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Impact on the tropical cyclone "Vongfong" forecast using the QuikSCAT wind data

LIU Chunxia[1,2]*, QI Yiquan[2], WANG Jing[2,3], WAN Qilin[1], CHU Peter[4]

1. Guangzhou Institute of Tropical and Marine Meteorology, Chinese Academy of Sciences, Guangzhou 510080, China
2. LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301,China
3. Remote Sensing Center, Zhongshan University, Guangzhou 510275,China
4. Naval Postgraduate School, Monterey, CA, USA

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Abstract

Since QuikSCAT is available in cloudy and rainy condition, its wind data are valuable in monitoring and real time forecasting the wind field, especially in sparse genesis regions of tropical cyclones. In order to understand and investigate the impact of QuikSCAT wind data, the three-dimensional variational data assimilation (3D-VAR) of scatterometric wind data has been employed for the tropical cyclone "Vongfong" in the year 2002. The result shows that the QuikSCAT wind data have positive impact on the analysis and forecasting. But the positive impact is slight. The present results suggest that how to assimilate QuikSCAT wind data effectively is important and will be a challenge to meteorologists.

Key words: QuikSCAT wind data, 3D-VAR assimilation, tropical cyclone

1 Introduction

Satellites offer an effective way to fill data voids, and also provide higher-resolution data than the conventional observations by ships and buoys on the sea. Up to now, satellites can be used to observe many marine factors, such as the surface sea temperature, wind speed and its direction, tropical rain and so on(Qi et al., 1996; Qi et al.,1998; Wang, 2001; Wang et al., 2000). How to use these data effectively in the operational weather prediction is always a challenge to us. The two-fold goals of this study are to describe how the scatterometric data are assimilated and evaluate the impact of the assimilation of the scatterometric data from the QuikSCAT.

Satellite scatterometer observation of the sea surface wind speed and its direction can improve the depiction of storms at sea. Some storms in their early stages are too small to be resolved by any operational numerical weather prediction products, and there is no obvious cloud signal. However, the scatterometer is available to study vortices. For instance, Liu (2001) used the QuikSCAT wind data to track such sea surface vortex in its early stage. A review on the application of scatterometric wind data in monitoring

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* Corresponding author, E-mail: cxliu@grmc.gov.cn

and understanding storms and in other weather systems was given by Liu(2002). The role of scatterometer data in monitoring and understanding storms was well-recognized in the past decade also (Veldoe et al., 2002).

The impact of scatterometer on numerical weather prediction has been studied for about 20 a. The studies demonstrated that satellite surface wind data had great potential in improving ocean surface analysis and numerical weather prediction, and suggested that the improved surface wind velocity data from advanced scatterometers such as European remote sensing satellite (ERS–1, ERS–2), NSCAT (National Aeronautics and Space Administration scatterometer) and QuikSCAT would result in an even further improvement in weather forecast. The study of Duffy and Atlas(1986) showed that the use of SASS winds resulted in a significant improvement in prediction of the storm Queen Elizabeth II. Stoffelen and Cats's (1991) study also showed that the scatterometer data could provide useful information in a small scale that could not be observed by other approaches. In order to assess the impact of ERS–1 scatterometer data, assimilations and forecasts using various combinations of simulated data in the Goddard earth observing system(GEOS–1) were performed and evaluated (Atlas et al.,2001). Its result showed that both the direction and speed information of ERS–1 are contributing to improving the analyses and forecasts of GEOS–1 in the Southern Hemisphere extratropics. In the Northern Hemisphere extratropics and tropics, however, the impact of ERS–1 on GEOS–1 model forecasts was negligible. Stoffelen and Anderson (1997) studied the impact of ERS–1 winds on the more recent operational version of the European Center for Medium-Range Weather Forecasts (ECMWF) data assimilation system (DAS), and, in their experiment, the analysis was clearly improved, but there was no significant improvement in the forecast accuracy beyond 12 h. In contrast, the results reported by Andrew and Bell (1998), who used the global DAS of the United Kingdom Meteorological Office (UKMO), showed substantial improvement in analysis and forecast accuracy in the Southern Hemisphere extratropics when ERS–1 wind vectors were assimilated. A series of data assimilation experiments were conducted to test the impact of NSCAT wind data in the global DAS of the National Centers for Environmental Prediction (NCEP) (Atlas et al., 1999). Their results indicated that the NSCAT wind data had a small positive impact in the Southern Hemisphere extratropics, but in the Northern Hemisphere extratropics the impact was neutral. The results of the initial evaluation of QuikSCAT demonstrated the potential for QuikSCAT wind data to improve meteorological analyses and forecasts, but also indicated that ambiguity removal and rain contamination problems limited the application of QuikSCAT wind data assimilation (Atlas et al., 2001), and their further results showed that there were a slight positive impact of QuikSCAT in the Northern Hemisphere extratropics and a larger positive impact in the Southern Hemisphere extratropics using the GEOS–3 data assimilation system. The early ECMWF QuikSCAT experiments also showed that there were only small positive and negative impacts on the global scores of forecast skill, but on particular storms and other regional-scale meteorological features the impacts are occasionally very positive (e.g., Figa and Stoffelen, 2000). Therefore most of the experimental results indicated that there were positive impacts of the assimilation of scatterometer on analysis and prediction of storms by using a regional numerical model.

