Retrieval of Sea Surface Wind Fields Using Multi-Source Remote Sensing Data

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Received: 10 April 2020; Accepted: 5 May 2020; Published: 7 May 2020

Abstract: Timely and accurate sea surface wind field (SSWF) information plays an important role in marine environmental monitoring, weather forecasting, and other atmospheric science studies. In this study, a piecewise linear model is proposed to retrieve SSWF information based on the combination of two different satellite sensors (a microwave scatterometer and an infrared scanning radiometer). First, the time series wind speed dataset, extracted from the HY-2A satellite, and the brightness temperature dataset, extracted from the FY-2E satellite, were matched. The piecewise linear regression model with the highest $R^2$ was then selected as the best model to retrieve SSWF information. Finally, experiments were conducted with the Usagi, Fitow, and Nari typhoons in 2013 to evaluate accuracy. The results show that: (1) the piecewise linear model is successfully established for all typhoons with high $R^2$ (greater than 0.61); (2) for all three cases, the root mean square error (RMS) and mean bias error (MBE) are smaller than 2.2 m/s and 1.82 m/s, which indicates that it is suitable and reliable for SSWF information retrieval; and (3) it solves the problem of the low temporal resolution of HY-2A data (12 h), and inherits the high temporal resolution of the FY-2E data (0.5 h). It can provide reliable and high temporal SSWF products.

Keywords: sea surface wind fields; piecewise linear model; tropical cyclones; Northwestern Pacific; sensor interoperability

1. Introduction

Tropical cyclones (TCs) are one of the most intense weather hazards out of all meteorological phenomena that form over tropical oceans [1]. In order to better prevent the disasters caused by TCs, it is necessary to continuously monitor sea surface wind field (SSWF) information, such as wind speed and direction, so as to protect life and property as much as possible [2,3]. These data contribute to improved warnings for ships at sea, and to improved global weather forecasts [4]. Accurate and high temporal resolution SSWF data are significantly important for meteorological and oceanographic applications [5,6].

Traditionally, the SSWF measurements are mainly detected or acquired from ships, buoys, and coastal monitoring stations. These measures are highly restricted, owing to the large ocean area as well as the coarsely and unevenly distributed monitoring stations. Microwave scatterometers (MSs) are often used to monitor global SSWFs due to their wide coverage and have the abilities of day-and-night operation and all-weather detection. They can be adopted to continuously and simultaneously detect marine dynamic environmental elements with high precision [7,8]. However, they are mainly sun-synchronous orbit satellites with low temporal resolution; one single satellite can only obtain
1–3 views per day. As a huge and complex weather system, TCs change rapidly in one day, and daily wind speed products struggle to meet the needs of monitoring and forecasting. Geostationary orbit satellites can observe a wide area frequently at a high temporal resolution every 10–30 min under all-weather conditions and are effective at observing TCs over the ocean [9]. However, due to the cover and occlusion of clouds, both visible and infrared bands cannot penetrate the cloud, so it is impossible to directly observe the SSWFs [10]. Therefore, any single satellite source cannot meet the needs of continuous SSWF observation during periods of TCs. Considering the advantages of multi-source data, the method of multi-source data combination has been widely applied to observe SSWFs. An inversion method based on multi-source data fusion has been shown to improve the accuracy of meteorological, marine, and other products in SSWFs [11]. Some researchers have inverted the sea surface wind speed by studying the correlation between brightness temperature and wind speed. The previous results showed that brightness temperature has a significant correlation with wind speed [12,13].

In this study, the relationship between infrared brightness temperature data (obtained from an infrared scanning radiometer) and wind speed data (obtained from a microwave scatterometer) was analyzed to establish an SSWF inversion model. Taking the typhoons Usagi, Fitow, and Nari as examples, the inversion model is used to retrieve SSWFs with high temporal resolution and large coverage. All relevant materials are presented in Section 2. A description of the multi-source remote sensing inversion model is presented in Section 3, while Section 4 introduces the inversion results and accuracy assessment. A discussion and conclusions are presented in Sections 5 and 6.

