Front. Earth Sci. 2015, 9(2): 192–201
DOI 10.1007/s11707-014-0461-8

RESEARCH ARTICLE

Assimilation of HY-2A scatterometer sea surface wind data in a 3DVAR data assimilation system–A case study of Typhoon Bolaven

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Abstract The scatterometer (SCAT) on-board China's HY-2A satellite has the capability to provide high resolution wind vector information over the global ocean surface. These wind vector data produced by the HY-2A scatterometer (HY-2A SCAT) are available to the data assimilation system with real-time information of high accuracy. In this paper, two experiments are designed to investigate the impact of HY-2A SCAT data in the three-dimensional variational assimilation system for the Weather Research and Forecast model (WRF 3DVAR). The powerful Typhoon Bolaven, which struck South Korea in August 2012, is selected for this case study. The results clearly demonstrate that HY-2A SCAT data can effectively complement the scarce observations over the ocean surface and improve the prediction of the wind and pressure fields of a typhoon. The case study of Typhoon Bolaven exhibits the significant and positive impact of HY-2A SCAT data on the numerical prediction of the tropical cyclone track.

Keywords HY-2A, scatterometer, data assimilation, sea surface wind, 3DVAR

1 Introduction

On 15 August 2011 (UTC), the China National Space Administration (CNSA) launched the HY-2A satellite. HY is an acronym for Hai Yang, which means ocean in Chinese (Yan, 2004). The major objective of the HY-2 mission is to measure ocean dynamic and environmental parameters in the microwave region (Lin, 2008). The main payload of the HY-2A satellite is a scanning scatterometer operating in the Ku-band, which is dedicated to the measurement of the surface winds. Space-borne scatterometers are commonly used to provide accurate information on the speed and direction of the sea surface wind. Accurate knowledge of the ocean surface wind fields is important for a wide range of applications, e.g., EI Nino prediction and monitoring, near-real-time assimilation into numerical weather prediction models (NWP), as well as climate studies (Dong et al., 2004). Since the launch of the first European Remote Sensing Satellite (ERS-1) in July 1991, global coverage of scatterometer data has been available without interruption by accessing the 22-year data record; that is until now.

With the development of observation technology, the amount of meteorological observations has become increasingly plentiful. However, observations for tropical cyclones (TCs) remain insufficient (Rogers, 2003) for various reasons, such as the satellite infrared data being affected by clouds, or the insufficient size of the initial vortex in a large-scale analysis field (Li et al., 2013). The lack of observation data regarding the initial conditions in the TC model will greatly reduce the accuracy of the TC prediction. The scatterometer, with its high spatial resolution, is one of the best instruments for monitoring early vortexes, their tracks across the ocean, and the evolution into full-blown hurricanes/typhoons (Liu, 2002). Global coverage of scatterometer data has been routinely available (Tomassini et al., 1998) to forecasters and researchers since the 1990s. The assimilation of the scatterometer wind data from the ERS-1 and the Second European Remote Sensing Satellite (ERS-2) started in January 1996 at the European Centre for Medium-Range Weather Forecasts (ECMWF). However, the ERS satellite does not always provide adequate coverage (Andrews and Bell, 1998; Rufenach, 1998) of TCs due to their narrow swaths (~ 500 km). This situation changed following the

Received September 2, 2013; accepted March 24, 2014

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launch of the NASA Quick Scatterometer (QuikSCAT) satellite in 1999, due to the capability of the onboard SeaWinds instrument (with a wide swath of 1,800 km) to offer near-continuous daily coverage of over 90% of the tropical oceans (Ebuchi et al., 2002). Since the failure of QuikSCAT and the permanent switch-off of the ERS-2 satellite, only the surface wind data from the Advanced Scatterometer (ASCAT) instrument on the Meteorological Operational satellite (METOP) and the scatterometer onboard the Oceansat-2 satellite (OSCAT) have been actively assimilated.

Many research studies have demonstrated that a scatterometer provides valuable information about the ambient surface wind fields in which tropical cyclones are embedded (Katsaros et al, 2002; Leidner et al., 2003). However, to the authors' knowledge, studies with detailed descriptions about the data assimilation of HY-2A SCAT are not currently available in any literature. The focus of this research is to investigate the impact of HY-2A SCAT data assimilation in the WRF 3DVAR under typhoon conditions. We conducted two assimilation experiments: one with and one without HY-2A SCAT. These experiments are denoted "HSCAT" and "CTRL," respectively. The study about HY-2A SCAT wind observations is motivated and inspired by the ongoing research in this area, and the results from our experiments can provide useful information for assimilating these observations in the operational system in the future. The remainder of the paper is organized as follows. Section 2 outlines the features of HY-2A SCAT. The assimilation methodology and the various aspects involved in the application of the TC observations are described in Section 3. In Section 4, a detailed analysis is presented for two groups of the data assimilation experiments regarding HY-2A SCAT wind observations, with TC Bolaven from August 2012 as the weather case study. Finally, conclusions and a discussion are presented in Section 5.

