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Original article

Evaluating and Adjusting ERA5 Wind Speed for Extratropical Cyclones and Polar Lows Using AMSR-2 Observations

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Abstract

Purpose. Wind speed accuracy in diverse storm systems is crucial for weather prediction, climate studies and marine applications. This study aims to evaluate the performance of the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation atmospheric reanalysis (ERA5) for wind speeds in extratropical cyclones (ETCs), polar lows (PLs) and tropical cyclones (TCs), as well as to propose a correction function for potential biases.

Methods and Results. We compared the ERA5 wind speeds with the data from the Advanced Microwave Scanning Radiometer-2 (AMSR-2) satellite for various storm events. Statistical metrics, including bias, root mean squared error (RMSE) and correlation coefficient (R), were calculated to quantify discrepancies between the two datasets. Based on the observed biases, a simple exponential correction function was proposed to adjust the ERA5 wind speeds. The effectiveness of the correction function was evaluated through visual comparisons and quantitative analyses. The analysis revealed that the ERA5 systematically underestimated wind speeds across large areas within ETCs, PLs and TCs compared to the AMSR-2 observations. The proposed correction function successfully improved the agreement between ERA5 and AMSR-2 wind speeds in ETCs and PLs. However, applying the same function to TCs revealed significant structural discrepancies between the ERA5 and the AMSR-2 wind fields within these systems.

Conclusions. This study demonstrates effectiveness of the proposed correction function in enhancing wind speed accuracy for ETCs and PLs, bringing them closer to AMSR-2 observations. However, further research is necessary to develop approaches for addressing wind speed biases in TCs, considering the unique characteristics and limitations of existing reanalysis data. This research contributes to improving our understanding and representation of wind speeds in diverse storm systems, ultimately aiding in more accurate weather forecasting and climate monitoring.

Keywords: extratropical cyclones, polar lows, tropical cyclones, reanalysis, wind speed adjustment, ERA5, AMSR-2, remote sensing

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1. Introduction

Marine applications heavily rely on accurate wind speed data for various purposes, including navigation, offshore operations, and monitoring environmental phenomena. The accurate representation of wind speed is particularly crucial in the context of tropical, extratropical, and polar cyclones, where even slight inaccuracies can lead to serious consequences such as shipwrecks, damage to offshore structures, and coastal flooding. Therefore, ensuring the precision of wind speed data is paramount to advancing our understanding and prediction capabilities in marine meteorology.

The European Centre for Medium-Range Weather Forecasts (ECMWF) provides valuable global reanalysis datasets, such as ERA5 and ERA-Interim, which serve as resources for researchers and operational meteorologists. While these datasets have significantly contributed to the understanding of atmospheric conditions, it is imperative to evaluate and improve their accuracy, especially in terms of wind speed representation.

Several studies, such as [1–11], have scrutinized the accuracy of wind speed data in ERA5 and ERA-Interim, revealing discrepancies that may impact the reliability of these datasets in marine applications. The ERA5's ability to predict low wind speed events compared to *in situ* wind speed measurements around the UK was evaluated; and the results show that ERA5 has biases in mean wind speed of 0.166 m/s and −0.136 m/s for onshore and offshore domains, respectively [1]. In [4], it is shown that while reanalysis data like ERA5 offer improved representation of wind speeds compared to earlier versions, discrepancies can still exist in specific regions, particularly for wind gusts in complex terrain.

The study [2] underscores the significance of reliable tropical cyclone information for storm surge forecasts and discusses the limitations of the ERA5 reanalysis data, particularly in high wind conditions. The authors found that the ERA5 reanalysis data underestimate maximum wind speeds during tropical cyclones in comparison to the IBTrACS (International Best Track Archive for Climate Stewardship) data. Thus, they suggested a wind reconstruction method to enhance the accuracy of the ERA5 representation, which aligns well with the data obtained from the SFMR (stepped frequency microwave radiometer) and SMAP (soil moisture active passive) L-band radiometer measurements.

