TYPHOON CENTER AUTOMATIC MONITORING MODEL BASED ON HY-2 AND QUIKSCAT VECTOR WIND PRODUCTS

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ABSTRACT: Centrally monitored typhoons generally rely on manual decisions made by meteorological professionals. Additionally, they lack a high level of automation and possess low efficiency. In this paper, we use microwave scatterometer data based on HY-2 and QuikSCAT to propose an automatic monitoring model of typhoon centers. First, we used a statistical interpolation method to obtain wind field data. Then, according to the visual characteristics of the typhoon wind field based on artificial monitoring rules, we formulated the minimum high wind speed area and wind direction vortex rules. Finally, in combination with the structural characteristics of the typhoon wind field, we proposed the typhoon center automatic monitoring model based on the vector superposition minimum modulus and classification. Using this model, we monitored typhoons Saola, Usagi, Florence and Ioke. The accuracy assessment results showed that this model can efficiently monitor typhoons. The results showed that the precision of the proposed model is close to that of the artificial monitoring method; however, it is more efficient for typhoon center monitoring.

1. INTRODUCTION

Tropical cyclones (TCs) are generated in tropical oceans due to activities in tropical and subtropical regions of low-pressure circulation. When the central maximum wind speed reaches 32.7 m/s, an event is called a typhoon or hurricane. Southeastern and eastern China have long coastlines close to the Pacific Northwest, making China one of the countries which most severely affected by typhoons. According to China Central Meteorological Observatory Tropical Cyclone Yearbook, large numbers of tropical cyclones affect China, including 31 in 2013. According to statistics, typhoon-related disasters cause economic losses of more than 20 billion yuan annually in China (Zhao, 2015). This is 10.2 times and 7.3 times more than damage costs in Japan and the Philippines, respectively, and 223 times costs in Vietnam. Thus, it is the largest country in the Asia-Pacific region affected by typhoons (Rozanova, 2010). Because typhoon energies and characteristics mainly depend on the typhoon center, monitoring of the typhoon center plays an important role in typhoon prevention and forecasting research (Bai, 2012). The determination of the typhoon center is important for typhoon path and typhoon weather predictions.

Typhoon center monitoring currently relies on the professional use of meteorological satellite cloud images combined with a variety of instruments, real-time observation data and artificial forecasting methods. To improve the objective, quantitative level and automation level of typhoon center monitoring, stationary satellite cloud images have been commonly used to automatically locate the typhoon center. Using satellite cloud images to monitor typhoon centers can be divided into two categories. 1) Monitoring by the morphological characteristics of typhoons. Li et al. performed cloud image data classification according to gray values. Using each gray level for binarization, mathematical calculations and regional growth processes, the typhoon cloud movement direction and spiral cloud band morphological characteristics were obtained. Sun and Fu extracted the movement characteristics and rotating morphological characteristics of typhoon cloud systems based on infrared and visible time series images. Liu et al. extracted spiral cloud bands based on the morphological characteristics of typhoons and used spiral line fitting for monitoring. These methods mainly described the morphological characteristics of typhoon cloud systems; however, typhoons are complex weather systems, and different stages have different characteristics. Because cloud images of typhoon cloud systems are various and complex, it is difficult to automatically extract quantitative descriptions and parameters based on unified morphological characteristics. 2) Monitoring by the dynamic image analysis method. First, researchers found the corresponding feature points, which were then used to determine the track. The tropical cyclone center was based on velocity vectors equal to zero, providing a basis for calculating the center of rotation. This method requires human involvement, and the cyclone center is not a real rigid body; thus, it is restricted by the frequency of cloud image data acquisition. Meteorological satellites are the main means of meteorological monitoring, and they have been widely applied to the monitor typhoon weather (Pan, 2013). They can obtain data over large areas and at high temporal resolutions using satellite cloud pictures. However, typhoon clouds in satellite cloud images exhibit a wide range of grey value changes (Wang, 2011). The typhoon segmentation processing in meteorological satellite cloud images is very important; however, it is difficult to perform. Additionally, meteorological satellite cloud images cannot provide the wind field intensity of quantitative information. In addition, because static meteorological satellites have low spatial resolution, the details in images are blurry in typhoon areas, and images are easily influenced by complex weather conditions, such as clouds and fog, resulting in poor observation results. In remote sensing observations of typhoons, traditional infrared and visible light remote sensing is significantly limited; therefore, microwave remote sensing data have a distinct advantage.