2 HY-2A SCAT wind data

2.1 Sensor characteristics and wind retrieval method

HY-2 is a second generation ocean observation satellite series approved by CNSA, Beijing in February 2007. The HY-2A mission represents a follow-up of the HY-1A and HY-1B missions. After being launched into space in 2011, the HY-2A spacecraft has been operated by the National Satellite Ocean Application Service (NSOAS); HY-2A was designed to have a nominal lifetime of three years. The HY-2A satellite revolves at a height of 970 km in a near-polar Sun-Synchronous Orbit with 99.3° inclination around the Earth. The SCAT is a Ku-band (13.256 GHz) pencil-beam conically scanning radar scatterometer. The SCAT uses a full-deramp pulse compression receiver with linear frequency modulation (LEM) capability, which increases the number of independent measurement samples to improve the measurement precision. The footprint used to determine the winds changes from 37 to 33 km, and the horizontal polarization beam HH and vertical polarization beam VV are at incidence angles of 41° and 49°, respectively. The swath is 1800 km (Wang et al., 2012) and covers 95% of the ocean surface in 24 h. The ground resolution is 25 km, and the analysis frequency is 13.256 GHz. The wind speed range of HY-2A SCAT is 2−24 m/s with an accuracy of 2 m/s or 10% of the maximum value. The wind direction range is 0−360°, and the wind direction precision is 20°.

Space-based scatterometers operating on polar-orbiting satellites provide both wind speed and direction through multiple looks at any one pixel in the swath as the spacecraft travels over the surface (Katsaros et al., 2001). Two wavelength bands, at frequencies of approximately 5 and 14 GHz (C-band and Ku-band, respectively), have been used with satellite scatterometers (Singh et al., 1986). The higher frequencies of the Ku-band allow greater sensitivity at low wind speeds into the wind direction, but exhibit greater influence from atmospheric precipitation compared to the lower frequencies of the C-band. The ocean surface wind vectors are retrieved from the geophysical model functions (GMF), which are largely based on empirical fits to the data (Hilburn et al., 2006).

2.2 Comparison of HY-2A SCAT wind speed measurements with buoy measurements

To illustrate the precision of the HY-2A SCAT wind data, buoy observations from the National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA) were selected for comparison with the HY-2A SCAT wind data in August 2012. The locations of NOAA/NDBC buoys are shown in Fig. 1(a). There were 46 buoys used in this study. The HY-2A SCAT wind data and buoy observations were co-located in time and space by choosing the HY-2A SCAT wind observation cells closest to the buoy locations in space and the buoy data closest to the HY-2A SCAT observations in time. The temporal difference between the HY-2A SCAT and buoy observations was restricted to less than 30 minutes, and the spatial difference between these two observations was less than 25 km.

Using the wind speed measured by the buoys at various heights (e.g., 3 m, 6 m, 10 m, and 12 m) above the sea surface is certain to lead to large errors when compared to the HY-2A SCAT wind speed (Yang et al., 2011). Instead, we convert all buoy-measured winds to a standard height of 10 m using the method below:

$$U_{10} = 8.87403 \times U_z / \ln(z/0.0016), \tag{1}$$

where U_z is the buoy wind speed at the height z, and in the

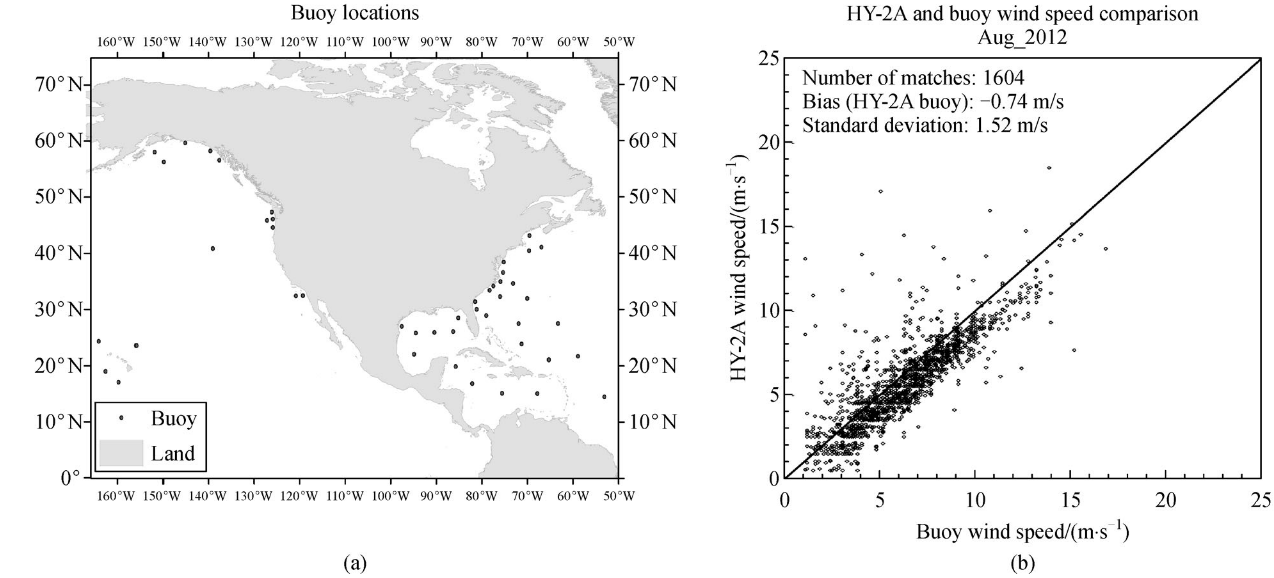


Fig. 1 The locations of NDBC buoys in this study (a) and comparison of the wind speed observed by HY-2A SCAT products with buoy data (b)

data set, each value of U_z is provided with the value of z. U_{10} is the wind speed adjusted to the height of 10 m (Thomas et al., 2005). Fig. 1(b) shows the difference between the HY-2A SCAT wind speed and the NDBC buoy. The wind speed observed by HY-2A SCAT is in good agreement with the buoy data in general, with a residual (HY-2A SCAT-buoy) of −0.74 m/s and a standard deviation of 1.52 m/s.

3 Model description and experimental design

3.1 Model description

The Weather Research and Forecasting Model (WRF) and its 3DVAR system were developed by the United States National Centers for Environmental Prediction (Barker et al., 2004). The WRF 3.4 version and WRF 3DVAR 3.4 version were used in this study. The WRF project is a multi-institutional effort to develop a next-generation mesoscale forecast and data assimilation system, which will advance the prediction of mesoscale precipitation systems.

The WRF model is a non-hydrostatic model with multiple options for various physical parameterization schemes. The major physics options in our experiments include the WRF Single-Moment 6-Class Microphysics scheme (WSM6), physics parameterization schemes (Hong and Lim, 2006), the Kain-Fritsch (KF) convective parameterization scheme, and the Yonsei University (YSU) boundary layer scheme (Shin and Hong, 2011). The domain of the WRF 3DVAR analysis and the WRF model simulation have 531×432 grid points, and the center of the domain is located at 24.9°N, 130°E. The horizontal resolution is 12 km, and the vertical levels are 51 in the WRF model framework; we utilized the no-nesting method and the Terrain-following coordinate (σ-coordinate) with the top of the atmosphere located at 10 hPa (Skamarock et al., 2001). The horizontal (grids) map for the model domain is shown in Fig. 2(a), and the observation map in Fig. 2(b) shows the observation coverage. The observation map presents the ocean surface wind field observed by HY-2A SCAT in the region simulated. The HY-2A SCAT observed the wind mainly at the right side of the typhoon center. The structure of the wind field around the typhoon center can be seen clearly in this figure. Generally, wind with speeds over 25 m/s exhibits larger errors and is considered to be less reliable; only the wind with mid- and low speeds and without precipitation observed by the scatterometer is an effective measure of the sea surface wind vector. Furthermore, over a calm ocean surface with a wind speed of less than 5 m/s, little or negligible backscatter occurs. Thus, in this study, non-rainy water vapor contents with wind observations between 5 m/s and 25 m/s are considered for use in the assimilation.

3.2 Assimilation methodology

The WRF 3DVAR system can produce a multivariate incremental analysis in the WRF model space (Zhang et al., 2009). This system adopts the incremental variational formulation, which is commonly used in an operational system. A method was also developed to seek an "optimal" estimate of the true atmospheric state at the analysis time