The paper [3] evaluated the surface winds of ECMWF ERA5 reanalysis in the Atlantic Ocean, and found that the reanalysis provided high-quality winds for non-extreme conditions with some site-dependent errors. They also compared two bias-correction models and concluded that the quantile mapping method offered significant improvement for strong winds, achieving a 10% reduction in root mean square error (RMSE) and a 50% reduction in bias compared to the original reanalysis.

The recent launch of spaceborne L-band radiometers operating at 1.4 GHz, such as soil moisture and ocean salinity [12, 13] radiometer and SMAP radiometer, has brought new capabilities for measuring sea surface wind speeds under rainy conditions [13]. However, for wind speeds below 30 kt/15 m/s, the performance of L-band radiometers in measuring wind speeds has been limited, with larger radiometer noise and lower sensitivity compared to higher frequency radiometers, i.e., Advanced Microwave Scanning Radiometer-2 (AMSR-2) [13]. Satellite radiometers, such as the radiometers of the AMSR series having combinations of C-band and X-band channels, are also able to determine wind speeds under rainy conditions [14–17].

This study aims to contribute to the ongoing efforts to enhance the accuracy of wind speed data by validating and correcting ERA5 wind speed data using a straightforward yet effective correction function based on the AMSR-2 wind speed retrievals. Through this validation and correction approach, we aspire to advance the reliability of wind speed data, fostering improvements in marine meteorology and bolstering our ability to mitigate the risks associated with cyclonic events.

2. Materials and methods

2.1. Methodology

To evaluate the accuracy of ERA5 wind speeds in various storm systems, we employed a multi-step approach. Firstly, we selected case studies encompassing diverse cyclone types: extratropical cyclones (ETCs), polar lows (PLs), and tropical cyclones (TCs). Next, we acquired wind speed data from both sources for each selected case. ERA5 data provided hourly wind speeds at a 10-meter height (U_{10}), while the AMSR-2 data consisted of swath measurements at specific times (several swaths per day dependently on the observation latitude). The AMSR-2 brightness temperature measurements were processed with an algorithm developed earlier [17] to obtain wind speed fields. This algorithm employs all six AMSR-2 C and X-band channel measurements to effectively separate the influence of rain from the wind signal. Subsequently, the corrected measurements at 6.9 GHz and 10.65 GHz are used to retrieve the sea surface wind speed (for more details see [17]).

Following visual comparisons of wind fields from both sources, we constructed the scatter plots to quantitatively assess the relationship between the ERA5 and AMSR-2 wind speeds. To quantify discrepancies, we calculated statistical metrics including bias (1), RMSE (2), and correlation coefficient (3). These metrics provided insights into the overall agreement and specific deviations between the two datasets.

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)\ , \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2}, \tag{2}$$

$$\text{R} = \frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2\sum_{i=1}^{n}(Y_i-\bar{Y})^2}}\ . \tag{3}$$

Finally, based on the observed patterns and the identified discrepancies, we proposed a simple and straightforward exponential function to adjust the ERA5 wind speeds. This function aimed to improve the agreement with the AMSR-2 observations while maintaining the spatial and temporal characteristics of the ERA5 data. The proposed function offered a practical solution for correcting potential biases in ERA5 wind speeds for the analyzed cyclone types.

2.2. Datasets

2.2.1. ERA5. This study utilizes the fifth-generation atmospheric reanalysis data from the Copernicus Climate Change Service (C3S). The data, known as ERA5 reanalysis, has a temporal resolution of 1 hour and a spatial resolution of 0.25° × 0.25°. To enhance the precision, historical wind field observation datasets are assimilated in the ERA5, incorporating data from such instruments as the AMSR-E, AMSR-2, GMI, SSM/I, MVIRI, SEVIRI, GOES, GMS, MTSAT, AHI, AVHRR, MODIS and SeaWinds, and *in situ* sources like weather stations, buoys, ship surveys, and airborne measurements. The gridded ERA5 reanalysis data effectively address the uneven temporal and spatial distribution of satellite and *in situ* data. These reanalysis data play a crucial role in establishing remote sensing satellite retrieval models and providing forcing fields for ocean models [18].