The emergence of spaceborne scatterometers has greatly improved observations of the ocean surface wind field. In the fields of marine and meteorological research, these methods provide fast, high precision and high spatial and temporal resolution sea surface wind field information around the world. Spaceborne microwave scatterometers have large coverage areas, make continuous observations and possess unique all-weather observation ability that is not affected by clouds and rain (Zhong, 2012), making them advantageous to other types of sensors under typhoon conditions. Based on the resulting data, microwave typhoon monitoring research has considerable application potential. Additionally, based on spaceborne microwave scatterometer data, the automatic typhoon monitoring model can automatically determine the typhoon center. Compared with traditional acquisition methods, automatic monitoring technology has high precision, short access time and is useful for associated studies. More scholars have begun to use microwave scatterometers to carry out typhoon center monitoring research. Zou et al. studied a tropical cyclone automatic recognition algorithm based on the HY-2 satellite scatterometer wind vector product, proposing a combined coarse and subtle search recognition method to automatically identify the sixth tropical storm in 2012 "Doksuri". The results show that the method effectively and accurately identified the tropical cyclone.

In this study, we proposed a typhoon center automatic monitoring method based on a microwave scatterometer and applied it to monitor many different typhoons and assess the applicability of the testing method. The second part of the article introduces the principles of the automatic monitoring typhoon center model. In the third part of the article, through typhoon and research data, the appropriate phase of the typhoon center is determined, and the mobile path is monitored. The fourth section compares the precision and applicability of the artificial monitoring method and the automatic monitoring method. The final part provides the conclusions.

2. TYPHOON CENTER AUTOMATIC MONITORING MODEL

The automatic monitoring method of the typhoon center mainly includes the following three steps: 1) cloud area with high wind speed determination; 2) vortex area with nearly center determination; and 3) typhoon center automatic extraction. The specific technical process is shown below.

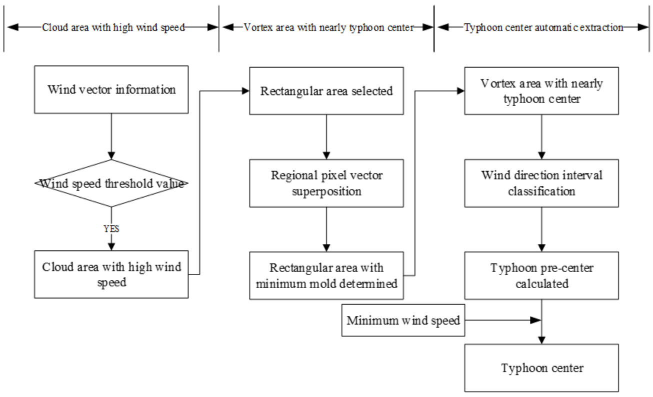


Figure 1. The process of the typhoon center automatic extraction model.

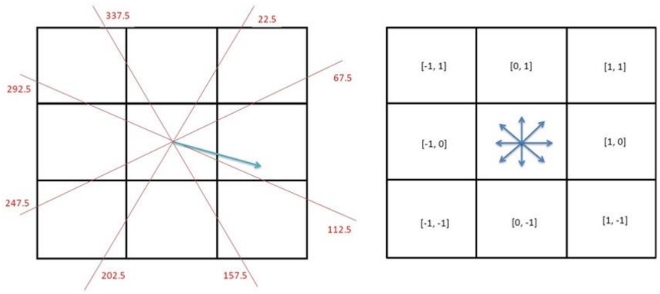
At the beginning of typhoon center identification, we need to assume a typhoon center in the initial monitoring data to determine the center of the 15° × 15° area of interest. In the second phase of monitoring data calculations, a region of interest is automatically determined from previous determinations of the center. The reading and preprocessing of microwave scattering data are included in the process. Sub-track data are used to assume where the central region of interest is located. Then, the source data are separately processed and stored in a standard grid matrix as ROI data after reading. Four matrices are created after the completion of data preprocessing, storing the longitude, latitude, wind speed and direction of each network.

2.1 Cloud area with high wind speed determination

Typhoon weather is characterized by strong winds because the strong ascending motion of the air current is caused by cumulus convection in the cloud wall of the typhoon core area in strong storms. The typhoon outsourcing area is close to the core area. There, the wind speed is slightly lower but still relatively strong, and it is caused large spiral rain bands. Therefore, the area surrounding the center of the typhoon is always accompanied by strong winds. Typhoon-level and hurricane-level winds near the center of the cyclone reach more than 32.7 m/s. Within regional boundaries, winds greater than 17 m/s are collectively known as cloud areas with high wind speed. According to the characteristics of the strong winds, the high wind speed region is determined. First, the threshold value of the wind speed matrix is set. The points of interest have wind speeds higher than 17 m/s. According to the points in the matrix, the area of the external rectangle is determined. Then, the matrix range and wind, latitude and longitude screening matrices are used to delete points with low speeds and obtain the cloud area with high wind speed.

2.2 Vortex area with nearly typhoon center determination

A very significant feature of tropical cyclones is the wind direction vortex point. In the typhoon center area, the wind is always revolving around the center (clockwise in the southern hemisphere). Near the center of the typhoon, the distribution of the wind direction is approximately symmetrical about the center. Thus, if a point near the center of the typhoon wind vortex appears in the region, it likely exists in the opposite (by 180°) wind direction as well. This feature is studied to determine the center of the vortex in the center of the typhoon.