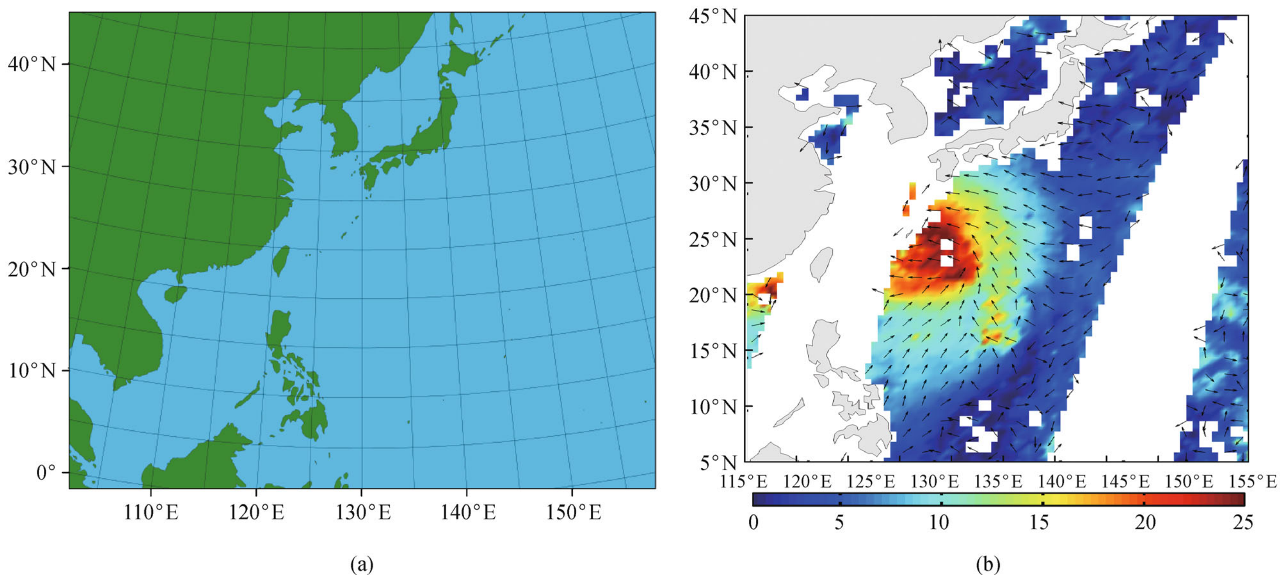


Fig. 2 The horizontal (grids) distribution for the model domain (a) and the HY-2A SCAT wind observations in the vicinity of Typhoon Bolaven on 25 August 2012 (b)

through the iterative solution of a prescribed cost-function (Gu et al., 2005). This problem can be summarized as the iterative solution of Eq. (2) to find the analysis state x that minimizes the cost function $J(x)$:

$$J(x) = J_b + J_o = \frac{1}{2}(x-x_b)^{\mathrm{T}}B^{-1}(x-x_b) + \frac{1}{2}\Big(y_o - H(x)\Big)^{\mathrm{T}}R^{-1}\Big(y_o - H(x)\Big), \quad (2)$$

where, J_b is a measure of the distance of the initial state from the background estimate, and J_o is a measure of the distance between the observation at the analysis time and the real state. The initial state is never precise, as it is the first guess of the real state. After solving Eq. (2), the optimal solution x is closer to the real state than the first guess, and is often defined as the analysis state (Lorenc 1986). The analyses' fit to individual data points is weighted by the estimates of their errors, B and R, which are the background and observation error covariance matrices, respectively (Ide et al., 1997). The cost function (2) assumes that the observation and background use Gaussian probability density functions with zero-mean errors. Because most of the data assimilation backgrounds are model forecasts from a prior time step, the background error covariance matrix (B) can be defined as the error covariance of model forecasts. In our experiments, we utilized the National Meteorological Center (NMC) method (Parrish and Derber, 1992) to estimate B by the forecast error, and the forecast errors are estimated with the difference of two (typically 12 and 24 hours) forecasts valid for the same time. The observation operator H is used to transform the gridded analysis x in the state space to observation space $y = H(x)$.

In the 3DVAR, $J(x)$ is solved iteratively using the conjugate gradient or the Quasi-Newton algorithm. Here, we only detail the particular aspect of the system, and we use a new method to describe the observation term J_o. In Eq. (2), $x = (u,v)$ is the analysis wind field, and $x_b = (u_b,v_b)$ is the background wind field. Here, u and v are the analyzed wind components, and the superscript T denotes transposition.

$$J_o = \left(\frac{u_i - u_{10}}{\sigma_u}\right)^2 + \left(\frac{v_i - v_{10}}{\sigma_v}\right)^2, \quad (3)$$

where u_i and v_i are the HY-2A scatterometer observations; u_{10} and v_{10} are the 10-m wind above the surface as the analysis wind components; σ_u and σ_v are the component observation errors for HY-2A scatterometer measurements, taken to be 2 m/s for both components by experience.

3.3 Experimental design TO HERE

The goal of these experiments is to assess the impact of HY-2A SCAT wind data in 3DVAR. Although this is the first time HY-2A SCAT wind data have been used in the WRF, previous work using OSCAT scatterometer data has shown significant impacts on the analysis and forecast of tropical cyclones (Prasad et al., 2013). Therefore, we focus our study on periods when the intense tropical cyclone Bolaven is active.