2.2.2. AMSR-2. The AMSR-2 onboard the GCOM-W satellite is a passive microwave radiometer measuring microwave radiation of the atmosphere-ocean system. The AMSR-2 measures the brightness temperatures (BT) of microwave radiation in 14 channels at the frequencies from 6.9 to 89 GHz at both polarizations over a 1450 km swath. Though the ability of satellite passive microwave radiometers to measure sea surface wind speeds has been proven many times over, the addition of new set of C-band channels in the AMSR-2 allowed efficiently separating the rain contribution in BT and retrieve high accuracy wind speeds even under rainy conditions [17].

2.3. Case studies

2.3.1. ETCs. Extratropical cyclones, large-scale weather systems in middle latitudes play a major role in shaping weather and climate across the North Atlantic (NA) and North Pacific (NP) oceans. These powerful storms, frequently crossing these vast regions, are associated with winter low pressures and can generate dangerously high sea states with significant wave height up to 20 m [19–23].

Based on the ERA5 hourly wind (U_{10}) and mean sea level pressure (MSLP) fields and the database of Ocean Prediction Center (OPC) Hurricane Force Low Climatology (https://ocean.weather.gov/), seven ETCs over NA and NP were selected (see Table 1). The maximum wind speed and the minimum pressure, representing the cyclone's peak intensity, were extracted from both AMSR-2 and OPC data. Visual comparisons of the wind fields from the AMSR-2 and ERA5 are presented in Fig. 1 (left and middle columns, respectively).