(a) (b)

Figure 2. Wind direction interval classification: (a) Wind direction classification and (b) Pixel assignment.

First, a 17 × 17 pixel matrix is selected, and the wind direction in eight regions is used in the classification. As shown in Figure 2 (a), the 360-degree boundary in accordance with 22.5, 67.5, 112.5, 157.5, 202.5, 247.5, 292.5 and 337.5 is divided into eight regions. To observe the direction of a point or pixel, eight communication points were classified. Then, wind directions were attributed to the eight communication points in the area. After the wind directions were assigned to different types of point vectors, the assignment vector of each class was generated, as is shown in Figure 2 (b). After superposition of the oppositely directed vector yields a zero vector, the iso-lateral superimposed (pointing angle> 90°) and superimposed vectors will decrease after the ipsilateral superimposed (pointing angle <90°) and superimposed vectors increase.

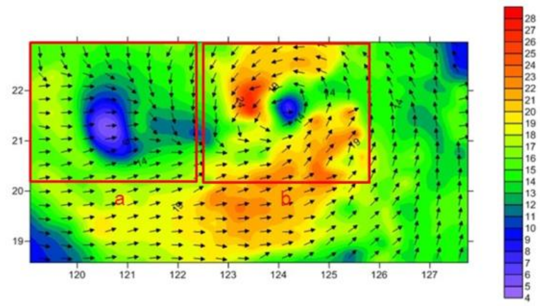


Figure 3. Rectangular region with vortex determined: (a) Non-vortex region and (b) Vortex region.

In this manner, the wind direction information associated with the typhoon area can be processed. If the two directions are opposite directions, i.e., the angle of the two wind directions is >90°, then the modulus of the superimposed vector is reduced. If the angle between the two wind directions is <90°, then the superposition vector modulus increases. Therefore, after all the wind directions in the rectangular box are superimposed, the superposition vector mode of the wind direction vortex region will be smaller than that of the non-vortex region. Figure 3 (a), a regional non-vortex region, and Figure 3 (b), a vortex region, show the same range of two rectangular regions. However, the region in (a) is larger than that in (b) in vector mode. Therefore, the wind direction vortex region can be determined by calculating the area of the superposition vector model. A 17 × 17 pixel matrix is encompasses the entire wind range by calculating the superimposed vector modes of all areas based on the minimum modulus (i.e., the superimposed vector mode minimum 17 × 17 pixel matrix). Thus, the typhoon vortex area near the center can be determined.

2.3 Typhoon center automatic extraction

By analyzing the characteristics of typhoon winds near the center of the vortex region, you can usually find winds around the center of rotation. In a circle, the direction of pixel changes is averaged and is a relatively continuous change. Thus, according to the feature, after the continuous range of the wind direction in the center of the vortex region is classified, the wind direction at the center of the typhoon is the center of the radiation type associated with each category. Thus, the center of each category is the center of the typhoon.

Figure 4 (a) shows the central vortex area of the typhoon. The wind direction of each pixel is classified in four consecutive intervals: (0°, 90°], (90°, 180°], (180°, 270°] and (270°, 360°]. When the vortex exhibits obvious characteristics, the classification results in the eye of the typhoon center and the classification results for each category are radially distributed. As shown in Figure 4 (b), four different categories are displayed in four different colors (and white represents no data points). The four categories are based on the four directions of the region, and the intersection point is the center of the typhoon.

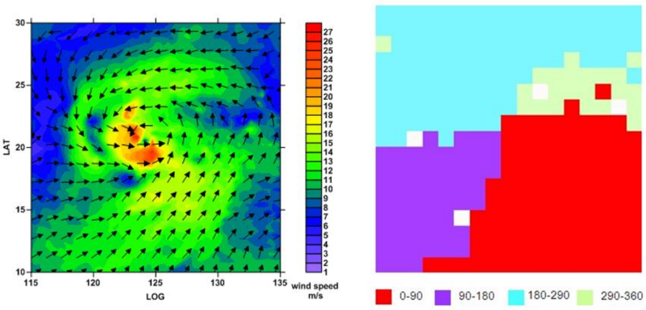


Figure 4. Typhoon pre-center extraction: (a) Vortex area with nearly typhoon center and (b) Classification results.

In the nearly central vortex area classification, classification results are obtained. Then, the classification result is divided into 3 × 3 rectangular windows. The total number of categories in each different window containing records is used to finally obtain the largest number of categories containing one or more windows, representing pre-centers. The typhoon center is a relatively calm area with relatively stable gas flow characteristics. Thus, wind from the typhoon center near the center of the vortex in the region will be relatively small. Thus, if the above method yields a unique center, it is considered a typhoon center. If a result includes multiple centers, take the minimum wind speed point as the center of the typhoon based on the pre-wind center.