However, how is the impact of scatterometer wind data on storm analysis and forecasting in the South China Sea? Up to now, the impact has been unknown. Thus, in this paper, the experiments with and without assimilation of scatterometer wind data are preformed, respectively. The data assimilation methodology used in the numerical weather prediction is outlined below, and the results of the experiments with assimilation of scatterometer winds are described. At the end, the main conclusions of the paper are presented, and some remaining problems are discussed.

2 Methodology of assimilation

2.1 QuikSCAT wind data

The National Aeronautics and Space Administration SeaWinds scatterometer on the QuikSCAT satellite is a specialized microwave radar that can be used to obtain near-surface wind speed and direction over the global oceans. QuikSCAT was launched on June 19, 1999, and has provided an almost continuous stream of measurements. The SeaWinds instrument uses a rotating dish antenna with two spot beams which, after processing of the backscatter data, provide wind measurements at 25-km grid spacing along 1 800-km-wide swath centered on satellite's nadir subtrack. The direction of wind is typically less accurate on the edges of the swath, where only one beam is available. The two problems of wind directions ambiguity and rain contamination must be noticed. In this study, the QuikSCAT wind data are the 3-level data supplied by the Jet Propulsion Laboratory (JPL) and the wind direction ambiguity removal has been done.

2.2 Method of data assimilation

The 3D–VAR assimilation method is used to assimilate QuikSCAT wind data in the paper. The assimilation method is based on the 3D–VAR assimilation system of the global and regional assimilation and prediction enhanced system (GRAPES) developed by the Innovative Research Center of National Weather Prediction (NWP) in China. It is applied to Arakawa-A longitude and latitude grid point in the horizontal coordinate and *P* plane in vertical coordinate in the GRAPES 3D–VAR assimilation system. The increment method is applied to calculating the cost function, and the LBFGS method is used to solve the minimization of the cost function. The control variables, which are geopotential height (or temperature), relative humidity (or absolute humidity), stream function and velocity potential, are different from model variables, and physically independent on each other in the assimilation system. The geostrophic balance is used to transform model variables to control variables. The cost function $J(X)$ and the grads of $J(X)$ in the GRAPES assimilation system are as follows:

$$J(X)=\frac{1}{2}\Big[(X-X_{\mathrm{b}})^{\mathrm{T}}B^{-1}(X-X_{\mathrm{b}})+(y-y_{\mathrm{o}})^{\mathrm{T}}O^{-1}(y-y_{\mathrm{o}})\Big],$$

$$y=\mathrm{H}(X),$$

$$\nabla J(X)=\left(B^{-1}+\mathrm{H}^{\mathrm{T}}O^{-1}\mathrm{H}\right)\times(X-X_{\mathrm{b}})-\mathrm{H}'O^{-1}[\mathrm{H}(X)-y_{\mathrm{o}}],$$

$$\mathrm{H}'=\frac{\partial H}{\partial X},$$

where X is the control variable; X_{b} is the background field; B is the covariance of background field error; O is the covariance of observational field error; y is the simulated observational value from background; y_{o} is the observational value; H is the observational operator; and H' is the tangential operator of the observational operator.