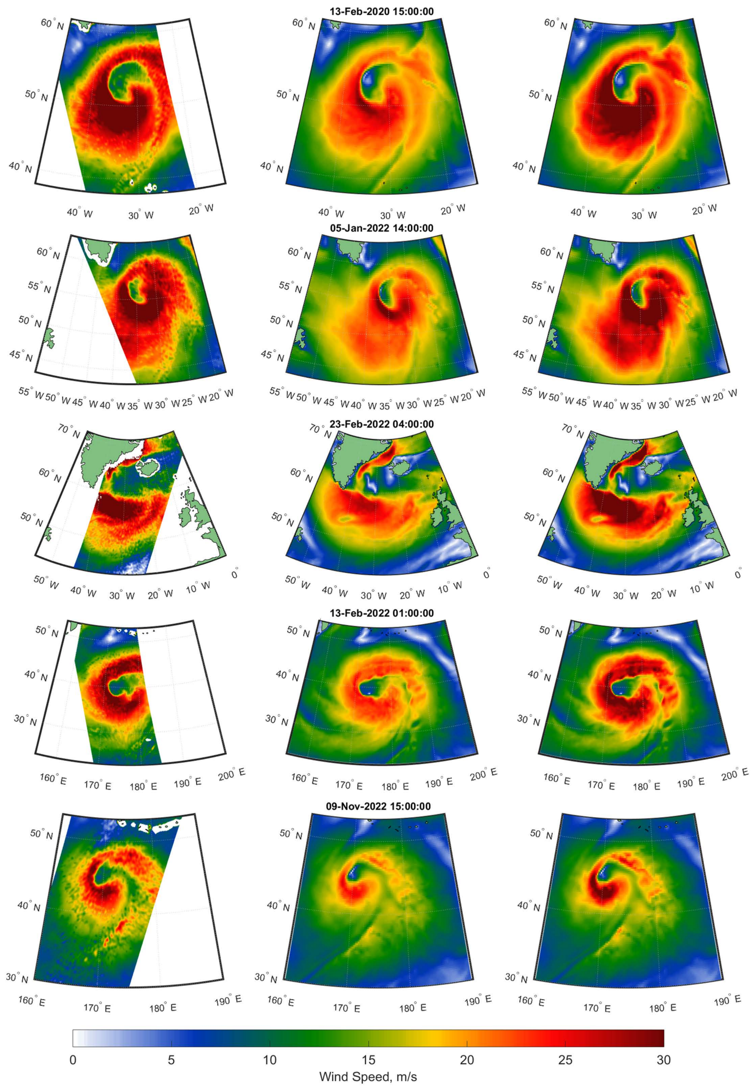
Table 1

Selected ETC cases

Start date	End date	Region	Min MSLP, hPa	Max U_{10}, m/s
11 February 2020	13 February 2020	NA	970	32
12 February 2020	15 February 2020	NA	929	48
03 January 2022	07 January 2022	NA	930	41
22 February 2022	24 February 2022	NA	957	45
12 February 2022	13 February 2022	NP	944	35
15 September 2022	17 September 2022	NP	940	35
09 November 2022	10 November 2022	NP	966	33

* Data are taken from the OPC database.

** Data are taken from the AMSR-2 database.



F i g. 1. Surface wind speed fields in considered ETCs. Left column: wind speeds estimated by the AMSR-2; middle column: the ERA5 wind speed estimations; right column: wind speeds adjusted using Eq. (4)

2.3.2. PLs. PLs present powerful cyclones of small scale, forming over warm open ocean near colder land or ice. These storms significantly impact high-latitude ocean waves, generating wave heights of 8–12 meters [24]. Unlike long-lasting tropical cyclones, PLs are short-time living (6–36 hours) and fast-moving (4–10 m/s), often changing direction unpredictably [25, 26].

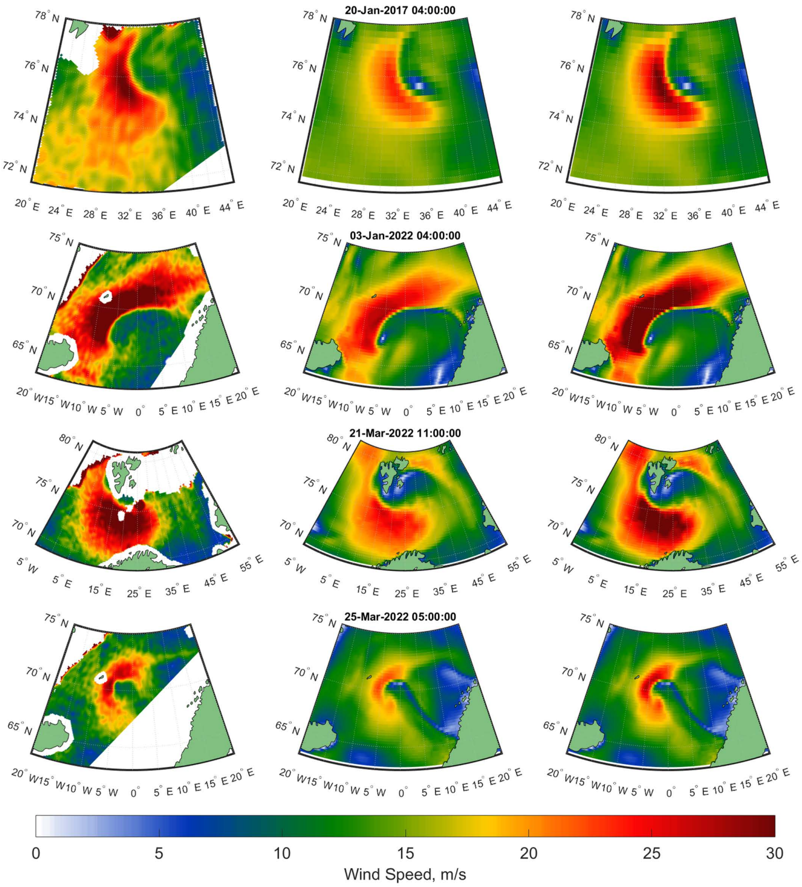
To validate wind speeds in the ERA5 reanalysis, this study focuses on the four powerful PLs with wind speeds exceeding 30 m/s with their center located far from land and ice (Table 2). Figure 2 shows the wind fields from the AMSR-2 (left column) and ERA5 (middle column) in the selected PLs.