2. Materials

2.1. Study Area

In this study, we selected the Northwestern Pacific and coastal areas as a study area (Figure 1). There are, on average, 26–28 tropical storms and typhoons each year, two or three of which can reach typhoon intensity. Typhoons here are seasonal and usually occur from July to September [14]. We chose three representative typhoons (Usagi, Fitow, and Nari) that occurred in 2013 to validate the effectiveness of the proposed model. Detailed information about the TCs is described as follows.

(1) Usagi was the 19th Northwestern Pacific typhoon in 2013. The storm began at 2:00 on September 17 (UTC +8) to the east of the Philippines, and then moved to the northwest. At 5:00 the next day, it became a tropical storm. At 11:00 on September 19, it grew into a severe typhoon and soon became a super typhoon, with a maximum wind speed of 60 m/s. At 19:40 on September 22, it made landfall at Shanwei City in Guangdong Province, China [1].

(2) Fitow was the 23rd Northwestern Pacific typhoon in 2013. It formed on September 30 over the Eastern Philippines and strengthened to a typhoon around 21:00 on October 2 (UTC +8). At 17:15 on October 6, it made landfall with a minimum pressure of 955 hPa and a maximum wind speed of 42 m/s at Fuding City in Fujian Province, China [15].

(3) Nari was the 25th Northwestern Pacific typhoon in 2013. The storm began at 2:00 on October 8 (UTC + 8) to the east of Philippines. At 21:00 on October 9, it became a tropical storm. At 21:00 on October 11, it made landfall for the first time at D’Aran City in Oruna Province, Philippines. It then continued to move westward, and at 7:00 on October 15 it made landfall again at Sanchi City, Quang Nan Province, Vietnam.
2.2. Data

2.2.1. Microwave Scatterometer Data

The HY-2A satellite (HaiYang-2A is a Chinese sun-synchronous polar orbiting marine satellite, which was launched in August 2011) microwave scatterometer is dedicated to determining the wind vector field (including wind speed and direction) of the sea surface. Its swath is about 1750 km and can cover more than 90% of global open sea area within one day [16]. The accuracy of the scatterometer data has been confirmed, which can characterize the SSWF [17]. Therefore, we chose the level 2B (L2B) products of HY-2A as sea surface wind speed data from the National Satellite Ocean Application Service (NSOAS) [18].

2.2.2. Infrared Scanning Radiometer Data

The FY-2E satellite (FengYun-2E is a Chinese operational geostationary meteorological satellite which was launched in June 2008) payload includes the Visible and Infrared Spin Scanning Radiometer (VISSR), which can directly measure the thermal radiation intensity of surface features. It provides effective brightness temperature data through an infrared channel (the spectrum range is 10.3–11.3 μm), and observations of the brightness temperature radiation are conducted twice every hour, with a spatial resolution of 5 km [19]. The brightness temperature datasets used in this study were downloaded from the National Satellite Meteorological Centre (NSMC) [20].

According to the life cycle of the three cyclones mentioned in Section 2.2 and the temporal resolution of the HY-2A and FY-2E satellites, we downloaded 2 HY-2A files and 48 FY-2E files, respectively, for SSWF inversion and verification. Specific information is shown in Table 1.
Table 1. Specific information about the HY-2A MS and FY-2E Visible and Infrared Spin Scanning Radiometer (VISSR) data.

| Typhoon Name | Date          | Time Range   | Number of Files | Satellite/Sensor | Spatial Resolution | Temporal Resolution |
|--------------|---------------|--------------|-----------------|------------------|--------------------|---------------------|
| Usagi        | 18 September 2013 | 00:00–23:30 | 2               | HY-2A/MS         | 25 km              | 12 h                |
|              |               |              | 48              | FY-2E/VISSR      | 5 km               | 0.5 h               |
| Fitow        | 3 October 2013  | 00:00–23:30 | 2               | HY-2A/MS         | 25 km              | 12 h                |
|              |               |              | 48              | FY-2E/VISSR      | 5 km               | 0.5 h               |
| Nari         | 12 October 2013 | 00:00–23:30 | 2               | HY-2A/MS         | 25 km              | 12 h                |
|              |               |              | 48              | FY-2E/VISSR      | 5 km               | 0.5 h               |