In the assimilation, the QuikSCAT wind data are assimilated according to the following formula:

$$J(X)=\frac{1}{2}\Big[(X-X_{\mathrm{b}})^{\mathrm{T}}B^{-1}(X-X_{\mathrm{b}})+(y-y_{\mathrm{o}})^{\mathrm{T}}O^{-1}(y-y_{\mathrm{o}})\Big]+J_{\mathrm{scat}},$$

$$J_{\mathrm{scat}}=\frac{\left(u_{10}-u_{\mathrm{scat}}\right)^{2}+\left(v_{10}-v_{\mathrm{scat}}\right)^{2}}{2\sigma_{\mathrm{scat}}^{2}},$$

and the grads of $J(X)$:

$$\nabla J(X)=\left(B^{-1}+\mathrm{H}^{\mathrm{T}}O^{-1}\mathrm{H}\right)(X-X_{\mathrm{b}})-\mathrm{H}'O^{-1}[\mathrm{H}(X)-y_{\mathrm{o}}]+\nabla J_{\mathrm{scat}}\ ,$$

where u_{scat} and v_{scat}, are the retrieved scatterometer wind; and σ^2_{scat} is the error variance of retrieved scatterometer wind components. The retrieved scatterometer wind is regarded as the observational wind at 10 m height, and u_{10} and v_{10} is the simulated observational value at 10 m height. In fact, stream function and velocity potential are instead of the u and v in the wind assimilation as in the GRAPES.

Here, the important problem is how to calculate the value of σ^2_{scat}. Liu and He (2003) have calculated the σ^2_{scat} by comparing QuikSCAT wind data with island wind in the South China Sea. The σ_{scat} is 3.6 m/s . In this paper, there are 14 levels in the vertical coordinate, which are 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70 and 50 hPa. The region is 0°~50°N, 80°~160°E, and the resolution is 50 km in horizontal coordinate.

2.3 Weather research and forecasting (WRF) model

The WRF model is used to predict intensities and tracks of the tropical cyclone "Vongfong" in this study. The model is a next-generation mesoscale model in USA, and it is jointly developed by several organizations, including the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL)/ National Oceanic and Atmospheric Administration (NOAA), the Center for the Analysis and Prediction of Storms (CAPS) at University of Oklahoma, the National Aeronautics and Space Administration (NASA), the Air Force Weather Agency (AFWA), and a number of collaborating institutes and universities. The WRF model can be applied to real weather simulations, as well as idealized studies. The model is designed to be platform independent, and it can be executed on both shared and distributed machines. The application of the WRF model focuses on simulations with a resolution of 1~10 km, though it may also be applied to lower resolution. The WRF is a fully compressible nonhydrostatic model, and its governing equations are written in flux form for the purpose of conservation of mass, dry entropy, and scalars. Two vertical coordinates are used such as terrain following height and terrain following hydrostatic pressure coordinate. Instead of using a B grid as in MM5 model, the WRF chooses an Arakawa C grid to gain a better accuracy in higher horizontal resolution simulations.

In this paper, 50 km horizontal resolution is used in forecasting experiments. There are 28 levels in vertical coordinates. The physical schemes applied are NCEP 3-class simple ice scheme (vapor, cloud/ice and rain/snow), RRTM longwave radiation scheme, Duhia shortwave scheme, Monin–Obukhov surface layer and thermal diffusion land surface layer scheme, and MRF boundary layer scheme, Betts–Miller–Janjic cumulus scheme.