Two sets of experiments are conducted to investigate the impact of HY-2A SCAT data on super typhoons. These runs are considered as control (CTRL) and experimental (HSCAT) by excluding or including ocean surface wind vector data from HY-2A SCAT, respectively. In the control experiment (CTRL), only the conventional data, such as temperature, pressure, and wind speed from the surface observations and upper air observations, are assimilated, and the analysis time is 0600 UTC 25 August 2012. In the HSCAT experiment, the HY-2A SCAT data and conventional data are both assimilated, and the analysis time is 0600 UTC 25 August 2012. The analysis fields from the assimilation system are respectively inputted in the WRF model and integrated forward 66 hours to generate the forecast field in the two groups of experiments.

Instead of directly using the Yin He Global Spectral Model (YHGSM) reanalysis data (Zhang et al., 2012) as the first guess in the 3DVAR experiments, the reanalysis data from the YHGSM is adopted in the WRF model, and a WRF simulation is first integrated from 0000 UTC 25 August 2012 for 6 h to provide a 3DVAR first guess. During the 6-h integration, a coarser resolution reanalysis of the data is expected to adjust to a higher resolution of a 12-km environment of the WRF, creating dynamically balanced fields for the assimilation experiment. Next, we run the CTRL and HSCAT data assimilation experiments as described above. Finally, the analysis fields from the assimilation system are inputted into the respective WRF models. For both of the forecast experiments, the model is integrated for 66 h starting from 0600 UTC 25 August to 0000 UTC 28 August 2012. The model initial conditions are chosen in such a way that the cyclone is fully covered by HY-2A satellite passes.

Note that in our quality control check, the scatterometer winds are rejected when wind speed is larger than 25 m/s in the first guess of the NWP or in the measurement from HY-2A SCAT. Because the wind speed bias would lead to unrealistically large correction at high speed, the wind speed threshold of 25 m/s is applied to the data so that winds over this value are discarded (de Chiara et al., 2012). HY-2A SCAT products contain land/sea ice fraction flags and rain contamination flags. In the HSCAT experiment, 11714 U wind components are used for the assimilation with 202 rejected, and 11,387 V wind components are used with 529 rejected. All Wind Vector Cells (WVC) in the wind solution closest to the NWP background wind with a Maximum Likelihood Estimator (MLE) value above the wind speed threshold are rejected.

4 Typhoon Bolaven

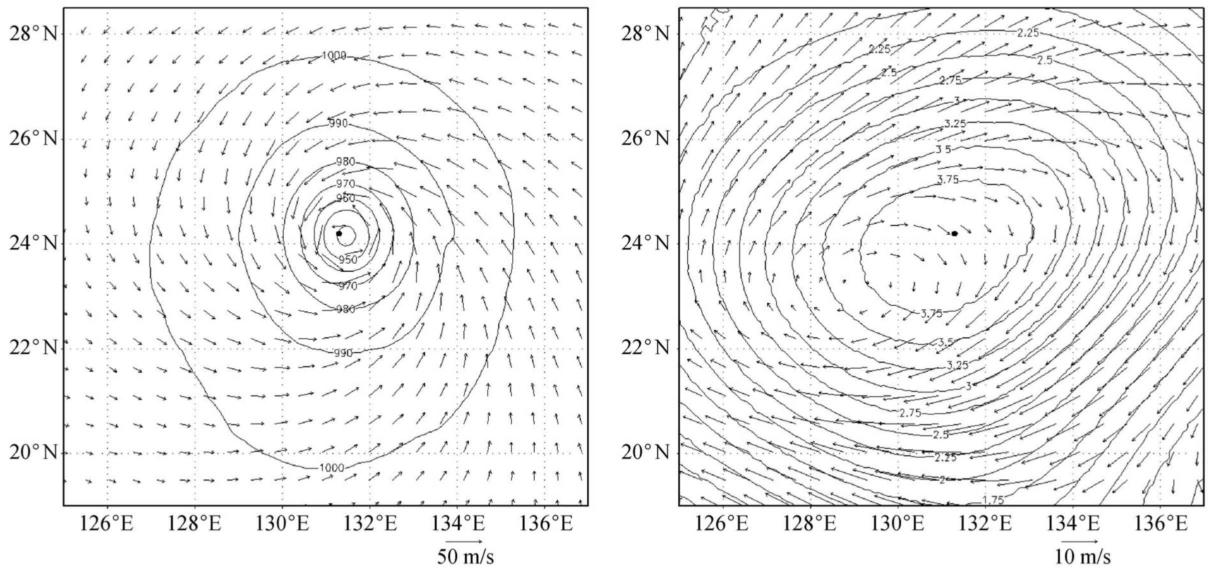
4.1 Synoptic description

Typhoon Bolaven is regarded as the most intense storm in 2012. After forming as a tropical depression on 19 August 2012 to the southwest of the Mariana Island in the west of the Pacific Ocean, Bolaven moved slowly west-north-westward and steadily intensified in a region favoring tropical development. The system was soon upgraded to a tropical storm after formation andcontinued to grow in size to become a typhoon on August 21st. On August 24th, Bolaven began turning toward the north-northwest along the subtropical range and the center crossed 135°E. Later that day, Bolaven reached its maximum intensity, with winds speed of 185 km/h and pressure of 936.87 hPa. By the morning of August 25th, Bolaven began to undergo an eyewall replacement cycle. An outer eyewall became more apparent late on August 25th with a clear second ring of deep convection surrounding the original eye. On August 26th, the storm became weaker and passed directly over Okinawa as it began accelerating toward the north. Gradually weakening, it then tracked northeastward yet still had tropical cyclone strength until 29 August 2012. It then turned eastward and was last noted on September 1st crossing the International Dateline.