2.2.3. Reference Datasets

HY-2A MS L2B wind products provide high-precision global SSWFs (compared with the in situ data, the error is less than 2 m/s) and play an important role in marine and meteorological research. Therefore, we use independent wind speed products as reference datasets to evaluate the accuracy of the model. For each typhoon, we selected two wind speed files with different acquire times: one for model inversion and the other for accuracy assessment.

3. Methods

3.1. Technical Process

The process detailed in Figure 2 includes the following steps: (1) wind speed data extraction from HY-2A; (2) brightness temperature data extraction from FY-2E; (3) temporal and spatial matching of wind speed and brightness temperature; (4) sea surface wind speed inversion model development; and (5) model validation.

![Figure 2. Flowchart of the technical process.](image)

3.2. Wind Speed Data Extraction from HY-2A

The MS L2B product of the HY-2A satellite is composed of header files and product data. The product data includes longitude, latitude, wind speed, wind direction, and other related information, which is stored in a hierarchical data format (HDF). First, we downloaded the HY-2A MS L2B products...
from NSOAS. We then transformed the wind direction to u- and v-wind components and interpolated the components. Finally, we generated wind speed and direction maps. We overlaid the wind speed map and wind direction map to produce a wind field map. According to the above-mentioned method, we acquire interpolated maps (with a spatial resolution of 25 km and a temporal resolution of 12 h) for wind speed, wind direction, and wind field (Figure 3).

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![Figure 3. Schematic diagram of the wind field process: (a) wind speed map; (b) wind direction map; (c) wind field map.](image)

3.3. Brightness Temperature Data Extraction from FY-2E

The cloud image product of the FY-2E satellite includes two parts: header files and data segments, which are stored in an advanced weather-satellite exchange format (AWX). Header files consist of a first-level header file, a second-level header file, a padding segment, and an extended segment. They mainly contain the acquire time, channel, projection type, and data information. First, we downloaded the FY-2E VISSR data from the NSMC. We then gridded the data information segment. Finally, we generated geocoded brightness temperature images using the kriging interpolation method (with a spatial resolution of 5 km and a temporal resolution of 0.5 h).

3.4. Temporal and Spatial Matching of Wind Speed and Brightness Temperature

3.4.1. Temporal Matching

As weather conditions differ over time, before spatial matching, temporal matching is first needed to ensure that the acquire time of the HY-2A data is close to that of the FY-2E data. Because the temporal resolution of the FY-2E data (0.5 h) is higher than that of the HY-2A data (12 h), we used the HY-2A data as the basis to match the corresponding FY-2E data. The schematic diagram of the temporal matching process is shown in Figure 4a.
wind speed. Among the parameters announced by the HY-2A satellite, the wind speed measurement range is 2–24 m/s [21]. Therefore, the image is divided into three segments: (1) high wind speed areas (HA, between 17 and 30 m/s); (2) low wind speed areas (LA, between 2 and 17 m/s); and (3) other areas (OA, areas without wind speed gridded points, with speeds less than 2 m/s or greater than 30 m/s). The results of region segmentation are shown in Figure 4b.

3.4.2. Spatial Matching

First, based on the wind speed data extracted from HY-2A, we used the kriging interpolation method to ensure that the interpolated values of gridded points were the same as the original data values. Second, based on the brightness temperature data extracted from FY-2E, we generated a geocoded brightness temperature image. We then compared the longitude and latitude coordinates of the wind speed map and the brightness temperature image, and established a whole spatial matching list. The specific locations of six sample points are shown in Figure 4b.