3. DATA AND METHODS FOR TESTING

3.1 Location and Description of Typhoons

The tropical cyclones that affect China are from the Pacific Northwest; therefore, this paper uses the Northwest Pacific region as the main research area, and tropical cyclones are chosen as the research objects. The largest area of tropical cyclones in the world is the Pacific Northwest. It is the only region where tropical cyclones occur each month.

This paper also chooses a secondary study area around the continental United States (North-East Pacific and North Atlantic), who performed spaceborne microwave scatterometer measurements known as QuikSCAT. Tropical cyclones are recurrent in the Northeast Pacific and the North Atlantic. Densely distributed medium-sized cities are located along the coastal regions of the United States; thus, accurate and rapid detection of tropical cyclones is important for the protection of lives and property along the coasts. We chose three TCs in the Northwest Pacific region, Saola, Haikui and Usagi, for the HY-2 monitoring experiment. We also chose two TCs in the Atlantic region, Florence and Gordon, in the Atlantic region and one TC, Ioke, in the Central North Pacific region for QuikSCAT monitoring.

3.1.1 Typhoon Saola: Saola was the ninth Northwest Pacific typhoon in 2012. It occurred at 8:00 on July 28, 2012 (UTC +8). It was generated in the ocean east of the Philippines (126.8° E, 14.4° N) and then moved toward China. At approximately 14:00 the next day, it intensified into a tropical storm. On July 30, 2012, it intensified into a typhoon, moving northwest toward the Fujian Provinces. Around 22:00 on August 1, 2012, Saola intensified into a strong typhoon. The wind near the center reached 42 m/s. After circling in the vicinity of Taiwan, it headed toward the coast of the Fujian Province, landing on the Fuding City in Fujian Province at 6:50 on August 3, 2012. Saola and the tenth typhoon (Damrey) almost simultaneously reached mainland China, resulting in a "double-typhoon" disaster, according to the relevant departments to preliminary statistics. Saola and Damrey triggered floods, hail, mudslides and other disasters in Jiangsu, Zhejiang, Fujian, Jiangxi and Shandong provinces. Six people were killed, two went missing and 102.7 million underwent emergency transfers.

3.1.2 Typhoon Usagi: Usagi was the nineteenth Northwest Pacific typhoon in 2013. The storm began at 2:00 on September 17, 2013 (UTC + 8) in the ocean east of the Philippines (130.8 ° E, 18 ° N). It then moved to the northwest, toward the China Guangdong coast. At around 5:00 the next day, it intensified into a tropical storm. On the same day at 20:00, it intensified into a typhoon and moved northwest toward Guangdong. At 11:00 on September 19, 2013, it intensified into a severe typhoon and soon became a super typhoon, with a maximum wind speed of 60 m/s. It impacted Kaohsiung, Taiwan, before landing in Guangdong. It then weakened to a severe typhoon at 19:40 on September 22, 2013, landing on Shanwei City in Guangdong Province.

3.1.3 Hurricane Florence: According to the Saffir-Simpson Hurricane Wind Scale, Florence was a level one hurricane that formed at 18:00 on August 3, 2006 (UTC) in the eastern Gulf of Mexico (320.6° E, 14.1° N). It then moved to the northwest, toward the west coast of the US. On August 5, 2006, it intensified into a tropical storm and lasted for a considerable time. At 18:00 on August 10, 2006, it intensified into a hurricane. On August 11, 2006, it turned to the northeast, and on August 13, 2006, the hurricane became a strong tropical cyclone. The next day at approximately 0:00, the hurricane center passed Saint-Pierre island, moving to the northeast. On May 16, 2006, hurricane "Florence" began to undergo deformation as a counterclockwise arc in the north-central Atlantic. At 6:00 on the 19th, it disappeared in the Atlantic Ocean south of Iceland.

3.1.4 Hurricane Ioke: Ioke began to form at 12:00 on August 16, 2006 (UTC) in Hilo Bay, Hawaii (144.7° E, 10.7° N). Over the next four days, it moved west. On August 20, 2006, it intensified into a tropical depression and moved to south of Honolulu. Thereafter, Ioke rapidly grew into a tropical storm. The US National Hurricane Center has defined tropical storms in the Pacific as tropical depressions since 2002. After 24 hours (at 0:00 on August 21, 2006), Ioke was upgraded to a hurricane. Based on data published by the Central Pacific Hurricane Center (CPHC), the wind speed reached 65 miles per hour (33.41 m/s). After 36 hours, Ioke continued to strengthen. At 6:00 on August 24, 2006, the CPHC reported that the central wind reached nearly 100 miles per hour (51.4 m/s). After 24 hours the wind reached a staggering 140 miles per hour (71.96 m/s), becoming a rare category five hurricane, with the center at 174.2° E, 19.1° N. Between 3:00 and 6:00 on August 27, 2006, Ioke crossed the International Date Line near latitude 17.7° N, and its name was changed to "super typhoon Ioke". The wind speed was maintained at 140 miles per hour (71.96 m/s) or more as it moved toward Wake Island. Thereafter, NHC stopped monitoring the event.

