This study presents a new approach for hurricane wind direction retrieval utilizing rainband streaks contained in synthetic aperture radar (SAR) images without hurricane eye information, based on the hurricane inflow angle. To calculate the wind direction field, a method for estimating the location of the hurricane center is given. In this paper, four Sentinel-1A (S-1A) images with a hurricane eye are used to clarify the center estimation method. Three S-1A SAR images without a hurricane eye are studied to evaluate the accuracy of the new method. The estimated locations of hurricane centers show good agreement with hurricane track data provided by the National Oceanic and Atmospheric Administration (NOAA)’s Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD), HurricaneCity, and the National Institute of Informatics (NII). To validate the estimated wind directions, the NOAA HRD dropwindsonde observations for Tropical Storm Karl are collected and compared. The wind directions retrieved by our approach are more consistent with visual inspection than the fast Fourier transform (FFT) method in subimages. Moreover, the retrieved wind speeds utilizing C-band model 5.N (CMOD5.N) are compared with wind speed estimations observed by Stepped Frequency Microwave Radiometer (SFMR). The results suggest that the proposed method has good potential to retrieve hurricane wind direction from SAR images without a hurricane eye and external data.

1. Introduction

Synthetic aperture radar (SAR) provides large coverage, high resolution, and all time and all weather condition measurements over the ocean. As an important tool for retrieving sea surface wind, SAR data have been utilized to observe and study hurricanes (Katsaros et al. 2000; Horstmann et al. 2013; Zhou et al. 2013; Li et al. 2013; Li 2015). In recent years, more and more hurricane images are collected by global SAR tasks, such as advanced synthetic aperture radar (ASAR), RadarSat, and Sentinel-1A/B. SAR images containing a hurricane eye are the most valuable SAR data for hurricane applications, because such images can show abundant detail and the whole structure of the hurricane. For a hurricane SAR image to contain hurricane eye information, it requires the radars to have scanned the hurricane eye, which is often fortuitous. Many hurricane SAR images are without a hurricane eye, and many of them are discarded during the data collection step. Can these eyeless SAR images be utilized for hurricane monitoring and forecasting applications? More specifically, can such SAR images be used for hurricane wind speed and direction retrieval even though they do not contain hurricane eye information?

During the 2016 hurricane season, the Satellite Hurricane Observation Campaign (SHOC) was designed by the European Space Agency (ESA) Sentinel-1 mission planning team to gather hurricane images. Among the 70 Sentinel-1 passes scheduled by the ESA mission planning team, more than 20 hurricane eye hits were gathered (Mouche et al. 2017); in other words, there are about 70% passes that missed the eye. If the wind direction field can be derived from these eyeless SAR images, then the outer hurricane wind field structure and wind speed retrieval can be studied at moderate level.
In general, there are three options for obtaining the SAR-collocated wind direction field. First, the discrete wavelet transform (DWT), the fast Fourier transform (FFT), and the gray-level co-occurrence matrix (GLCM) are capable of deriving wind directions from the periodic streaks (Du et al. 2002; Gerling 1986; Zheng et al. 2018). These streaks, which are parallel to wind directions, are caused by atmospheric boundary layer (ABL) rolls and are more visible in an SAR image at low than at high wind speeds (Alpers and Brügger 1994; Huang et al. 2018). The inflow characteristics of the hurricane wind field can be used as a criterion to remove directional ambiguity. However, the wind streaks are not pervasive at every point of an SAR image because of the intensity variation of atmospheric boundary layer rolls, which adds difficulties to using the DWT or FFT method. Second, wind directions can be derived by the inflow angle, which is defined as the arctangent of the ratio of radial and tangential wind components. The average hurricane inflow angle is approximately 20° (Powell 1982). An observation-based parametric model for the hurricane inflow angle is given by Zhang and Uhlhorn (2012), with a mean inflow angle of 22.6° ± 2.2° (95% confidence), and the bias of the inflow angle is less than 30°. Based on this model, the inflow angle field can be calculated by storm intensity, motion speed, motion direction, and the radius of the maximum wind speed. However, sometimes these variables are unknown during the real-time process of wind velocity inversion without the assistance of external data. As the third option, one can use external wind direction data as an input, for example, scatterometer data (such as Windsat) or model data (such as ECMWF). These data often have a lower resolution than SAR images; interpolation is needed; and, moreover, they often have a negative time matching with the SAR images. Thus, external wind direction data may not be suitable for real-time wind speed inversion.