3.4.3. Region Segmentation

According to the following principles, the image was divided into three segments based on wind speed. Among the parameters announced by the HY-2A satellite, the wind speed measurement range is 2–24 m/s. More noise and errors are introduced when the wind speed is greater than 30 m/s [21]. Therefore, the image is divided into three segments: (1) high wind speed areas (HA, between 17 and 30 m/s); (2) low wind speed areas (LA, between 2 and 17 m/s); and (3) other areas (OA, areas without wind speed gridded points, with speeds less than 2 m/s or greater than 30 m/s).

3.5. Sea Surface Wind Speed Inversion Model

Best regression model selection: In this study, we built four commonly used regression models to predict wind speed, including a linear model, an exponential model, a logarithmic model, and a power model. \( F(x) \) represents wind speed, and \( x \) represents brightness temperature (grayscale value). We then used the determination coefficient \( (R^2) \) to select the best regression model. The higher the \( R^2 \), the better the fit.

Piecewise regression based on the best model: First, based on a spatial matching list of wind speed \( (F(x)) \) and brightness temperature \( (x) \), four regression models were used to build inversion models, and the model with the highest \( R^2 \) was selected as the best model. Second, according to the region segmentation results, the best model was used to fit the three areas (HA, LA, and OA, respectively). Therefore, a piecewise regression model was established. Finally, based on the time-series FY-2E infrared scanning radiometer data and piecewise regression model, the time-series SSWF data with high temporal resolution (0.5 h) were successfully generated.
3.6. Model Validation

First, three representative typhoons (Usagi, Fitow, and Nari) that occurred in 2013 were selected to evaluate the effectiveness of the sea surface wind speed inversion model. Next, two statistical metrics were used to estimate the inversion accuracy: the root mean square error (RMSE) and the mean bias error (MBE) of the wind speed estimates. The MBE is the average of the error, indicating over- or underestimation. The RMSE is a combined measure of the bias and variance associated with an estimator. The RMSE and MBE values are given as

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n}},$$  \hspace{1cm} (1)

$$\text{MBE} = \frac{\sum_{i=1}^{n}(\hat{x}_i - x_i)}{n},$$  \hspace{1cm} (2)

where $n$ is the number of reference points, $x_i$ is the reference wind speed of the $i$th point, and $\hat{x}_i$ is the inversion wind speed of the $i$th point. The lower the RMSE and MBE, the better the prediction.

4. Results

4.1. Sea Surface Wind Speed Inversion Model Establishment

Best regression model selection results: According to the temporal and spatial matching process, we successfully obtained two matching lists of the typhoon Usagi on September 18th. The first group of the matching list was at 9:00, with a total of 390 matching points. The second group of the matching list was at 22:00, with a total of 544 matching points. The first group was used for accuracy assessment, and the second group was used for modeling. Four regression models (a linear model, an exponential model, a logarithmic model, and a power model) were fitted separately. The SSWF inversion maps by four regression models are shown in Figure 5.

The $R^2$ and accuracy assessment results are shown in Table 2. The $R^2$ of these four models were all around 0.6, which proves that the brightness temperature and the wind speed are positively correlated, and can be adopted for further inversion. We tested the significance of four models respectively. All groups demonstrated the $p$ value less than 0.001, which confirmed that the regression models were statistically significant. Among the four models, the linear regression model had the maximum $R^2$ of 0.61 and the lowest RMSE of 2.55, indicating the best fitting effect between the brightness temperature and wind speed. Therefore, the linear model was selected as the best regression model in this paper.

| Models          | Equation                      | $R^2$ | RMSE (m/s) |
|-----------------|-------------------------------|-------|------------|
| Linear Model    | $F(x) = 0.2245x - 24.7755$   | 0.61  | 2.55       |
| Exponential Model| $F(x) = 0.3449^{0.0166x}$   | 0.60  | 2.57       |
| Logarithmic Model | $F(x) = 37.556 \ln x - 188.28$ | 0.58  | 4.46       |
| Power Model     | $F(x) = 3.4036 \times 10^{-7}$ | 0.59  | 3.98       |