3.2 Remote Sensing Data

HY-2 was launched on August 16, 2011, and it commenced operation in October 2011. It is a sun-synchronous polar-orbiting satellite with a scatterometer that uses pencil beams operating at a frequency of 13.225 ± 0.003 GHz (Ku-band). Two pencil beams sweep in a circular pattern at incidence angles of 38° (horizontally polarized) and 44° (vertically polarized), with a resolution of 25 km. The measurement range for wind speed is 2–24 m/, with an accuracy of 2 m/s (or 10%), while that for wind direction is 0–360°, with an accuracy of 20°. Level 2B data are collected because the swath data are not averages of the ascending and descending data. We collected data during the periods of July 28–August 8, 2012 (for Saola and Haikui) and September 17–23, 2013 (for Usagi).

QuikSCAT was launched in 1999 by the US Jet Propulsion Laboratory (JPL). It provides ocean surface wind retrieval at a resolution of 25 km. By 2003, data at intervals of 12.5 km were produced by postprocessing. Techniques for producing even finer resolutions have been explored. QuikSCAT provides retrievals with swaths of 1800 km. It can cover approximately 90% of the global oceans each day and passes over certain areas twice daily. The parameters and retrieval methods of QuikSCAT products are similar to those of HY-2. However, QuikSCAT cannot send back available data for present conditions, and we were unable to obtain recent valid data. We collected historical QuikSCAT Level 2B products from September 7–25, 2006 to monitor Florence and Gordon and August 23–27 to monitor Ioke.

The scatterometers measure microwaves backscattered by the wind-roughened ocean surface, which is affected by wind speed and direction. The geophysical model function (GMF) can provide multiple ambiguity retrievals of wind speed and direction in a wind vector cell. Both QuikSCAT and HY-2 used the SeaWinds model function and maximum likelihood (MLE) as an objective function to optimize retrieval. Unique retrievals were selected using an ambiguity removal algorithm with circular median filtering technology and MLE.

3.3 Ground Truth Data Acquisition

To assess the results of monitoring research, we acquired ground truth data from the China National Meteorological Center (CNMC) for typhoons Saola and Usagi and from the US National Hurricane Center (NHC) for Hurricanes Florence and Ioke. The CNMC data were obtained by analyzing information from various sources, such as radiosondes, reconnaissance flights, ground-based radar and various satellite products. We selected latitude and longitude information and maximum wind speed for ground validation. These data were collected at 6-h or 3-h intervals before the typhoon level was reached and at 1-h intervals during typhoons. The NHC data were acquired from sources such as aircraft measurements, airborne radar, buoys, passing ships and satellite products. The best-track data are available at 6-h intervals. Because of the difference between the time intervals of the two data sets, we adjusted the CMNC data to 6-h intervals to ensure correlation.

3.4 Method

This study involved the following steps: 1) data preprocessing; 2) determination of typhoon intensity and center using the traditional method and the proposed automatic model; 3) intensity development and track monitoring; and 4) accuracy assessment.

3.4.1 Data preprocessing: We acquired 25-km resolution wind field grid data and interpolated the data. We adopted the kriging interpolation method to ensure that the interpolated values of gridded points were the same as the original data values. First, we constructed wind speed contours to acquire a regional wind speed map. Then, we transformed the wind direction to u and v wind components and interpolated these components. We constructed wind direction maps using the vector addition method. Finally, we matched the coordinates and superimposed the maps to process the wind speed and direction maps, yielding the regional wind field.

3.4.2 Determination of typhoon intensity and center: Typhoon intensity, which is a reflection of the maximum wind speed near the center of the typhoon, is an important indicator of typhoon characteristics and hazards and is the only standard used to determine the typhoon level. The location of the center or the eye of a typhoon is determined by its structure and characteristics. The center of a typhoon is an area of relatively low pressure; thus, a large pressure gradient can be observed near the center, and an eye wall forms around the center. The eye is usually a relatively calm area, but the eye wall is the region where winds are the strongest. Scatterometers monitor typhoon intensity using backscatter measurements and geophysical model functions. The gridded wind speed data from the study area have been analyzed to find the strongest wind speed, reflecting the typhoon intensity.

3.4.3 Intensity development and track monitoring: By adopting the cubic spline interpolation method, we were able to observe the TCs using HY-2 and QuikSCAT products. We matched the appropriate time points in the interpolation results to the ground truth data sequence to obtain the track and intensity development of the six TCs.