3 Results

The analyses and forecasting experiments with and without the scatterometer winds assimilation were preformed at GMT 12:00 on August 17, 2002. At this time the tropical cyclone "Vongfong" was in the early stage and its intensity was weak. The QuikSCAT wind data are from the JPL, and T213 is the background field in the assimilation system. Two experiments were performed. One is the control experiment without the QuikSCAT wind data, and the other is the QuikSCAT data assimilation experiment. Their results of analysis and prediction are as follows.

3.1 Impact on tropical cyclone analysis

Figure 1 displays the 1 000 hPa analytic wind field from the control experiment, which is preformed without the scatteromter winds assimilation. Figure 2 shows the 1 000 hPa analytic wind field with scatterometer winds assimilation. Comparing Figs 1 with 2, the different points between them are as follows.

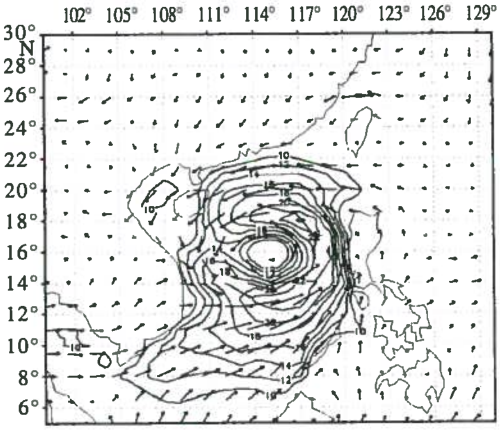

Fig. 1. 1 000 hPa wind (m/s) field from the control experiment at 12:00 Z, August 17,2002.

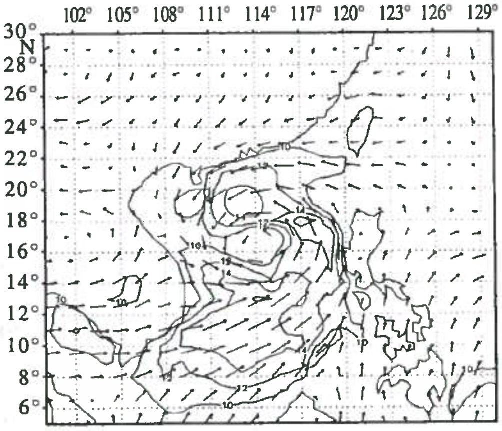

Fig. 2. 1 000 hPa wind (m/s) field from the QuikSCAT wind data assimilation experiment at 12:00 Z, August 17, 2002.

(1) The obvious difference is in the strong wind structure of tropical cyclone and maximal wind speed near the center of tropical cyclone. The maximal wind speed in Fig. 1 is over 22 m/s, bigger than that in Fig. 2. The observational maximum surface wind is less than 20 m/s, and at this time the maximum surface wind speed reported by Guam Forecast Office is 30 kt, which means the wind speed is approximately 15 m/s, and according to the best track given by the Central Meteorological Office, China Meteorological Administration (CMA), the maximum surface wind speed is 15 m/s. It shows that the assimilated QuikSCAT wind data can improve the tropical cyclone intensity, which is referred to maximal wind speed near the center of tropical cyclone.

The meso-scale wind structure in the wind data assimilation experiment is also clearer than that in the control experiment.

(2) Another difference is that the TC position in the control experiment is located in the south of 16°N, but that in the scatterometer winds assimilation experiment is located in the north of 16°N at the level 1 000 hPa. The TC center positions at the level 850 hPa in the two experiments (see Table 1) are different too. Comparing them with the TC position of best track given by the Central Meteorological Office, CMA, the TC position in the assimilation experiment is better than that in the control experiment. Therefore, the assimilation with the QuikSCAT wind data has positive effect on tropical cyclone "Vongfong" intensity and position analysis at low level.