Piecewise regression model establishment results: Based on the best regression model selection and region segmentation results, a piecewise regression model was established. A three-stage regression model was fitted, using different inversion equations for each segment, and further integrated to obtain the final inversion model. For the typhoon Usagi, a total of 544 points were matched at 22:00 on September 18th, for piecewise regression modeling. For the typhoon Fitow, a total of 615 points were matched at 22:00 on October 3rd, for piecewise regression modeling. For the typhoon Nari, a total of 580 points were matched at 22:00 on October 12th, for piecewise regression modeling.
Figure 5. The sea surface wind field (SSWF) inversion maps by four regression models; the rectangular box represents the place where the inversion accuracy is low: (a) the linear model; (b) the exponential model; (c) the logarithmic model; (d) the power model.

In addition, for the first segment (OA), most areas had no observation wind speed points, or had large noises and errors. In order to ensure the accuracy of the inversion results, we masked them. Therefore, the ranges of the three segments based on the grayscale value were defined as follows: (1) Usagi: 0–146, 146–205, and 205–255; (2) Fitow: 0–150, 150–205, and 205–255; and (3) Nari: 0–160, 160–190, and 190–250. The piecewise regression model establishment results are shown in Figure 6.
typhoon Nari, a total of 580 points were matched at 22:00 on October 12th, for piecewise regression modeling.

In addition, for the first segment (OA), most areas had no observation wind speed points, or had large noises and errors. In order to ensure the accuracy of the inversion results, we masked them. Therefore, the ranges of the three segments based on the grayscale value were defined as follows: 1) Usagi: 0–146, 146–205, and 205–255; 2) Fitow: 0–150, 150–205, and 205–255; and 3) Nari: 0–160, 160–190, and 190–250. The piecewise regression model establishment results are shown in Figure 6.

\[
F(x) = 0.1577x - 15.804  \\
R^2 = 0.63
\]

\[
F(x) = 0.3057x - 47.958  \\
R^2 = 0.61
\]

\[
F(x) = 0.3843x - 61.9213  \\
R^2 = 0.63
\]

\[
F(x) = 0.1273x - 10.091  \\
R^2 = 0.63
\]

\[
F(x) = 0.3344x - 43.7273  \\
R^2 = 0.63
\]

\[
F(x) = 0.2341x - 24.3659  \\
R^2 = 0.64
\]

Figure 6. Piecewise regression model results: (a) the second segment result of Usagi; (b) the third segment result of Usagi; (c) the second segment result of Fitow; (d) the third segment result of Fitow; (e) the second segment result of Nari; (f) the third segment result of Nari.

4.2. Model Validation Results

First, we took Usagi on September 18th as an example. Because the temporal resolution of FY-2E satellite data was 0.5 h, there are 48 images in a day (00:00–23:30). Therefore, using the specific piecewise regression model, we successfully inverted 48 scenes of corresponding wind speed maps. Here, we selected nine scenes of inversion results (1:00, 3:00, 5:00, 7:00, 11:00, 13:00, 15:00, 17:00, and 20:00) to display. According to Figure 7, we can accurately extract the sea surface wind speed at each moment (the redder the color is, the greater the wind speed is), and we can further determine the range of the strong wind area (green area) and the possible location of the typhoon eye (the center of the red area). In addition, combined with the results of sea surface wind field at nine scenes, we can accurately determine the moving direction of Usagi on September 18th (moving westward). Similar results were inverted for Fitow and Nari.

We then calculated two statistical metrics (RMSE and MBE) to estimate the inversion accuracy for all three typhoons. (1) Usagi: 390 points were successfully matched between the inversion result and the HY-2A wind speed product at 9:00 on September 18th. The wind speed accuracy was calculated, and the RMSE and MBE are 1.99 and 1.82 m/s. (2) Fitow: 430 points were successfully matched between the inversion result and the HY-2A wind speed product at 9:00 on October 3rd. The wind speed accuracy was calculated, and the RMSE and MBE are 2.10 and 1.35 m/s. (3) Nari: 360 points were successfully matched between the inversion result and the HY-2A wind speed product at 9:00 on
October 12th. The wind speed accuracy was calculated, and the RMSE and MBE are 2.20 and 0.94 m/s. Therefore, the results of RMSE and MBE are in the ranges of 1.99–2.20 m/s and 0.94–1.82 m/s, indicating that the accuracy of the proposed piecewise linear model is relatively high. The metrics results are shown in Table 3.