3.4.4 Accuracy assessment: For typhoon track accuracy assessment, we calculated the great-circle distance (GCD) between TC centers in the ground truth data set and monitoring results. The mean and standard deviation values were used as the basis for the evaluation. We assessed the performance of HY-2 products after comparing the statistical evaluation results of HY-2 and QuikSCAT.

The GCD is the shortest distance between any two points on the surface of a sphere. In this study, we regard the Earth as a sphere and follow McCaw's recommendation of considering the mean radius as approximately 6371.01 km. $M (E_1, N_1)$ and $T (E_0, N_0)$ (where E_0 and E_1 are the longitudes, N_0 and N_1 are the latitudes) are monitoring data and ground truth data. The GCD between M and T is represented as follows:

$$\mathrm{D} = \mathrm{R} \cdot \cos^{-1}[\cos N_1 \cdot \cos N_0 \cdot \cos(E_1 - E_0) + \sin N_1 \cdot \sin N_0] \quad (1)$$

Where D is the GCD, and R is the mean radius of the Earth.

For typhoon intensity accuracy assessment, we performed a t-test to check for any significant difference between the means of the observation and ground truth data. We compared the results of the t-test, as well as other statistical results such as mean error and scatter index of data, for HY-2 and QuikSCAT to evaluate the performance of HY-2 data for typhoon intensity monitoring.

4. APPLICATION

4.1 Typhoon Saola

From July 28, 2012 to August 1, 2012, the HY-2 satellite microwave scatterometer observed Saola nine times, detecting typhoon wind vortex structure features five times, and the automatic monitoring method successfully acquired the typhoon center five times.

Figure 5 shows the five views of Saola based on the microwave scatterometer wind field, which uses the center of the typhoon based on the automatic monitoring algorithm. It automatically determines the center of the vortex wind field, exhibiting good agreement with validation data. This method can quickly, objectively and accurately determine the center of the typhoon. Figure 7 (a) compares the track of the typhoon center produced by the proposed method and the CMNC best track.

The GCD of Saola's maximum error distance is 86.75 km, and the minimum is 78.62 kilometers. The average error distance is 82.29 km, which corresponds to approximately three pixels of HY-2 scatterometer data. The standard deviation of the error is 6.06 km, suggesting that the error is more stable in this case.

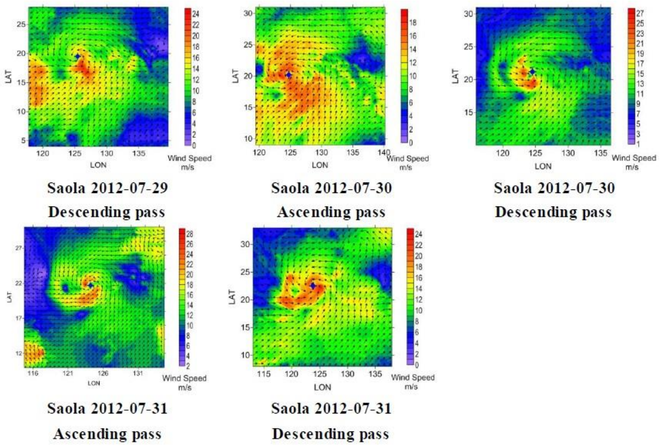


Figure 5. HY-2 wind fields for Saola (the location of the center is indicated by the blue symbol).

4.3 Typhoon Usagi

From September 17-23 2013, the HY-2 satellite microwave scatterometer observed Usagi nine times, detecting typhoon wind vortex structure features six times, and the automatic monitoring method successfully acquired the typhoon center six times.

Figure 6 shows the six views of Usagi based on the microwave scatterometer wind field, which uses the center of the typhoon based on the automatic monitoring algorithm. The automatic determination of the center of the vortex wind field was unsatisfactory, and it cannot quickly and accurately determine the center of the typhoon. Figure 7 (b) compares the track of the typhoon center produced by the proposed method and the CMNC best track.

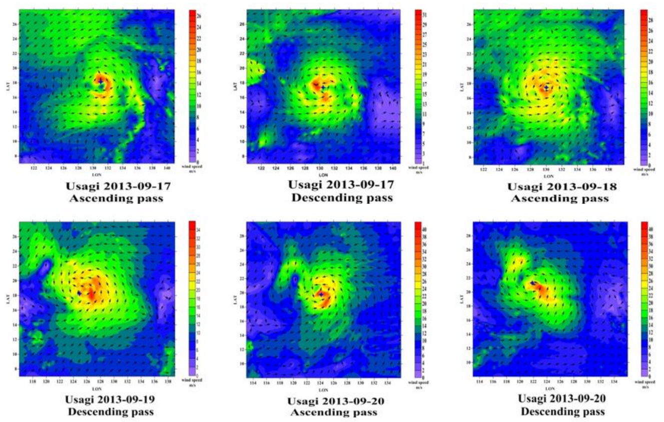
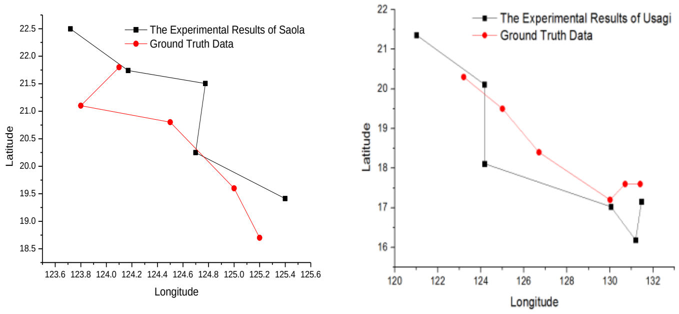