How does the QuikSCAT wind data influence the higher layer wind and relative humidity fields? Figure 3 describes the vertical change of wind from 90° to 135°E along 16°N. The results in Fig. 3 show that the bigger difference wind speed is in the area of tropical cyclone circulation between 14° and 18°N, 110° and 120°E (see Fig. 4), and this wind difference also extends to above 700 hPa. The difference of wind speed between the assimilation experiment and the control experiment is negative. That means the wind speed from the control experiment is bigger than that from the assimilation experiment. In other words, the storm intensity of assimilating experiment is weaker than that in the control

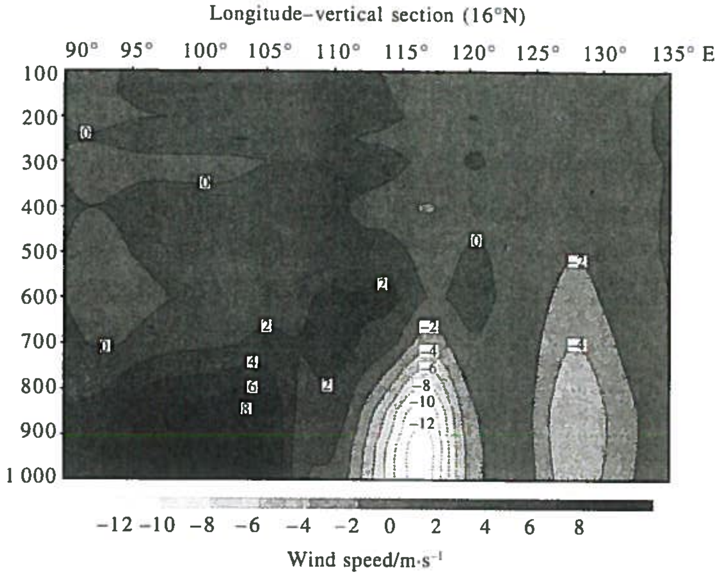

Fig. 3. The difference between the wind speeds in the QuikSCAT wind data assimilation experiment and the control experiment at 12:00 Z (GMT), August 17, 2002.

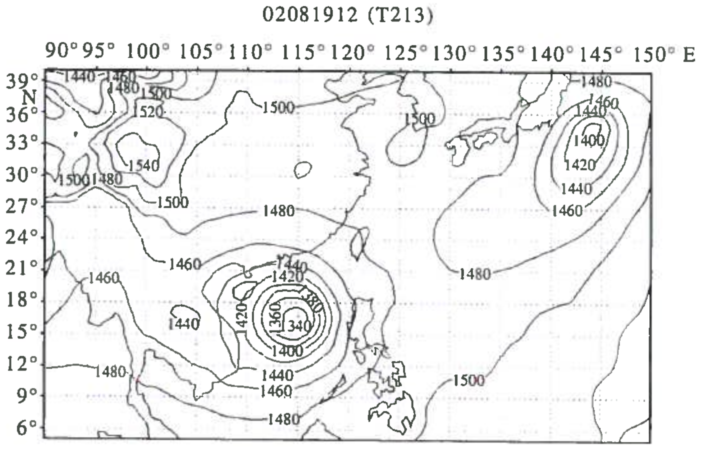

Fig. 4. T213 850 hPa geopential height (m).

experiment.

To sum up, these results show that the QuikSCAT wind data assimilation can improve the TC's analysis intensity and position. The wind data assimilation using 3D–VAR can affect the wind and geopotential height fields at the boundary layer or higher level, although the QuikSCAT wind data are assimilated only at the surface.

3.2 Impact on tropical cyclone forecast

In order to investigate the impact of scatterometer wind data, the forecasting experiments with and without the QuikSCAT wind data assimilation are performed. Table 1 displays 48 h intensity forecasting to "Vongfong" with and without scatterometer wind data assimilation, and Table 2 displays 48 h track forecasting to "Vongfong" in the above two experiments. Table 1 indicates that the maximum wind speeds at surface in the control experiment are bigger than those in the experiment with scatterometer wind data assimilation, and the latter is closer to the

Table 1. 48 h intensities prediction with and without the QuikSCAT wind data assimilation and the observation. v_{max} means the maximum wind speed of tropical cyclone center, and SLP_{min} means the minimum sea level pressure of tropical cyclone center