![Image of wind speed fields](a, b, c, d, e, f, g, h, i)

Figure 7. The sea surface wind field of Usagi at different times: (a) 1:00; (b) 3:00; (c) 5:00; (d) 7:00; (e) 11:00; (f) 13:00; (g) 15:00; (h) 17:00; (i) 20:00.

Table 3. The metrics results for typhoons Usagi, Fitow, and Nari.

| Typhoon | Reference Data Time        | Number of Verification Points | RMSE (m/s) | MBE (m/s) |
|---------|-----------------------------|------------------------------|------------|-----------|
| Usagi   | At 9:00, on September 18th  | 390                          | 1.99       | 1.82      |
| Fitow   | At 9:00, on October 3rd     | 430                          | 2.10       | 1.35      |
| Nari    | At 9:00, on October 12th    | 360                          | 2.20       | 0.94      |

5. Discussion

5.1. Comparison between the Piecewise Linear Model and the Whole Linear Model

Based on the same matching datasets, we used the piecewise linear model and the whole linear model to compare the fitting effects of the three typhoons. There were no observation wind speed points and no large errors, so the first segment (OA) did not participate in the modeling. The piecewise
linear models for Usagi, Fitow, and Nari are shown in Figure 6, and the whole linear model results are shown in Table 4. Comparing the results between Table 4 and Figure 6, we find that the $R^2$ of the piecewise linear model is higher than that of the whole linear model for all three typhoons, which shows that the piecewise model is better than the whole model.

| Typhoon | Segment                     | Equation                                      | Grayscale Range | $R^2$ |
|---------|-----------------------------|-----------------------------------------------|-----------------|-------|
| Usagi   | Whole (HA and LA)           | $F(x) = 0.2245x - 24.7755$                   | $146 \leq x \leq 255$ | 0.57  |
| Fitow   | Whole (HA and LA)           | $F(x) = 0.2476x - 28.1428$                   | $150 \leq x \leq 255$ | 0.58  |
| Nari    | Whole (HA and LA)           | $F(x) = 0.2778x - 34.6794$                   | $160 \leq x \leq 250$ | 0.59  |

In addition, taking Usagi as an example, we produced wind speed maps by the piecewise linear model and the whole linear model, respectively. We found (1) that the extent of HA in the piecewise map was smaller than that in the whole map, which is closer to real situations, and (2) that the inversion value range of the piecewise model is 2–28 m/s, and the inversion range of the whole model is 0–22 m/s. The former was closer to the real wind speed range. Therefore, through piecewise fitting of the brightness temperature data, the interference between different data was reduced, and more accurate wind speed results were retrieved.

5.2. Limitations of the Proposed Piecewise Model

According to the results from 144 brightness temperature images of the three typhoons, the limitations of the proposed piecewise model include the following.

1. The quality of the microwave scatterometer products. This model is a wind-based method, and highly depends on the quality of the wind speed products, which impacts the accuracy of inversion results the most. First, rain is one of the main sources of error in scatterometer winds. Extremely high rain rates exist near the core of a typhoon eye, and backscatter is dependent more on rain than on wind. Second, the inability to resolve the maximum winds in the inner cores of most typhoon eyes is due to insufficient retrieval resolution and instrument signal saturation (which limits the maximum retrievable wind speed, even under rain-free conditions) [22]. Therefore, the proposed model is not suitable for wind speeds greater than 30 m/s. Finally, the swath of the HY-2A microwave scatterometer is about 1750 km and can cover more than 90% of global open sea areas within one day. However, 10% of the sea areas are still not covered. In addition, it is ineffective in the land area. Therefore, the proposed model is not suitable for those areas.