Figure 6. HY-2 wind fields for Usagi (the location of the center is indicated by the blue symbol).

The GCD of Usagi's maximum error distance is 115.26 km, and the minimum is 64.87 kilometers. The average error distance is 85.74 km, which corresponds to approximately three pixels of HY-2 scatterometer data. The standard deviation of the error is 20.17 km, reflecting a larger error in this case.



(a) (b)

Figure 7. Comparison of HY-2 and CNMC tracks for (a) Saola and (b) Usagi.

4.4 Hurricane Florence

From September 7-14, 2006, the QuikSCAT satellite microwave scatterometer observed Florence fifteen times, detecting typhoon wind vortex structure features eight times, and the automatic monitoring method successfully acquired the typhoon center eight times (Figure 8).

The GCD of Florence's maximum error distance is 168.24 km, and the minimum is 40.19 kilometers. The average error distance is 103.56 km, which corresponds to approximately four pixels of QuikSCAT scatterometer data. The standard deviation of the error is 133.44 km (Figure 10 (a)). In this case, the error is more unstable, and the typhoon centers of the third and final images yielded large errors.

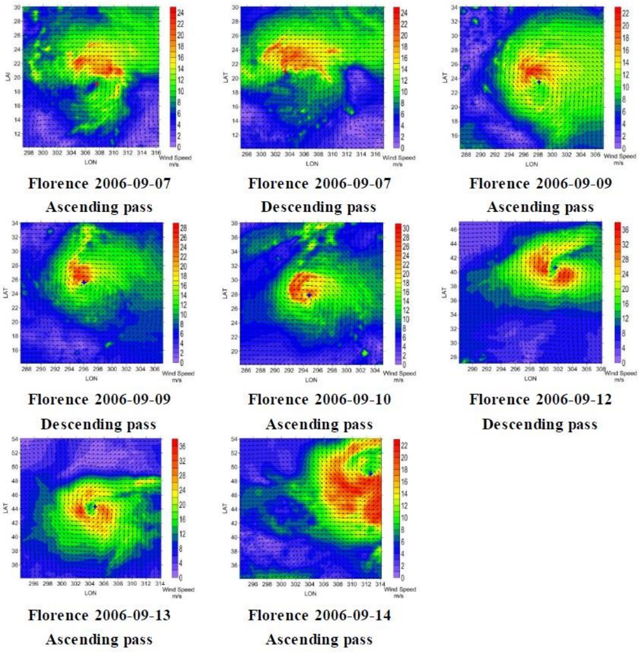


Figure 8. QuikSCAT wind fields for Florence (the location of the center is indicated by the blue symbol).

4.5 Hurricane Ioke

From August 20-27, 2006, the QuikSCAT satellite microwave scatterometer observed Ioke sixteen times, detecting typhoon wind vortex structure features seven times, and the automatic monitoring method successfully acquired the typhoon center seven times (Figure 9).

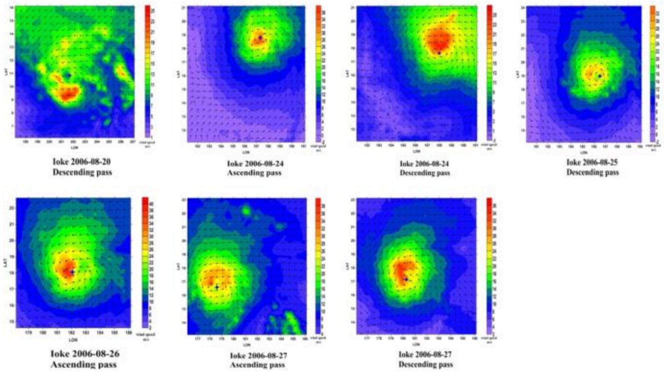
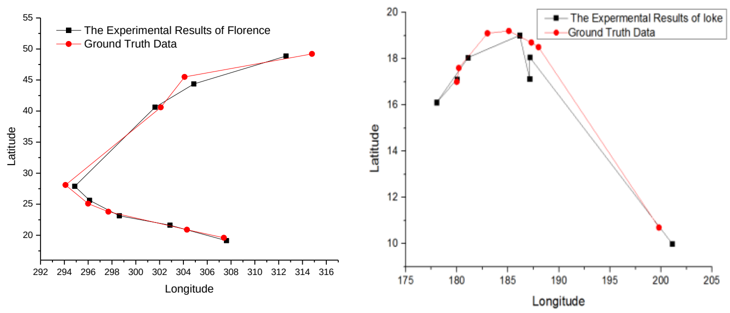


Figure 9. QuikSCAT wind fields for Ioke (the location of the center is indicated by the blue symbol).

