although the usual initialization method of implanting a bogus vortex based on the TC size, position, and intensity into the model initial state has made many successful predictions of TC movement and structure, detailed procedures of the bogus method vary from one form to another. The model fields of the initial vortex often lack objectivity with dynamic and physical consistency.

In recent years, the data assimilation method is playing an increasingly important role for TC forecasts because it can offer an optimal way to produce the best possible estimate of the TC model initial state through combining observations and background information. In this study, it is evident that assimilation of the QuikSCAT data has successfully improved the TC initial fields and patterns as well as the TC track and intensity forecasts with the MM5 three-dimensional variational data assimilation scheme. The improvements presented here for 12 cases of TC predictions have demonstrated such potential benefits for operations so that a research initiative is currently underway to extend the work. It has to be emphasized that the 12 TC cases in this study represent the best situations for the QuikSCAT data assimilation because their circulations were almost completely covered by the QuikSCAT swath. However, the situation of other TCs only partially covered by the QuikSCAT swath must be considered if the QuikSCAT data assimilation for TC forecasts is to go into operation. It is therefore an important task that more verification of data assimilation forecasts of TCs partially covered by the QuikSCAT swath should be carried out in the future.

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