As mentioned above, the mean inflow angle is a simple and effective wind direction input method. Once the hurricane eye is determined, the corresponding wind directions can be given by a polar coordinate system. There are many studies concerning eye determination (Jin et al. 2014; Lee et al. 2017; Jin et al. 2017). To estimate the centers of tropical cyclones without their eyes in the SAR images, a method is given in Li (2017) based on the visual saliency and the pattern matching. In this paper, a new approach for determining eyes is presented based on rainband streaks in SAR hurricane images. Through comparing several hurricane SAR images with rainfall data, Katsaros et al. (2000) found that some streaks coincide with rainbands and others are between the rainbands. Most streaks have a circular orientation feature centered on the hurricane center. In general, hurricane rainfall has two significant effects on C-band SAR imaging: 1) raindrops induce volumetric scattering and attenuation in the atmosphere and 2) rain damps the short-wavelength gravity waves and alters the roughness of the ocean surface by generating splashes and ring waves (Zhang et al. 2016; Tsimplis and Thorpe 1989; Tournadre and Quilfen 2003; Xu et al. 2015). Most dark streaks present in the SAR images are the finescale rainbands. To establish the wind direction field of the hurricane SAR images without eye information, the circular-arc streaks can be used to estimate the hurricane center location; neither clear wind streaks nor external data are needed.

Based on the collocated wind direction field, the wind field can be derived from both co- and cross-polarization SAR images. From 1970s, a large number of geophysical model functions (GMFs) have been established to bridge the gap between the normalized radar cross section (NRCS) from SAR and the sea surface wind speed at 10-m height. To derive wind speed from a copolarization (VV or HH) SAR image, the radar relative wind direction and the local incidence angle are needed (Stoffelen and Anderson 1997; Hersbach et al. 2007; Hersbach 2010). The radar relative wind direction is the angle between wind direction and azimuth look direction. Unfortunately, the copolarization NRCS becomes saturated at wind speeds higher than 25 m s⁻¹, leading to a low precision using GMFs (Zhou et al. 2013; Shao et al. 2017), while the cross-polarization (VH or HV) signal does not saturate for wind as strong as 55 m s⁻¹, which is related only to wind speed and radar incidence angle (Hwang et al. 2015; Zhang et al. 2017; Mouche et al. 2017).

In this study, a new hurricane wind direction retrieval method from SAR images is proposed that is based on the Sobel edge detector, hurricane center estimation, and inflow angle theory. The information from SAR data, hurricane cases, and external wind observations used in this study is described in section 2. The methodology of our wind direction retrieval method is presented in section 3. Experiments, validations, and results are shown in section 4. Error sources and advantages of our method are analyzed and explained in section 5. Conclusions are summarized in section 6.

2. Dataset

The Sentinel-1A (S-1A) launched by ESA can provide C-band single-polarization (HH or VV) and dual-polarization (VV, VH or HH, HV) SAR data with four sensor modes. The extra wide swath (EW) mode is the highest priority, as its noise-equivalent sigma zero (NESZ) is expected to be lower than the interferometric
wide swath (IW) mode (Mouche and Chapron 2015; Mouche et al. 2017). The EW mode image is up to 410 km wide with a spatial resolution of 20 m × 40 m (range by azimuth) and covers incidence angles from about 18.9° to 47.0°. The EW mode image has five subswaths and contains both VV-polarized and VH-polarized observations, which is suitable for hurricane research and monitoring. Compared with the VV-polarized signal, the VH-polarized signal does not saturate for wind as strong as 55 m s\(^{-1}\) and is insensitive to wind direction (Shao et al. 2017; Zhang et al. 2017). The VV-polarized data can be applied only for outer hurricane or tropical storm (TS) wind field retrieval. After radiometric calibration and noise reduction, rainbow streaks can be seen clearly in S-1A VV-polarized and VH-polarized hurricane SAR images. Although there are discontinuities at the subswath boundaries in VH-polarized S-1A images (Park et al. 2018), rainband detection can still be used based on experiential exclusion of the boundaries.