4.2 Analysis and forecast impact

On August 25th, the United States Navy Joint Typhoon Warning Center (JTWC) estimated the center pressure of the storm to be 940 hPa, the maximum wind speed to be 50 m/s, and the storm developed into a super typhoon. Figure 3 shows the center position of Bolaven at the initial time before assimilation. The typhoon center in the first guess field is nearly symmetrical as shown in Fig. 3(a). The position of the center from the first guess is located at 24.1°N, 131.4°E, which is very close to the position of the weather forecast center observation, located at 24.2°N, 131.3°E. The center pressure of the *in situ* observations is 942.3 hPa. Compared with the JTWC data, the typhoon intensity in the first guess at the initial time is slightly higher. The wind field spins counter clockwise around the typhoon center. The wind speed at the center is slightly higher, reaching a maximum speed of 52.5 m/s to the right of the center. Figure 3(b) shows the analysis increment of wind and the mean sea level pressure (MSLP). After assimilation of the HY-2A SCAT wind data, the increment in the MSLP is positive, and the center of the increment is near the typhoon eye region with a maximum increment of 3.8 hPa. However, the wind speed increment in the typhoon center spins clock-wise, which is the opposite direction in the first guess, indicating that the wind field in the vicinity of the typhoon center is weakening and is consistent with the transformation of the MSLP.

Figure 4 depicts the zonal vertical sections of the temperature anomaly, wind speed anomaly and geopotential height anomaly though the center of Typhoon Bolaven at 0600 UTC 25 August 2012 for the CTRL and HSCAT experiments. The area for calculating the anomaly is from 20°N to 30°N latitude and from 126°E to 136°E longitude. The two top panels show the temperature anomaly for both experiments. Bolaven is still a warm core system at the 350 hPa level. The middle panels show the zonal vertical section of wind speed anomaly. Although the HY-2A SCAT wind field is limited in the low-level atmosphere, the



(a) (b)

Fig. 3 Analysis of Typhoon Bolaven at 0600 UTC 25 August 2012. (a) First guess of the wind speed and the MSLP (hPa); the arrow above 50 indicates that the wind speed is 50 m/s with this length. (b) Analysis increments of the wind speed and the MSLP, the arrow above 10 indicates that the wind speed is 10 m/s with this length.

ability of 3DVAR to propagate the surface wind information throughout the troposphere can be clearly seen in this example, where the HSCAT analysis refines the location of the typhoon center, the horizontal wind speed, and the pressure change with the height throughout the troposphere. In comparison to the CTRL experiment, the HSCAT experiment showed the intense wind speed center splitting into two just to the right of the typhoon center under 600 hPa. In addition, the height of the maximum wind speed was reduced and the intervals of the pressure increased. According to the JTWC forecast, in the morning of 25 August 2012, Bolaven began to undergo an eyewall replacement cycle and the structure degraded slightly. These features indicate that the typhoon's simulation in the HSCAT experiment is more consistent with the actual event. The two bottom panels in Fig. 4 show the geopotential height anomaly for both experiments. The scatterometer data can tune the analysis field of the wind speed more directly than for the analysis fields of temperature and geopotential height. Although a marginal difference appears in the panels of the temperature and geopotential height anomalies, the HY-2A SCAT observations can still fine-tune some information about the temperature and geopotential height in the high-level atmosphere and positively affect the typhoon forecast.

4.3 Storm track

Figure 5(a) shows the predicted typhoon tracks from the CTRL and the HSCAT data assimilation experiments starting at 0600 UTC 25 August 2012. The typhoon track is described according to the lowest surface pressure in the typhoon central area. The observed track is also plotted for comparison. Starting at 0600 UTC 26 August, the observed cyclone moved from the northwest to the north. All of the tracks derived from the experiments are similar to the *in situ* observation track, and nearly overlap before Typhoon Bolaven underwent a transition. On the whole, the typhoon track predicted by the HSCAT experiment is better than the track from the CTRL experiment and is closer to the observation track. The results indicate that the assimilation of HY-2A winds produces an improved simulated track throughout the integration when compared with CTRL.