Time (GMT)	Observation		Control experiments		QuikSCAT wind data assimilated experiments	
	v_{max}/m·s^{-1}	SLP_{min}/hPa	v_{max}/m·s^{-1}	SLP_{min}/hPa	v_{max}/m·s^{-1}	SLP_{min}/hPa
2002-08-17-12:00	15	990	24	993	17	993
2002-08-17-18:00 (6 h forecasting)	18	990	40	978	32	980
2002-08-18-00:00 (12 h forecasting)	18	988	46	982	40	985
2002-08-18-06:00 (18 h forecasting)	20	985	47	970	44	970
2002-08-18-12:00 (24 h forecasting)	20	985	48	978	40	981
2002-08-18-18:00 (30 h forecasting)	20	985	37	968	41	974
2002-08-19-00:00 (36 h forecasting)	23	985	32	980	35	982
2002-08-19-06:00 (42 h forecasting)	25	980	32	972	28	972
2002-08-19-12:00 (48 h forecasting)	30	980	30	982	24	985

Table 2. 48 h track prediction with and without the QuikSCAT wind data assimilation and the best track

Time	Best track		Control experiments			QuikSCAT wind data assimilated experiments		
	North latitude/(°)	East longitude/(°)	North latitude/(°)	East longitude/(°)	distance error/km	North latitude/(°)	East longitude/(°)	distance error/km
2002-08-17-12:00	16.5	113.4	16.1	114.9	115.0	16.1	114.7	132.5
2002-08-18-00:00 (12 h forecasting)	16.5	113.0	16.5	114.8	85.3	16.8	113.8	91.5
2002-08-18-12:00 (24 h forecasting)	17.1	112.0	16.2	113.9	170.8	16.5	113.2	144.0
2002-08-19-00:00 (36 h forecasting)	18.5	111.8	16.6	114.2	299.2	16.7	113.8	291.4
2002-08-19-12:00 (48 h forecasting)	21.1	110.7	17.4	114.0	529.9	17.2	113.8	541.9

observational TC intensities. The results from the two experiments show that scatterometer wind data assimilation can improve the 6~36 h forecasting intensity of control experiments, because the intensity prediction error of control experiment is bigger than that of assimilation experiment, and 6 hPa over than that of assimilation experiment. And the maximum difference of wind speed between two experiments is about 8 m/s. The intensity predication error referred to the sea pressure and the wind speed in the control experiment is bigger slightly than that in the assimilation experiment. In other words, the results from the prediction experiments show that the QuikSCAT wind data assimilation can improve 6~36 h intensity prediction of tropical cyclone.

For the track prediction (Table 2), the prediction results show that the 12 h prediction distance error in the control experiment is less than that in the assimilation experiment. However, the 24~36 h distance error is bigger than that in the assimilation experiment. So, the results indicate that the assimilating experiment could improve the 24~36 h track prediction of tropical cyclone. But the impact of assimilation on the 12 h track prediction is negative. And the results also show that the 12 h prediction distance error is less than 100 km, and the 24 h distance error is less than 200 km. So the track prediction can be regarded availably.

However, the 48 h prediction is not good. Figure 4 shows the 48 h prediction at the level 850 hPa of T213. According to Fig. 4, the TC center is in the south of 18°N, and in the experiment the T213 analysis and prediction are used as boundary condition and assimilation background field. For the 48 h prediction, the impact of preliminary condition on prediction becomes relatively weaker than that of boundary condition. So, the big distance error of 48 h TC prediction could be due to the error of T213 itself.

Therefore, we realize that assimilation experiment can improve TC intensity prediction and track prediction. But the impact of assimilating QuikSCAT wind data on TC prediction is positive slightly. In succession, we focus on the vertical change of physical fields when the QuikSCAT wind data are assimilated. Analyzing the mean fields such as geopotential height, wind speed and relative humidity of TC circulation (Fig. 5), we can find that the difference of geopotential height between control and as-