Accumulating a collection of hurricane SAR observations and matching wind vector measurements is a major challenge. Contrary to most other polar orbit missions, SAR missions do not continuously acquire data and follow a predefined mission planning (Mouche et al. 2017). In this study, seven S-1A dual-polarization EW mode SAR images are collected. Four images with a hurricane eye are chosen to introduce the center estimation method, as shown in Figs. 1a–d. Three S-1A SAR images without a hurricane eye are studied to derive wind directions and to evaluate the accuracy of the new method, as shown in Figs. 1e–g. The details of the hurricanes and collected S-1A data are shown in Table 1.

The hurricane center information is collected as reference. The information of Hurricane Lester’s center is provided by HurricaneCity with a 7-min difference from the S-1A sensing time. The center data of Tropical Storm Karl has a 1-min time difference with the S-1A sensing time, and is given by the National Oceanic and Atmospheric Administration (NOAA)’s Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD). The center data of Typhoon Megi from the National Institute of Informatics (NII) and the center data of Hurricane Gaston from NOAA have a time interval of 6 h.

To validate the estimated wind directions of Tropical Storm Karl, we collect collocated NOAA global positioning system (GPS) dropwindsonde data. GPS dropwindsones are deployed from the aircraft and drift down on a parachute measuring vertical profiles of pressure, temperature, humidity, and wind as they fall. They are released from NOAA hurricane research aircraft along the flight track. At 10-m height, the accuracy of the wind speed measurement is about 0.5–2.0 m s\(^{-1}\) (Hock and Franklin 1999). Only sea surface wind vector measurements are used, whose pressure level of observation is 1070.0 hPa. There are six collocated dropwindsonde data in total, four at 0900 UTC and two at 1000 UTC 24 September 2016.

To validate the retrieved wind speed of Tropical Storm Karl, the NOAA HRD WP-3D Stepped Frequency Microwave Radiometer (SFMR) sea surface wind speed observations are collocated between 0926 and 0949 UTC 24 September 2016. On board the NOAA hurricane research aircraft, the SFMR measures nadir microwave emissions, expressed in terms of a brightness temperature from sea surface at six C-band frequencies (4.55, 5.06, 5.64, 6.34, 6.96, and 7.22 GHz) (Zhang and Perrie 2012), which is a function of the sea surface wind speed and the rain rate. Sea surface wind speeds along the flight track are calculated assuming a linear increase in wind speed with brightness temperatures. The SFMR wind speed measurements are within ~4 m s\(^{-1}\) rms error of the dropwindsonde-estimated surface wind speeds and within ~5 m s\(^{-1}\) of the direct 10-m wind speed measurements (Uhlhorn et al. 2007). There are a total of 136 collocated points between Tropical Storm Karl’s SAR image and the SFMR data, with a time difference between 37 min and 1 h. Figure 1h shows the information of Sentinel-1A SAR track over Tropical Storm Karl (pink frames), Tropical Storm Karl’s track (black line), dropwindsonde locations (green stars), and NOAA43 aircraft flight track (blue line).

3. Methodology

On the edge of dark rainband streaks in a SAR image, the gradient of pixel intensity changes greatly. One can retrieve these dark streaks by calculating the pixel intensity gradient at every pixel point in the SAR image, based on the Sobel detection operator, which is a commonly used edge detection method. In this study, four S-1A hurricane images with a hurricane eye are used to obtain the empirical range value of the rainband pixel gradient. The edge detection results with different NRCS gradient values in VV-polarized images and VH-polarized images are shown in Figs. 2 and 3, respectively. It is noteworthy that the pixels with a lower gradient value could induce incomplete wind streaks in the image as a high-frequency noise (Figs. 2a–h and 3a–I), while the pixels with a higher gradient value may be the edge of an island or a rain cluster (Figs. 2m–t and 3q–t) interfering with the rainband feature detection. In the VV-polarized images, the pixels with empirical gradient values between 5 and 7 (Figs. 2i–l) are retrieved as the edge of dark streaks of a rainband. In the VH-polarized
FIG. 1. (a)–(g) Seven S-1A hurricane SAR images used in this study. Only VV-polarized images are shown. (h) S-1A SAR track over Tropical Storm Karl at 1026 UTC 24 Sep 2016 (pink frames), Tropical Storm Karl track (black line), NOAA HRD GPS dropwindsonde locations (green stars), and NOAA43 flight track (blue line) with onboard SFMR between 0532 and 1218 UTC 24 Sep. The red dot is the hurricane center at the SAR sensing time.
images, the empirical gradient range of rainband streaks are 6–8 (Figs. 3m–p), slightly higher than that in the VV-polarized images. The feature of circular-arc streaks is evident in those images with empirical gradient values. After deriving the rainband streaks, those streaks contaminated by island features should be discarded.