The GCD of Gordon's maximum error distance is 116.86 km, and the minimum is 63.71 kilometers. The average error distance is 79.27 km, which corresponds to approximately three pixels of QuikSCAT scatterometer data. The standard deviation of the error is 17.52 km, which is relatively stable, suggesting that the monitoring results are of high accuracy (Figure 10 (b)).



(a) (b)

Figure 10. Comparison of QuikSCAT and NHC tracks for (a) Florence and (b) Ioke.

The accuracy assessment results are shown in Table 1.

Table 1 Statistical results of the accuracy assessment (distance unit: km)

	Max Error	Min Error	Mean Error	Std. Deviation
Saola	86.76	78.62	82.29	6.06
Usagi	102.81	64.87	85.74	20.17
Florence	168.24	40.19	103.56	133.43
Ioke	116.86	63.71	79.27	17.52

5. DISCUSSION AND CONCLUSION

5.1 Discussion

In this study, we compared the performance of the traditional manual method and the proposed automatic method. We used HY-2 and QuikSCAT microwave scatterometer data to monitor the track and intensity development of Saola, Usagi, Florence and Ioke. We assessed the accuracy of each track by computing the GCD between the track points of each time step. We calculated the means and standard deviations and assessed the accuracy of the intensity by performing t-tests and computing the mean errors and scatter index values.

According to the monitoring results, the automatic monitoring model and artificial monitoring model provide similar results for the center of the typhoon. For the intensity and the moving path of the GCD index, the artificial monitoring model is more accurate. In the full cycle of typhoons, the artificial monitoring technology is better than the automatic monitoring model based on monitoring effectiveness. However, the automatic monitoring technology has obvious temporal advantages. It not only avoids the time-consuming and complicated process of artificial monitoring but also reduces the workloads of workers. It is advantageous to weather forecasters, providing more accurate judgments of typhoon paths and intensities. Additionally, it provides a better basis for frontline decision making. It yields relatively objective monitoring results, with high speed, high precision and strong practicability. It can meet the needs of meteorological operations and provides a good foundation for tropical cyclone path prediction.

5.2 Conclusion

This research, which was based on the vector superimposed minimum model and wind direction classification, established a new technology: the typhoon center automatic monitoring model. The method was applied to six different TCs and compared with the traditional manual monitoring method. The proposed method has the advantages of high precision, fast processing speed, broad applicability and satisfactory accuracy. The method combines the regional structure of the typhoon wind field through three typical wind field characteristics, the high wind speed cloud area, the vortex area in the center of the typhoon and automatic monitoring of the typhoon center, which eventually approaches the typhoon center. This method can be implemented as an automatic process control in computer programs, and it does not require human intervention throughout the process. Thus, it yields faster, more accurate and completely objective typhoon center results. In real time monitoring of typhoons, this fast, objective and accurate extraction model can provide technical support for operational backgrounds, making typhoon monitoring quicker, more efficient and more effective and reducing human error caused by the operator. This method can be applied not only to real-time monitoring of typhoons but also to historical typhoon data-related research. Each year, at least 20 typhoons affect China's coastal areas, reaching over 30 in some years. This automatic process-oriented approach can process vast amounts of data, determine a typhoon center's information quickly and provide access to large quantities of data and results.

However, according to research findings, this monitoring method becomes significantly better with typhoon maturity, particularly for the typhoon period and extinction period. This is because the automatic monitoring method depends on the vortex structure, which becomes more obvious with maturity, while observations are less obvious during the generating period and extinction. Thus, further improving the applicability of the method is one of the future research directions. In addition, the HY-2 microwave scatterometer’s wind field data stability should be improved. In the case of extremely high wind speeds, the wind vector information near the typhoon center will result in inversion failure, and the wind direction must be used to eliminate ambiguous solutions (deviation from the normal wind direction vortex by approximately 90° or 180°). The typhoon center determination techniques described here, whether artificial or automatically determined, use the wind field as a data source. Thus, improving the quality of the wind field based on microwave scatterometer data improve the results of typhoon analyses. Further research will focus on scatterometer wind field inversion optimization under extreme weather conditions. Another focus will be improving the quality of regional typhoon wind field data preprocessing.

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