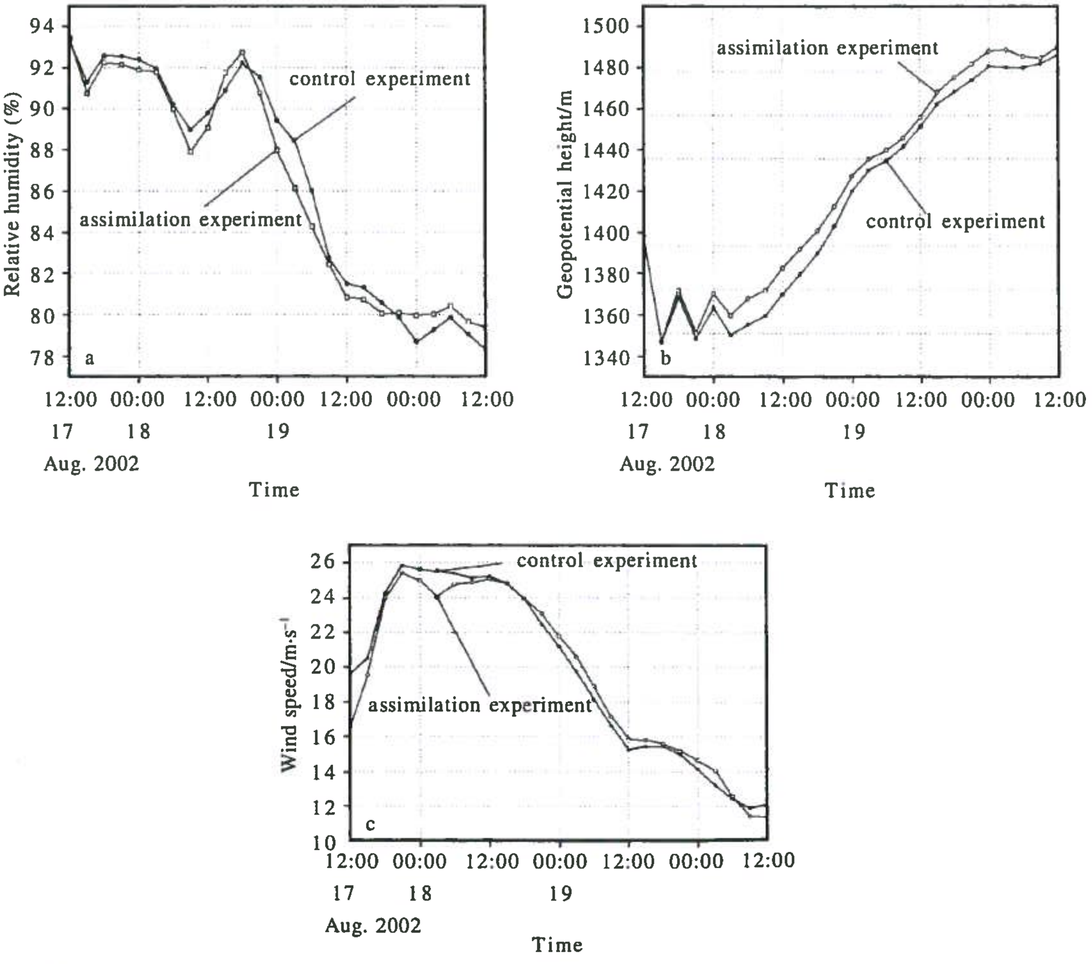

Fig. 5. Regional mean of relative humidity (a), regional mean of geopotential height (b) and regional mean of wind speed in the control experiment and the assimilation experiment at 850 hPa (c).

similation experiments is less than 10 m, the difference of wind speed is less than 30 m/s, and the difference of relative humidity is less than 5%. The differences of geopotential height and relative humidity are close to observational errors among these physical fields. On the other hand, in order to investigate why the TC intensity and track forecasting improve ineffectively by the QuikSCAT wind data assimilation, here we present Fig. 6. Figure 6 shows that the wind speed difference between control experiment and assimilation experiment is less than 10 m/s or so, and the difference of geopotential height is 10~30 m, the difference of temperature is 1.5~2.0 °C, and the difference of relative humidity is less than 5%. The results indicate that these differences may be close to the observational error. So, from Figs 5 and 6, it is realized that the assimilation only at the surface layer results in just a little improvement to the TC circulation prediction in the boundary layer, and the improvement only lasts for 36 h. The analysis experiments show that the impact of assimilation on surface wind is effective, but the impact of assimilation on surface wind is ineffective to the TC prediction.