After several clear and continuous rainbands are detected, one can find out that the hurricane center is at the center of the circle composed of circular-arc streaks, but the specific location is uncertain. As it is well known, low wind speeds at the periphery of the hurricane have little influence on the rainband feature. Those streaks are far from the center and are shown as a circular-arc structure, called “noninflow rainband streaks” in this study. However, moderate to high winds have a large influence on the streaks near the center. They are referred to as the “inflow rainband streaks,” shown as inflow streaks parallel to the wind direction. One can calculate the radial lines through the midpoint of each streak or through the center for the noninflow rainband streaks. Based on the hurricane inflow angle, the radial lines are through the center after a 20° clockwise rotation for the inflow rainband streaks. Every two lines can provide an estimated location of the hurricane center. By this method, several radial lines are calculated. The mean value of all intersection points is the estimated final location of the hurricane center. More clear rainband streaks will improve the center estimation accuracy.

The origin of the polar coordinate system is then placed at the estimated hurricane center, and the direction field is calculated based on a 20° inflow angle. In the Northern Hemisphere, the direction of the hurricane wind is counterclockwise. Figure 4 is a flowchart of the proposed method.

<table>
<thead>
<tr>
<th>Hurricane name</th>
<th>Category</th>
<th>Date</th>
<th>Start time (UTC)</th>
<th>Stop time (UTC)</th>
<th>Acquisition mode</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaston</td>
<td>TS</td>
<td>26 Aug 2016</td>
<td>2116</td>
<td>2117</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Gaston</td>
<td>2</td>
<td>29 Aug 2016</td>
<td>2141</td>
<td>2142</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Gaston</td>
<td>2</td>
<td>30 Aug 2016</td>
<td>0946</td>
<td>0947</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Lester</td>
<td>3</td>
<td>30 Aug 2016</td>
<td>1445</td>
<td>1446</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Lester</td>
<td>4</td>
<td>31 Aug 2016</td>
<td>0315</td>
<td>0316</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Karl</td>
<td>TS</td>
<td>24 Sep 2016</td>
<td>1026</td>
<td>1027</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
<tr>
<td>Megi</td>
<td>1</td>
<td>26 Sep 2016</td>
<td>0934</td>
<td>0935</td>
<td>EW</td>
<td>VV + VH</td>
</tr>
</tbody>
</table>

4. Experiments and validations

Experiments and validations procedures are designed to test the accuracy of center estimation and the wind direction retrieval method. Three hurricane SAR images with an eye over Hurricane Lester, Typhoon Megi, and Hurricane Gaston, and three hurricane SAR images without an eye over Hurricane Gaston and Tropical Storm Karl are used. The image over Hurricane Lester at 0315 UTC 31 August 2016 is excluded, since the quantity of rainband streaks is poor. We select five streaks of Hurricane Gaston, five streaks of Hurricane Lester, and seven streaks of Typhoon Megi to estimate their respective hurricane centers. Figure 5 shows the estimation results. In Fig. 5, the white lines are radial lines, the green frames outline the streaks used, the yellow dots are the estimated hurricane centers, and the red dots are hurricane centers given by HurricaneCity, NII, or NOAA HRD's track data. For Hurricane Lester, the estimated center is located at 18.0°N, 134.2°W at 1445 UTC; the center's location given by HurricaneCity is 18.1°N, 134.4°W. For Hurricane Gaston, the estimated center is located at 26.0°N, 49.7°W; the center's locations given by NOAA HRD are 25.8°N, 49.1°W at 1800 UTC and 26.7°N, 50.3°W at 0000 UTC. For Typhoon Megi, the estimated center's location is 21.6°N, 125.6°E; the center's locations provided by NII are 21.6°N, 125.9°E at 0600 UTC and 21.9°N, 125.3°E at 1200 UTC.