2. The parameters of the regression model change case by case. Because a typhoon is a complex weather system with drastic changes, there is no fixed piecewise linear model to retrieve SSWF information. Even for different days of the same typhoon, it is suggested that a new piecewise linear model is established to retrieve the wind speed.

6. Conclusions

In this paper, we proposed a piecewise linear model to retrieve SSWF information using two different satellite sensors (a microwave scatterometer and an infrared scanning radiometer). The model was applied to the Usagi, Fitow, and Nari typhoons, based on 144 brightness temperature images. The results show that (1) for all three typhoons, compared to the original MBE of the satellite scatterometer (2 m/s) [21], the results of RMSE and MBE are in the ranges of 1.99–2.20 m/s and 0.94–1.82 m/s, which indicate that it is suitable and reliable for SSWF inversion; and (2) it solves the problem of the low temporal resolution of HY-2A (12 h), and inherits the high temporal resolution of FY-2E data (0.5 h). Although this new SSWF inversion model can obtain a relatively high precision wind speed (the error is about 2 m/s) and a high temporal resolution (0.5 h), it can also be studied from the following two aspects: (1) the inversion accuracy needs to be further improved so that it can be
compared with land/ship/other observational data; and (2) the temporal resolution needs to be further improved so that it can be used in near real time.

**Author Contributions:** Conceptualization: T.H. and Y.W.; methodology: T.H.; validation: Y.W. and Y.L. (Yao Li); result analysis: T.H.; investigation: Y.L. (Yue Li) and Y.W.; writing—original draft preparation: T.H. and Y.W.; writing—review and editing: Y.L. (Yao Li); visualization: Y.L. (Yue Li); supervision: D.Z.; funding acquisition: T.H. and D.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Key R&D Program of China under contract #2017YB0502800 and #2017YFB0502805, the Zhejiang Provincial Natural Science Foundation of China (Grant No. LY19D010004), and the Science and Technology Program of Hangzhou (Grant No. 20191203B19).

**Acknowledgments:** The HY-2A and FY-2E datasets were provided by the National Satellite Oceanic Application Center and the National Satellite Meteorological Centre, respectively.

**Conflicts of Interest:** The authors declare that there are no conflicts of interest.

**References**

1. Hu, T.; Wu, Y.; Zheng, G.; Zhang, D.; Zhang, Y.; Li, Y. Tropical cyclone center automatic determination model based on HY-2 and QuikSCAT wind vector products. *IEEE Trans. Geosci. Remote Sens.* 2019, 57, 709–721. [CrossRef]

2. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 2005, 436, 686–688. [CrossRef] [PubMed]

3. Said, F.; Long, D.G. Determining selected tropical cyclone characteristics using QuikSCAT’s ultra-high resolution images. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 2011, 4, 857–869. [CrossRef]

4. Atlas, R.; Hoffman, R.N.; Leidner, S.M.; Sienkiewicz, J.; Yu, T.-W.; Bloom, S.C.; Brin, E.; Ardizzone, J.; Terry, J.; Bungato, D.; et al. The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bull. Am. Meteorol. Soc.* 2001, 82, 1965–1990. [CrossRef]

5. Wang, Z.; Zhao, C.; Zou, J.; Xie, X.; Zhang, Y.; Lin, M. An improved wind retrieval algorithm for the HY-2A scatterometer. *J. Oceanol. Limnol.* 2015, 33, 1201–1209. [CrossRef]

6. Zhang, G.; Perrie, W.; Li, X.; Zhang, J.A. A Hurricane morphology and surface wind vector estimation model for C-band cross-polarization SAR. *IEEE Trans. Geosci. Remote Sens.* 2017, 55, 1743–1751. [CrossRef]

7. Allen, J.R.; Long, D.G. An analysis of SeaWinds-based rain retrieval in severe weather events. *IEEE Trans. Geosci. Remote Sens.* 2005, 43, 2870–2878. [CrossRef]