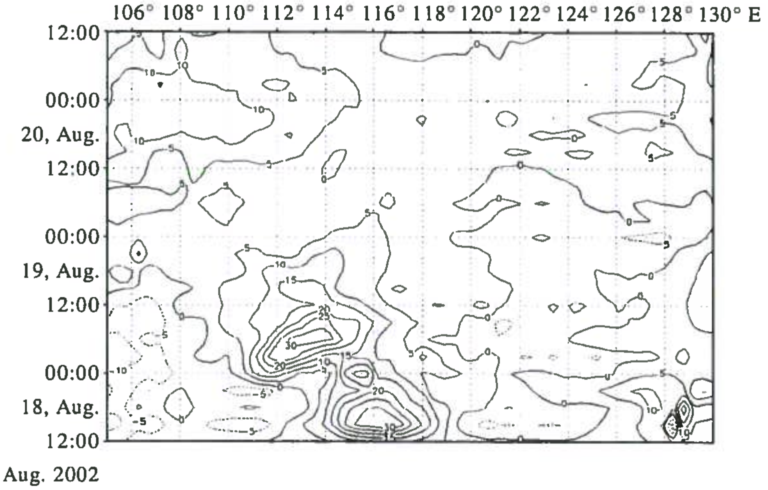

Fig. 6. Geopotential height (m) difference between the assimilation experiment and the control experiment.

4 Conclusions and discussion

This paper describes the impact of QuikSCAT wind data assimilation on the TC intensities and tracks analysis and prediction by the experiments with and without the QuikSCAT wind data, and the results show that the QuikSCAT wind data assimilation can improve the TC center intensities and surface wind structures. The QuikSCAT wind data are only put on the lowest level of the model with the 3D–VAR assimilation system, but their effect extends from surface through mid-high layers.

For forecasting experiments, the forecasts from 6 to 24 h show that the QuikSCAT wind data assimilation has positive impact on the TC intensities and especially surface wind and sea level pressure. The forecasting experiments show that the QuikSCAT wind data assimilation affects the TC intensities, center position and tracks. The prediction results indicate that the 12 h track predication in the assimilation experiment is slightly worse than that in the control experiment. But, for the 24 h track prediction, the forecasting of the assimilating

QuikSCAT wind data experiment is better than that of the control experiment, and the distance error of QuikSCAT wind data assimilation experiment is 26.8 km less than that in the control experiment.

However, the TC intensities both in the control and assimilation experiments are stronger than observation. The TC tracks from the two forecasting experiments are not satisfactory due to unperfect background fields from T213. But the results also show that the QuikSCAT wind data assimilation has positive impact on the analysis and forecast of the TC intensity and track.

Therefore, this preliminary study indicates the impact of the QuikSCAT wind data assimilation on the TC analysis and prediction, and the results suggest that the QuikSCAT wind data assimilation can improve the TC analysis and forecast. However, the impact of the QuikSCAT wind data is slight for the forecasts. The possible reason is that the background fields in the data assimilation system influence the prediction. So, the impacts of the scatterometer wind data on the numerical weather prediction have a dependency on the data assimilation system used to conduct the experiments. Perhaps two problems should be attended here to new data like the QuikSCAT wind data. The first is the issue of data redundancy, that is, does the new data resource provide new information to the data assimilation system (DAS)? It maybe depends on the skill of the DAS and the type and the quality of data being assimilated. The second is whether the new data have been effectively utilized. Perhaps some demonstrable improvements in analysis could be rejected in a forecasting model. Data rejection typically occurs when a single variable or level is improved without consistent balanced increments to other variables and levels. For the scatterometer data we know that effective utilization requires that the assimilation properly treats the nature of these data, correctly weights the data, accounts for the observational errors, and allows the data to influence other variables and levels.

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