The new center estimation method is then applied to cases without a hurricane eye in the SAR image. Two S-IA VV-polarized images of Hurricane Gaston and one image of Tropical Storm Karl are used. Based on Sobel edge detection, five or six rainband streaks with a spatial scale from about 50 to 300 km are derived in these images. For Hurricane Gaston on 29 August, the estimated center is located at 31.1°N, 55.3°W at 2142 UTC; the centers' locations given by NOAA are 31.4°N, 55.4°W at 1800 UTC and 31.4°N, 54.9°W at 0000 UTC. For Tropical Storm Karl, our estimated center is located at 31.9°N, 63.5°W at 1026 UTC; the center provided by NOAA is located at 32.0°N, 63.9°W at 1025 UTC. The estimation of the hurricane center shows a good result in six cases.

The origin of the polar coordinate system is then placed at the estimated hurricane center, and the direction field is calculated based on a 20° inflow angle (Figs. 6a–c). We compare the retrieved wind directions with the wind directions derived from three SAR subimages (red frames in Figs. 6a–c) containing clear wind streaks, utilizing the
Fig. 2. Sobel detection of rainband streaks with different NRCS gradient range in S-1A VV-polarized hurricane SAR images.
FIG. 3. Sobel detection of rainband streaks with different NRCS gradient range in S-1A VH-polarized hurricane SAR images.
FFT method. The results are shown in Figs. 6d–f. The size of the subimage is about 25 km × 25 km in Fig. 6a, and 100 km × 100 km in Figs. 6b and 6c. The average difference between the FFT results and our results is 9.1° (FFT minus our approach) with a standard deviation of 6.6° in a spatial scale of 19 km. Figures 6d–f show that the wind direction retrieved by our approach is more consistent with visual inspection than FFT.

The retrieved wind directions of Tropical Storm Karl are also validated by comparing with sea surface wind vectors observed by NOAA HRD GPS dropwindsondes. The results are shown in Table 2. According to six collocated data, the average difference of the wind direction between dropwindsondes and our approach is 9.2° and the standard deviation is 13.5°. The Pearson correlation coefficient (PCC) between the dropwindsonde data and our result is 0.88 (P value = 0.02), showing a strong correlation. The point with the highest error is very close to the hurricane center.

The wind field of Tropical Storm Karl is retrieved to validate the wind direction indirectly. The CMOD5.N algorithm is used in this study, which is suitable for C-band VV-polarized SAR wind speed retrieval for winds lower than 30 m s⁻¹ (Monaldo et al. 2016). A comparison of wind speed between retrieved winds and NOAA SFMR observation winds is shown in Fig. 7. There are a total of 136 matching points between the SAR and SFMR data with a time difference less than 1 h. Most winds are between 10 and 20 m s⁻¹, which is within the effective retrieval range for CMOD5.N; the RMSE is 2.60 m s⁻¹; and the bias is −1.34 m s⁻¹ using SFMR winds minus the retrieved winds from SAR.
The results show good agreements between SAR and SFMR wind speeds, indicating the validity of the wind directions retrieved at matchup points using the SAR image.

5. Discussion

This new method does not need wind streaks or external data input, and can be used to retrieve the continuous field of wind direction from SAR images without a hurricane eye. For those reasons, it has a wide scope of application and can be conveniently used for real-time monitoring and forecasting of hurricanes. By this method, moderate wind speed can be retrieved fast and easily utilizing VV-polarized SAR images. Meanwhile, it can provide an option of wind direction retrieval for VH-polarized hurricane images. On the other hand, wind retrieval from eyeless SAR images contributes to making full use of available hurricane SAR observations.