Table 2

Selected PL cases

Start date	End date	Region	Min MSLP*, hPa	Max U_{10}**, m/s
18 January 2017	21 January 2017	WA	960	31
03 January 2022	03 January 2022	WA	950	45
21 March 2022	23 March 2022	WA	970	37
24 March 2022	25 March 2022	WA	995	32

* Data are taken from the ERA5 database.
** Data are taken from the AMSR-2 database.



F i g. 2. Surface wind speed fields in considered PLs. Left column: wind speeds estimated by the AMSR-2; middle column: the ERA5 wind speed estimations; right column: wind speeds adjusted using Eq. (4)

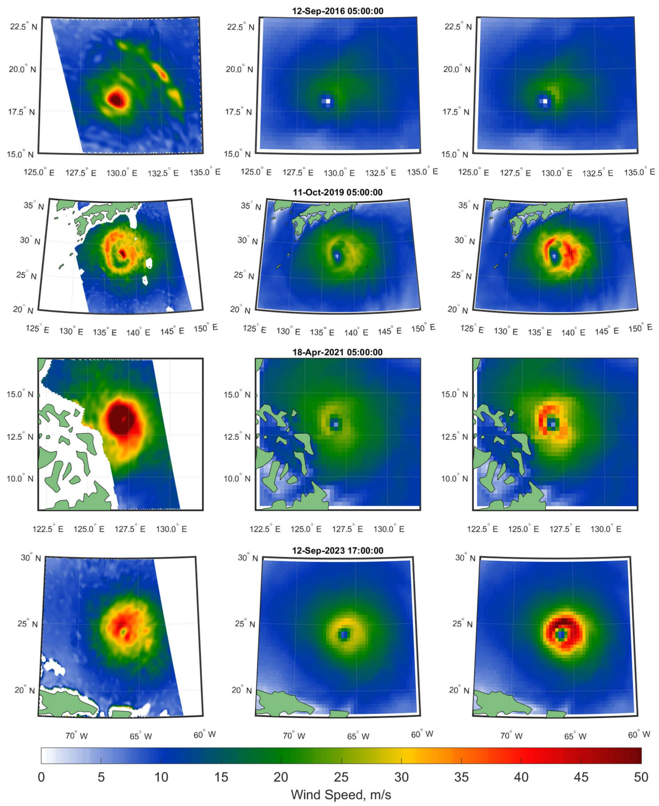
2.3.3. TCs. While wind speeds in ETC and PL systems do not exceed 50 m/s, we also explored higher wind speeds by analyzing TCs (typhoons and hurricanes) listed in Table 3, taken from the IBTrACS database. Figure 3 shows the wind speed fields from the AMSR-2 (left) and the ERA5 (center) in the selected TCs. Figure 3 reveals not only ERA5 lower wind speeds as compared to the AMSR-2 wind speeds but also significant in the overall radial wind pattern. These discrepancies make meaningless the direct pixel-by-pixel comparisons of wind speeds. Due to the observed discrepancies between the ERA5 and AMSR-2 wind fields in TCs, this study presents a modification function for the ERA5 wind speeds based on the data from ETCs and PLs, not including TCs.