To illustrate the accuracy of the typhoon track improved by the HY-2A SCAT winds, Figure 5(b) depicts the position errors from the two experiments. The position errors are almost the same at the initial time, and the transformation tendency of the two experiments is also similar. In fact, compared with CTRL, the track error was significantly smaller in the HSCAT assimilation, except at the integration time of 12 hours. The results demonstrate that after assimilation of the HY-2A SCAT wind observations over the ocean surface, the accuracy of the typhoon track forecast improved significantly.

5 Discussion and conclusions

Although the numerical prediction of tropical cyclones has been improved tremendously over the past few decades, there are still some difficulties due to insufficient

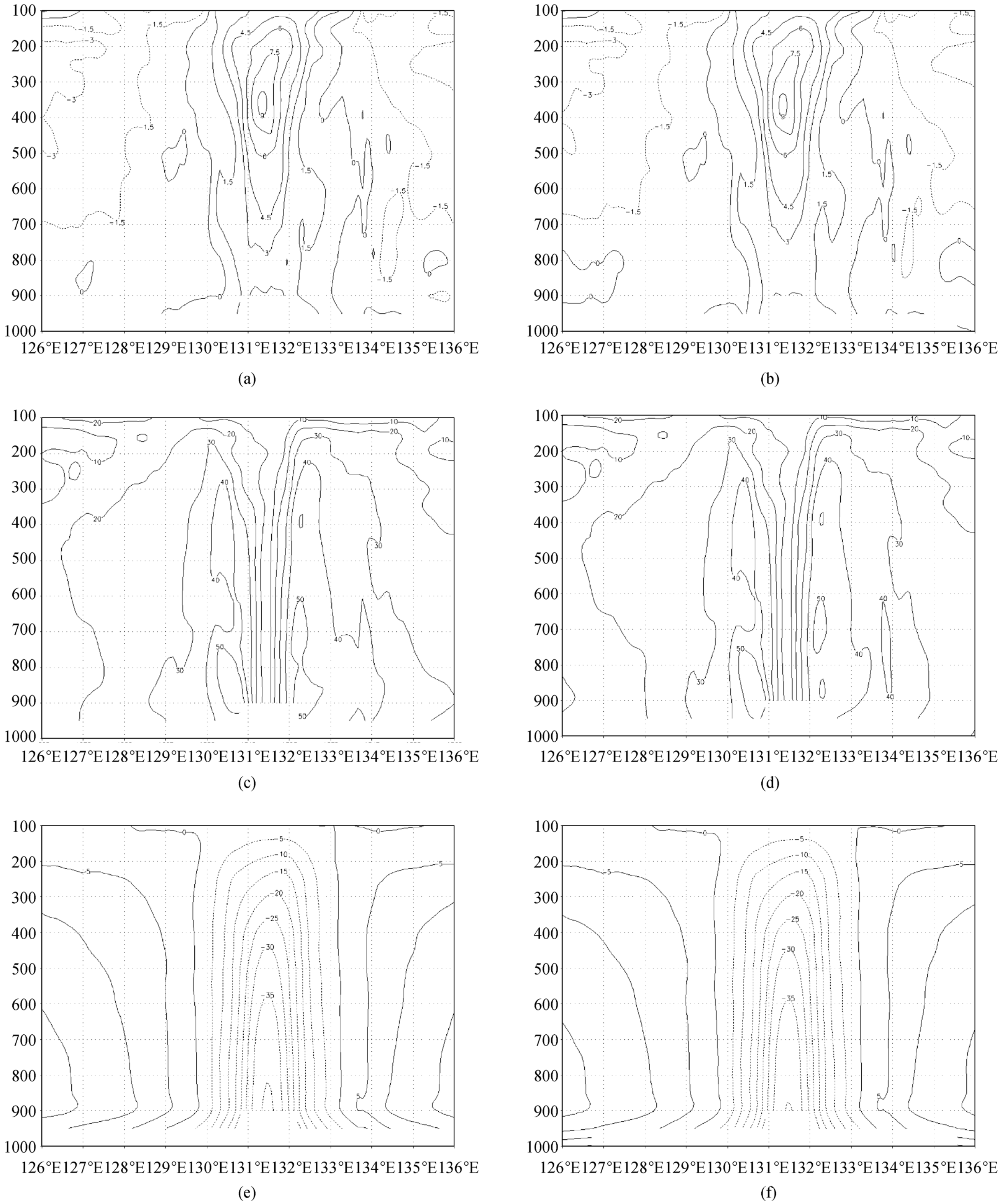


Fig. 4 The zonal vertical sections of Typhoon Bolaven valid at 0600 UTC 25 2012: temperature anomaly (K) from CTRL (a) and HSCAT (b); wind speed anomaly (m/s) from CTRL (c) and HSCAT (d); geopotential height anomaly (gpm) from CTRL (e) and HSCAT (f)

observations over the oceans and the limitations of numerical models. Compared with the numerical model, the accuracy of the initial condition becomes increasingly important in improving the analysis of the tropical cyclone.