In this study, hurricane center estimation is the first step of wind direction retrieval. The estimation error is caused by the limited availability of clear and continuous rainband streaks and the semiempirical process of selecting the streaks. The selection of rainband streaks is not one and only. In the six cases we studied, no fewer than five rainband streaks are detected in order to decrease the error caused by subjectivity. For Hurricane Gaston and Typhoon Megi, the estimated centers are located between the two centers referenced for the times just before and after SAR sensing time. The error of the estimated center location is $0.2^\circ$ in longitude and $0.1^\circ$ in

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>Location</th>
<th>Distance from center (km)</th>
<th>Wind direction from dropwindsonde (°)</th>
<th>Wind direction from our approach (°)</th>
<th>Error (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0900</td>
<td>33.0°N, 64.4°W</td>
<td>120.6</td>
<td>35.0</td>
<td>32.7</td>
<td>2.3</td>
</tr>
<tr>
<td>0900</td>
<td>32.0°N, 65.1°W</td>
<td>113.0</td>
<td>−5.1</td>
<td>−11.9</td>
<td>6.8</td>
</tr>
<tr>
<td>0900</td>
<td>32.3°N, 65.7°W</td>
<td>172.7</td>
<td>−5.0</td>
<td>−5.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0900</td>
<td>31.0°N, 65.7°W</td>
<td>202.6</td>
<td>−34.9</td>
<td>−41.6</td>
<td>6.7</td>
</tr>
<tr>
<td>1000</td>
<td>31.4°N, 65.0°W</td>
<td>123.1</td>
<td>−45</td>
<td>−34.8</td>
<td>−10.2</td>
</tr>
<tr>
<td>1000</td>
<td>32.0°N, 64.0°W</td>
<td>9.4</td>
<td>−25.5</td>
<td>2.7</td>
<td>−28.2</td>
</tr>
</tbody>
</table>
For Tropical Storm Karl, the error is 0.4° in longitude and 0.1° in latitude. Compared with the other five cases, the estimated center of Tropical Storm Karl is not as accurate. However, the wind direction validations show a good result, because the wind direction in the outer hurricane field changes more slowly than in the center area at the same spatial scale, based on the inflow angle model. The error in direction retrieval caused by center estimation is higher in the center area than in the outer area, which can be seen in Table 2. Another source of error is utilizing the mean inflow angle instead of the asymmetrical wind direction. The inflow angle is known to vary in the hurricane wind field (Zhang and Uhlhorn 2012). The accuracy of the retrieved wind direction will influence the wind speed retrieval from VV-polarized SAR images according to GMFs. One needs not and should not apply the proposed method to a hurricane SAR image with an eye, because that will cause an error in the wind direction retrieval, especially near the hurricane center. As mentioned previously, the major problem is the collection of hurricane SAR images and collocated external data, especially over category 4 and 5 hurricanes. More hurricane cases need to be studied to provide a statistically meaningful validation of the proposed method.

6. Conclusions

In this paper, a wind direction retrieval method for hurricane SAR images without an eye is proposed. Based on the Sobel edge detection operator, dark circular-arc streaks of rainbands can be retrieved from hurricane SAR images. According to four hurricane cases, the empirical gradient range of rainband streaks is 5–7 in VV-polarized SAR images and 6–8 in VH-polarized SAR images. These streaks are divided into two types, “inflow rainband streaks” and “noninflow rainband streaks,” according to their shape features. The radial lines of two types of streaks are calculated to provide an estimated location of the hurricane center. The wind direction field is then calculated by a 20° inflow angle and a polar coordinate system.

A comparison between the estimated hurricane centers with the best track data shows consistent results in six cases. To validate the validity of the wind direction retrieval method, the wind directions retrieved by the proposed method are compared with the wind directions retrieved by the FFT method in three subimages; the average difference is 9.1° with a standard deviation of 6.6°. Our approach is more consistent with visual inspection of the subimages we selected. For Tropical Storm Karl, six collocated GPS dropwindsondes data are collected to validate our retrieved wind directions, showing an average difference of 9.2°, a standard deviation of 13.5°, and a PCC of 0.88 (P value = 0.02). Based on the retrieved wind directions, CMOD5.N is utilized to retrieve wind speeds of Tropical Storm Karl. Compared with the SFMR-measured winds, the RMSE is 2.60 m s\(^{-1}\) and the bias is \(-1.34\) m s\(^{-1}\), indicating that the inversion result is fairly accurate and that the proposed wind direction retrieval method is reliable.

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