T a b l e 3

Selected TC cases

Tropical cyclone	Start date	End date	Min MSLP*, hPa (date)	Max U_{10}*, m/s (date)
Super Typhoon MERANT	08 September 2016	14 September 2016	890 (Sep 13 06Z)	87.45 (Sep 13 12Z)
Super Typhoon HAGIBIS	04 October 2019	12 October 2019	890 (Oct 7 12Z)	82 (Oct 7 10Z)
Super Typhoon SURIGAE	11 April 2021	30 April 2021	882 (Apr 17 12Z)	87.45 (Apr 17 12Z)
Major Hurricane LEE	01 September 2023	17 September 2023	926 (Sep 8 06Z)	74.5 (Sep 8 06Z)

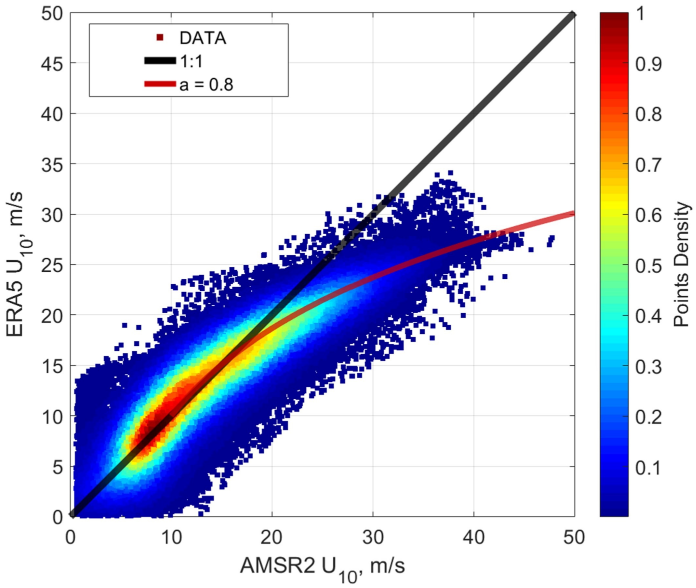
* Data are taken from the IBTrACS database.



F i g. 3. Surface wind speed fields in considered TCs. Left column: wind speeds estimated by the AMSR-2; middle column: the ERA5 wind speed estimations; right column: wind speeds adjusted using Eq. (4)

3. Results

Visual analysis of Figs. 1–3 reveals that the ERA5 underestimates wind speeds across large areas of the storms as compared to the AMSR-2 wind speeds (left vs. middle columns). These discrepancies are further emphasized in Fig. 4, which shows a scatter plot of wind speeds. While the ERA5 estimations never exceed 35 m/s, the AMSR-2 wind speeds reach significantly higher values (up to 50 m/s). The clear deviation from the 1:1 line in the scatter plot, especially for wind speeds above 10 m/s, confirms the underestimation of wind intensity by the ERA5 as compared to the AMSR-2 wind speeds. Table 4 (first row) summarizes the statistical metrics calculated using Eqs. (1–3) for the full range of wind speeds depicted in Fig. 4.



F i g. 4. Scatter plot of wind speeds between AMSR-2 and ERA5 for PLs and ETCs. The color scale shows points density

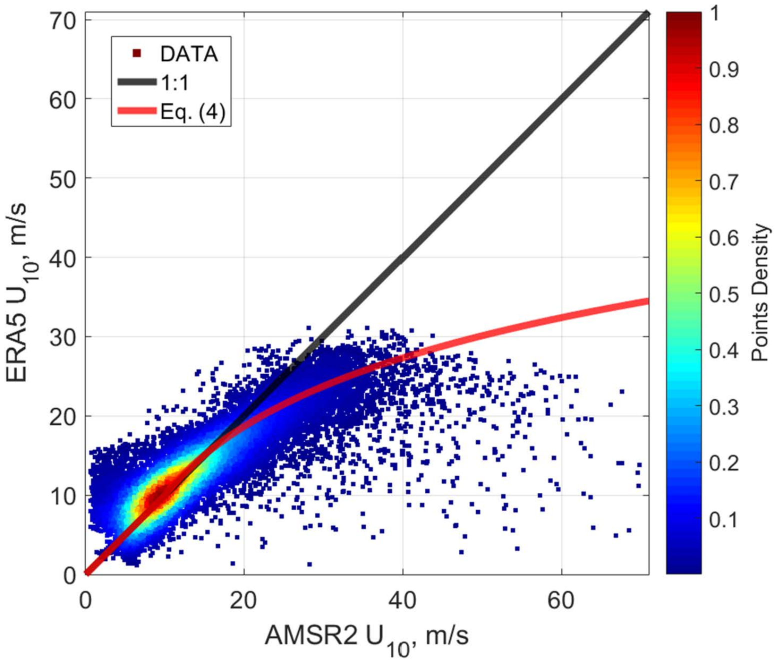
Building on the methodology, presented in section 2.1, we propose a simple and efficient exponential function to adjust the ERA5 wind speeds to the AMSR-2 wind speeds:

$$U_{10_c} = \begin{cases} U_{10} & , \; U_{10} \leq 10, \\ U_{10_p} \exp\left[a\left(\frac{U_{10}}{U_{10_p}} - 1\right)\right] & , \; U_{10} > 10, \end{cases} \quad (4)$$

where a is a constant and $U_{10_p} = 10$ m/s.

Determining the ideal coefficient a for this function can be challenging. Therefore, we use the statistical metrics calculated in Eqs. (1–3) (as presented in Table 4). This analysis reveals that a value of $a = 0.8$ yields the best results. Due to the bias RMSE and R in Table 4, the adjustment function, where $a = 0.8$, significantly reduces the underestimation of wind speeds by ERA5, bringing them to closer agreement with the observations.

Visual comparisons of the corrected wind fields (illustrated in the right column of Figs. 1–3) with the AMSR-2 data reveal good agreement in both ETCs and PLs. However, discrepancies in radial distribution of wind speeds and the shape of TCs between the ERA5 and the AMSR-2 (see Fig. 3) raise concerns about applying Eq. (4) directly to these atmospheric systems. As shown in the scatterplot of Fig. 5, the adjustment function (4) can be applied only to the wind speeds of ERA5 up to 40 m/s, yet the wind speed within the TCs reaches to about 70 m/s. Therefore, we conclude that the proposed correction function is beneficial for improving wind speeds of ERA5 in ETCs and PLs, but its application to TCs requires further investigation.



F i g. 5. Scatter plot of wind speeds between AMSR-2 and ERA5 for TCs. The color scale shows points density

T a b l e 4

Statistical metrics for full range of wind speeds in PLs and ETCs shown in Fig. 4

a	Bias	RMSE	R
Original Data	−0.79	2.88	0.92
0.70	−0.89	2.66	0.93
0.75	−0.47	2.46	0.94
0.80	−0.03	2.45	0.94
0.85	+0.43	2.66	0.94

Conclusion

This study is aimed to evaluate the accuracy of the ERA5 wind speeds in diverse storm systems and propose a correction function to address potential biases. Our analysis focused on ETCs, PLs, and TCs.

The findings demonstrate that the ERA5 systematically underestimates wind speeds across large areas within ETCs and PLs as compared to the AMSR-2 retrieved surface wind speeds. We developed a simple exponential correction function based on statistical metrics to improve the agreement between the ERA5 and the AMSR-2 wind speeds. Visual comparisons and quantitative analyses confirmed the effectiveness of this correction function in both ETCs and PLs, successfully reconstructing the observed wind field patterns and maximum wind speeds.

However, applying the same correction function to TCs requires caution. Fundamental discrepancies exist between the ERA5 and the AMSR-2 winds in representing the overall wind field structure within TCs. This suggests that applying the function to TCs directly might not fully capture the complexity of their wind fields.

Therefore, we conclude that the proposed correction function offers a valuable tool for enhancing wind speed accuracy in ETCs and PLs bringing them closer to the AMSR-2 sea surface wind speeds. Further investigations are necessary to develop tailored approaches for addressing wind speed biases in TCs considering the unique characteristics and limitations of existing reanalysis data.

This research contributes to improving our understanding and representation of wind speeds in diverse storm systems, ultimately aiding in more accurate weather forecasting, climate monitoring and marine applications.

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