8. Zheng, M.W.; Li, X.M.; Sha, J. Comparison of sea surface wind field measured by HY-2A scatterometer and WindSat in global oceans. *J. Oceanol. Limnol.* 2019, 37, 38–46. [CrossRef]

9. Honda, T.; Miyoshi, T.; Lien, G.Y.; Nishizawa, S.; Yoshida, R.; Adachi, S.A.; Terasaki, K.; Okamoto, K.; Tomita, H.; Bessho, K. Assimilating all-sky Himawari-8 satellite infrared radiances: A case of typhoon Soudelor (2015). *Mon. Weather Rev.* 2018, 146, 213–229. [CrossRef]

10. Jin, S.; Wang, S.; Li, X.; Jiao, L.; Zhang, J.A.; Shen, D. Center location of tropical cyclones without eyes in SAR images based on salient region detection and pattern matching. *IEEE Trans. Geosci. Remote Sens.* 2017, 55, 280–291. [CrossRef]

11. Zhang, G.; Yang, J.; Liu, A.K.; Li, X.; Pichel, W.G.; He, S. Comparison of typhoon centers from SAR and IR images and those from best track datasets. *IEEE Trans. Geosci. Remote Sens.* 2016, 54, 1000–1011. [CrossRef]

12. Gabarró, C.; Font, J.; Camps, A.; Vall-llossera, M.; Julià, A. A new empirical model of sea surface microwave emissivity for salinity remote sensing. *Geophys. Res. Lett.* 2004, 31, 1–5. [CrossRef]

13. Zhang, M.; Qiu, H.; Fang, X.; Lu, N.M. Study on the multivariate statistical estimation of tropical cyclone intensity using FY-3 MWRI brightness temperature data. *J. Trop. Meteorol.* 2017, 23, 146–154. [CrossRef]

14. Hu, T.; Wang, X.; Zhang, D.; Zheng, G.; Zhang, Y.; Wu, Y.; Xie, B. Study on typhoon center monitoring based on HY-2 and FY-2 data. *IEEE Geosci. Remote Sens. Lett.* 2017, 14, 2350–2354. [CrossRef]

15. Xu, H.; Zhai, G.; Li, X. Precipitation efficiency and water budget of typhoon Fitow (2013): A particle trajectory study. *J. Hydrometeorol.* 2017, 18, 2331–2354. [CrossRef]

16. Jiang, X.; Lin, M.; Liu, J.; Zhang, Y.; Xie, X.; Peng, H.; Zhou, W. The HY-2 satellite and its preliminary assessment. *Int. J. Digit. Earth* 2012, 5, 266–281. [CrossRef]
17. Zhang, D.; Zhang, Y.; Hu, T.; Xie, B.; Xu, J. A comparison of HY-2 and QuikSCAT vector wind products for tropical cyclone track and intensity development monitoring. *IEEE Geosci. Remote Sens. Lett.* **2014**, *11*, 1365–1369. [CrossRef]

18. National Satellite Ocean Application Service. Available online: https://osdds.nsoas.org.cn (accessed on 6 May 2020).

19. Lu, X.; Meng, Q.Y.; Gu, X.F.; Zhang, X.D.; Xie, T.; Geng, F. Thermal infrared anomalies associated with multi-year earthquakes in the Tibet region based on China’s FY-2E satellite data. *Adv. Space Res.* **2016**, *58*, 989–1001. [CrossRef]

20. National Satellite Meteorological Centre. Available online: http://satellite.nsmc.org.cn/portalsite/default.aspx (accessed on 6 May 2020).

21. Zhang, Y.; Lin, M.; Song, Q. Evaluation of geolocation errors of the Chinese HY-2A satellite microwave scatterometer. *IEEE Trans. Geosci. Remote Sens.* **2018**, *56*, 6124–6133. [CrossRef]

22. Brennan, M.J.; Hennon, C.C.; Knabb, R.D. The operational use of QuikSCAT ocean surface vector winds at the National Hurricane Center. *Weather Forecast.* **2009**, *24*, 621–645. [CrossRef]