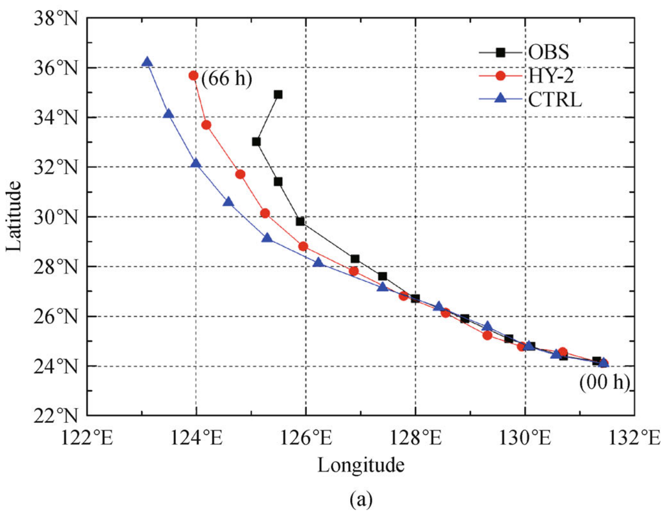


Fig. 5 (a) Tracks of Typhoon Bolaven (2012). The black line represents the best track. The red line represents the HSCAT runs starting at 0600 UTC 25 August 2012. The blue line represents the CTRL runs for the same time. (b) The track errors of Bolaven for 66 hours. The red line represents the CTRL runs, and the black line represents the HSCAT runs.

This study investigates the improvement of HY-2A SCAT observations on Typhoon Bolaven in the WRF 3DVAR data assimilation system. Cases with and without HY-2A SCAT data are considered. Three important conclusions based on the results of this study can be drawn:

1) The marine surface wind observed by HY-2A SCAT was evaluated in comparison with the NDBC buoy observations at the height of 10 m. The wind speed from HY-2A SCAT is in good agreement with the buoy observations, with a residual (HY-2A SCAT-buoy) of −0.74 m/s. The standard deviation is 1.52 m/s, which is much smaller than the mission requirement of 2 m/s. In other words, the accuracy of HY-2A SCAT can satisfy the mission requirement. The good quality of HY-2A SCAT wind field data can be comparable to those obtained by other scatterometers.

2) The HY-2A observations can improve the prediction of Typhoon Bolaven's tack and intensity. In the HSCAT experiments, 3DVAR ran with a special observation term in the cost function. Although the HY-2A SCAT wind data are single level observations at 10 m above the ocean surface, they still can influence the atmospheric state in the model system from the lower level to the higher level.

3) The assimilation of HY-2A SCAT wind data can tune the wind and pressure in the background field and produce a better typhoon track prediction. This method also improves the estimate of the typhoon warm center structure and the moisture field.

The results indicate that wind observations from HY-2A SCAT have great potential for improving cyclone prediction. In the experiments, other satellite data are excluded to isolate the result of HY-2A SCAT. It would be interesting to examine the impact of HY-2A SCAT in a system with microwave radiometers and other satellite data sources. In this study, the 3DVAR assimilation system was used to investigate the improvement of HY-2A SCAT wind data on typhoons. However, as in the 3DVAR scheme, all of the observations were translated from the observation time to the nearest analysis time. In a four-dimensional variational (4DVAR) data assimilation system, all of the observations can be introduced in the analysis at the time of observation (Willenent and Lasserre-Bigorry, 2001), which could be very important for satellite data including the HY-2 SCAT winds. In future research, HY-2A SCAT wind observations with a time dimension can be integrated into the 4DVAR assimilation system to improve the analysis quality of tropical cyclones.

Acknowledgements This study was supported by the Special Scientific Research Project for Public Interest (GYHY201006015), the National Natural Science Foundation of China (Grant Nos. 41375113 and 41228007). The HY-2A wind speed products are obtained from the Chinese National Satellite Ocean Application Service (http://www.nsoas.gov.cn/NSOAS_En/index.html). The buoy wind data are downloaded from the NOAA/NDBC website (www.ndbc.noaa.gov).

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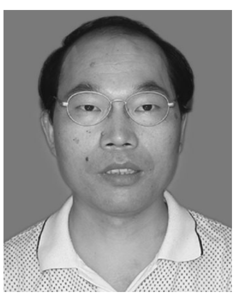

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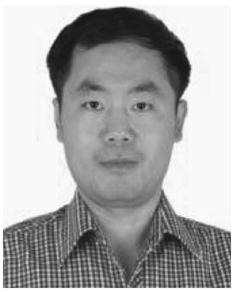

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